IS ON LIST

PROCEEDINGS, Twenty-Fifth Workshop on Geothermal Reservoir Engineering
Stanford University, Stanford, California, January 24-26, 2000
SGP-TR-165

ALTERATION, GEOTHERMOMETRY, AND GRANITOID INTRUSIONS IN WELL GMF 31-17, MEDICINE LAKE VOLCANO GEOTHERMAL SYSTEM, CALIFORNIA

Susan Juch Lutz[1], Jeffrey B. Hulen[1], and Alexander Schriener Jr.[2]

1. Energy & Geoscience Institute, 423 Wakara Way, Salt Lake City UT 84108 U.S.A, e-mail: sjlutz@egi.utah.edu
2. CalEnergy Company, Inc., 950 West Lindsey Rd., Calipatria, CA 92233

ABSTRACT

Glass Mountain Federal 31-17, with a total depth (TD) of 2678 m, is one of three deep geothermal wells capable of commercial production at the summit of the large, Pleistocene-Holocene, Medicine Lake shield volcano, on the eastern flank of the Cascade Range in northeastern California. Well 31-17 encountered strong flows of high-temperature (up to 260°C) geothermal fluids in intensely propylitized Quaternary volcanics. The volcanic sequence is dominated by basalt and basaltic andesite, but includes some zones of rhyolite and dacite in the upper 900 m of the well. From 2460 m to TD, the mafic volcanics are contact metamorphosed and intruded by hornblende quartz diorite. The quartz diorite is probably part of a larger pluton that floors the active geothermal system. Hydrothermal alteration in well 31-17 shows a distinct vertical zonation, with an uppermost zeolite-smectite zone above a thick and intense argillic zone, which in turn overlies the propylitic production zone. Modern temperature logs for the well show a cool isothermal interval through the zeolite-smectite zone, a steep conductive interval (up to 500°C/km) through the argillic zone (the cap on the geothermal system), and a near-isothermal (at about 250°C) zone to total depth in the propylitic interval. Fluid-inclusion temperature data (from low-salinity inclusions) show two distinct trends; one resembling the modern temperature profile; another reaching maxima of 373°C and also exceeding, by up to 20°C, temperatures appropriate for a boiling point curve emanating from the modern water table. These fluid-inclusion thermal maxima, the curve they roughly define, and the presence of deep, high-temperature alteration phases like actinolite, clinopyroxene, talc, and biotite virtually mandate that the corresponding temperature regime was supported by a large, cooling pluton. If this igneous body is sufficiently young and large, it is also the likely still-cooling heat source for the modern geothermal system.

INTRODUCTION

Medicine Lake volcano (MLV) is a massive, Pleistocene-Holocene shield volcano situated on the eastern flank of the Cascade Range in northeastern California (Fig. 1). The volcano hosts a large, active, high-temperature (up to 288°C; Iovenitti and Hill, 1997), liquid-dominated geothermal system now being evaluated by CalEnergy and Calpine Corporations (Richard et al., 1998). The system is perhaps the most promising, currently undeveloped, electrical-grade geothermal resource in the contiguous United States.

Despite its size and high temperature, the MLV geothermal system is nearly devoid of surficial manifestations (Iovenitti and Hill, 1997). Initial interest in the property was spurred mainly by the presence of voluminous Holocene rhyolites, as possible evidence for a concealed and still-cooling felsic plutonic heat source. During the 1980s, a thermal-gradient drilling program outlined a 10 x 7 km thermal anomaly centered on the volcano's broad, shallow summit depression. On the basis of the program's encouraging results, four deep, production-scale exploration wells were subsequently drilled within the thermal anomaly (Fig. 1): GMF 68-8, 87-13, and 31-17, as well as ML 17A-6. The latter two boreholes are featured on the cross-section of Figure 2.

