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Paper Title: The Structural Controls on the Medicine Lake Geothermal System

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☐ Draft Paper Rejected
☑ Draft Paper Accepted
  ☐ Oral Presentation
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  ☐ Both
  ☑ Publication in Transactions

Exploration Session
Wed 9/13/06

Comments: This paper describes the fractures in the Medicine Lake Resource Area very well
Also, it describes correlations between parameters such as density & depth.

Reviewer and Affiliation: Guy Nelson
Utility Geothermal Working Group

Date: May 8, '06

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Title The Structural Controls on the Medicine Lake Geothermal System
Theme Geology
Author(s) and Affiliations Clausen, Nemcok, Moore, Hulen (EGI), Stark, Beall (Calpine) Bartley (U of U)
Name of Speaker Steve Clausen
Title and Organization Energy & Geoscience Institute
☑ Student Paper

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The Structural Controls on the Medicine Lake Geothermal System

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Keywords: Cascade Range, volcanic hosted geothermal systems, fracture networks, Glass Mountain

Abstract

The volcanic rocks that host the geothermal system at Medicine Lake, California contain numerous fractures. Mechanically, the rocks can be separated into two groups. The first group is represented by brittle lava flows, which sustain fractures. The second group consists of tuffs and pyroclastic deposits, which are relatively incompetent and unfractured. Logging of fractures in six coreholes indicates that the degree of fracturing increases with depth in both types of lithologies. These data suggest that regional structures have played a major role in fracture formation at Medicine Lake.

Introduction

The Cascade Range of the Pacific Northwest has long been hosts a number of geothermal systems. Despite the abundance of young volcanic features and direct evidence of high temperatures, the geothermal systems of the region are poorly characterized and their development has progressed slowly. A major challenge to energy production in the region has been locating high permeability fracture zones in largely impermeable volcanic host rock. An understanding of these fracture networks will be one of the keys to harnessing these geothermal resources.

In this paper, we present an initial characterization of the fracture networks in the volcanic rocks that host the geothermal system at Medicine Lake Volcano. This site was selected for study because of the extensive collection of core samples and lithologic, structural, geophysical, and temperature data that is available. The sample collection totals about 15.8 km of core from 18 wells. Core samples are critical for this study because they allow characterization of fracture aperture, permeability, age relationships, and kinematics (e.g. Nemčok and Lisle, 1995; Nemčok and Gayer, 1996). Subsequent investigations will consider the effects of the regional in situ stress regime on fracture reactivation, aperture and ultimately permeability.

Geologic Setting

Medicine Lake Volcano is located on the eastern flank of the Cascade Range in northern California, approximately 50 km NE of Mt. Shasta (Fig. 1). The volcano is situated in the transition zone between the Cascade Range to the west and the extensional Basin and Range province to the east. A combination of active volcanism and crustal extension appear to control the anomalously high heat flow in the study area. Medicine Lake Volcano is located at the intersection of the NE-SW trending Mt. Shasta-Medicine Lake fault zone and the N-S trending Klamath Falls-Falls River Graben. These features are associated with a concentration of volcanic vents. Normal faulting is common locally and includes NW-SW striking basement faults. NE-SE striking faults are also present (Fig. 1).

The largest volcano by volume in the Cascades, Medicine Lake Volcano covers an area of 2000 km^2 and has a volume of 600 km^3 (Fig. 2; Donnelly-Nolan, 1988). The lower flanks of the volcano are dominated by basalt and basaltic-andesite flows, while the upper portions are predominantly andesitic and rhyolitic in composition (Donnelly-Nolan, 1988). Rhyolite flows include the impressive Glass Mountain flow for which the Glass Mountain Known Geothermal Resource Area (KGRA) is named. Many of these silica rich flows are very young, the last eruption of rhyolite occurring only 900 years ago.

Medicine Lake lies in a depression surrounded by a constructional ring formed by these young rhyolite flows. Evidence from drilling shows very little ash flow tuff present within this depression. This suggests that classic caldera collapse is unlikely (Hulen and Lutz, 1999).

