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Like other volcanic-hosted, high-temperature geothermal systems, the one now active in the Quaternary Medicine Lake Volcano (MLV), northeastern California, is capped by hydrothermally altered and mineralized rock which serves as a hydrologic seal. This natural cap, up to a kilometer thick, helps preserve the integrity of the system by retarding the escape of thermal energy, and by impeding the influx of surrounding and overlying cool groundwaters. It is an essential feature of the MLV system, within which California Energy General Corp. (CalEnergy, a subsidiary of MidAmerican Energy Holding Co.) and Calpine Corp. have delineated sizable sectors for electric-power production.

The MLV cap is an argilllic alteration feature, dominated by montmorillonite and saponite. These smectite-group swelling clays together locally account for more than a third of the cap-rock volume (some tuffaceous units are entirely argillized). The smectites are accompanied variously by zeolites (at higher elevations), chlorite (at deeper levels), mixed-layer clays, illite, calcite, hematite, and pyrite. These minerals replace original volcanic glass, feldspar, and ferromagnesian phases, but more importantly they plug fractures which otherwise could be throughgoing fluid conduits.

Smectites are components of the most effective geothermal cap-rocks. Unlike brittle minerals such as calcite, these clays tend to flex rather than break when stressed, enabling caps to withstand tectonic disruption. Saponite-family smectites like those in the MLV cap-rock have an added advantage. They are stable to at least 300°C, rendering them, once precipitated, all but impervious to natural or production-induced thermal perturbations.

Introduction

MLV, a massive Quaternary edifice just east of the Cascade Range in northern California (Fig. 1), hosts a large, active, high-temperature (up to 288°C; Iovenitti and Hill, 1997) geothermal system,* now being evaluated by CalEnergy and Calpine (Richard et al., 1998). This system is one of the most promising currently undeveloped geothermal resources in the contiguous United States.

Despite its size and high temperature, the MLV system has almost no active surface expression. It was targeted by various geothermal exploration companies during the early 1980s (Richard et al., 1998) primarily on the basis of its abundant Holocene felsic volcanics, providing possible evidence for a still-cooling plutonic heat source (Smith and Shaw, 1979). Twenty-six temperature-gradient boreholes (Fig. 1) outlined a 10 x 7 km thermal anomaly. Results of the drilling program, along with a detailed geological, geophysical, and geochemical assessment of the MLV, were used between 1985 and 1991 to guide the siting and drilling of four production-scale exploration wells in the volcano’s shallow summit depression (Fig. 1). Three of these wells, in the Telephone Flat area, produced

*As defined for this article, and modified from Hochstein (1990), the Medicine Lake geothermal system encompasses the entire volume of rock directly or indirectly affected by convecting hot waters transferring heat from a source (a cooling pluton) to a sink (ultimately, the free surface). The cap on the system is its essentially impermeable outer envelope, or shell, through which heat travels outward principally by conduction. The geothermal reservoir is the permeable portion of the system that is capable of commercial thermal-fluid production.
Geothermal fluids at temperatures and flow rates favorable for electric-power generation (Iovenitti and Hill, 1997).

CalEnergy and Calpine have proposed to install geothermal power plants at MLV, with the former’s Telephone Flat facility to be rated at 48.8 megawatts (MW) (Iovenitti and Hill, 1997). The Energy & Geoscience Institute (EGI - University of Utah), with support from the U.S. Department of Energy’s (DOE) Office of Geothermal Technologies, is completing a detailed geologic characterization of the resource, designed not only to assist CalEnergy and Calpine in optimizing their exploration and development of the MLV geothermal system, but also to benefit the entire geothermal community by improving understanding of such volcanic-hosted systems anywhere in the world.

The first phase of the EGI research program has centered on understanding one of the system’s most essential features, a largely impermeable, clay-rich alteration zone which envelops the system and helps isolate it hydrologically from surrounding, nongeothermal groundwaters more typical of the region as a whole. Additional research in the near-term will encompass three-dimensional lithologic, structural, and alteration mapping of the deeper MLV subsurface, with emphasis on the productive geothermal reservoir identified in the Telephone Flat area.

