3D MT Resistivity Imaging for Geothermal Resource Assessment and Environmental Mitigation at the Glass Mountain KGRA, California

William Cumming[1] and Randall Mackie[2]

[1]Cumming Geoscience
[2]GSY-USA, Inc.

Keywords
Exploration geophysics resistivity magnetotellurics

ABSTRACT

MT and TDEM surveys acquired in 2005 were integrated with existing MT and TDEM data recovered from obsolete formats to characterize the geometry of the geothermal reservoir in the Glass Mountain KGRA. The objectives of this project were to mitigate the drilling costs and environmental impact of the ongoing geothermal development at Glass Mountain by more efficiently focusing exploration wells on the most promising target zones.

Although the 1D and 2D inversions used for the initial review of the MT were superior to the MT analyses completed in the 1980's at Glass Mountain, advances made in 3D MT inversion over the course of the project led to its use as the primary tool in the resistivity interpretation. The improved MT imaging supported a detailed correlation of MT resistivity with data from 5 exploration wells and 21 temperature gradient holes, validating both the 3D MT computation and the interpretation of resistivity in geothermal settings based on the temperature sensitive clay transitions.

An interpretation based on the correlation of the 3D MT resistivity with well properties indicated that most of the previous exploration wells had been targeted close to but not in the center of areas that appeared most likely to be permeable. Such characterizations can be considered in the context of both potential environmental impacts and reservoir engineering analyses in assessing drilling target priorities. The details of this Glass Mountain MT project are elaborated in a report to the California Energy Commission, currently under review.

Introduction

The Glass Mountain Known Geothermal Resource Area (KGRA) is located in northern California, about 50 km northeast of Mt. Shasta (Figure 1). Exploration wells and temperature gradient holes drilled in the 1980's demonstrate that 440 to 515°F (227 to 268°C) geothermal reservoirs exist in and near two areas for which Calpine Corporation has obtained power purchase agreements, the Fourmile Hill and Telephone Flat Areas (Calpine-Siskiyou Geothermal Partners L.P. 2004). Exploration has also identified several other prospects covered by Calpine leases. The data sets given greatest emphasis in targeting exploration wells at Glass Mountain were temperature gradient holes (TGH's), geological structure analysis and resistivity surveys, particularly time domain electromagnetics (TDEM) and magnetotellurics (MT).

Although MT surveys have become a standard method for geothermal well targeting worldwide, the existing MT data at Glass Mountain had not been fully integrated into recent resource interpretations because of their obsolete format. For the most recent well, 88A-28 drilled in the Fourmile Hill area in 2002, the well targeting interpretation emphasized TDEM although it had a much smaller depth of investigation than MT. The 88A-28 well demonstrated the existence of a geothermal resource but had uneconomic deliverability (Calpine-Siskiyou Geothermal Partners L.P. 2004).

After 2002, there was a hiatus in drilling at Glass Mountain following the testing of 88A-28 but the greater interest in geothermal power development as energy prices rose led to increased expectations that drilling would soon resume. At the same time, environmental standards were changing and the value of minimizing the impact of geothermal development increased. This geophysical review and MT study was directed at reducing the exploration costs and environmental impact of geothermal development at Glass Mountain by improving well targeting. Improving 3D MT imaging, validating the clay-oriented approach to interpreting geothermal resistivity data, and providing a more complete case history of an MT application to the exploration of a geothermal resource in California were subsidiary goals. The plan for the study included the release of data sets that others could use to test alternative analysis approaches. A draft report on this MT project and supporting data sets was submitted to the California Energy Commission in March 2007.

