Geothermal exploration at Newberry Volcano, central Oregon

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Key Words: Newberry Volcano, Geophysical Exploration, DOE IET Grant 109

ABSTRACT

Data generated by Davenport Newberry, including surveys conducted in conjunction with the DOE Innovative Exploration Technologies (IET) Grant 109 program, and detailed geologic mapping performed by the U.S. Geological Survey, are being used to better understand the geology, volcanic history and geothermal potential of Newberry Volcano. Currently Davenport is mid-way through the exploration program, which will include additional temperature gradient wells. The information reported here is an interim view of a work in progress. The western flank of the volcano is underlain by plutons associated with Newberry Volcano, some of which are young enough to still be quite hot. Two deep exploration wells have been drilled by Davenport Newberry, 55-29 and 46-16. 55-29 intersected extensive fracturing that was isolated and had no evidence of hydrothermal activity, and is currently the center of EGS development. 46-16 intersected open fractures hosting hydrothermal fluid and has a sustained discharge of non-condensable gasses associated with hydrothermal fluid. A bridge at approximately 5000 ft. in 46-16 has precluded flow-testing of the well. Micro-earthquakes under the western flank show that there is on-going brittle rock breakage taking place. The first of two micro-seismic surveys are indicating areas with a consistent linear and vertical geometry of continuous noise that may be related to vertical fluid movement. The combination of traditional and innovative exploration tools, and the integration of insight from each field of expertise into team-balanced modeling has lead to the advances in understanding of Newberry Volcano and of how to explore more effectively for both traditional hydrothermal and EGS geothermal resources. The final integrated model of Newberry Volcano and development of geothermal resources will be completed after the additional temperature gradient data become available.

INTRODUCTION

Newberry Volcano has been the focus for geothermal exploration for more than thirty-five years. The main attraction for explorationists has been the size of the volcano, the long history of volcanic eruptions on the volcano, and the character of the eruptions. Perceived conflicting cultural use of the volcano by various interests was resolved in 1990 with the passage of the Newberry National Volcanic Monument legislation, which set aside the central part of the volcano, including the caldera, and related young volcanic vent areas to the north, as a national monument, to be administered by the U.S. Forest Service. The legislation specifically designated the area outside the monument as open for timber harvest and geothermal exploration.

One of the major vexing aspects of assessing the geothermal potential of the flanks of the volcano has been the deep water table. The distance between the topographic surface and the permanently saturated groundwater level precludes any surface manifestations of geothermal activity that might otherwise reach

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the topographic surface. The flanks of Newberry Volcano are truly a "blind" geothermal exploration target. The first generation of temperature gradient holes drilled on the flanks of the volcano, by CalEnergy, GRI and Occidental Petroleum (Santa Fe) identified deep temperature gradients of up to 8^{o}F per 100 ft. on the west flank and of 6.4^{o}F per 100 ft. on the south flank of the volcano. Two deep exploration wells drilled in a small area on the upper northwest flanks of the volcano by CalEnergy in the mid 1990s had bottom-hole temperatures of 550 and 600^{o}F, though showed no potential for economic geothermal production. The targets for these two wells were perceived ring fractures associated with collapsing caldera structures.

Davenport Newberry began exploration efforts on Newberry Volcano in 2006. The first round of exploration began with reprocessing all available geophysical data for the area. This was followed by close-spaced MT and gravity surveys, centered on the west flank, north of Paulina Creek. These efforts lead to the drilling of two deep exploration wells. The first, 55-29, encountered multiple isolated fractures, temperatures on the 600oF range, and no indication of hydrothermal activity. This well is now being used by a joint venture between Davenport Newberry and Alta Rock for EGS testing. The second well, 46-16, encountered high temperatures, open fractures containing hydrothermal minerals, and a sustained fluid flow. Initial attempts to flow test this well resulted in bridging of the well bore at about 5000 ft. Therefore no equilibrated geophysical logs were able to be run, and until the bridge is cleared, no flow testing of the resource is possible. The bridge is permeable enough that a sustained flow of non-condensable gasses is produced by the well, with shut-in well head pressure of 575 to 600 psi.

Davenport Newberry, in conjunction with the U.S. Department of Energy through their Grant 109 program, is mid-way through a second round of exploration, this time looking at the entire western flank and the southern flank of the volcano. This program combines specific traditional exploration tools with an innovative adaption of a passive microseismic technique recently developed for the oil and gas industry. Each of the team members are brought together to share insights and considerations to produce a combined model rather than each producing a separate model in isolation. While these efforts have been underway LIDAR became available for the entire volcano, and first results from a local seismic monitoring array as part of the EGS program produced results on the west flank. These sources of information are being folded into the team discussions and will be contributing to the geologic and geothermal exploration model for Newberry Volcano.

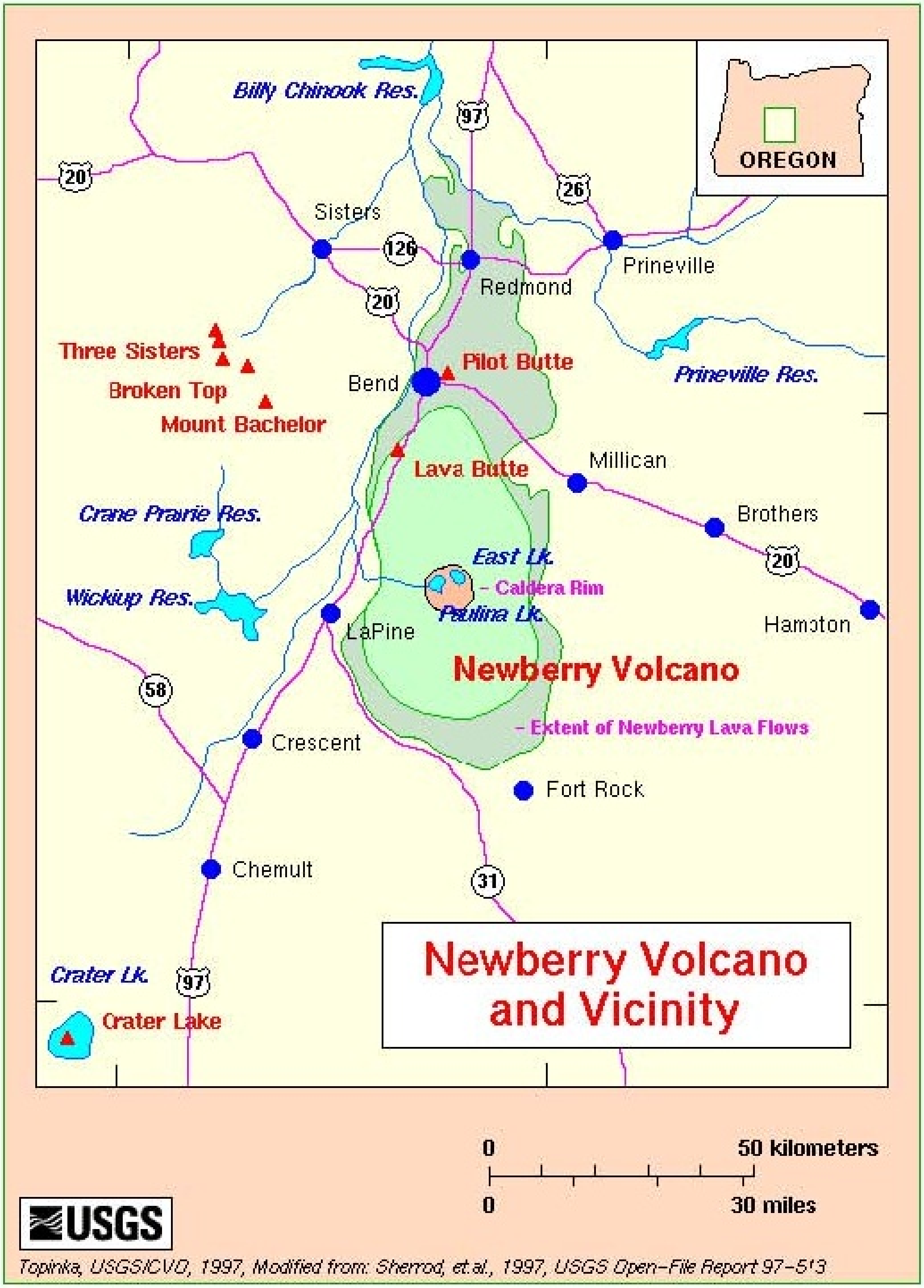

Figure 1: Location of Newberry Volcano, Oregon, from USGS.

