DOE/EE-0106

CONF-9604116-22

U.S. Department of Energy

Proceedings
Geothermal Program Review XIV

Keeping Geothermal Energy Competitive in Foreign and Domestic Markets

April 8-10, 1996
Berkeley, California

Sponsored by:
U.S. Department of Energy
Assistant Secretary for Energy Efficiency and Renewable Energy
Office of Geothermal Technologies

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GEOLOGIC RESEARCH AT THE GEYSERS

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ABSTRACT

Geologic research at The Geysers vapor-dominated geothermal field during the past year has yielded new information on the nature of steam-reservoir porosity and permeability; the origin of the caprock; mechanisms of lateral sealing; the evolution of The Geysers hydrothermal system; and specific reservoir controls in and immediately above "the felsite", an hypabyssal, batholith-sized pluton largely responsible for The Geysers' existence. Our research has shown that (1) fluid conduits above the felsite may be dominantly vuggy, high-angle hydrothermal veins; (2) latest-stage hydrothermal calcite in such veins may seal them at the margins of the steam reservoir; mixed-layer clays are probably the corresponding seals in the caprock; (3) steam entries in the felsite are concentrated along the top of the youngest intrusive phase in the pluton — a 1 m.y.-old granodiorite; (4) steam entries in the felsite show a negative correlation with massive borosilicate enrichments.

INTRODUCTION

The governing goal of ESRI's geologic research effort at The Geysers steam field, northwest-central California (Fig. 1) is enabling its geothermal operators to better understand the highly complex, vapor-dominated system they exploit. The geology of The Geysers is fundamental to this understanding; the fields's rocks and porosity networks are its first-order controls. The more we know about these controls, the more accurately can indigenous reserves be calculated, and the more effectively can injection strategies be designed for maximum yield. Our work this year has involved: (1) Petrographic, mineralogic, and stable-isotopic analysis of hot but non-productive geothermal wells drilled beyond the field's presently defined borders; (2) baseline geologic characterization of drill core from The Geysers Coring Project; and (3) completion of data acquisition and analysis for The Geysers felsite mapping project. One of us (JNM) has also been working closely with consultant Mark A. Walters to characterize whole-rock ^{18}O distributions and their implications in the northwestern portion of the steam field. We briefly discuss progress in each of these endeavors except the last in the text which follows.

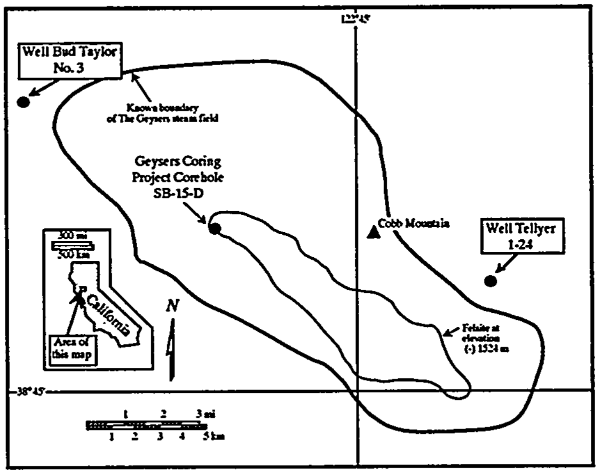

Figure 1. Location map

PERIPHERAL, NON-PRODUCTIVE, STEAM-EXPLORATION BOREHOLES

Deep geothermal wells drilled beyond the currently defined margins of The Geysers geothermal system to date have been hot (>200°C) but non-productive, yet many penetrate the same metaclastic rocks that host the bulk of the steam reservoir. To begin investigating this discrepancy, we have completed a detailed petrographic, mineralogic, and oxygen-isotopic investigation of drill cuttings from two such "dry holes" — Sunoco's Bud Taylor No. 3 just northwest of the field, and MCR's Tellyer 1-24 to the east (Fig. 1). Both wells were drilled to depths in excess of 3000 m in similar rock sequences, and although non-productive encountered temperatures in excess of 200°C in the late Mesozoic, Franciscan- Assemblage metamorphic rocks which they penetrated.

