PROCEEDINGS, 48th Workshop on Geothermal Reservoir Engineering
Stanford University, Stanford, California, February 6-8, 2023
SGP-TR-224

Exploring for Superhot Geothermal Targets in Magmatic Settings: 2022 Field Campaign at Newberry Volcano

Hannah Pauling[1], Adam Schultz[2], Esteban Bowles-Martinez[2], Xiaolei Tu[2], Chet Hopp[3], Alain Bonneville[4], and Amanda Kolker[1]

[1] National Renewable Energy Laboratory, Golden CO 80401, USA

[2] Enthalpion Energy LLC

[3] Lawrence Berkeley National Laboratory (LBNL)

[4] Geosciences Consulting LLC

Hannah.Pauling@nrel.gov

Keywords: geothermal exploration, supercritical resources, superhot EGS, geophysics, gravity, magnetotellurics, joint inversion

ABSTRACT

This paper presents preliminary results from a subset of work carried out as part of a multinational research project entitled DErisking Exploration for multiple geothermal Plays in magmatic ENvironments (DEEPEN), supported by the U.S. Department of Energy (DOE) and Geothermica, a joint effort by EU member states and associated countries. The DEEPEN project will develop a customized approach to exploration for supercritical and superhot geothermal plays in magmatic systems, which will be applied to two demonstration sites. This paper summarizes field activities carried out at the U.S. demonstration site, Newberry Volcano in central Oregon. The objective of this work effort is to refine the subsurface model of Newberry Volcano, with special focus on deeper zones including the magmatic plumbing system and other key geologic elements. New data collection included gravity and wideband magnetotelluric (MT) surveys, as well as reinstallation of a seismic network. The National Renewable Energy Laboratory (NREL) and Enthalpion Energy LLC (Enthalpion) worked with the Deschutes National Forest Fort Rock District to use a low ground disturbance method of MT deployment to collect MT data inside the caldera and other restricted areas inside the National Volcanic Monument. This opened these areas to geophysical exploration for the first time in decades. Sites along and adjacent to the south rim of the volcano constituted the primary survey objectives. A team from Lawrence Berkeley National Laboratory (LBNL), the U.S. Geological Survey (USGS), and AltaRock also began the process of reinstalling the seismic network from the AltaRock enhanced geothermal system (EGS) demonstration in anticipation of further development activities at the site. The data ingestion, reduction, and analysis phase of the project is ongoing. We are currently processing the MT and gravity data and are developing a new, highly GPU-accelerated, 3D joint MT and gravity inversion to better localize the south rim/south flank conductive target and better understand its relationship to deep heat, fluid sources, and surface extrusive features. Joint inversions, which have not yet been undertaken at Newberry, will allow us to obtain constraints on the geologic model that cannot be determined from each method in isolation, improving our ability to image key geologic features at depth.

1. INTRODUCTION

The DEEPEN (DErisking Exploration for multiple geothermal Plays in magmatic ENvironments) project aims to reduce exploration risk for geothermal fluids in magmatic systems by developing an improved framework for interpretation of exploration data using the play fairway analysis (PFA) methodology. DEEPEN has leveraged existing data sets from magmatic-related geothermal fields to develop a customized PFA approach to exploration for multiple geothermal resource types or "plays" (hydrothermal, superhot enhanced geothermal system [EGS], and supercritical) in magmatic systems (Kolker et al., 2022). This methodology will be tested at two demonstration sites: Newberry Volcano (OR, USA) and Hengill Volcano (Iceland).

A DOE-funded EGS field demonstration project at Newberry produced a detailed conceptual geological model for the system, which provided a baseline for more detailed investigations of conventional hydrothermal and superhot geothermal systems (Cladouhos et al., 2016). The existing model was built on: 1) individual 3D inversions of gravity/micro-gravity and magnetotelluric (MT) array data, 2) ground deformation observations, 3) published seismic tomography and forward modeling work, 4) microseismicity observations, and 5) thermo-chemical-mechanical model construction. To-date however, no joint inversions (e.g., MT-gravity-seismic) have been undertaken at Newberry. In addition, the coverage of the existing MT data set in certain parts of the volcano is quite sparse, limiting the resolution of certain zones, some of which are of particular interest to DEEPEN (e.g., an upwelling conductive zone, which could either be attributed to a hydrated melt body and/or hydrothermal feature, and zones within the N-S trending rift zone that may provide a structural control on magma migration and fluid migration).