With support from the Department of Energy (Office of Geothermal and Wind Technologies), the Energy & Geoscience Institute (EGI) is working closely with CalEnergy and Calpine to refine and expand these companies' already detailed geologic and thermohydrologic characterization and modeling of the MLV system. The aim of the study is improved understanding -- for more cost-efficient and environmentally-sound exploration and development -- not only of this particular resource but of similar systems anywhere on the planet. Our inaugural study of the MLV system was focused on the nature, origin, and controls of the essentially impermeable hydrothermal caprock on the system (Hulen and Lutz, 1999). This account introduced, but did not elaborate upon, the characteristics of the deeper, hotter system penetrated by the four production-scale wells. Utilizing the results of petrographic examination, X-ray diffraction (XRD), secondary-mineral geothermometry, and fluid-inclusion microthermometry of cuttings and

Strat, alteration, temp
X-Sections

core samples from well 31-17, we herein enlarge upon the earlier study to explore the deeper reaches of the MLV system. The focus of this investigation is on hydrothermal alteration mineralogy and zoning, documented for other parts of the system by Bargar and Keith (1999), as well as Hulen and Lutz (1999). We also examine the intriguing granitoid intrusions encountered not only deep in this well but in neighboring 17A-6 (see also Lowenstern et al., 1998), and speculate about the potential role of the plutons in powering the volcano's still actively convecting geothermal system.

GEOLOGIC SETTING

MLV is situated on the eastern flank of the Cascade Range where these mountains adjoin the western Basin and Range Province in northeastern California. The volcano is the largest in the Cascade Range, surpassing in volume even neighboring Mt. Shasta and Mt. Lassen. MLV is situated atop the Modoc Plateau, a broad volcanic highland developed in the extensional environment of the Cascade/Basin-Range transition zone. As documented by Donnelly-Nolan (1988 and 1990), the lower flanks of MLV are dominated by basalt and basaltic andesite. Higher on the volcano, however, high-silica lavas are common, including the Holocene (1,000a) Glass Mountain rhyolite (Fig. 1). Several other youthful volcanic centers of basaltic through rhyolitic composition form a discontinuous, constructional rim enclosing the MLV summit depression (Fig. 2). Donnelly-Nolan (1988) has suggested that the rim-and-depression topography signals the presence of a broad caldera at the crest of MLV. Drilling results, however, show that in spite of the obvious ring-fracture volcanism, there is little evidence of wholesale caldera collapse (Hulen and Lutz, 1999).

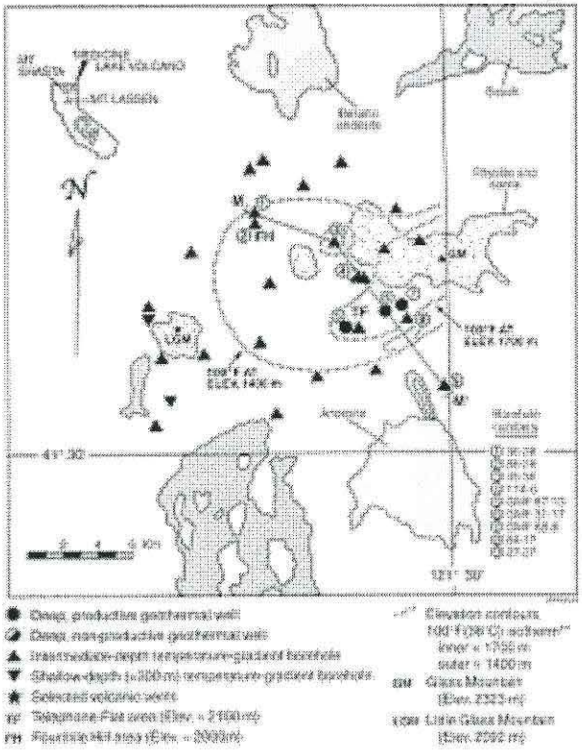

Fig. 1. Location map showing a portion of the Medicine Lake volcano, encompassing its summit depression and associated thermal anomaly, as well as the Telephone Flat and Fourmile Hill geothermal project areas. Patterned areas are Holocene volcanics, including the 1,000 year-old Glass Mountain flow. Deep production well GMF 31-17 is located in the center of Telephone Flat, inside the 100°F-at-1700m elevation contour.