GEOLOGIC SETTING

Newberry Volcano in Deschutes County, Oregon, is a large bi-modal Quaternary volcano with a central caldera approximately 4 miles by 5 miles across (Figure 1). The volcano is situated near the junction of three geologic provinces and is bounded along the north by the Brothers Fault Zone. Newberry Volcano has been active for approximately the last 600,000 years. The expansive moderately sloping north and south flanks of the volcano are composed predominantly of basalt and basaltic andesite lava flows, pyroclastic deposits and cinder cones. The east and west slopes are made up of silicic tuffs and lahars, in addition to basaltic material. The central highlands are constructed largely of silicic lavas and pyroclastic deposits.

Silicic lavas (i.e. MacKay Butte Domes, West Flank Dome, Southwest Flank Dome) on the western flank of the volcano date from 400,000 to 600,000 years old. The most recent major caldera-related eruptions resulting in significant ash and pyroclastic deposits occurred approximately 300,000 and 80,000 years ago. A large-volume basaltic eruption occurred about 72,000 years ago, resulting in the extensive Bend Lavas which covered an area some 20 miles to the north of the central caldera. 6,000 years ago numerous basaltic eruptions occurred along the northwest fracture zone. The most recent eruption, a silicic obsidian flow and associated pumice fall vented from within the caldera, has been dated at 1350 years before present.

Two geologic structural patterns dominate the area of Newberry volcano. First is the volcanic and caldera-related structure of Newberry Volcano itself. Second is the roughly northwest and northeast trending fault pattern of the Basin-and-Range. The west-northwest trending Brothers Fault Zone structure does not appear to extend southward through the volcano. Arcuate vent crater and ring-fracture patterns are the most dominant structural features of the volcano. The caldera rim is a composite of a number of overlapping smaller rim features. Ring fractures are best developed on the upper north flank of the volcano, and are identified more by arcuate vent patterns than by identifiable fracture or fault traces. Lahar deposits from the volcano and a thick mantle of ash from the eruption of Mt. Mazama (Crater Lake) about 7,000 years ago tend to hide or obscure many small or subtle structural features on the flanks of the volcano.

Extensional fault patterns of the Basin-and-Range province dominate the surface morphology south and east of Newberry Volcano. This pattern extends through the volcano and becomes obscure as it intersects the Cascade Range. The trend of this extensional faulting is generally northwest and northeast in the vicinity of Newberry Volcano. Vents for the series of basaltic andesite eruptions that occurred about 7,000 years ago are aligned to the Basin-and-Range fault pattern. The vents reach from Lava Butte, along Highway 97 well off the northwest flank of Newberry Volcano, to vents and fissures across the upper north flank and into the caldera, to vents on the southern flank of the volcano. The vent patterns of these eruptions suggest that the Basin-and-Range structure may cut through and both precedes and supersedes the caldera structure.

EXPLORATION RESULTS 2006-2012

Deep Exploration Wells

Davenport Newberry drilled two deep exploration wells in 2008, 55-29 and 46-16. The location of these two wells, the two deep exploration wells drilled by CalEnergy Company (86-21 and 23-22) are noted on Figure 2.

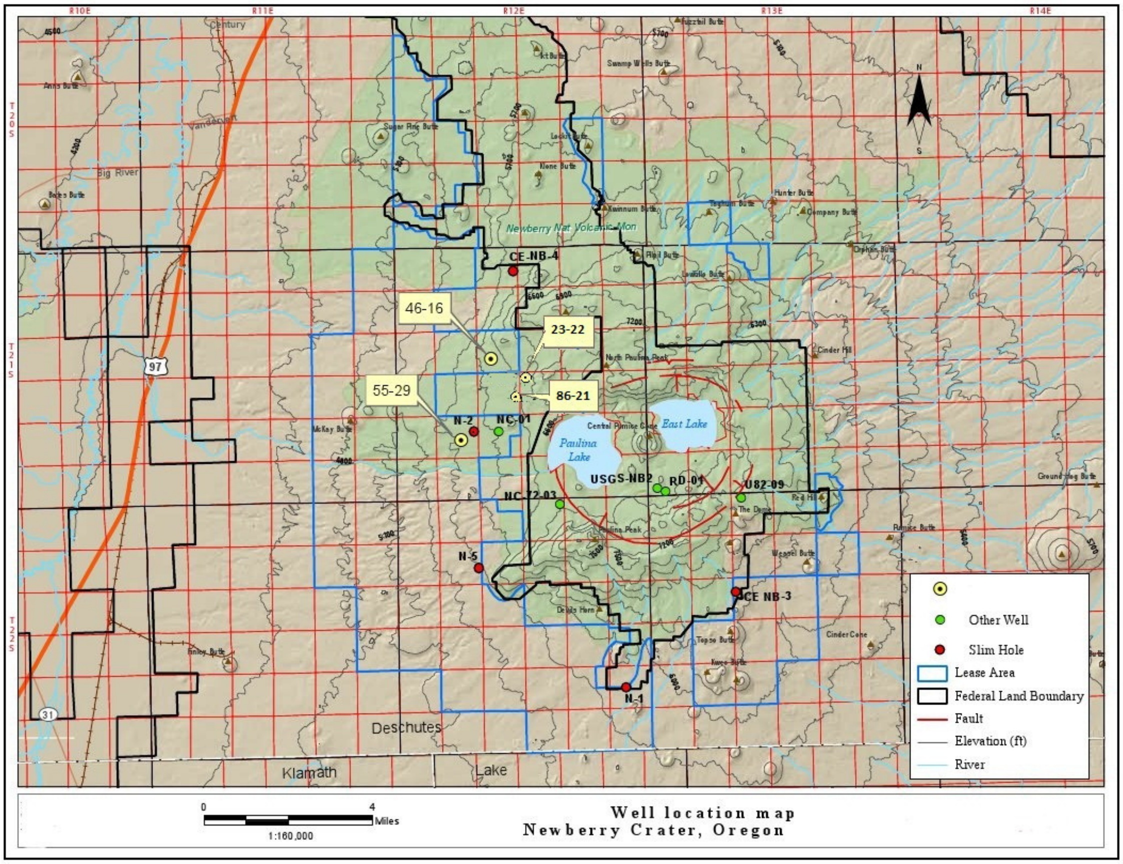

Figure 2: Map showing the locations of the four deep exploration wells on the northwest flank of Newberry Volcano.

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. Indications of multiple fractures were intersected while the hole was being drilled. Some fractures were associated with CO_2 discharge, though no hydrothermal precipitations minerals were observed in the cuttings. This indicates that fractures with some open volume were encountered in these wells, though they were isolated and without extended connectivity with larger fracture systems. Flow testing after the well was drilled confirmed the isolated nature of the fractures.