The objective of this work effort is to refine and expand the subsurface model of Newberry Volcano, with special focus on deeper zones including the magmatic plumbing system and other key geologic elements. This paper describes the new data collection (MT, gravity, and seismic) with Enthalpion Energy LLC (Enthalpion) and Lawrence Berkeley National Laboratory (LBNL), which aims to fill in station coverage along the south rim, south flank, and northwest flank of the volcano. This will provide enhanced spatial resolving power, enabling better understanding and distinction between deep magmatic sources, permeable pathways, and conditions at depths (3,000–5,000 m) that span the brittle-ductile transition and where supercritical conditions are believed to exist.

2. GRAVITY AND MAGNETOTELLURICS

2.1 Previous Work

Recently published work showing results of 3D MT inversion has revealed a relatively resistive unit beneath the west flank of the volcano at depths of ~3,000 m that is consistent with the conceptual geological model's interpretation that the west flank is likely underlain by a pluton that may contain significant residual heat (Bowles-Martinez and Schultz, 2020). The area is bounded to the north and to the south by zones of enhanced conductivity. The edge of the resistive west flank abutting the more conductive zone to the north zone contains well 46-16, which outgasses CO_2 of magmatic origin, suggesting a permeable pathway may exist to the magmatic source beneath the caldera within the northern section of the west flank. Seismic tomography and forward modeling have shown that an accumulation of melt exists beneath the northern section of the caldera at depths as shallow as 3,000–4,000 m. 3D inversion of MT data that spans the entire western half of the volcano including the caldera and flank produced a result that is insensitive to the existence of the partial melt within this putative magma chamber. This lack of detectible conductivity was inferred to be due to a (dry) rhyolitic melt composition that does not contrast with the rhyolitic host rock.

The 3D resistivity model, shown in Figure 1, also reveals a strongly conductive zone that is detectible at depths of 3,000–4,000 m beneath the south rim of the volcano and that shallows into the hydrothermal system immediately beneath the caldera infill that is known to exist from wells located in the caldera and also from the hot springs that flow into the two caldera lakes. Once above this complex hydrothermal zone, the projection of the conductive feature shallows immediately below the Big Obsidian Flow, the most recent (1300 ybp) eruptive feature at Newberry. The upwelling conductive zone, which could be attributed to a hydrated melt body and/or a hydrothermal feature, is only poorly resolved because the existing MT data collected in that part of the volcano are quite sparse. That zone appears to extend to magma chamber depths beneath the south flank of the volcano. The high conductivity may be associated with a deep fluid pathway. This part of the volcano is also associated with a N-S trending rift zone that is interpreted both south and north of the caldera, and that may provide a structural control for deeper magma migration.