The rocks of Bud Taylor No. 3 differ little from their regional counterparts outside the steam field. The penetrated argillites and metagraywackes contain abundant metamorphic calcite and pumpellyite to total depth; these phases are virtually absent from similar rocks in the steam field proper. Although the Bud Taylor rocks are very hot, temperature logs reveal a purely conductive geothermal gradient. We conclude that these rocks did not receive the permeability-enhancing "ground preparation", including hydrothermal fracturing and carbonate-dissolution, experienced by otherwise similar steam-reservoir rocks (Hulen and Moore, 1995)

By contrast with those in Bud Taylor No. 3, the rocks of non-productive Tellyer 1-24 (Figs. 1 and 2) are nearly identical to those penetrated by nearby producing steam wells to the west — all have been extensively altered and mineralized by the hot-water system which immediately preceded formation of the modern steam field (McLaughlin et al., 1983; Moore and Gunderson, 1995). Whole-rock oxygen-isotopic ratios reflect this fluid-rock interaction — del^{18}O values systematically decrease downhole with approach to felsic intrusive rocks below 3200 m (Fig. 2). The critical difference between the rocks of 1-24 and those of nearby steam wells is that otherwise open veins in the former contain abundant, late-stage, hydrothermal calcite. We believe that this calcite "chokes off" what would otherwise be productive steam channels. This late vein calcite could be an important lateral permeability barrier around the entire steam reservoir (Hulen and Moore, 1995).

THE GEYSERS CORING PROJECT

The Geysers Coring Project (GCP; Hulen et al., 1995), a DOE-Industry collaborative venture, was conceived and undertaken principally to improve understanding of The Geysers' porosity and permeability controls and fluid-saturation characteristics. The drilling phase of the project recovered 237 m of continuous core from the uppermost part of the steam reservoir and its immediately overlying caprock. This footage nearly triples the total amount of core now available for study from The Geysers. Detailed research projects on the core by collaborating investigators from around the country are in progress to determine the nature of fluid-storing and transmitting open spaces; lithologic and mineralogic controls on reservoir vs caprock development in similar rock sequences; physical properties of reservoir rocks which might assist their remote geophysical characterization; the tectonic-hydrothermal history of this part of The Geysers; and the degree to which specially preserved cores remain saturated with indigenous reservoir fluid. Preliminary results of these studies have been published in various journals, and were presented at a researchers' meeting chaired by JBH and held in conjunction with this program review at Lawrence Berkeley Laboratory. At this meeting, plans were made to assemble the research summaries as papers in a special issue of the journal "Geothermics".

Our baseline characterization of core from GCP corehole SB-15-D has provided valuable new insight into the steam-reservoir/caprock transition zone and the nature of porosity and permeability throughout The Geysers field. For one thing, we now know that the difference between the relatively tight caprock and the uppermost steam reservoir in otherwise similar rocks in this sector of the field is in the type and abundance of clay in young hydrothermal veins.

These veins, commonly vuggy and high-angle, were formed by the hot-water system antecedent to the steam field. They contain a wide variety of hydrothermal phases, including wairakite, adularia, and bladed calcite (Fig. 3). The veins are superficially similar throughout the entire length of core, but there are critical differences related to the caprock/reservoir transition. For one thing, deeper veins, in the reservoir, contain epidote along with more abundant wairakite and adularia; shallower, caprock veins are deficient in calc-silicates, but contain abundant, expandable, mixed-layer illite/smectite and chlorite/smectite (Fig. 3). We believe that the these swelling clays, deposited at strategic locations, prevent otherwise permeable veins from acting as fluid conduits. Devoid of these clays, similar, deeper veins in the steam