Well 46-16, which was drilled approximately 1 mile WNW of CalEnergy Exploration's well 23-22, encountered greenschist facies metamorphosed volcanic rock at a depth of 7,200 ft. The well was drilled in a southerly direction to explore an east-west gravity boundary with the thought that this boundary may represent a tectonic structure. The well was drilled depth of 11,600 ft., and had an estimated bottom-hole temperature of between 600^{o}F and 700^{o}F. Druze epidote and epidote-quartz crystal clusters, formed in open fractures from geothermal fluid, were observed in the cuttings at 7,330 ft., 7,360-70 ft., 9,280 ft., 9,350 ft., and 9,400 ft. No precipitated pyrite or other sulphur-bearing minerals were observed associated with these fractures. Significant increases in gasses were observed during drilling, , particularly pronounced in the 9,000-9,500 ft. range (Figure 3). Temperature data indicate fluid movements associated with fractures were encountered in the vicinity of 11,100-11,500 feet. The rock had been thermally metamorphosed to the greenschist facies, and is mechanically brittle, capable of hosting fractures when stressed. No major fluid loss was encountered, though many small fracture zones were observed.

Well 46-16 was located to explore a linear gravity boundary. This well was located further westward of the current caldera boundary than any of the previous deep exploration wells. This deep exploration well encountered significant evidence of a hydrothermal system, but flow testing of this well was never accomplished due to bridging near the 5,000 ft depth. Due to the bridging, this well will have to be worked over before being flow tested, likely requiring running a string of casing thru the unstable formation zone.

Approximately one year after the well was shut in, it was discovered that the well was producing a steady flow of non-condensable gasses, and that the water level in the well had dropped to approximately 2,070 ft. below the ground level. This elevation for static water is markedly different from that in the water wells, and from the regional groundwater elevation, showing that the fluid system encountered in well 46-16 is separate and distinct from any other fluid system so far encountered on the volcano.

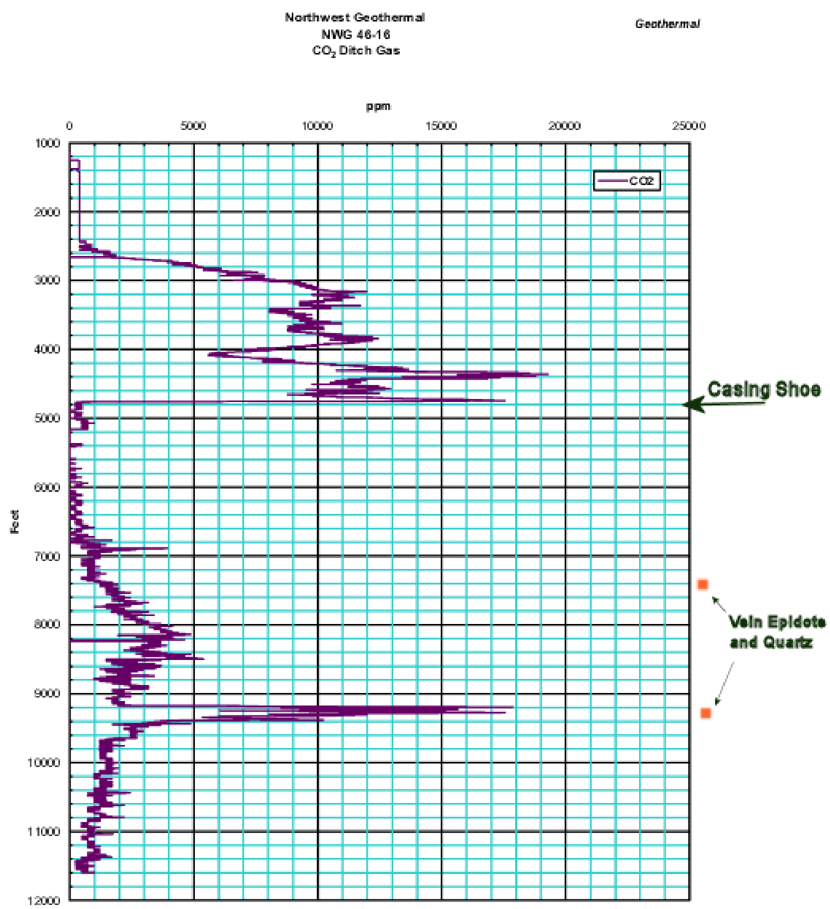

Figure 3: A graph showing CO_2 values measured by Epoch Mudlogging during drilling of well 46-16. To the right are noted the depth of the casing shoe and the location of hydrothermally precipitated druse quartz and epidote observed in the drill cuttings.

Figure 4 shows the temperature gradient profiles of three of the deep exploration wells, 46-16, 55-29 and 86-21. The equilibrium temperature profile for well 55-29 (green in Figure 4) shows a good straight conductive gradient without formation fluid flow. This matches well-site data observed while the hole was being drilled. The profiles for well 46-16 (red and blue lines in Figure 4) show significant purtibtions indicative of formation fluid flow affecting the temperature profile of the well.

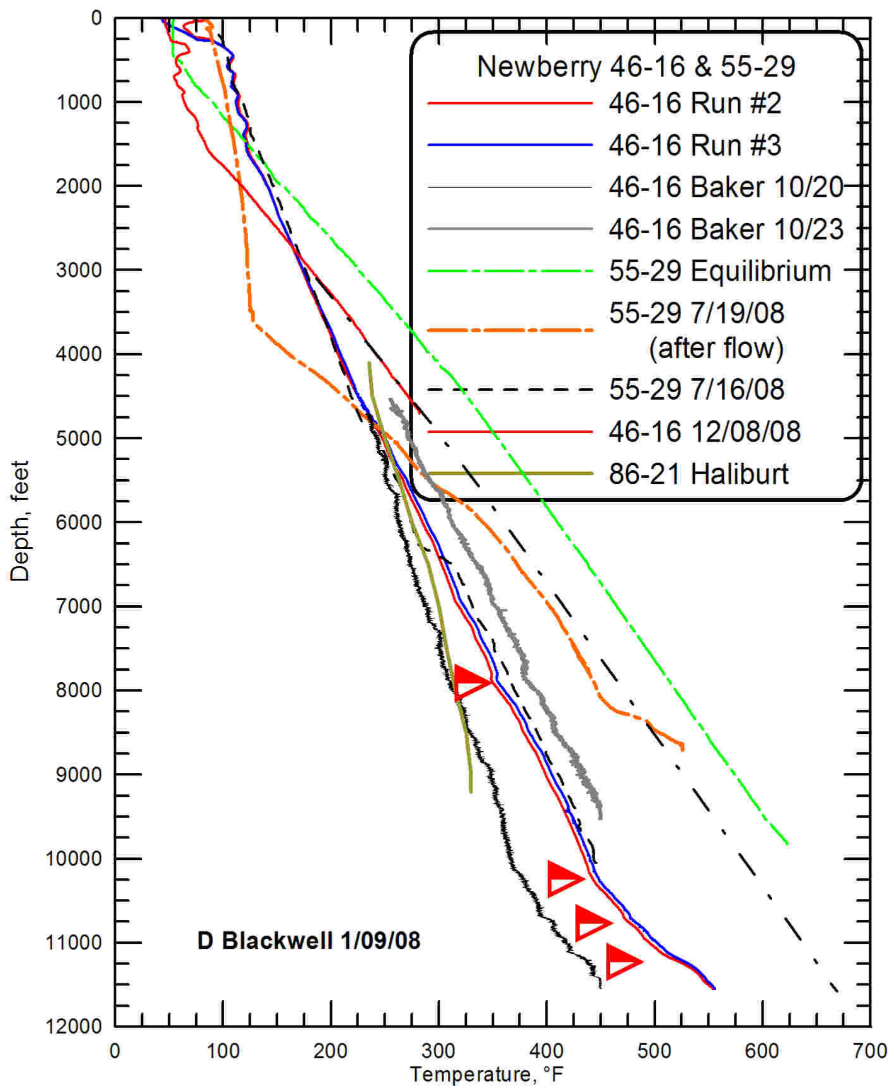

Figure 4: Temperature plots of deep exploration wells 46-16, 55-29 and 86-21. The red arrows are locations where Dr. D.D. Blackwell observed evidence in the temperature profiles of formation fluid flow.