Exploration drilling has revealed extensive sheets of rhyolitic to dacitic volcanic rocks, in the depth range 100 to 1100 m (Fig. 2), that are not widely exposed at the surface. This relationship could in part reflect concealment by surficial deposits, or could indicate

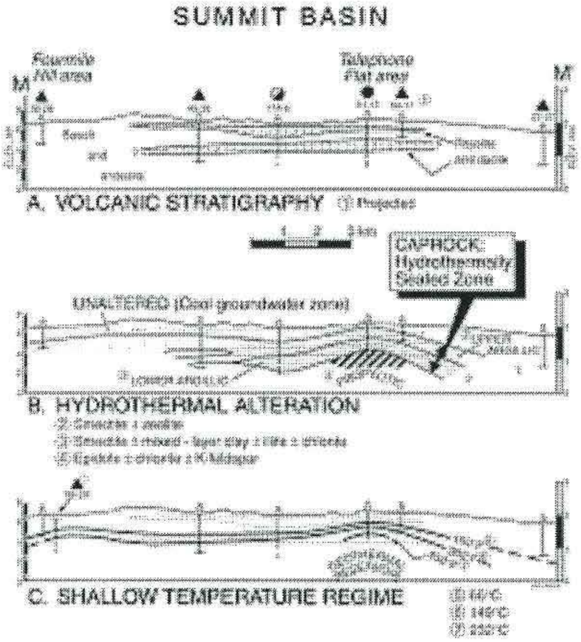

Fig. 2. Stratigraphic, alteration, and temperature cross-sections through upper portion of Medicine Lake volcano. A – Highly simplified Quaternary volcanic stratigraphy. The section is dominated by basalt, basaltic andesite, and andesite, but includes tongues of rhyolitic and dacitic flow, dome, and pyroclastic rock in the upper 1000 m of the wells. B – Generalized hydrothermal zoning in shallow portions of the boreholes. The key feature is a thick impermeable, argillic zone that inhibits the escape of hot waters from the underlying geothermal reservoir. C – Isothermal cross-section. The geothermal system intersected in well 31-17 reaches a temperature of about 275°C.

localized distribution of the felsic units as viscous flow-dome complexes and subvolcanic intrusions.

THE GEOTHERMAL SYSTEM

Three wells in the Telephone Flat area of the summit depression (Fig. 1) tap a high-temperature, liquid-dominated geothermal reservoir capable of commercial production. Thermal waters of the reservoir are unusually benign, with total-dissolved-solid and non-condensible gas contents averaging only 2500 ppm by weight (Iovenitti and Hill, 1997). A shallow, perched, cool groundwater zone masks the deep hot geothermal reservoir (Iovenitti and Hill, *ibid.*), apparently separated from that reservoir by an essentially impermeable caprock of argillic alteration (Hulen and Lutz, 1999; Fig. 2). The groundwater zone, generally extending to a depth of 200-400 m, is characterized by near-isothermal cool temperatures (<50°C). The argillically sealed caprock is marked by very steep conductive thermal gradients, up to at least 500°C/km. The underlying convective geothermal system, like the caprock, is essentially isothermal to great depth (at least 2600 m) but at temperatures at or above 250°C.