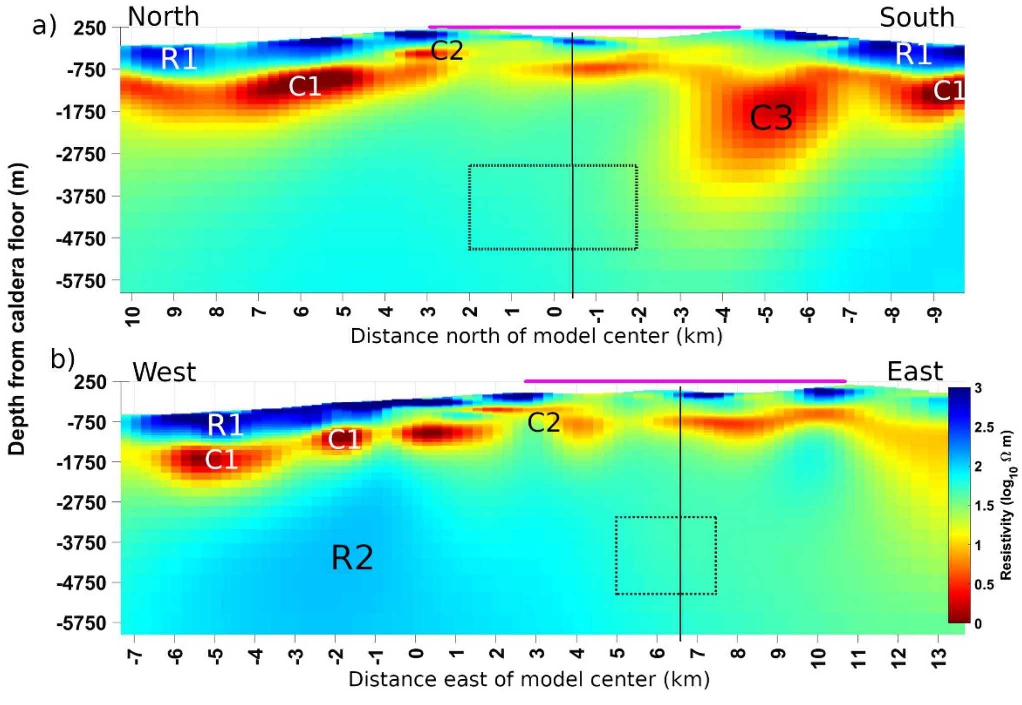

Figure 1: Cross sections of previously developed 3D MT resistivity model (Bowles-Martinez and Schultz, 2020). Magenta line covers area within caldera. Depths are relative to caldera floor. R1 = resistive unaltered surface material; R2 = west flank pluton; C1 = conductive hydrothermal alteration zone; C2 = conductive caldera rim; C3 = conductive south rim fluid conduit. Vertical lines mark cross section intersection point. (a) North-south cross section through center of caldera. (b) West-east cross section through caldera.

The conceptual geological model developed previously for Newberry Volcano will serve as a baseline for more detailed investigations of conventional hydrothermal, EGS, and superhot/supercritical EGS. The existing model was built in part on individual 3D inversions of gravity/micro-gravity and MT array data, ground deformation observations, and published works by other groups from seismic tomography and forward modeling work and microseismicity observations, as well as thermo-chemical-mechanical models. The model was also constrained by geochemical and petrological constrains from well cores, cuttings, and well logs. The current model does not capture the entirety of the magmatic plumbing system beneath Newbery Volcano, as surface investigations were concentrated within the

EGS study area (AltaRock geothermal leases on Newberry's west flank), although data from prior MT and gravity surveys elsewhere on the volcanic edifice, almost entirely excluding the east flank were also included.

2.2 New Data Collection

New data collection during the summer of 2022 included gravity and wideband MT surveys. The National Renewable Energy Laboratory (NREL) and Enthalpion Energy LLC (Enthalpion) worked with the Deschutes National Forest Fort Rock District to use a minimal ground disturbance method of MT deployment ("subaerial MT") developed at Oregon State University to collect MT data inside the caldera and other restricted areas inside the National Volcanic Monument. This opened these areas to geophysical exploration for the first time in decades.

During the first month of the project, sites were identified along and adjacent to the south rim (including inside the caldera) that constitute the primary survey objectives related to a previously detected upwelling high conductivity zone. This zone appears to extend from magma chamber depths and recent eruptive feature—the Big Obsidian Flow (location shown in Figure 2). Additionally, the southern and northwestern flank sites would address secondary objectives of examining structures potentially associated with the boundary of a deeply buried pluton on the western flank and provide additional information on deep crustal faulting that likely controls the location of the volcanic center.

Several gravity station locations were identified as candidate wideband MT station locations. A Lacoste and Romberg Model D gravimeter provided by Pacific Northwest National Laboratories was used for the gravity measurements; six Zonge ZEN Rx6 wideband MT receivers, 18 Geotell ANT/4, and six Geotell ANT/7 (as spares) wideband induction coil magnetic field sensors were used for the MT measurements. In a conventional MT installation, the induction coil sensors are buried underground. In order to minimize ground disturbance and gain access to the volcanic monument, a subaerial, tilted tripod configuration was utilized for the induction coils. At each MT station, nonpolarizing electrodes and electric field dipole cables were deployed with a clamping system used to assemble the induction coils (this assembly is henceforth referred to as a "MT system"). One MT system was reserved as a fixed-position remote reference unit, deployed in the northern part of the northern polygon of the survey area, and another MT system was used as a spare. Four of the systems comprised a relocatable array, deploying (nominally) two stations per day, operating for two days per station, and then relocating in a rolling pattern across the survey area. A remote reference station in the north flank area was maintained for the duration of the survey. In the south flank, pairs of stations were installed concurrently to provide a fallback remote reference in the event the north flank remote reference station experienced a data drop-out.