Petrographic and chemical analyses of rock chip samples from exploration wells 55-29 and 46-16 are currently underway at Southern Methodist University in Dallas, Texas. The purpose of these analyses is to attempt to identify and possibly correlate lithologic units encountered in the drill holes, and, for samples from the deeper portions of the wells, to look for possible matches with Oligocene, Miocene and Pliocene formations cropping out in areas off the edge of the volcano. Until these analyses are completed, gamma logs (Figures 5 and 6 below) of the four deep exploration wells can be used to compare lithologies. 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. As observed in the logs in Figure 5, there is no recognizable correlation between the lighologies between the four holes, even though they are remarkably close together (Figure 2). Perhaps earlier 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 lithologic correlation.

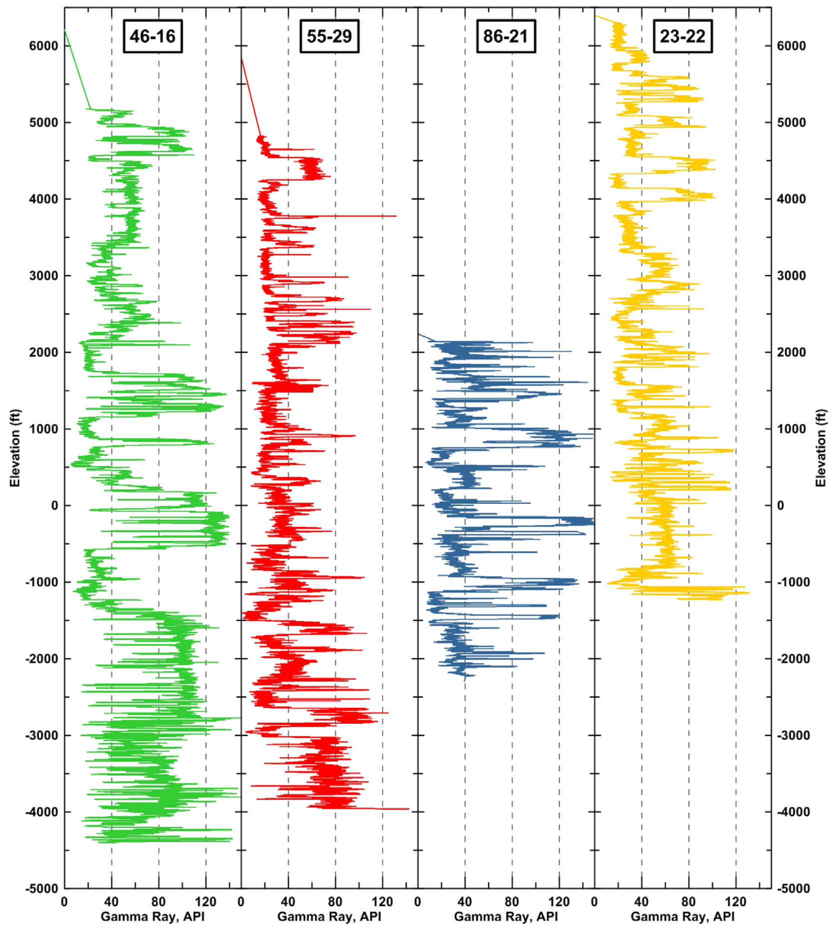

Figure 5: Gamma logs of each of the four deep exploration wells drilled on the northwest flank of Newberry Volcano.

The gamma logs shown in Figure 5 are from each of the four deep exploration wells drilled on the northwest flank of Newberry Volcano. Unfortunately the two CalEnergy company wells, 86-21 and 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 pose a more difficult problem. No normal or strike-slip faults have been identified on the surface or in any of the geophysical surveys.

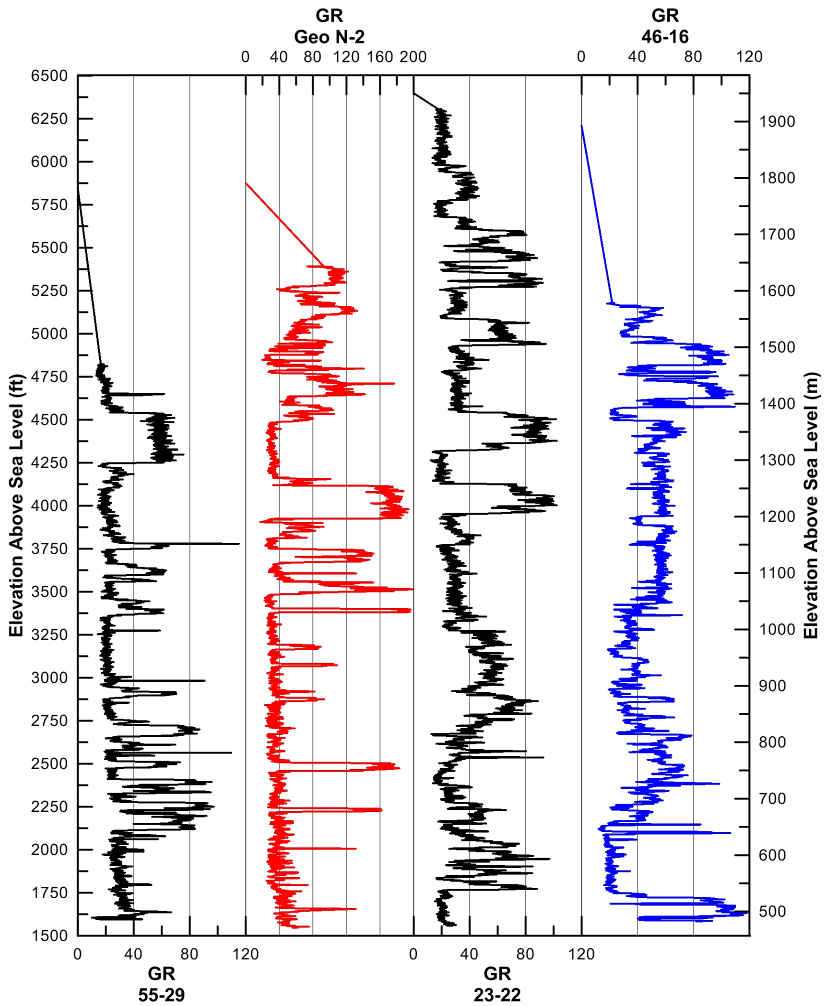

Figure 6: Gamma logs of the upper 4,000 ft. of wells 55029, N-2, 23-22 and 46-16 on the northwest flank of Newberry Volcano. These sections of the wells show details of the gamma logs penetrating into the shallow electrically conductive layer.

The gamma logs shown in Figure 6 show details of the upper approximately 4,000 ft. of four wells. These logs show lithologic details down into the shallow MT electrical conductive horizon (see MT section below). These logs show a lack of lithologic patterns associated with the lower temperature clay and zeolite facies alteration associated with the electrical conductor horizon.

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 Engineering Co. Figure 7, below, is a map showing 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. Paulina Creek is shown as a blue line.