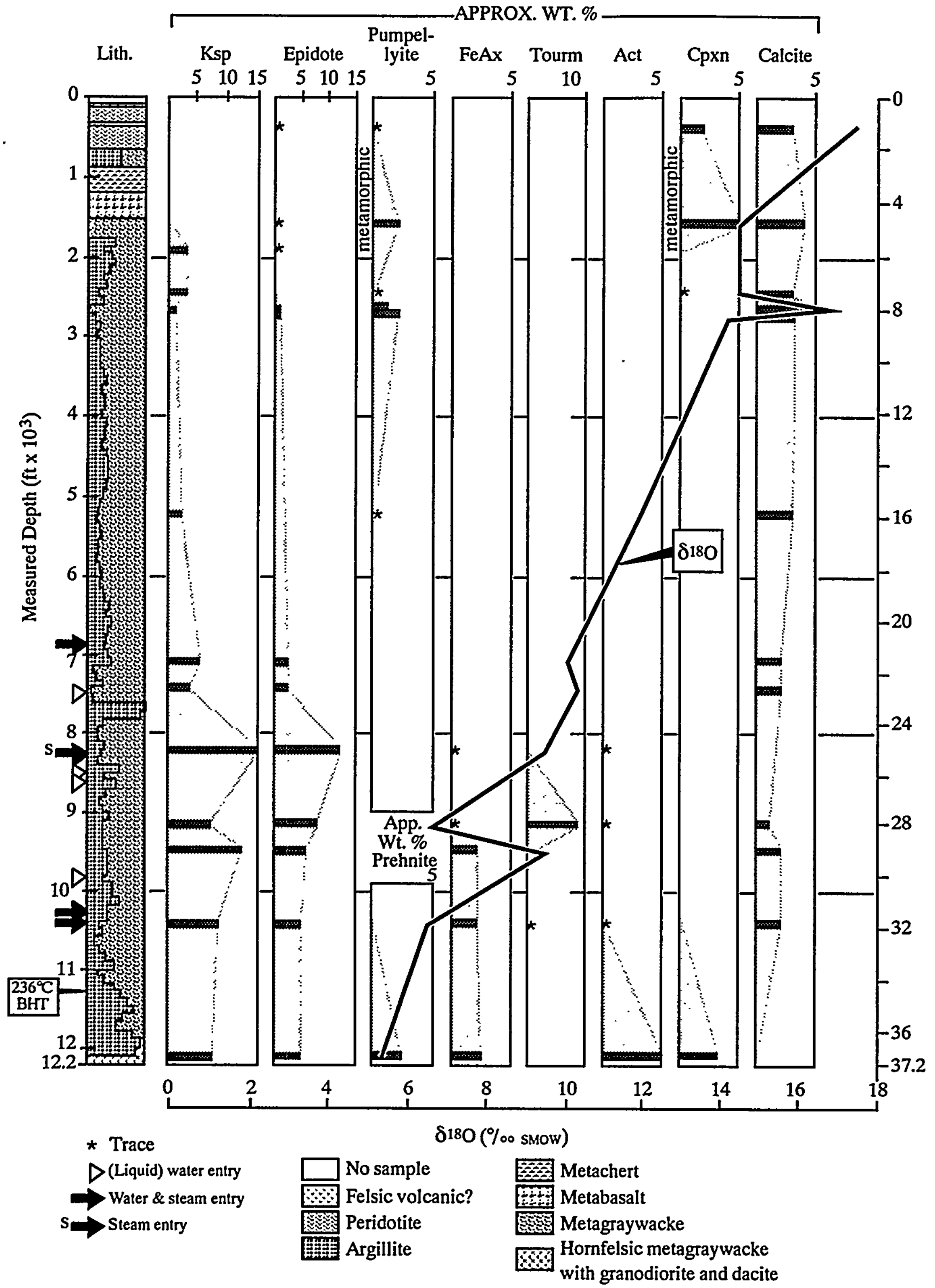

Figure 2. Well Tellyer 1-24: Whole-rock $\delta^{18}O$ values vs downhole distributions of various secondary minerals. Lith. = Lithology. Ksp = Potassium feldspar. FeAx = Ferroaxinite. Tourm = Tourmaline. Act = Actinolite. Cpx = Clinopyroxene. BHT = Bottom-hole temperature.