Regional & Local Geologic Setting

The Quaternary MLV is the largest in or adjacent to the Cascade mountain chain, surpassing in bulk even the neighboring, more conspicuous, and higher-elevation volcanoes Lassen and Shasta (Fig. 1). MLV is a shield-shaped feature covering nearly 2000 km², and its relatively subdued topography belies an estimated volume of 600 km³ (Donnelly-Nolan, 1990). The summit of MLV (elev. 2.4 km) stands about 1.3 km above the surrounding terrain as a one km-wide volcanic rim or rampart encircling a shallow elliptical basin 6 x 4 km in area (Figs. 1 and 2). Anderson (1941) and Donnelly-Nolan (1988, 1990) interpreted this rim-and-basin topography as likely reflecting caldera collapse. Deep drilling (up to 3000 m), however, has shown that the major contact between the MLV sequence and the underlying Pleistocene-Miocene (?) basaltic succession is not obviously offset across the rim. Rather than reflecting caldera collapse, the summit basin is the result of constructive volcanism around its rim (A. Schriener, Jr., personal communication, 1999).

The summit rim of MLV is the highest feature in the Modoc Plateau, a regional landform developed on the thick, monotonous, Warner basalt sequence (one age date, about 1 Ma; Thompson, 1981), in turn resting upon the Miocene Cedarville-series basalts.
The Geothermal System

The Hot Spot, a small area of heated ground on the western flank of 1,000 year-old Glass Mountain, is the sole, obvious surface indication of the large, concealed, active geothermal system delineated by 26 temperature-gradient boreholes and four geothermal wells (Fig. 1). Hydrothermally altered rocks crop out in at least two other locations on the volcano, but are cool and not obviously associated with active thermal phenomena.

The four geothermal wells were drilled to depths ranging from 948 m to 2932 m. Three completed in the Telephone Flat area—GMF 87-13, 68-8, and 31-17—tap a high-temperature, liquid-dominated geothermal reservoir, and are capable of commercial production. The fourth well, 17A-6, encountered commercial temperatures in similar reservoir rock, but mechanical difficulties forestalled adequate flow testing (J. Beall, personal communication, 1999). Hot waters produced from the wells have chemical signatures which are not unusual for volcanic-hosted geothermal systems, but are among the most "benign" in the world, with total-dissolved-solid and noncondensible gas contents averaging only 2500 ppm (by weight) each (Iovenitti and Hill, 1997). For the deeper MLV boreholes (Figs. 3 and 4). The groundwater corresponds to a near-isothermal interval increasing from <10°C near-surface to only 25-30°C at 300-400 m. Such a profile likely reflects efficient advection of the cool groundwaters in MLV’s permeable, shallow volcanic units (a “rain-curtain” effect; Swanberg et al., 1988; Iovenitti and Hill, 1997). By contrast, the underlying cap is typified by steep, conductive thermal gradients, ranging from about 200°C/km (e.g. borehole 45-36; Fig. 3) to about 500°C/km (e.g. well GMF-31-17; Fig. 4). The steepness of these gradients is due to the combined effect of intensive convective heating at the base of the cap; cooling by groundwaters at its top; and relative cap-rock impermeability, which forces conductive heat transfer.

Hydrothermal Alteration & Sealing

The cap on the MLV system is by no means unique. These tightly sealed zones are the inevitable consequence of the redistribution of chemical components by convectively circulating hot waters (Facca and Tonani, 1967; Norton, 1979). Proximal to a heat source, the waters have minimum density and maximum capacity to dissolve silica and other constituents from the rocks through which they percolate. This combination induces the fluids to ascend buoyantly, transporting large volumes of dissolved solids and gases to a geothermal system’s more distal regions. Here, such phenomena as boiling, cooling, and mixing with groundwater cause silica, clays, carbonates, and other minerals to precipitate. At the same time, gases exsolved from the ascending fluids may react with groundwater and lower its pH, resulting in clay alteration of rock-forming phases like glass and feldspar.