While densifying the MT and gravity arrays along the northwestern flank of the volcano remains of interest, less emphasis was placed on completing the full gravity and MT array in the northwestern flank subarray (the presumed northern edge of a deep plutonic heat source) in order to complete the highest priority south rim and flank target arrays (the presumed upwelling highly conductive zone). The plan for the MT survey was to provide sufficient density of station coverage to best image the previously identified conductive anomaly rising from magma chamber depths beneath the south rim, and shallowing next to the Big Obsidian Flow inside of the caldera. Within the south flank sub-array, coverage along the eastern part of the south flank was de-emphasized to ensure adequate density to image the main anomaly, and to cross the putative rift zone that INSAR data suggests may link with deep regional crustal faults to the south. This goal was achieved, and a comprehensive gravity and wideband MT data set was obtained. Road conditions in the north flank survey area also proved challenging, with station locations requiring excessively long hikes because of downed timber inhibiting road access. Minor damage to survey vehicles was incurred during attempts to gain access in that area, and disruptions due to the ongoing COVID-19 pandemic further reinforced the decision to focus resources on the south rim and flank areas. However, a new gravity loop and a long-running MT data set were obtained in the north flank area where there was little to no previous coverage. New gravity and MT stations are listed in Table 1.

Table 1: Gravity and MT stations installed during 2022 field campaign.

	Gravity	Magnetotellurics (MT)
South Rim	122	25
South Flank	102	17
North Flank	9	1 (Remote reference station)
Total	233	43