Most of the production wells drilled to date at Medicine Lake Volcano are located SE of Medicine Lake at Telephone Flat (Fig. 1 and 3). This area sits at the intersection of the depression and NE-SW trending faults. Deep wells located NW of the lake at Four Mile Hill encountered lower temperatures. This area also sits at the intersection of the depression and NE-SW trending faults.

Methodology

This study presents a progress report on structural and lithologic investigations being conducted on the core holes. Investigations have been completed on six wells, three located within the Medicine Lake depression and three outside (Fig. 1). The wells were prioritized on the basis of temperature, depth, proximity to mapped faults and whether they lay inside or outside the Medicine Lake depression. Temperature and depth data were provided by Calpine Corporation.

Each of the wells had been continuously cored with nearly 100% recovery. This provided an uninterrupted sample from top to bottom. Rock type, fracture density, degree of pore-filling, the pore and fracture filling mineralogy, fracture dip angle, rake of the slickensides and evidence of fracture reactivation were recorded. Mineralized surfaces and those with slickensides were presumed to be natural fractures; fresh surfaces were presumed to be drilling induced. Drilling induced fractures were not included in the data set presented in this study. Thus, some of the natural fractures, which lack slickensides or mineralization, may not be represented in the data set. Because the core was not oriented at the time of drilling, selected samples were taken for paleomagnetic orientation for further studies.

Data was obtained on over 500 fractures. The fracture data is compiled in Figure 4 as histograms with a bin size of 25 m.

Results

Figure 4 illustrates the difference in fracture density between the lava flows and tuffs or pyroclastic deposits. The volcanic deposits were divided into these two groups because of the differences in their rheologies. Deposits of poorly welded or non-welded tuff, ash and debris flows have deformed penetratively and contain few fractures. In contrast, the denser, more rigid lava flows responded to the stresses in a much more brittle manner. Both groups display higher fracture densities with increasing depth

Of the approximately 500 fractures logged, many exhibited slickensides. The relative motion on the vast majority of fractures is dip slip, but fractures with strike slip and oblique slip displacement are also present in each well. Paleomagnetic orientations will be used to obtain the exact orientations of selected fractures.

Matrix vs. Fracture Permeability

Although no major fluid entries were encountered in the coreholes, permeable zones are indicated by temperature reversals in two wells, 88-28 and 87-13. Logging of these wells indicates that these zones of higher permeability are fracture zones in dense lava flows. These fractures are have been mineralized, but the channel ways have not been completely sealed.

Many of the lava flows are characterized by vesicular tops and flow breccias at their base. Despite the high porosities of these zones, mineralization is typically only weakly developed, particularly in the upper portions of the coreholes. In 88-28, the most intensely mineralized of the wells studied, the degree of filling increases with depth and vesicles below about 750 m are completely filled. However, vesicles in lava flows in 87-13, a deeper corehole are only partially filled to total depth. We infer from these observations that despite the high porosities of these zones, they are poorly connected across the field and that the fractures serve as the primary conduits for fluid

Mechanical Stratigraphy

Strong correlations were found between fracture density, lithology and depth in the Medicine Lake Volcano cores (Fig. 4). The dense, brittle lava flows sustained the majority of the fracturing. In contrast, the tuffs and pyroclastic deposits sustained relatively little fracturing. Thus the lava flows must serve as the primary hosts for the reservoir fluids, whereas the less competent tuffs and pyroclastic deposits act as intervening barriers to upward flow.

Fracture density increases with depth in each of the studied wells. Because the stress necessary to fracture rock increases with depth, it can be assumed that the modern day stress regime is not responsible for the increase in fracturing with depth. A more likely hypothesis is the difference in tectonic history between older rocks at depth and younger deposits near the surface. Because of the volcano's proximity to both the extensional regime of the Basin and Range to the east and the compressional regime to the west, it is likely that tectonic conditions and the local stress regime have varied significantly during the recent past. Thus deeper and older rocks may have undergone more fracturing than younger, shallower deposits. Further study is required to test this hypothesis.