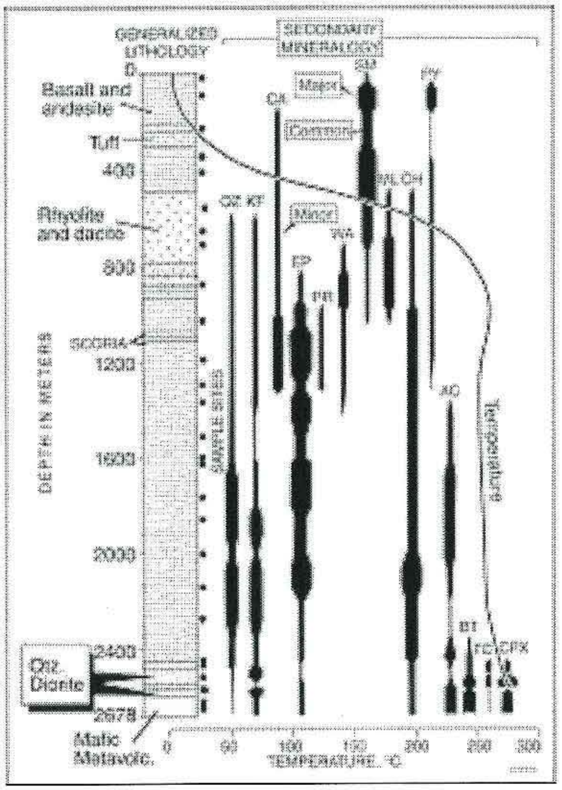

Fig. 3. Generalized lithologic column, distribution of hydrothermal alteration minerals, and measured wellbore temperatures in Medicine Lake volcano geothermal well 31-17. QZ = quartz, KF = potassium felspar, CA = calcite, EP = epidote, PR = prehnite, WA = wairakite, SM = smectite, ML = mixed-layer illite-smectite, CH = chlorite and chlorite-smectite, PY = pyrite, AC = actinolite, BT = biotite, TC = talc, CPX = clinopyroxene. Major = 15-50%; Common = 5-15%; Minor = 1-5%; thin vertical lines = tr-1% (Lithology by Hulen, Lutz, and Unocal Geothermal)

GEOTHERMAL WELL GMF 31-17

Temperature Regime – A static temperature profile for well GMF 31-17, provided for this investigation by CalEnergy Corporation, is typical for the four deep production-scale geothermal wells completed to date (Fig. 3). The profile is slightly different than a more recent and detailed profile completed in 1998 by the U.S. Geological Survey (see Williams and Grubb, this volume), but the broader features of the earlier and later profiles are reasonably comparable. The thermal profile of Figure 3 shows the characteristic MLV shallow, near-isothermal profile above a steep conductive leg, in turn above a thick and essentially isothermal interval. As documented by Hulen and Lutz (1999), and discussed in more detail below, the steep conductive segment of the profile corresponds to a zone of particularly intense argillic alteration, the MLV system's functionally impermeable caprock.

Stratigraphy and Lithology – The complex volcanic sequence penetrated by well GMF 31-17 is typical of the stratigraphy for the summit depression of MLV (Figs. 2 and 3). The well penetrates principally basalts, basaltic andesites, and andesites. The original mafic mineralogy is commonly obscured by hydrothermal alteration; however, unaltered chips contain various amounts of primary clinopyroxene and orthopyroxene. Below a depth of about 1400 m, the grain size of these mafic volcanics increases; diabasic textures are common; and most of these rocks can be described as microdiabase and microdiorite. Some of the coarser varieties may represent subvolcanic intrusives.

Between about 200 m and 900 m depth, the mafic volcanics of 31-17 are interstratified with felsic volcanic rocks, including flows, tuffs, and possibly subvolcanic intrusives. As noted above, the extent and thickness of these felsic units in the subsurface is not duplicated in outcrop on the flanks of the volcano. Geochemical analyses and major-element oxide contents of selected, fresher samples (all are at least slightly altered) confirms the felsic nature of these rocks. On the total alkali vs silica plot of Le Bas et al. (1986; Fig. 4), four of these samples plotted solidly within the dacite to rhyolite fields (up to 73% SiO_2; 9.4% K_2O plus Na_2O). Textures of these felsic volcanics are commonly cryptocrystalline to microcrystalline, with spherulitic devitrification and relict