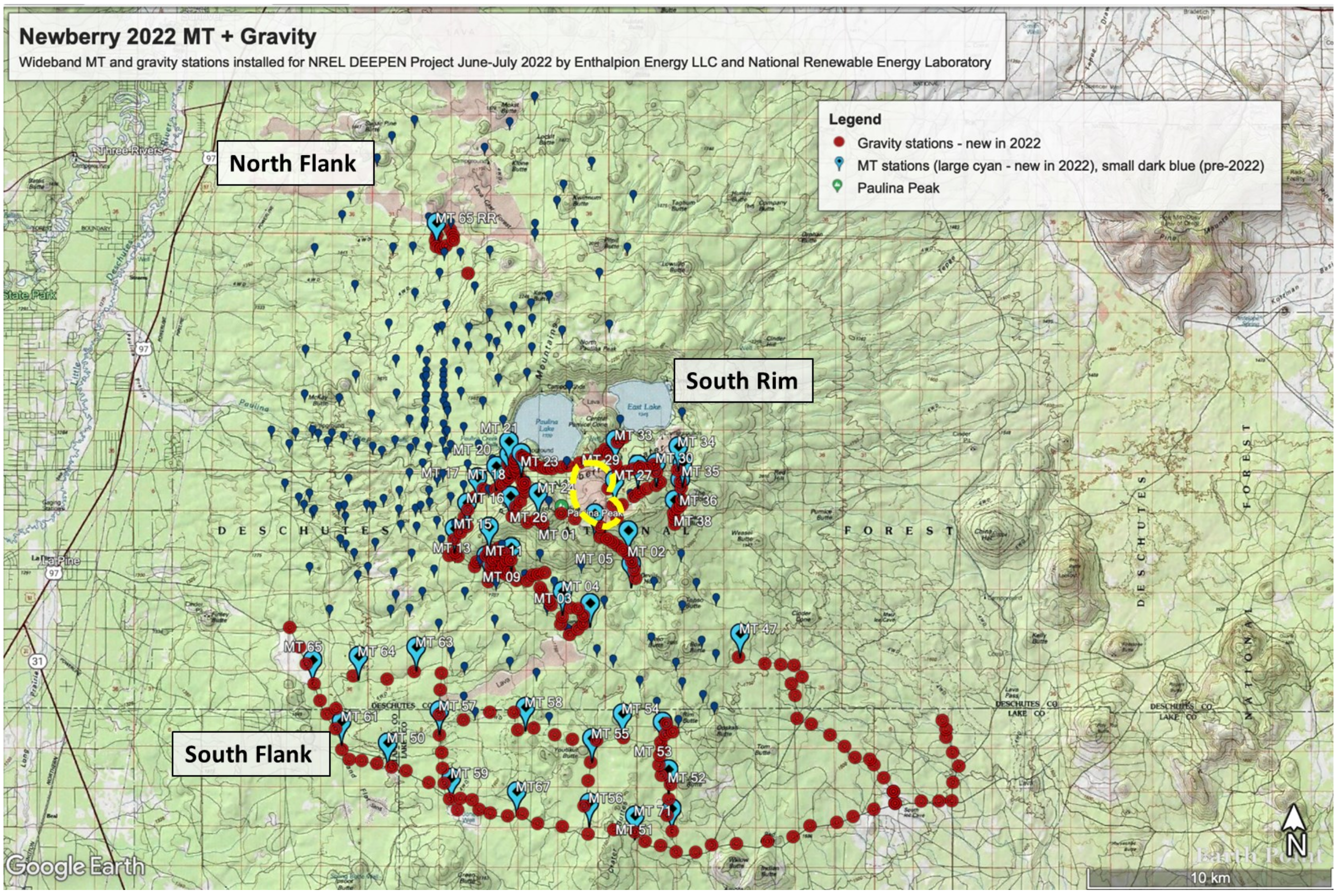

Figure 2: Wideband MT and gravity stations installed June and July 2022 by Enthalpion and NREL. Yellow dashes outline the location of the Big Obsidian Flow.

An initial field data quality assessment suggested the gravity data are of high quality. The main consideration in MT data reduction and analysis is to maintain a remote reference station to enhance the signal-to-noise ratio in the MT long-period "dead band" centered on approximately 1 Hz, a frequency band with low levels of natural signal source. The remote reference station provides simultaneous data on the magnetic field that is used to reduce the effects of spatially incoherent noise in the local magnetic field measurements at each MT station. We maintained a remote reference station in the north flank area for the duration of the survey, sampling the electric and magnetic fields at 1,024 samples per second continuously. After several checks on the station showing normal operations, when the station was extracted, the final run collected only four days of data before the run terminated for unknown reasons. This potentially impacted the south flank data set, however the installation of pairs of stations separated by the greatest possible distance in the south flank area minimized these impacts.

3. SEISMIC

3.1 Previous Work

Newberry has been the target of several different seismic deployments over the last 35 years, beginning with two large active-source seismic surveys in 1983 and 1984. The first was a 120-station refraction transect centered on Newberry (Catchings and Mooney, 1988) and the second was a redeployment of the same 120 instruments surrounding the volcano for the purposes of P-wave seismic tomography (Achauer et al., 1988). Both experiments attempted to infer the presence and location of partial melt below the edifice using explosive sources. In 1987, the Pacific Northwest Seismic Network (PNSN) installed one single-component monitoring seismometer (SEED id: UW.NCO) on the East flank (easternmost blue triangle in Figure 3). This was the only continuously recording sensor near Newberry until 2011. In 2008, a team led by the University of Oregon deployed a 75-station seismic line to record an explosive source from a separate experiment to the northeast (Beachley et al., 2012). Again, this transect attempted to better constrain the geometry and melt content of the magma body beneath Newberry. In 2011, PNSN installed a permanent, dedicated eight-station continuous seismic monitoring network as part of the larger Cascade Chain Volcano Monitoring network (code CC, Figure 3), which interfaces with the Cascades Volcano Observatory. The sensors currently maintained by PNSN at Newberry can be viewed at https://pnsn.org/volcanoes/newberry.

All other seismic data acquisition at Newberry has revolved around the AltaRock EGS demonstration project on the northwest flank (Cladouhos et al., 2016). A 15-station seismic monitoring network was installed starting in August of 2012 in advance of the first stimulation (a subset of this network is shown in purple in Figure 3). The network comprised seven surface sensors and eight sensors installed in dedicated monitoring boreholes, all of which were 2-Hz, three-component geophones. This network functioned through the end of the project in 2015 when the network was dismantled. Three borehole sensors (NN17, NN19, and NN21) were transferred to PNSN to be incorporated into their network. NN17 went offline in 2016, but NN19 and NN21 have remained operational. Most waveform data from the experiments detailed above are publicly available via the IRIS Data Management Center.

3.2 New Data Collection

In October 2022, a team from LBNL, the U.S. Geological Survey (USGS), and AltaRock began the process of reinstalling the seismic network from the AltaRock EGS demonstration as part of the DEEPEN project. Given that the surface geophones contributed only poor-quality signal-to-noise for all but the largest microearthquakes, only the borehole sensors are being reinstalled. The downhole geophones, manufactured by IESE of New Zealand for the original network, have remained in the boreholes since they were originally installed but still appear to be functioning normally. As mentioned above, NN19 and NN21 are currently maintained by PNSN, so only stations NN07, NN09, NN17, NN18, NN24, and NN32 are to be reinstalled (purple inverted triangles; Figure 3). In October, all surface electronics, including solar panels, batteries, cell modems, and digitizers, were installed at all sites except NN32. Data are currently being streamed to LBNL and will eventually be archived in near-real-time at the IRIS Data Management Center, making them publicly available. In the spring of 2023, we will return ahead of the planned stimulations to install two new sensors, one in NN18 and one in NN32 and attempt to improve the coupling of all sensors.