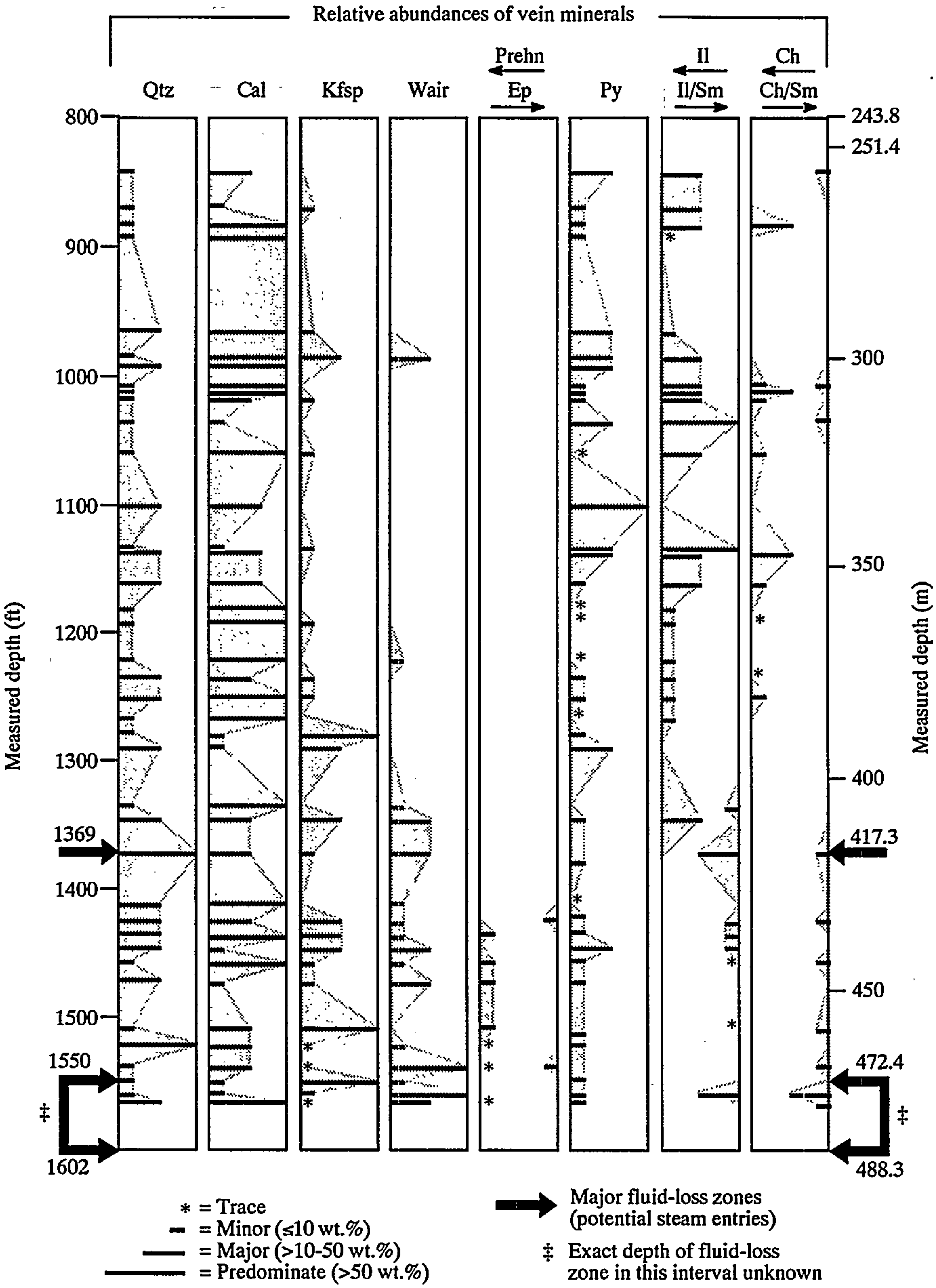

Figure 3. Downhole mineralogy and vertical mineral zoning of selected, representative, Geysers hydrothermal veins in core from corehole SB-15-D. Qtz - quartz; Cal - calcite; Kfsp - potassium feldspar (adularia); Vair - wairakite; Prehn - prehnite; Ep - epidote; Py - pyrite; Il - illite; Il/Sm - mixed layer illite/smectite; Ch chlorite; Ch/Sm - mixed layer chlorite/smectite.