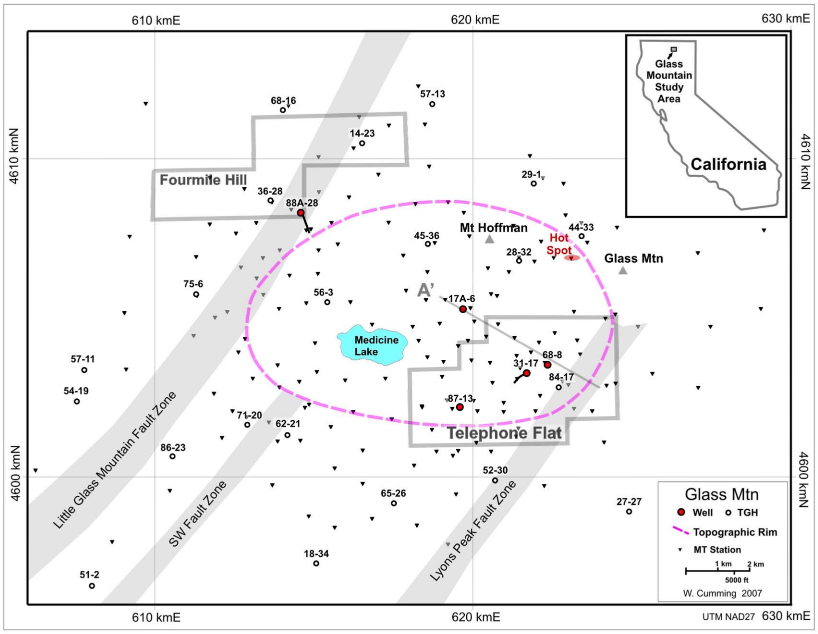

Figure 1. Glass Mountain study area with geothermal features.

Geology

Figure 1 shows the rim of the Medicine Lake Volcano, a shield volcano that, despite its low relief of about 1200 m, is the largest by volume in the Cascades because of its area of over 2000 km^2. Most of the edifice has been built over a period of about 500 ka over Pliocene basalts, initially by mainly basalt and basaltic-andesite eruptions, and later of andesite and rhyolite (Donnelly-Nolan, 1990). Much of the rhyolite is very young. The last and largest rhyolite eruption, at Glass Mountain, is dated only 900 years ago.

The rim highlighted in Figure 1 encloses a central basin that hosts Medicine Lake, leading some investigators to conclude that it is a caldera collapse feature. However, the absence of significant thicknesses of ash flow tuff in deep well cores, and the absence of mapped ring fault scarps indicates, instead, that the elliptical ridge-line is a coalescence of eruptive centers along a ring fracture system (Clausen et al. 2006). Elevation monitoring suggests that the ring fracture is probably related to vertical deformation, currently 8 mm/y subsidence inside the basin (Lisowski et al., 2004). Local structures are influenced by a combination of volcanism and regional extension associated with the transition from the Cascades to the west and the Basin and Range to the east (Hulen and Lutz 1999). Medicine Lake Volcano is elongated along the northerly trending, extensional Klamath Falls-Fall River Graben where it is intersected by the northeasterly trending Mt- Shasta-Medicine Lake fault zone (Donnelly-Nolan 1990). Within three northeasterly fault zone strands shown in Figure 1, fractures are deflected where they intersect the ring fracture (Clausen et al. 2006). Such intersections have been the target of earlier geothermal exploration in this area (Calpine-Siskiyou Geothermal Partners L.P. 2004).

The likely heat source for the geothermal system at Medicine Lake Volcano is ongoing basaltic magma intrusion that has re-melted crust and generated many small granite bodies beneath the volcano over the past 100 ka (Lowenstern et al. 2003). A larger granite intrusion that is partially within the geothermal system is older, about 300 ka, with hydrothermal alteration dated at 171 ka, indicating that the hydrothermal system is long-lived, probably has had several episodes of renewed hydrothermal activity, and was probably much hotter in the past than at present (Lutz et al. 2000).

The review of the nature of permeability in the Glass Mountain wells by Clausen et al. (2006) concluded that fractures in dense rocks accounted for most of the open permeability field-wide whereas the primary permeability in the breccias at flow boundaries tended to be filled. The relatively low permeability in the Glass Mountain KGRA was attributed to the nature of the intense propylitic hydrothermal alteration, much of which originated in older, higher temperature geothermal systems that may have critically reduced porosity and permeability. On the other hand, well test data also indicated that permeability may have been significantly damaged by drilling and testing operations (Calpine-Siskiyou Geothermal Partners L.P. 2004). The 3D MT analysis raised the additional possibility that the production wells were targeted close to but not into the trends that were imaged by the MT as being most promising for encountering high permeability.

Geophysical Acquisition and Analysis

The geophysical acquisition and analysis included recovering 105 legacy MT stations from obsolete formats and combining them into a modern digital MT data base with 91 new MT stations acquired by GSY-USA, Inc. in 2005 (Figure 2). Resistivity data from 348 legacy TDEM and 91 new TDEM stations were integrated with the MT. The interpretation also considered results from 838 gravity stations. After an initial review, several data sets, including an early HEM experiment, several lower quality MT surveys and two VES surveys were not included. All of the utilized data were assembled into a single data base for analysis.