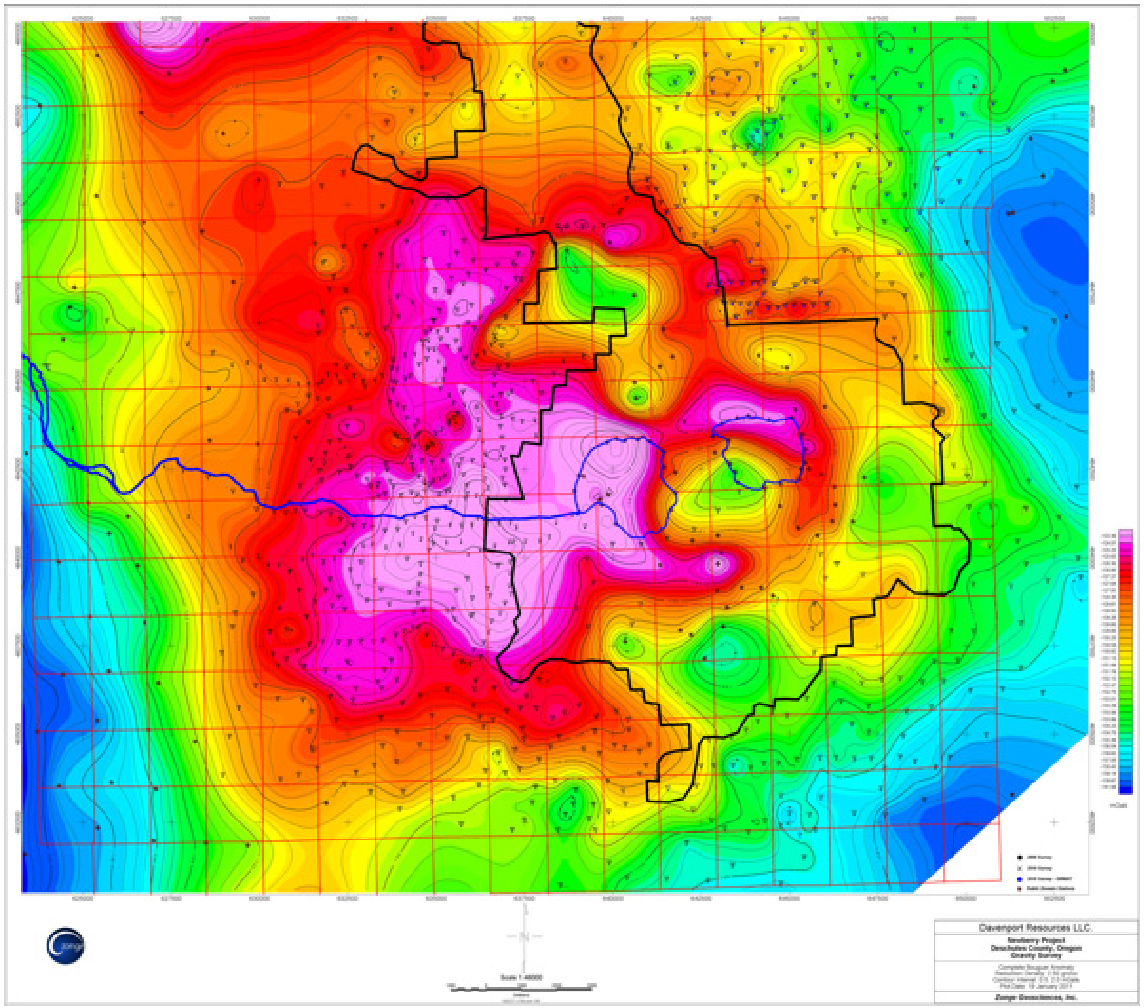

Figure 7: Complete Bouguer Anomaly with a density reduction value of 2.5 g/cc.

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 N-NW and E-SE. The gravity high-density rock (magenta in Figure 7) underlying the western flank and portions of the caldera are interpreted as plutons. This interpretation is supported by granodiorite encountered in both CalEnergy wells (86-21 and 23-22), and by felsic dikes encountered in well 55-29. High temperature gradients observed on the upper west flank and high temperatures measured in all four deep exploration wells indicate that at least some of the plutons underlying the west flank are young enough to still be hot. The gravity data in and of itself, however, is not capable of distinguishing individual plutons or the relative ages of the plutons. Temperature gradient measurements and the MT data both indicate that deeper temperatures drop off toward the west, indicating that the plutons to the west are cooler and older. The distribution of the plutonic rock indicates that the volcano has been migrating eastward over time.

Three interesting gravity low areas (green in Figure 7) stand out in the data, lining up in a N-NW trend. One is near the center of the caldera, a smaller one is under a portion of the north rim, and the third one underlies, though does not geometrically correlate with, arcuate vent trends outside of the caldera rim. The gravity low inside the caldera might reflect diminishing plutons under that part of the volcano, or might be associated with a catastrophic caldera-forming eruption 79,000 to 80,000 years ago. The reason for the other two is open to conjecture at this time.

MT

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 2007. The second, carried out by Zonge Engineering in 2011, provided in-fill on the western flank and expanded to the north and south slides of the volcano. Figure 8, below, shows the combined station locations from both surveys and the location of select 2-D slices through parts of the volcano. 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. The first passes at MT modeling showed the traditional shallow electrical conductor layer blanketing the west flank, underlain by a deeper electrically resistive mass. The 3-D modeling, by design, showed only a smoothed or generalized image of the volcano, and lacked insight into any subtle details of the volcano at depth. Subsequent to an integrated team meeting, and with tighter constraints on the modeling, more useful information emerged. Particular attention was paid to the details of the shallow electrical conductive layer. Traditionally in active volcanic terrane, the base of this layer is used as a simple interpretation of a boundary between lower temperature clay and zeolite alteration and higher temperature greenschist facies alteration. This interpretation infers a temperature rather than measures a temperature, and is unable to account for the time variable.

The four 2-D slices shown below in Figures 9, 10, 11 and 12 were selected because they pass through critical areas on the west flank where a significant portion of the high-density gravity anomaly occurs (Figures 7and 8), and gamma logs from deep wells (i.e. Figures 5 and 6). The confidence level for the modeled imagery on the lines is related to the MT station density (1, 2 and 3 digit numbers along the top of the lines denote MT station numbers), with higher station density inferring higher confidence and lower station density inferring lower confidence. The most striking insight to emerge from the latter MT data processing is the detail and complexity of the shallow conductor layer, both in varying intensity and geometry.