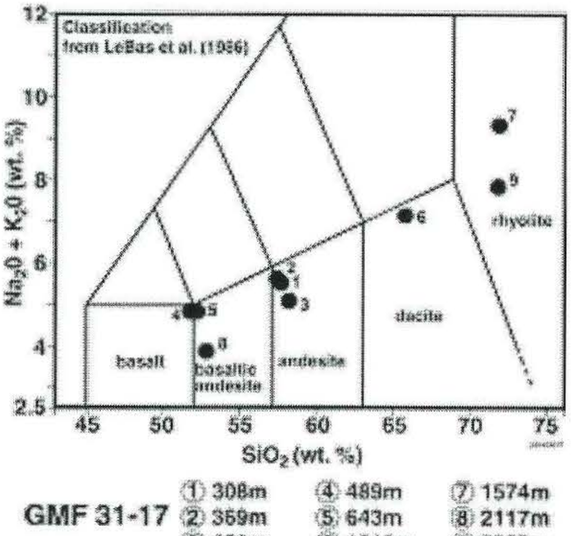

Fig. 4. Classification of volcanic rocks based on whole-rock chemical analyses of selected, weakly altered samples from well 31-17 (data from CalEnergy).

perlitic cracks. These textures suggest that at least part of the felsic sequence cooled quickly to glass in surficial volcanic deposits.

Between 2460 m and TD at 2678 m, well GMF 31-17 penetrated alternating intervals of mafic metavolcanics and hornblende quartz diorite. The metavolcanics are compositionally equivalent to the basalts and basaltic andesites higher in the borehole, but have been recrystallized (with microdiabasic textures preserved) extensively to clinopyroxene, orthopyroxene, biotite (relatively coarse and porphyroblastic), and ilmenite with minor garnet. It is likely that the plagioclase, though texturally preserved from its primary configuration, has been converted to a more sodic variety.

The quartz diorite intrusions in the metavolcanic interval are medium-crystalline, subhedral-granular aggregates of plagioclase and quartz with minor hornblende; an unknown altered mafic mineral; minor ilmenite and primary K-feldspar; accessory apatite; and a trace of zircon. K-feldspar actually accounts for 15-23% of these intrusions, and if it were primary, the rocks would be quartz monzodiorites (Fig. 5). However, the distinctive texture of most of the K-feldspar (see below) suggests that it is a replacement phase and that the appropriate designation for this granitoid is quartz diorite.

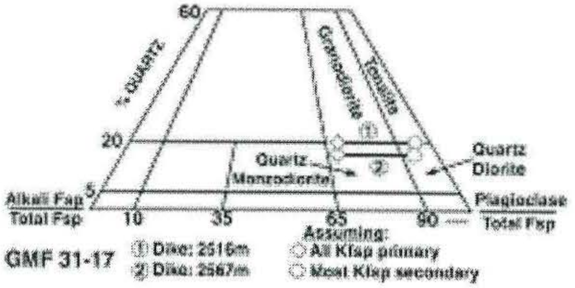

Fig. 5. Classification of granitoid intrusions from well 31-17 using mineralogical compositions for felsic to intermediate plutonic rocks. Unaltered samples plot as quartz diorite with less than 10% primary potassium feldspar. Potassically altered samples contain up to 23 wt% potassium feldspar (semi-quantitative X-ray diffraction analyses).

Hydrothermal Alteration – The entire rock column penetrated by 31-17 is moderately to intensely hydrothermally altered, and in well-zoned assemblages with depth (Fig. 3). In common with other deep wells in MLV, 31-17 encountered three dominant alteration zones, from the top down: (1) zeolite-smectite; (2) argillic; and (3) propylitic. In addition, the deep quartz diorite intrusions are potassically altered. Bargar and Keith (1999) provided detailed descriptions of the zeolite-smectite and argillic zones in non-productive thermal-gradient coreholes of MLV. These authors also described the very top of the propylitic zone in the lower reaches of summit-depression corehole ML 28-32 (not shown on Figure 1).