An expected outcome of the TDEM data analysis was that, although it appeared to image resistivity to a depth of 300 m, it was misleading when used to image to greater depths, as had happened when targeting well 88A-28. However, an unexpected outcome was that, over the very resistive surface volcanics that cover much of the Glass Mountain area (as at most Cascades volcanoes), TDEM tends to give misleading MT static corrections. The Sirotem TDEM system using 100 m loops produced realistic looking data over thick resistors that resulted in models often as much as a factor of 10 too low in resistivity. The more expensive EM37 and Protem 57 surveys using 300 m loops performed in a manner that was better for interpreting TDEM alone but still distorted MT static corrections by producing models over thick resistive terrain up to a factor of 3 too high in resistivity. As a result of this analysis, the conventional approach to static correction of the MT using synthetic curves derived from TDEM models was modified. A static shift was applied only in cases where the MT apparent resistivity did not fit within a maximum indicated by EM37/Protem57 TDEM data or a minimum indicated by Sirotem TDEM data.

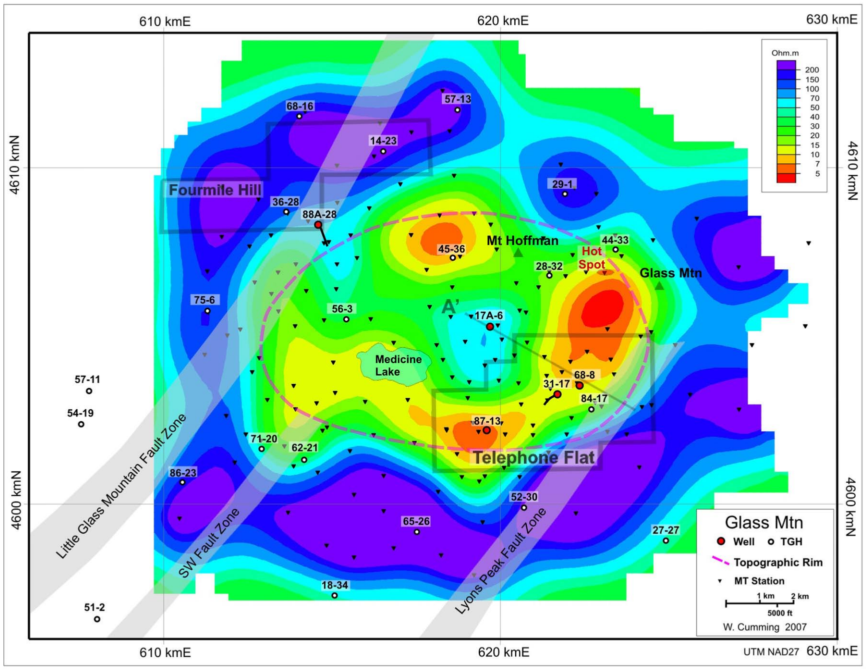

Figure 2. Glass Mountain 3D MT resistivity at 1700 m elevation.

The resistivity maps and cross-sections used in the final interpretation were primarily from the final 3D inversion, although 1D and 2D MT interpretations were also made for quality assurance. Because most published case histories of geothermal MT applications used 1D imaging approaches, a standard 1D map of the base of the clay cap was prepared (Anderson et al., 2000). It highlighted areas where the base of the clay cap was especially shallow. However, 1D cross-sections were much less effective in imaging spatial resistivity variations relevant to the hydrology of the geothermal system. The 2D inversions required that a 2D orientation be identified for each station, an often problematic task that sometimes produced misleading results when compromises were necessary. Neither the 1D nor 2D inversions reliably produced resistivity images that matched reservoir properties as well as the 3D inversion. As the 3D MT inversion improved, it largely replaced 2D imaging in the interpretation process, although 1D inversion retained a role in shallow interpretation and quality assurance.

The most significant advance in the 3D MT inversion was the recognition that smaller model elements and more densely sampled MT frequencies were required to image geothermal targets. Adjustments to the algorithm improved computational efficiency so that it became feasible to compute inversions for more finely sampled models and data. The final model had 25 m thick blocks from the surface to the base of the clay cap. A variety of other improvements were related to data preparation rather than to the algorithm itself. For example, careful editing of the MT data to eliminate noise proved to be more important than expected. Adjusting the legacy MT data so that it could be correctly processed in the 3D inversion took much more time than expected because the older MT formats did not conform to modern standards. Because of the unpredictability of the issues encountered, it may sometimes be more cost-effective to reacquire MT data rather than to recover it, although issues like access restrictions or interference from power plants often make recovery of legacy data the best option.