Conclusions

The major conclusions of this study are:

1. Permeability in the system is fracture controlled.
2. There is a positive correlation between fracture density and the extent of pore mineralization.
3. Competent lava flows contain numerous fractures whereas incompetent tuffs and pyroclastic deposits do not.
4. Fracture density increases with depth and therefore age of the rocks.

Acknowledgments

This research was funded by the Department of Energy under contract.DE-FG36-04GO14298. We thank the management of Calpine Corporation for generously making the results of geoscientific studies on Medicine Lake Volcano available to us for study. Mitch Stark, Joe Beall and Julie Donnelly-Nolan generously shared their knowledge of the area with us.

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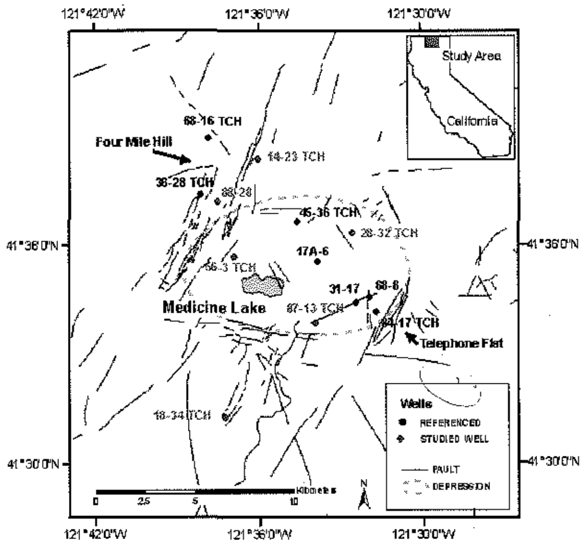

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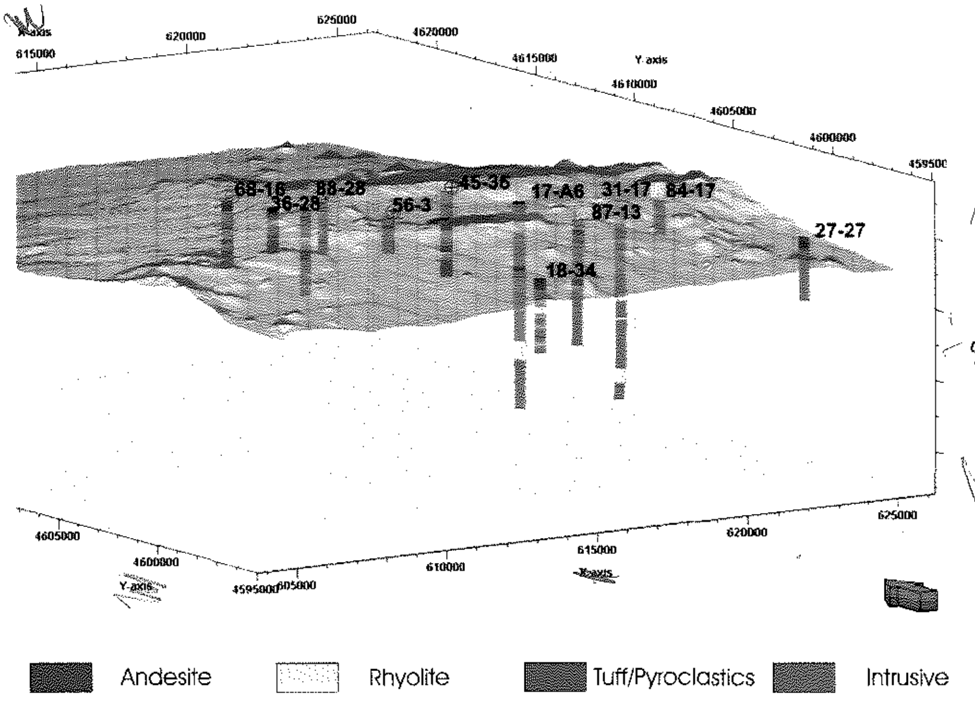
Figure 1: Map of the Glass Mountain KGRA, Medicine Lake, California illustrating the locations of the major faults and key wells. For clarity, not all of the wells drilled in the area are shown.