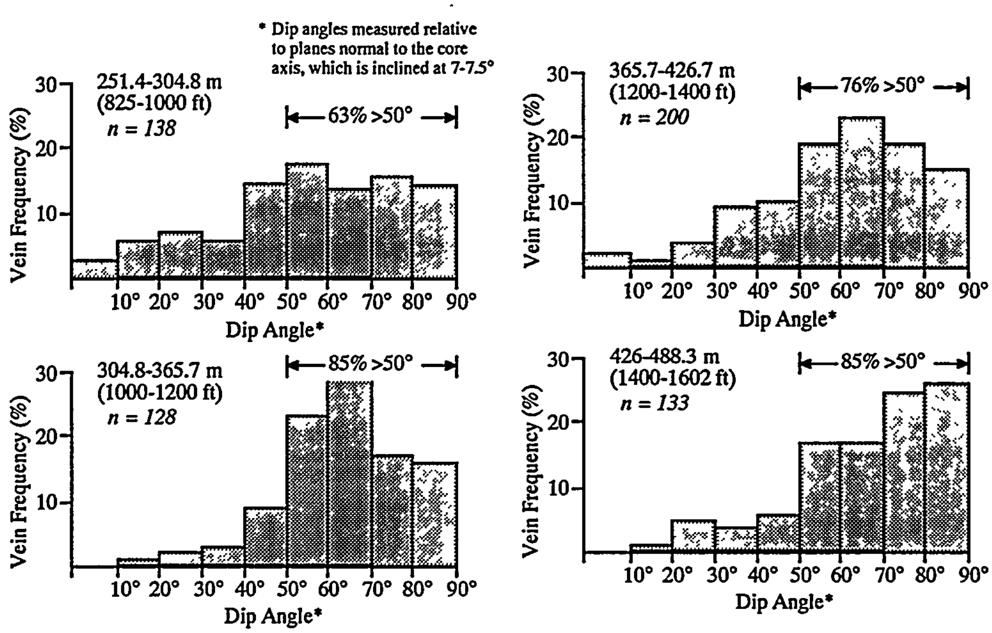

Figure 4A. Dip-angle distributions for Geysers hydrothermal veins in core from successively deeper intervals of corehole SB-15-D. Note predominance of high-angle veins in all intervals.

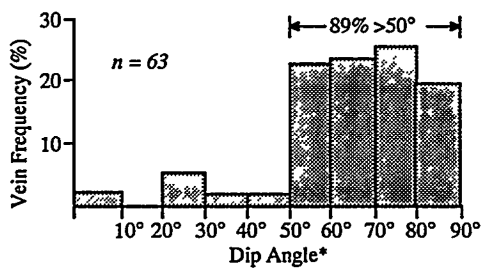

Figure 4B. Dip-angle distributions for all SB-15-D Geysers hydrothermal veins with vuggy porosity.

reservoir provide excellent fluid passageways (Hulen and Nielson, 1995a; 1995b).

Another intriguing finding from our baseline geologic characterization of the SB-15-D core: Both past (now sealed) and present (open, vuggy) fluid channels — the Geysers hydrothermal veins — are clearly high-angle features (Fig. 4; Hulen and Nielson, 1995b). This fact apparently conflicts with the findings of Beall and Box (1989) and Thompson and Gunderson (1989), who presented convincing evidence that steam-bearing fractures in reservoir metagraywacke at The Geysers were principally lower-angle features. A possible explanation for this discrepancy is that SB-15-D, drilled into a shallow "bubble" at the the top of the reservoir (e.g. Gunderson, 1990) is not fully representative of the reservoir. Still, many of the other Geysers metagraywacke cores archived at ESRI do host relatively high-angle hydrothermal veins. We believe strongly that another corehole, drilled deeper into the reservoir, would allow more definitive direct characterization of these open veins and other critical elements of the field's permeability network.

One of us (JBH) is also collaborating with Peter Persoff of Lawrence Berkeley Laboratory in the detailed hydrologic characterization of representative core plugs from SB-15-D (Persoff and Hulen, 1996); and with Greg Boitnott of New England Research (see Boitnott and Boyd, 1996) in an attempt to correlate measured permeabilities and electrical and acoustic properties of selected cores with corresponding mineralogical and textural parameters. In the first study, it was demonstrated that unless disrupted by megascopically invisible microfractures, 1 X 2" metagraywacke core plugs were virtually impermeable, on the order of a few tens of nanodarcies. The second study is still in progress, but it can be reported here that there are obvious mineralogic reasons for observed differences in the measured sonic and resistivity values.