The standard smectite-illite conceptual model used to explain resistivity patterns at most geothermal reservoirs (Gunderson et al., 2000), albeit seldom emphasized in publications on California geothermal MT data sets, was validated at Glass Mountain by correlating MT resistivity with alteration zoning and temperature logs (Figure 3). In addition, an induction resistivity log from Glass Mountain well 17A-6 was directly used to assess the performance of the MT resistivity imaging. The top of the argillic alteration zone in which smectite alteration is most intense correlates with the lowest resistivity and with the geometry of the associated isotherms, validating the smectite-illite model for resistivity interpretation (Gunderson et al., 2000). Because the most reliable indication of the average (bulk) permeability pattern in a geothermal reservoir is the pattern of natural state isotherms, the correlation of resistivity patterns with temperature was used to extend the interpretation of permeability to undrilled areas. Conceptual models based on the resistivity images indicate that major structures are both permeable zones and boundaries in the Glass Mountain KGRA and suggest a strategy to target lower risk directional wells.

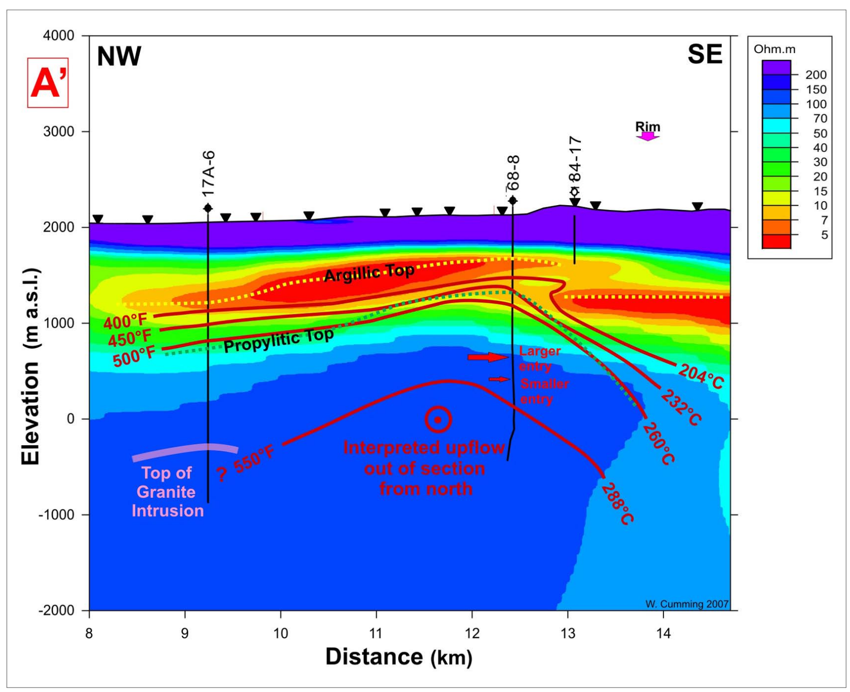

Figure 3. Glass Mountain 3D MT resistivity cross-section through wells 17A-6 and 68-8 showing the correlation of resistivity with temperature and alteration.

Conclusions

Resource areas at Glass Mountain identified in earlier drilling and surveys have been confirmed but the new MT analysis suggests that the existing wells tended to target the periphery of the reservoirs, particularly in the case of wells 88A-28 at Fourmile Hill but also in the case of most wells at Telephone Flat (Figure 2). Areas where the resistivity pattern indicated that smectite alteration was poorly developed or that the base of the smectite zone became very deep are higher risk for geothermal well targeting. New target areas derived from the MT resistivity images are consistent with the temperature and entry patterns of existing wells (Figure 3).

One proposed target in the Telephone Flat area is interpreted as a >550°F (290°C) upflow located northwest of well 68-8, probably beneath the Glass Mountain rhyolite flow (Figures 2 and 3). The production wells 68-8 and 31-17 are on the southern margin of this interpreted upflow (Figure 2). The lack of MT data over the Glass Mountain rhyolite flow is a significant source of uncertainty in this interpretation. However related risks can be compared to those of the other targets imaged by the MT and considered in the context of reservoir engineering economics, environmental impacts and regulatory constraints.

The Glass Mountain resource analysis and methodology outlined in this paper are more fully discussed in a draft report currently under review by the California Energy Commission. As improvements in multi-processor computing reduce the cost of 3D MT inversion, it has become a standard method of imaging MT resistivity surveys. The validation of the clay-oriented interpretation of geothermal resistivity data at Glass Mountain provides a conceptual basis for improving interpretations of resistivity data at geothermal fields in California. The release of the digital MT data and supporting geological information used for this project is directed at supporting tests of alternative analysis approaches and promoting continued integration of new data sets to further improve the interpretation of the Glass Mountain geothermal resource.

Acknowledgements

This study was supported, in part, by a California Energy Commission GRDA Resource Development Project, Grant No. GEO-02-007.

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