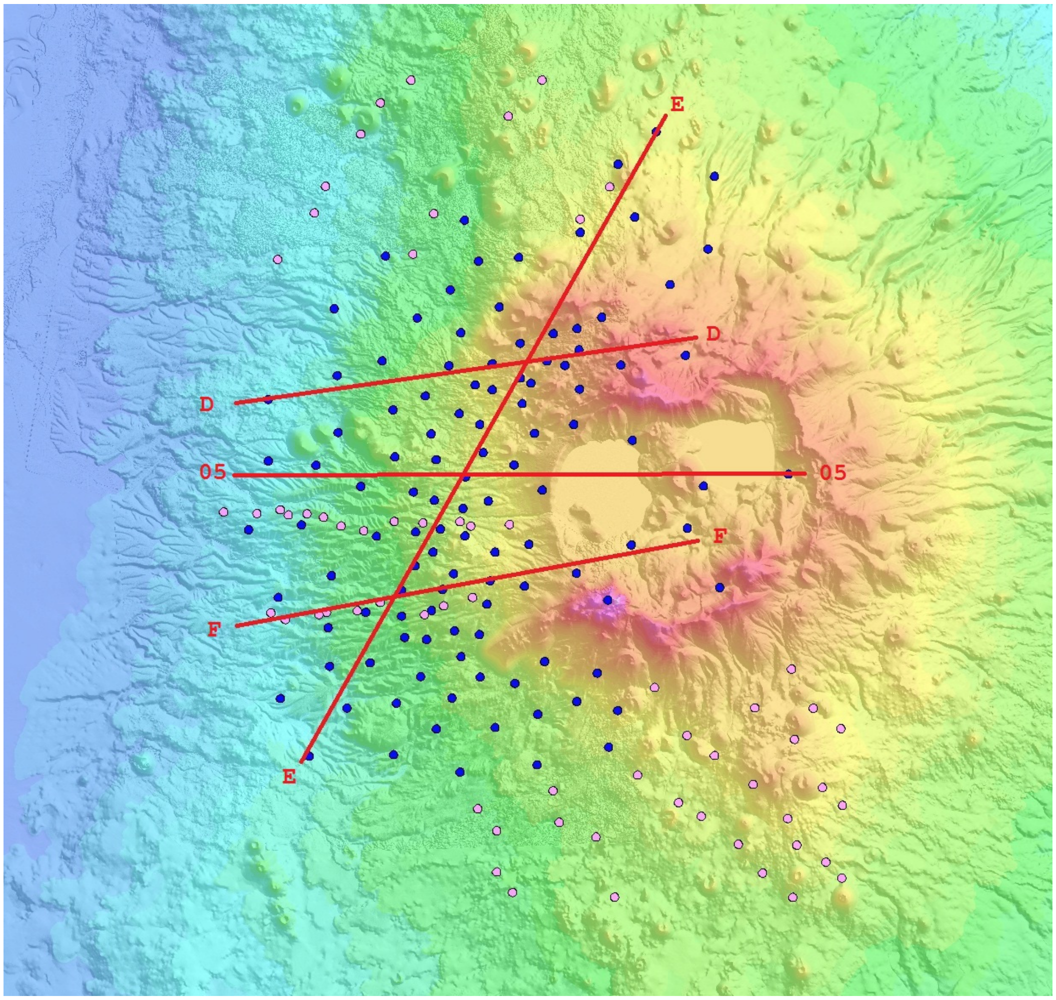

Figure 8: Map of Newberry Volcano showing MT station locations. The red lines show the location of four MT slices of Figures 9, 10, 11, and 12. The blue dots identify MT station locations from the 2007 survey. The red dots identify MT station locations from the 2011 survey

MT Line D, Figure 9 below, 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.

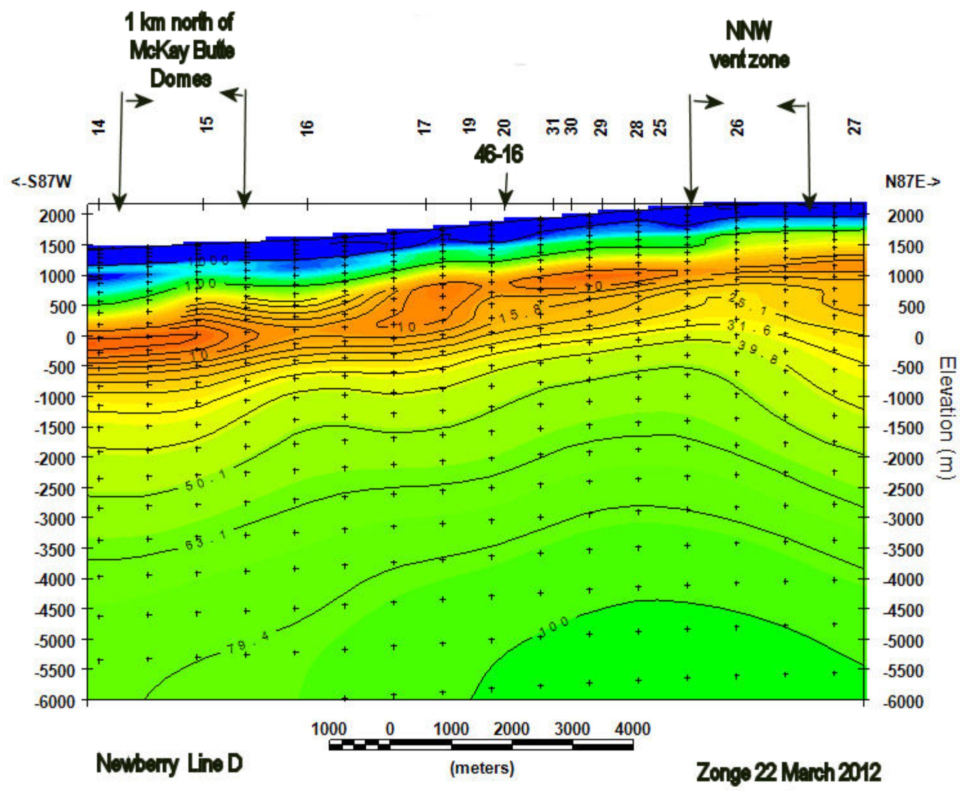

Figure 9: 2-D MT slice Line D. The two digit numbers across the top identify MT stations.

MT Line E, Figure 10 below, strikes N-NE, 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 7) and associated eruptive history of the west flank that is not present under the northern flank. As with Line D above, the N-NW volcanic vent zone is not identified in Line E by any variation in electrical resistivity.

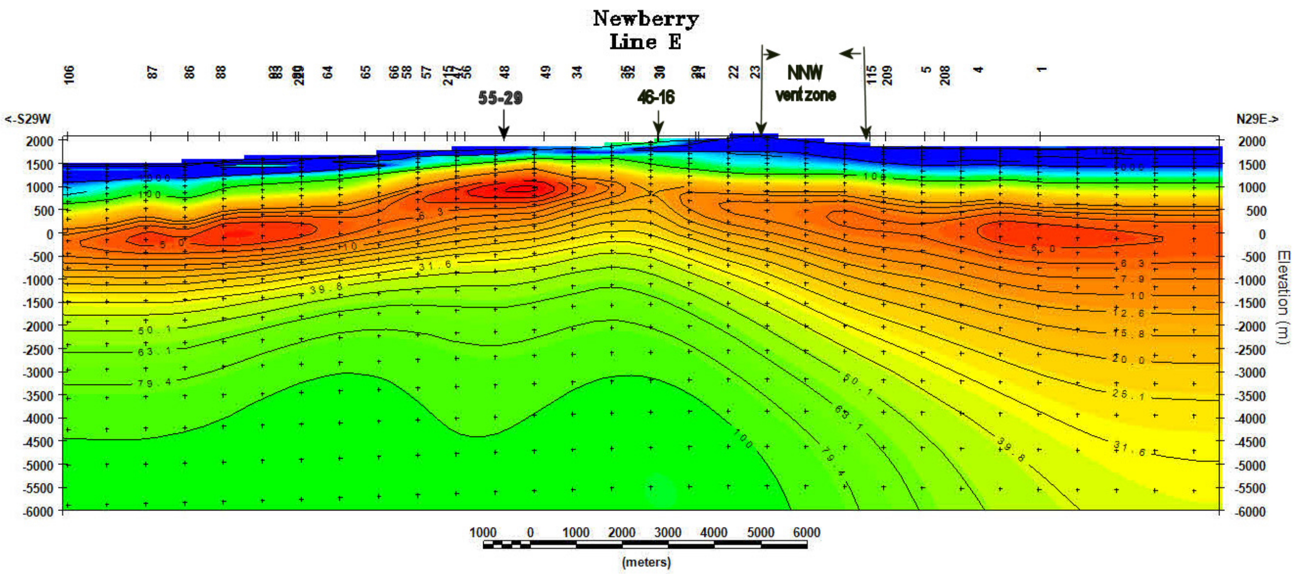

Figure 10: 2-D MT slice Line E. The one, two and three digit numbers across the top identify MT stations.