Little different from many others around the world, the MLV cap is a secondary geothermal feature, likely formed by some combination of the processes described above. This cap, however, is apparently enhanced by its development in the upper reaches of the volcano, where glassy rhyolite and dacitic rocks are concentrated. Although dense varieties of these rocks—flow and dome interiors—are no more altered than their basaltic counterparts, some felsic pumiceous flow/dome carapaces and tuffs are massively altered to clay-mineral aggregates.
GRC Extends Support for Medicine Lake Projects

Editor's Note: On July 20, the GRC sent the following letter of support for the Calpine and CalEnergy geothermal power plant projects in the Medicine Lake region of northern California to U.S. Forest Service Chief Michael P. Dombeck.

Dear Mr. Dombeck,

The Geothermal Resources Council (GRC) is a diverse, non-profit educational association with over 800 individual and corporate members throughout the United States and around the world. As a forum for professionals within the industry, a principal goal of the GRC is to encourage development of geothermal resources in ways that are compatible with the environment.

The GRC believes that Calpine Corp.’s Fourmile Hill, and CalEnergy Co.’s Telephone Flat geothermal power projects — proposed for construction in the Medicine Lake area of northern California — fulfill our criteria for environmentally sound development of geothermal resources.

Geothermal energy development offers a sustainable alternative to traditional forms of electrical generation, with relatively low environmental site impacts; almost negligible (and totally controllable) impacts on air and water quality; and significant reductions in greenhouse gas emissions per kilowatt of power produced. Yet like other gifts of the earth, geothermal resources can only be developed where they are found and proven to be economic. The Medicine Lake area offers a uniquely suitable geothermal resource for environmentally sound, sustainable energy development, with minimal impacts to the surrounding forest and population.

The GRC has supported development of geothermal resources in the Medicine Lake Highlands since the first federal leases were issued in 1982. The 20-year history of leasing and exploration within this high-quality geothermal resource area indicate that its development is considered an integral part of the multiple-use management plan for the Modoc National Forest. The long history of geothermal exploration and evaluation in the region also demonstrates the care which geothermal developers take in considering the impacts of their activities on prospective sites.

With sponsorship by Calpine and CalEnergy — and assistance by the Oregon Institute of Technology’s renowned Geo-Heat Center — the GRC convened a workshop in 1997 on geothermal development in the Medicine Lake area. Our goal was to provide objective information to local participants through instruction on geothermal geology, exploration, drilling, well casing, plant design and operations. Participants also toured the Calpine and CalEnergy project areas, where we discussed environmental issues and concerns over conflicts with recreational uses of the area.

Since then, the GRC’s review of environmental impact documents for the Fourmile Hill and Telephone Flat geothermal projects concludes that all issues raised during the OIT workshop (including air and water quality, noise, scenic impacts, Native American heritage, etc.) have been adequately and responsibly addressed by Calpine and CalEnergy. In addition, the projects meet all of the requirements of Geothermal Steam Act, the U.S. Forest Service management plan, and terms of geothermal leases already issued by the U.S. Department of Interior.

The GRC and its members are convinced that development of these power plants post no long-term or significant effects on the environment in the Medicine Lake Highlands, while offering a number of benefits, including indigenous, clean and sustainable power production; substantial tax and lease revenues for federal, state and local governments; and the “ripple effect” spawned throughout the local economy by project construction and operations employment.

Considering the benefits of geothermal resource development in general — and of the Medicine Lake projects in particular — the GRC encourages the U.S. Forest Service and other federal, state and local agencies to approve development of the geothermal power plants proposed by Calpine Corp. and CalEnergy Co.

Sincerely,

Ted J. Clutter
Executive Director, Geothermal Resource Council
The MLV cap is an argillic alteration zone (Figs. 2, 3 and 4), mineralogically and texturally similar to the one encountered above the geothermal system of Newberry volcano, another Quaternary shield about 240 km to the north (Keith and Bargar, 1988; Swanberg et al., 1988). In the MLV argillic cap, volcanic glass, feldspar (especially plagioclase), and ferromagnesian minerals like pyroxene have been moderately to intensely altered to various combinations of smectite and mixed-layer clays with or without chlorite (at deeper levels), calcite and other carbonates, zeolites (at shallower levels), quartz, potassium feldspar, hematite, and pyrite. These minerals also fill voids and plug fractures, which are otherwise potential conduits for the ingress of cool groundwater. Beneath the cap, the system is characterized by propylitic alteration, dominated by epidote and chlorite with lesser wairakite, prehnite, calcite, quartz, potassium feldspar, and pyrite.