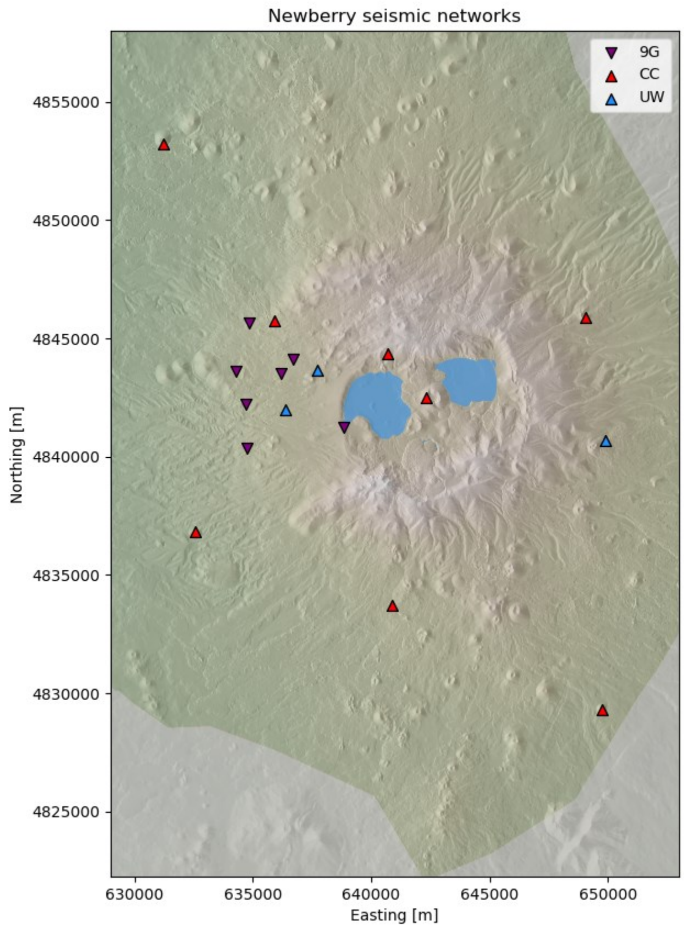

Figure 3: Current or planned seismic networks at Newberry. Purple inverted triangles show network 9G, the partially re-installed borehole network on the AltaRock demonstration lease, red upright triangles show CC (Cascade Chain Volcano Monitoring) network sensors, and blue triangles indicate PNSN network stations. All data are currently, or will soon be, publicly available in near real-time.

4. DATA PROCESSING AND INVERSION

The data ingestion, reduction, and analysis phase of the project is ongoing. A new, highly GPU-accelerated, 3D joint MT and gravity inversion is being developed that will be used to better localize the south rim/south flank conductive target and better understand its relationship to deep heat, fluid sources, and surface extrusive features. By jointly inverting multiple geophysical data sets, which has not yet been undertaken at Newberry, we aim to improve our ability to constrain conditions and rock properties at depth. Combining gravity and MT models and densifying the MT and gravity arrays with new stations in the areas of interest allows us to obtain constraints on geochemistry/petrology that cannot be determined from each method in isolation.

The final reduction of the gravity data set has been completed, with a complete Bouguer anomaly (CBA) set now available. Figure 4 shows the interpolated, band-pass filtered and regional CBA in map views. Initial gravity inversions are being developed from the CBA data (the CBA shown here accounts for the change in gravitational acceleration due to the difference in elevation of a given gravity station relative to the reference datum—typically the GRS80 ellipsoid—including irregularities in the terrain near the gravimeter, and it corrects for the additional or missing mass from the rocks that exist between the elevation of the gravity station and the reference datum).