The zeolite-smectite zone is characterized by weak to moderate alteration of the volcanic host rocks to various combinations and textures of smectite, calcite and other carbonates, and the zeolites heulandite, laumontite, and mordenite; hematite and chalcedony are locally present (Hulen and Lutz,1999; Bargar and Keith, 1999). The argillic zone provides the essential top-seal, or caprock, on the MLV geothermal system. The smectites (saponite and montmorillonite), commonly account for >20% of the rock and are the key alteration phases of the argillic zone. Minor and variable amounts of quartz, calcite and other carbonates, pyrite and hematite are also present. Mixed-layer clays (illite/smectite, chlorite/smectite), and chlorite accompany the smectite in the deeper part of the argillic zone.

The downward transition from the argillic to the propylitic zone in GMF 31-17 is relatively abrupt, coinciding with the base of a thick dacite to rhyolite interval (at about 800 m depth) and with the change from a steeply conductive to a hot-isothermal profile (Fig. 3). These relationships suggest that the caprock may be controlled both by lithology (chemically unstable or glassy felsic volcanics), and the alteration mineralogy (abundant swelling clays).

As in volcanic-hosted geothermal systems worldwide, epidote (pistacite) is the key propylitic alteration phase in well 31-17. The epidote replaces plagioclase as well as mafics in combination with other secondary phases, and is particularly abundant as a vesicle-filling mineral, forming epidote amygdules locally accounting for 25% of the affected rock. Chlorite, the other dominant propylitic mineral, preferentially replaces original mafic constituents. In the groundmass of the altered volcanic rocks, particularly the mafic varieties, chlorite is usually accompanied by microcrystalline leucoxene (unresolvable titanite-anatase mixture) of secondary origin. Fibrous actinolite makes its appearance in the propylitic zone at a depth of about 1350 m in well 31-17, and remains present to the bottom of the borehole. Prehnite and wairakite are confined to the upper reaches of the propylitic zone (Fig. 3), whereas minor to moderate amounts of secondary quartz and potassium feldspar are more dominant in the lower half of the zone. Traces of pumpellyite are found in a chloritic gouge at about 1550 m.

Below about 2400 m depth, the alteration can best be described as weak to moderate potassic, superimposed (in the case of metavolcanics, Fig. 3) on metamorphic recrystallization. In the metavolcanics, the principal potassic alteration phase is microcrystalline, brownish-green, secondary biotite, occurring as an alteration product of pyroxenes, actinolite, and plagioclase, and also occurring with those phases and quartz in irregular veinlets. Secondary biotite is also present in the quartz diorite, but seldom accounts for more than 3-4% of the rock. In these plutonic rocks, secondary potassium feldspar is the main potassic phase. The Kspar forms thick, irregular rims, possibly replacing albite, on primary plagioclase crystals. The Kspar is turbid and "clouded" with vapor-rich fluid inclusions. Thin veinlets of this feldspar are also locally present. Actinolite replaces both primary hornblende in the quartz diorite, and an unknown former mafic constituent that was most likely a pyroxene.

Fluid-Inclusion Microthermometry- Fluid-inclusion homogenization-temperature ranges for selected vein samples from GMF 31-17 are presented in Figure 6. The data were collected by J. Reynolds, of Fluid Inc., in 1989, and were provided for this investigation by CalEnergy. The data are plotted at the sampling depths relative to modern measured temperatures and to a reference boiling-point curve emanating from the modern base of the cool groundwater zone (about 350 m depth) in this part of the MLV summit depression.