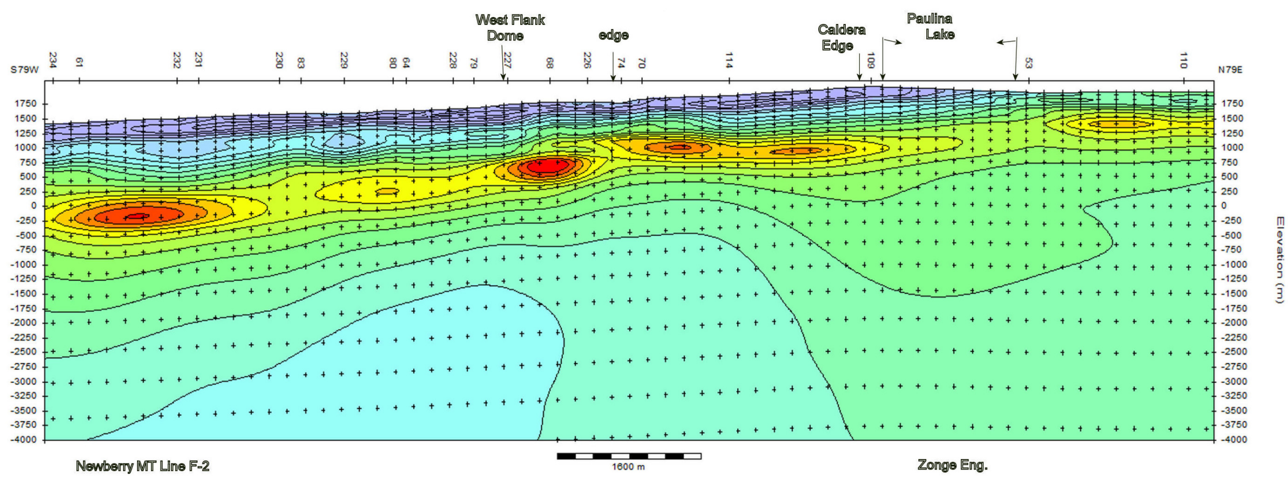

Figure 11: 2-D MT slice Line F. The two and three digit numbers across the top identify MT stations.

MT Line F, Figure 11, strikes E-NE covering the west flank south of Paulina Creek and continuing into the caldera. The varied character of the shallow electrical conductor layer is striking in this line. This figure shows discrete lenses of very high electrical conductivity, inferred to represent intensity of clay and zeolite alteration. This image shows a clear break in the line at the point identified as "edge". This arrow marks the location where, on the surface, the area to the east is shown on surface to be largely unbroken by linear breaks and indications of tectonic strain. This "edge" follows an arcuate pattern, and on slice E occurs to the SW of well 55-29.

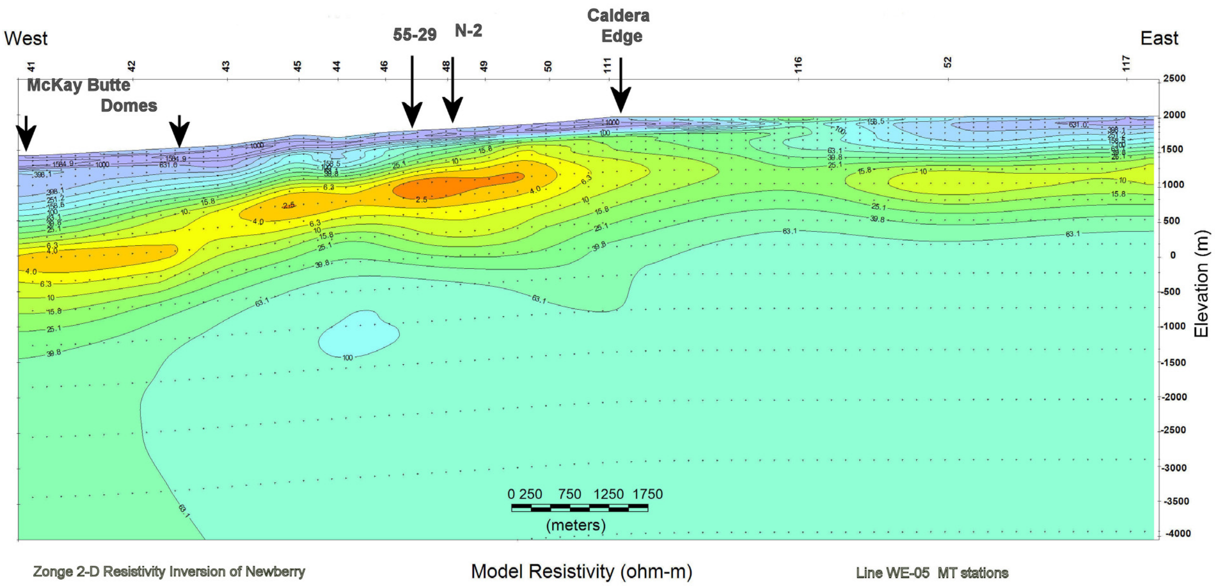

Figure 12: 2-D slice Line 05. The two and three digit numbers across the top identify MT stations.

MT Line 05, Figure 12, strikes E-W covering the west flank north of Paulina Creek and continuing into the caldera. The density of MT stations on the upper west flank is high enough to produce a good view of the shallow electrical conductive zone from the edge of the caldera westward past wells N-2 and 55-29. On this line, well 55-29 is observed to be located toward the western edge of a very high electrical conductivity lens, inferred here to represent advanced clay and zeolite alteration of the rock. Well N-2 is located more centrally within this alteration zone. The MT station density is sparse within the caldera, and likely tells little of the actual electrical resistivity at depth within the caldera.

Micro-earthquake Data

Lawrence Berkeley National Laboratory, as part of the Alta Rock EGS demonstration project on Newberry Volcano, set up a seismic network to monitor for earthquake activity. The array picked up a small earthquake (M 0.8) and lesser aftershocks on the flank of the volcano. Figure 13 shows the location of the earthquake and one aftershock as purple dots. Also shown are the locations of the two Davenport Newberry deep exploration wells. The identification of these earthquakes shows a number of things. First, there is enough tectonic strain currently in the vicinity of the volcano to cause rock breakage. Second, the rock at depth, including the greenschist facies volcanic rock identified in the deep wells, is brittle enough to break when placed under strain. This type of natural breakage is required to create permeability that can host hydrothermal systems. This agrees with evidence of open fractures and hydrothermal flow in well 46-16.

Figure 13: Earthquake locations from Ernie Major (Lawrence Berkeley National Laboratory) data. Purple dots are the earthquake locations. Yellow stars identify 55-29 (south) and 46-16 (north) well locations.

Micro-seismic monitoring

As part of the Davenport Newberry DOE Grant 109 program for innovative exploration techniques, Apex Highpoint conducted passive seismic data acquisition and analysis using 4 cased wells on the southwest quadrant of Newberry Volcano. The purpose of this program is to install a vertical array of geophones in each of four wells to monitor microseisms generated by fluid flow. This experimental program is designed as a test effort to adapt technology from the oil and gas industry to geothermal exploration.

Initial questions regarding transferring this tool to a volcanic environment were: (1) would the array be able to pick up deeper signals at reasonable distances from each monitoring hole to be useful, and (2) would surface microseismic noise drowned out any deeper signals. Holes were drilled down to the 700 ft. depth range, cased, and cemented. The cemented casing would improve the geophone contact with the formation and the depth would markedly reduce surface noise. The survey data show that a massive amount of deeper microseismic signals were collected, rather than too little. These seismic data are currently being analyzed, looking for recurring three dimensional geometric patterns that would indicate upward-moving fluid flow. Because of the massive amount of data collected, the results of the analyses will not be available for a few more months.