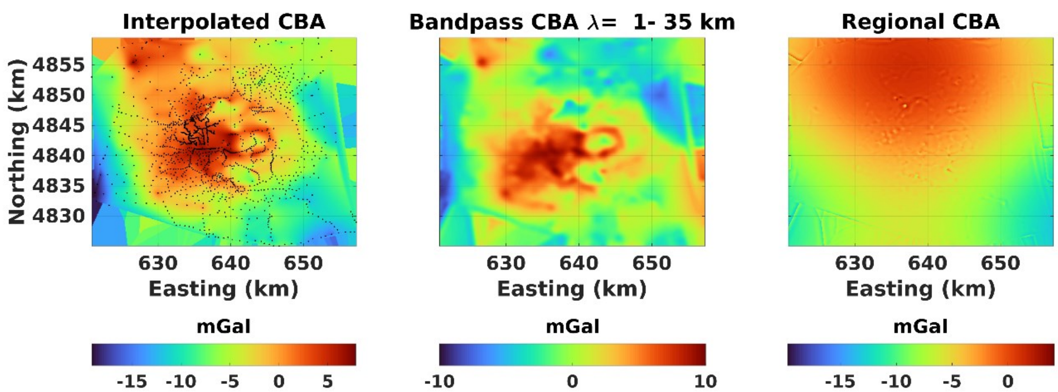

Figure 4: Maps of complete Bouguer anomaly (CBA). The left panel shows the interpolated (gridded) CBA with a 100 m * 100 m grid. The black dots represent the positions of gravity stations used in the inversion—these include both legacy stations and those obtained by us in 2022 under the support of the DEEPEN project. The middle panel is the bandpassed CBA in the wavelength band between 1 and 35 km. The differences between the bandpassed and the gridded but unfiltered data are shown in the right map, which mostly consist of regional trends, which is not of interest to this study.

A map view of the density variations at a model elevation of 640 m above sea level (approximately 1,290 m below the caldera floor) is seen in Figure 5 (for reference the top of Paulina Peak, the highest point on the caldera rim, is 2,435 m above sea level; the surface of Paulina Lake/caldera floor is 1,930 m above sea level). Gravity values predicted by the density model are a close fit to the observed gravity values, shown by the map of data residuals in Figure 6.

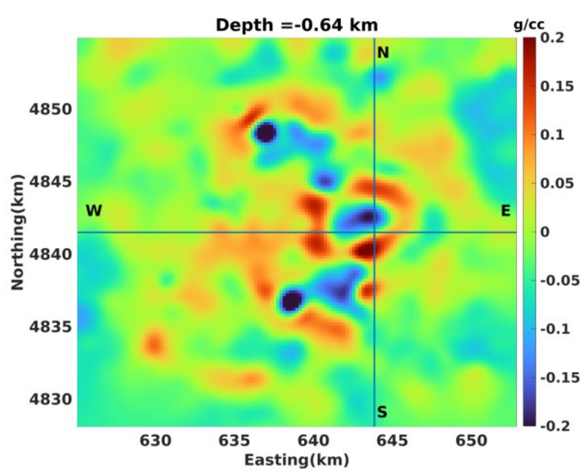

Figure 5: A horizontal section (map view) of the inverted density model at the depth of -0.64 km below sea level. The grid size for the inversion is 100 m * 100 m. The red regions correspond to density highs, and the blue are density lows. The original CBA without gridding and filtering are used in this inversion. For reference the top of Paulina Peak, the highest point on the caldera rim, is 2.4 km above sea level; the surface of Paulina Lake/caldera floor is 1.9 km above sea level.

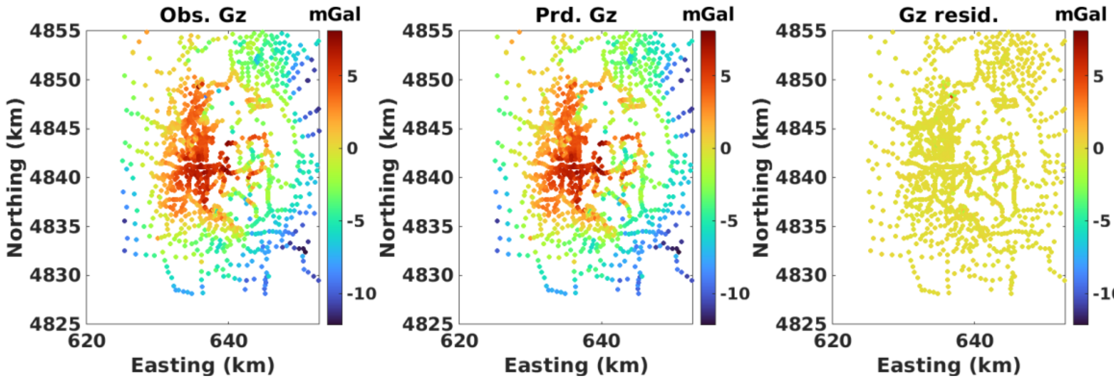

Figure 6: Maps of data fit. The observed and predicted gravity data and their residuals are presented on the left, middle, and right panels.