With a few notable exceptions, these fluid inclusions (primary, for the most part, in quartz and epidote) contained dilute aqueous fluids (<0.8 wt % NaCl equivalent) and homogenized to the liquid phase upon heating to the appropriate temperature. Although comparable in apparent salinity, homogenization temperatures (T_h) for these inclusions plot distinctly into two different groups (I and II; Fig. 6). Group I inclusion T_h closely track the modern measured temperature profile (and mimic the more recent temperature log of Williams and Grubb [this volume] even more faithfully). Hypersaline inclusions (group III; Fig. 6) with T_h >400°C were found as secondary inclusions in vein quartz at a depth of 1170 m. Hypersaline secondary inclusions were also noted and photographed for this investigation in primary quartz in the quartz diorite intrusions toward the bottom of the borehole; these are three-phase (liquid-vapor-halite) and are comparatively rare, accompanying the prevalent single-phase-vapor secondary inclusions in the intrusions.

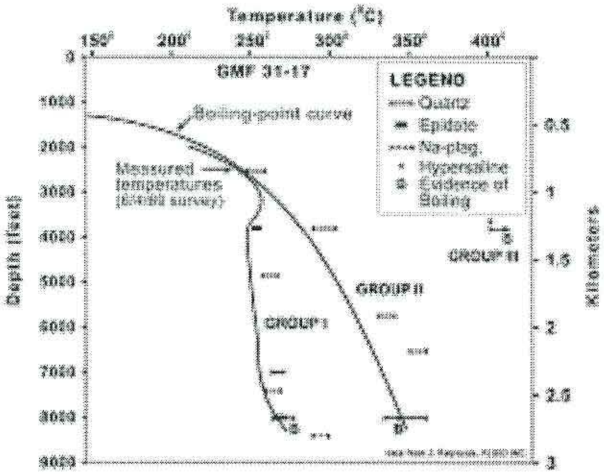

Fig. 6. Fluid-inclusion homogenization temperatures, measured well temperatures (June 4, 1989 survey), and a reference boiling-point curve using the modern water table elevation (about 350 m) for well GMF 31-17.

DISCUSSION AND CONCLUSIONS

Hydrothermal alteration mineralogy and zoning in well GMF 31-17, when compared with modern measured temperatures and fluid-inclusion homogenization temperatures, support the following conclusions, interpretations, and speculations:

> 1 – The impressive present-day temperature regime below the MLV argillic caprock is nonetheless considerably cooler than thermal maxima in the modern reservoir interval as indicated both by temperature-sensitive secondary minerals and by fluid-inclusion T_h. As an example, the first appearance of actinolite in the well, at a depth of about 1382 m, should correspond to a minimum temperature of about 290°C (e.g., Browne, 1996). The modern temperature at this depth is 250°C, and the maximum value extrapolated from fluid-inclusion T_h is close to 310°C (Fig. 6).

2 – The dramatic cooling indicated by the foregoing relationships – perhaps up to 90°C at deeper levels – is curiously not recorded as a continuum by the fluid-inclusion data. The data clearly plot into two discrete paleotemperature trends. The reasons for the discontinuity remain to be determined.

3 – The highest temperatures implied by hydrothermal phases such as actinolite, secondary biotite, clinopyroxene, and talc (>300°C;), and by fluid-inclusion T_h maxima (as high as 373°C, Fig. 6) that systematically increase with depth, strongly suggest that the requisite heat was supplied by a large cooling pluton (e.g., Norton, 1979). The quartz diorite intrusions in GMF 31-17 are relatively small, but nearby well ML 17A-6 penetrates several hundred meters of similar plutonic rock (see also Lowenstern et al., 1998). If the postulated stock beneath the Medicine Lake geothermal system is sufficiently young (say, <500,000 yr depending upon its bulk), then it is probably the still-cooling heat source that supports the active MLV geothermal system. Confirmation of this supposition would require rigorous mathematical modeling of heat and mass transfer within and around the cooling pluton.