SL elevation (masl)

Figure 2: View of the study area looking northeast. Lithologic logs of study well are displayed along the well traces.

15
95

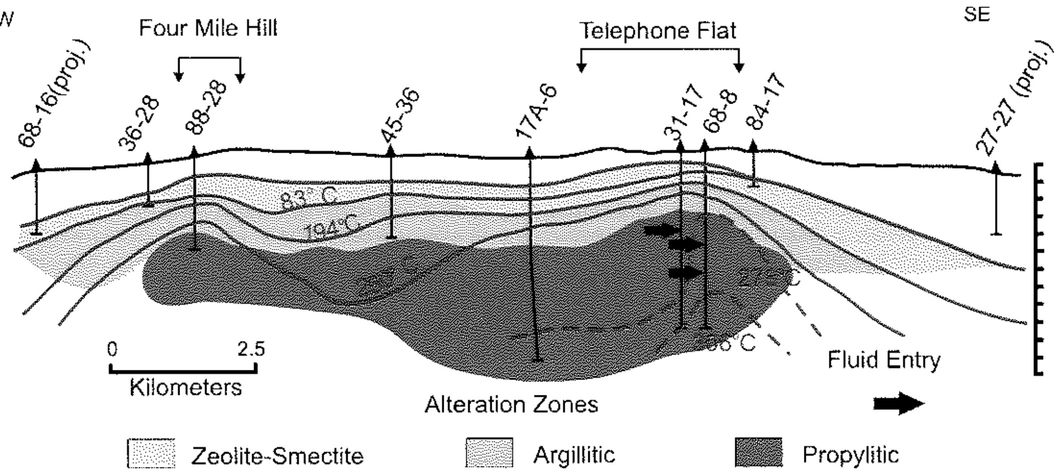


Figure 3: NW-SE cross section through the Medicine Lake geothermal system showing measured temperatures and mineral zones. Major fault zones cross the section at Four Mile Hill and Telephone Flat.

NE-trending

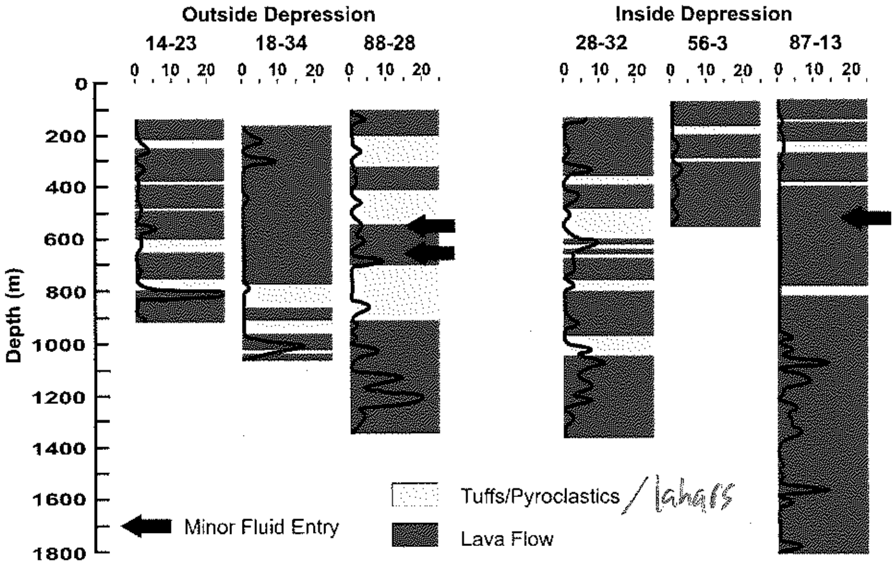


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Figure 4: A histogram of fracture densities as a function of depth is shown in blue. Lava flows are shown in green; tuffs and pyroclastic deposits in yellow. 14-23, 88-28 and 18-34 are located outside the Medicine Lake depression. 56-3, 87-13 and 28-32 are located within the depression.

log begin at the
Depth ~~dat~~ top of
cored section