LIDAR

LIDAR imagery of Newberry Volcano became available to the Davenport Team 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 7) and the LIDAR image. The large gravity low north of Paulina Lake is located in the upper right corner of the LIDAR image (Figure 14a), where relatively young volcanic vents form a topographic high. Figure 14a shows LIDAR coverage of Newberry Volcano with an illumination direction of N80E. Figure 14b shows the same image as Figure 14a, though with some of the tentatively identified patterns marked. The magenta line 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 strongly electric conductor lens in both Figures 11 and 12. Currently, without ground truthing and with additional MT data processing, it is difficult to draw any solid conclusions from these observations.

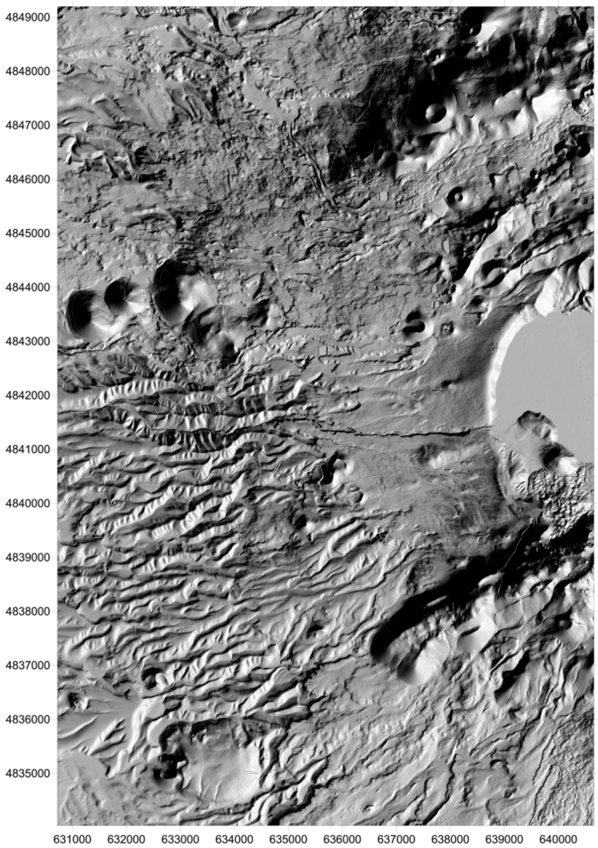

Figure 14a

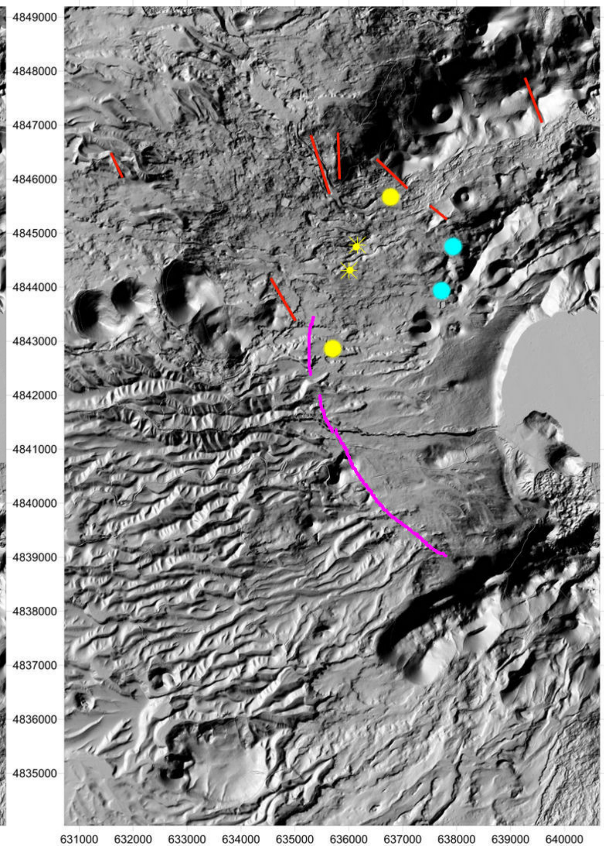

Figure14b

Figure 14a LIDAR image of the west flank of Newberry Volcano.

Figure 14b: 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 the recorded earthquake (also identified on Figure 7). 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.

Discussion

The information contained in this report is an interim view of a work in progress. The data generated to date provide a new and different understanding of the volcanic history of Newberry Volcano. The integrated results of the geophysical studies suggest that both the application and interpretation of MT surveys for geothermal exploration in volcanic terrain needs to be reevaluated.

Well 46-16 intersected high temperature, open fractures hosting hydrothermal minerals and a shut-in well-head pressure of approximately 600 psi. Until the bridged section of the well is resolved, no flow test or complete sampling of both liquid and gas phases of the hydrothermal fluid from the fractures is possible. This well was directionally drilled to the south to cross a gravity boundary. The well data provide *prima facie* evidence that an active hydrothermal system was intersected. The MT profiles of Figures 9 and 10 show well 46-16 to be located in a weaker shallow electrical conductivity zone between higher electrically conductive lenses. The gamma log in Figure 6 shows well 46-16 intersected very little basalt above 2,000 ft. above sea level. The lithologic notes show that well 46-16 intersected abundant welded silicic tuff and lesser amounts of cemented tuff units between 4,500 and 2,000 ft. elevation. Well 23-22, located approximately 5,000 ft. SE of well 46-16 (Figure 2) is not represented on any of the MT slices. The lithology for this well, however, shows mafic lava flows and volcanic debris deposits from 4,000 to 1,500 ft. elevation above sea level. This agrees with the gamma log for this section of well 23-22 in Figure 6.

The MT data do not show a large electrical conductor signature in the vicinity of well 46-16, suggesting that a large clay alteration zone does not overly the hydrothermal system. Typical hydrothermal systems associated with advanced kaolinite clay alteration in the shallow fluid discharge area have elevated sulphur. The extensive clay alteration is driven by sulfuric acid. Low sulphur hydrothermal systems typically have modest smectite alteration, a feature that would not be as easily detected as broad kaolinite alteration by MT measurements.

The lithology of the wells (Davenport Newbery well files) through the shallow electrical conductor zone does not show horizontal stratigraphic correlation. The gamma logs of Figure 6 reflect this variability. Wells 55-29 and N-2 are about 3,000 ft. apart. Both the gamma log and the lithologic descriptions show the well N-2 to have penetrated extensive basalt flows from an elevation of about 3,500 ft. above sea level to TD at just above 1,500 ft. above sea level. For the same depth section, well 55-29 encountered less than half the amount of basalt flows, and substantial cemented tephra and clastic lithic deposits. The MT profile of Figure 12 shows well 55-29 to be located near the western edge of a very high electrical conductivity lens and well N-2 to be located further into this electrical conductivity lens. The limited well data suggest that basalt flows may have accumulated in a low topographic area east of well 55-29. Additional lithologic data from proposed temperature gradient wells on the west flank of the volcano should provide better understanding of the complex geology in this area.

Conclusions

The authors interpret the high-density gravity anomaly underlying the west flank of Newberry Volcano as the cumulative effect of shallow Newberry Volcano plutons, increasing with age and decreasing in temperature from east to west. The data indicate that the center of volcanic activity for Newberry Volcano and related intrusive igneous rock had been to the west of the current caldera and has migrated eastward. If this scenario is correct, buried volcanic features similar to those observed in the present caldera could be expected under portions of the west flank, now buried by subsequent volcanic deposits. The geometry and alteration intensity of the highly electrically conductive lenses may reflect a combination of buried volcanic structures and a thermal alteration boundary. Overlapping and eastward migrating volcanic structures can explain the absence of stratigraphic correlating deposits between wells in close proximity on the western flank of the volcano.

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