4 – The thermal profile interpolated from the fluid-inclusion T_h maxima approximates the shape of a boiling point curve (Fig. 6). However, this curve exceeds, by up to 20°C, the analogous curve appropriate for the geothermal system's contemporary water table (discounting higher-elevation "perched" water tables) about 350 m below modern ground level. The simplest explanation for this discrepancy is that the water table was correspondingly higher when the high-T_h fluid inclusions were entrapped.

Bargar and Keith (1999) noted that some fluid-inclusion T_h for other, generally shallower, MLV boreholes plotted well above the reference boiling curve even for the modern ground surface (not the case for GMF 31-17). They plausibly explained this discrepancy by suggesting that 150 m of Pleistocene glacial ice supplied the requisite additional fluid pressures.

ACKNOWLEDGEMENTS

This research is being funded by the Department of Energy, Office of Geothermal and Wind Technologies (Grant No. DE-FG07-001D13891). We greatly appreciate the enthusiastic support of CalEnergy and Calpine Corporations; these companies' generous donation of valuable cuttings and core samples as well as subsurface temperature and other reservoir data; and CalEnergy's permission to publish this paper. The characteristically detailed and insightful alteration and fluid-inclusion work of Keith Bargar and Terry Keith (U.S. Geological Survey) at MLV laid a firm foundation for this investigation. Louise Spann completed X-ray diffractometry of the cuttings and core samples. Brad Didericksen and Ron Wilson prepared the illustrations.

REFERENCES

Bargar, K.E., and Keith, T.E.C., 1999, Estimated temperatures for geothermal drill holes at Medicine Lake volcano, northeastern California, based on fluid-inclusion and hydrothermal mineralogy studies: U.S. Geological Survey, Open-File Report 97-716 (released June 1999), 116 p.

Browne, P.R.L., 1996, Hydrothermal alteration: Auckland, New Zealand, University of Auckland, Geothermal Institute, Lecture Series Handbook, 66 p.

Donnelly-Nolan, J.M., 1988, A magmatic model of the Medicine Lake volcano, California: Journal of Geophysical Research, v. 93, p. 4412-4420.

Donnelly-Nolan, J.M., 1990, Geology of Medicine Lake volcano, northern California Cascade Range: Geothermal Resources Council, Transactions, v. 14, pt. II, p. 1395-1396.

Hulen, J.B., and Lutz, S.J., 1999, Altered volcanic rocks as hydrologic seals on the geothermal system of Medicine Lake volcano, California: Geothermal Resources Council Bulletin, v. 7, September/October, p. 217-222.

Iovenitti, J.L., and Hill, D.G., 1997, Baseline hydrogeology evaluation report for the Telephone Flat project, Medicine Lake, California: Emeryville, California, Weiss Associates, Report prepared for CalEnergy Corporation (August 20, 1997), 34 p. plus illustrations and appendices.

LeBas, M.J., Le Maitre, R.W., Streckeisen, A., and Zenetti, B., 1986, A chemical classification of volcanic rocks based on the total alkali-silica diagram: Journal of Petrology, v. 27, p. 745-750.

Lowenstern, J.B., Donnelly-Nolan, J.M., and Grove, T.L., 1998, Granite inclusions in Holocene lavas of Medicine Lake volcano, California, USA – Clues to subsurface geology:

IAVCEI, Abstracts Volume, Capetown, South Africa, July 1998, p. 36.

Norton, D.L., 1979, Transport phenomena in hydrothermal systems – The redistribution of chemical components around cooling magmas: Bulletin Mineralogie, v. 102, p. 472-486.

Richard, M., Shuster, D., and McClain, D., 1998, Medicine Lake milestones: Geothermal Resources Council Bulletin, April/May, p. 70-75.

Williams, C.F., and Grubb, F.V., 2000, Thermal constraints on the sealing efficiency of the caprock overlying the Medicine Lake hydrothermal system: Stanford University, 25th Workshop on Geothermal Reservoir Engineering, Proceedings (this volume).