MT data processing is ongoing. The subaerial, tilted tripod configuration utilized for the induction coils requires additional processing to rotate the data to conventional cardinal coordinates. Algorithmic modifications were made to accelerate the data reduction effort given the large volume of wideband MT data obtained. This includes improvements to the remote reference processing workflow to speed final data reduction. New approaches were implemented to speed the inversion step by inverting the diagonal of the Jacobean matrix when appropriate, rather than the full matrix. This builds on previous accelerations in the forward modeling step by efficient use of GPU acceleration. Additional improvements have been made to the time series processing workflow as well, particularly when bias from high-voltage electric power transmission lines is detected. Improvements to the MT inversion module to improve model convergence speed are still underway. Once this is complete, the MT-only inversion and MT-gravity joint inversion will follow.

5. CONCLUSION

New geophysical data collected at Newberry Volcano during the 2022 field campaign included new gravity and wideband MT surveys and the reinstallation of the seismic network from the AltaRock EGS demonstration project. Enthalpion and NREL collected data at 233 new gravity stations and 43 new MT stations in the north flank, south flank, and south rim areas of the volcano, including a new gravity loop and a long-running MT data set in the north flank area where there was little to no previous coverage. Four borehole seismic sensors from the AltaRock EGS demonstration project have been reinstalled, and two sensors will be installed in spring 2023. Data are currently being streamed to LBNL.

The data ingestion, reduction, and analysis phase of the project is ongoing. This phase includes work on algorithmic modifications to accelerate the data reduction effort given the large volume of wideband MT data obtained, as well as other improvements to the remote reference processing workflow and the MT modeling algorithm. Initial gravity inversions have been developed from the CBA data. A new, highly GPU-accelerated, 3D joint MT and gravity inversion is being developed that will be used to better localize the south rim/south flank conductive target. With better models of the conventional and unconventional geothermal resources beneath Newberry Volcano, we will be able to refine our preliminary methodology for de-risking exploration methods for supercritical and superhot geothermal resources. These types of resources remain untapped to date, but if exploited, could mean orders of magnitude more electricity generated from a single well.

5. ACKNOWLEDGEMENT

Funding for this work was provided by U.S. Department of Energy, Office of Energy Efficiency and Renewable Energy, Geothermal Technologies Office to the National Renewable Energy Laboratory, operated by Alliance for Sustainable Energy, LLC, for the U.S. Department of Energy under Contract No. DEAC36-08GO28308, and to Lawrence Berkeley National Laboratory under Award Number DE-AC02-05CH11231. Additional funding was provided to other members of the Geothermica consortium through their corresponding EU Member States and Associated Countries. The views expressed herein do not necessarily represent the views of the DOE or the U.S. Government. The United States Government retains and the publisher, by accepting the article for publication, acknowledges that the United States Government retains a nonexclusive, paid-up, irrevocable, worldwide license to publish or reproduce the published form of this work, or allow others to do so, for United States Government purposes.

REFERENCES

Achauer, U., Evans, J.R., and Stauber, D.A.: High-resolution seismic tomography of compressional wave velocity structure at Newberry Volcano, Oregon Cascade Range, Journal of Geophysical Research, 93 (1988), 10135-10147.

Beachley, M.W., Hooft, E.E., Toomey, D.R., and Waite, G.P: Upper crustal structure of Newberry Volcano from P-wavetomography and finite difference waveform modeling, Journal of Geophysical Research, 117 (2012).

Bowles-Martinez, E. and Schultz, A.: Composition of Magma and Characteristics of the Hydrothermal System of Newberry Volcano, Oregon, From Magnetotellurics, Geochemistry, Geophysics, Geosystems, 21 (2020).

Catchings, R.D., and Mooney, W.D.: Crustal structure of the Columbia Plateau: Evidence for continental rifting, Journal of Geophysical Research, 93 (1988), 459-474.

Cladouhos, T. T., Petty, S., Swyer, M.W., Uddenberg, M.E., Grasso, K., and Nordin, Y.: Results from Newberry Volcano EGS Demonstration 2010–2014, Geothermics, 63 (2016), 44-61.

Kolker, A., Taverna, N., Dobson, P., Benediksdóttir, A., Warren, I., Pauling, H., Sonnenthal, E., Hjörleifsdóttir, V., Hokstad, K., and Caliandro, N.: Exploring for Superhot Geothermal Targets in Magmatic Settings: Developing a Methodology, Transactions, Geothermal Rising Conference (2022).