Montmorillonite and saponite, the two cap-rock smectites, together account for five to 15 percent of the upper argillic zone, and 15 to 50 percent of the lower (Fig. 2). Both varieties (combined for clarity in Figs. 3 and 4) occur in all rock types, but saponite is concentrated in the more mafic MLV units. This clay is a hydrous iron-magnesium silicate which differs from montmorillonite in having significantly greater thermal stability—up to at least 300°C (Eberl et al., 1978) vs. a maximum of about 180°C for montmorillonite-family clays in most active geothermal systems (Reyes, 1990; Browne, 1996).

**Discussion and Conclusions**

Existence of the essentially impermeable cap on the MLV geothermal system is required by static thermal profiles for temperature-gradient boreholes and geothermal wells. Beneath the summit basin, many of these profiles have roughly the same configuration: cool-isothermal above steeply conductive above hot-isothermal. This pattern can only correspond to a situation wherein heat transferred from the top of a hot convection cell through a hydrologically tight zone—a cap—is swept laterally from the top of that zone by cool and continually replenished groundwater.

In common with other clays, smectites, the dominant alteration minerals in the MLV cap-rock, tend to flex rather than break when stressed (unlike brittle phases such as quartz and calcite). This mechanical behavior helps preserve not only the cap but the entire geothermal system. Saponite, the most common smectite in the cap, has an added advantage: it can withstand higher temperatures than montmorillonite without degradation. Conceptually, a natural or production-induced heating event which might compromise a montmorillonitic seal would leave one formed of saponite relatively unaffected.
Geothermal Geology

In all geothermal systems, a major role of the cap is to suppress or curtail the escape of buoyant, high-temperature thermal fluid. Equally important (if not more so) in the MLV and similar systems, the cap prevents massive cool groundwater incursion. Such an influx not only could reduce system temperatures below commercial values, but could ultimately quench a system entirely.

Acknowledgments

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References


Jeff Hulen is a senior geologist for the Energy & Geoscience Institute (EGI), University of Utah. He has specialized in active and fossil high-temperature hydrothermal systems and their effects since 1969. Hulen has also investigated the connections between geothermal systems, oil reservoirs, and sediment-hosted gold deposits in the Basin and Range province. He is currently Chief Scientist for the U.S. Department of Energy (DOE)-sponsored Awibengkok (Indonesia) geothermal research project, and previously served in a similar capacity for multi-agency scientific drilling projects in the Valles caldera (New Mexico), Creede caldera (Colorado), and The Geysers (corehole SB-15-D, co-sponsored by Unocal Geothermal and the DOE Office of Geothermal Technologies). Hulen has authored or coauthored more than 130 papers in the geothermal, petroleum, and mining-based literature, and is the co-author (with R.V. Fisher and Grant Heiken) of Volcanoes, Crucibles of Change (Princeton University Press, 1997), which the New York Times Book Review commended for directly addressing a recent call from the National Science Foundation to “…make the case about why science and technology matter in peoples’ lives.”

Sue Lutz is a research geologist and manager of the X-ray diffraction laboratory for EGI. She received her B.Sc. (1982) and M.S. (1989) from the University of Utah, where, in addition to her work at EGI, she is currently a Ph.D. student investigating the hydrothermal history of Nevada’s Dixie Valley geothermal system, Nevada. In 1982, Lutz was Distinguished Student of Field Geology for the National Association of Geology Teachers. She was also a Distinguished Lecturer on sequence stratigraphy at Brigham Young University in 1994, and won first prize at the Geothermal Resources Council photo contest in 1998. Lutz has focused her research on hydrothermal alteration mineralogy and zoning as well as vein mineralogy and paragenesis as tools for improved understanding of active, high-temperature geothermal systems. She has worked on a several such systems in the United States and abroad, including Medicine Lake and Coso, California; Dixie Valley, Nevada; and Awibengkok, Indonesia.
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