THE GEYSERS FELSITE MAPPING PROJECT

This long-term project has been devoted to mapping rock types, alteration, mineralization, and metamorphism of The Geysers felsite and its hornfelsic halo. It has involved detailed petrographic analysis of 1200 grain-mount thin sections of air-drilled cuttings and 50 thin sections of felsite cores retrieved from various portions of The Geysers steam reservoir. Supplemental techniques employed in the study include oxygen-isotope analysis; whole-rock geochemistry (including trace elements); X-ray diffraction, scanning electron microscopy; and electron microprobe analysis of individual primary and secondary phases in the pluton. The data-acquisition and interpretation phase of the project is now complete.

The felsite, coaxial with and intimately related to The Geysers steam field (Fig. 1; Hulen and Nielson, 1993), was first identified by Unocal Corporation's Alex Schriener and Gene Suemnicht (1981). Samples from most of this igneous intrusion are small-diameter drill cuttings, so the pluton has traditionally been viewed as monolithologic. As a result of our studies, we now know that the felsite actually consists of at least three major intrusive phases. There are also several large and compositionally varied dikes above the main pluton which are almost certainly genetically related to the main mass of the felsite.

The three main phases of the felsite are an older granite and probably coeval microgranite porphyry and a younger granodiorite. The older intrusives, dated by Dalrymple (1992) at >1.3-1.4 Ma, predate the overlying Cobb Mountain volcanic center, but the granodiorite, which Pulka (1991) dated at about 1 Ma, is the same age as the the Cobb Mountain dacite. The dacite and granodiorite are also extremely similar chemically, even their rare-earth-element concentrations. We believe strongly that the dacite and granodiorite are intrusive-extrusive equivalents.

Based on the distributions of igneous rock types, key secondary minerals (for example, tourmaline and ferroaxinite),and major steam entries, the granodiorite among all three intrusive phases appears to have been the major influence in formation of The Geysers hydrothermal system. Intensely mineralized portions of the pluton and its overlying contact-metamorphic halo show no correlation with the configurations of the earlier granite and microgranite porphyry. They are clearly related to the granodiorite, particularly those portions of this intrusive which reached the highest elevations. Moreover, major steam entries are concentrated along and just above the top of the granodiorite.

Surprisingly, these steam entries show a negative correlation with intensity of mineralization in the felsite. In many epithermal and mesothermal mineral deposits, clearly formed by ancient geothermal systems, there is clear evidence that veins and mineralized breccia bodies were repeatedly used as major fluid-flow conduits; they are also zones of weakness most liable to rebreak (with consequent permeability enhancement) when subjected to renewed stresses, either tectonic or hydrothermal in origin. Many banded epithermal veins, in fact, show evidence of hundreds of mineralizing epidodes, bearing witness to repeatedly vigorous fluid flow along the same channels. This does not seem to have been the case in The Geysers felsite.

We know from scattered cores and from secondary-mineral textures in cuttings (e.g. free, euhedral crystals) that the mineralization in the felsite is in fact dominantly open-space filling. In numerous wells, this mineralization, mostly tourmaline and ferroaxinite, accounts for more than 30% of the rock for tens of meters downhole. We suspect that these intensely mineralized zones may be fully-sealed magmatic-hydrothermal breccia bodies. Whatever their origin, however, they are no longer the permeable conduits they clearly once were. In our felsite-study wells, very few steam entries occur in these zones; however, many are found in felsite with secondary-mineral contents of <1%.

The relationships noted above would seem to have important implications for, among other things, the design of injection strategies for optimum placement of injectate deep into the pluton. Injection into nonmineralized zones along the top of the granodiorite might be expected to yield the best results.

These and other critical aspects of the felsite have been plotted on a series of strategically positioned level maps and cross-sections through the igneous body. These maps and cross sections should shortly be available for distribution. Manuscripts summarizing the felsite research project are in the final stages of preparation

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