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SECONDARY MINERALOGY AND OXYGEN-ISOTOPE GEOCHEMISTRY OF TWO PERIPHERAL STEAM-EXPLORATION BOREHOLES AT THE GEYSERS GEOTHERMAL FIELD, CALIFORNIA

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ABSTRACT

Two deep, non-commercial, steam-exploration boreholes completed in similar Franciscan-Assemblage (late Mesozoic) metaclastic sequences peripheral to The Geysers steam field show dramatic differences in: (1) the intensity of hydrothermal alteration and vein mineralization: and (2) the corresponding extent of fluid-rock interaction revealed by whole rock oxygen-isotopic ratios. In borehole Bud Taylor No. 3, completed at a depth of 3237 m just northwest of the field, hydrothermal alteration and veining are minimal, metamorphic calcite and pumpellyite persist to the bottom of the well, and $\delta^{18}O$ values range between about +12 and +14‰ — values which are also regionally prevalent in the Franciscan Assemblage. In the 3717 m-deep borehole Tellyer 1-24, just east of the field: (1) hydrothermal alteration and veining (including K-feldspar, epidote, ferroaxinite, and tourmaline) are relatively intense below about 800 m; (2) most Franciscan calcite has apparently been removed by dissolution; and (3) $\delta^{18}O$ values show a progressive downward decrease from about +17‰ in near-surface samples to about +5‰ at total depth. These secondary mineral and oxygen-isotopic signatures are virtually identical to those prevailing in the steam reservoir, within which downward-increasing temperature was largely responsible for the observed whole-rock $\delta^{18}O$ values. However, by contrast with rocks hosting the steam reservoir, those penetrated by Tellyer 1-24 contain hydrothermal vein calcite to nearly the deepest levels penetrated. This vein calcite may block what would otherwise be productive steam channels.

INTRODUCTION

Although numerous deep exploration boreholes have been drilled beyond the currently defined margins of The Geysers geothermal field (Fig. 1), and almost all of these wells have been very hot (>200°C), none have encountered commercially viable steam entries. Yet many of the rocks penetrated are similar to those hosting much of the steam field —veined, massive metagraywackes with interbedded argillites. What makes these lithologies favorable as steam-reservoir hosts within The Geysers, but apparently unfavorable outside the field? The answer is no doubt complex, but a likely contributing factor is a difference in "ground preparation", including fracturing, brecciation, hydrothermal alteration, and vein mineralization. To begin testing this concept, we have completed reconnaissance petrographic, mineralogic, and whole-rock oxygen-isotope analyses of Franciscan metagraywackes in two deep, but non-productive exploration boreholes peripheral to The Geysers — Sunoco Energy Company borehole Bud Taylor No. 3 and MCR Geothermal Corporation borehole Tellyer 1-24 (Fig. 1). Neither hole encountered commercially productive steam conduits, despite drilling to depths in excess of 3000 m near rocks known to be steam-bearing. Bud Taylor No. 3 discharged hot water and steam from a single entry (Fig. 2), and Tellyer 1-24 found ten subcommercial entries which yielded varying proportions of water and steam (Fig. 3). Exploring possible reasons for the lack of commercial steam in what appears to be favorable steam-reservoir rock in these two boreholes is the focus of this investigation. In view of the many excellent published summaries available on the regional and local geologic setting for The Geysers, we will not attempt a recapitulation here. The interested reader is referred especially to Thomas et al. (1981), Walters et al. (1988), Truesdell et al. (1992), and to the collected papers in McLaughlin and Donnelly-Nolan (1981) and Stone (1992).

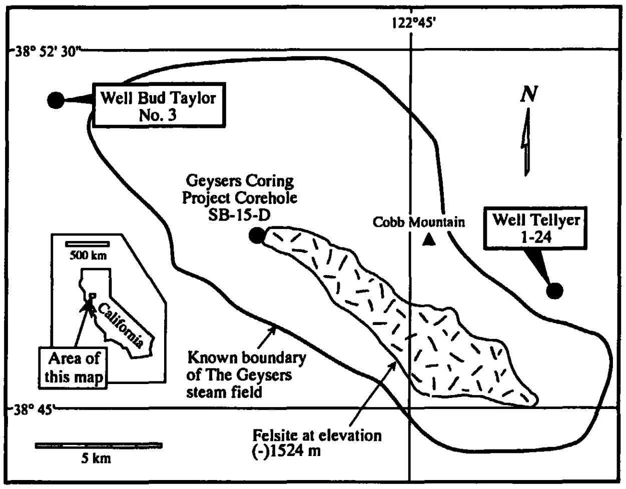

Figure 1. Location map

METHODS AND PROCEDURES

In order to make meaningful comparisons between petrographic and isotopic analyses performed on these rocks and those from wells in the steam field, the techniques used by Hulen et al. (1991, 1992) and Gunderson and Moore (1994) were followed. For the isotopic analyses, metagraywacke chips from representative intervals of each borehole were cleaned of drill steel with a hand magnet after being rinsed in deionized water to remove drilling mud. The samples were treated with acid to eliminate potential contamination from

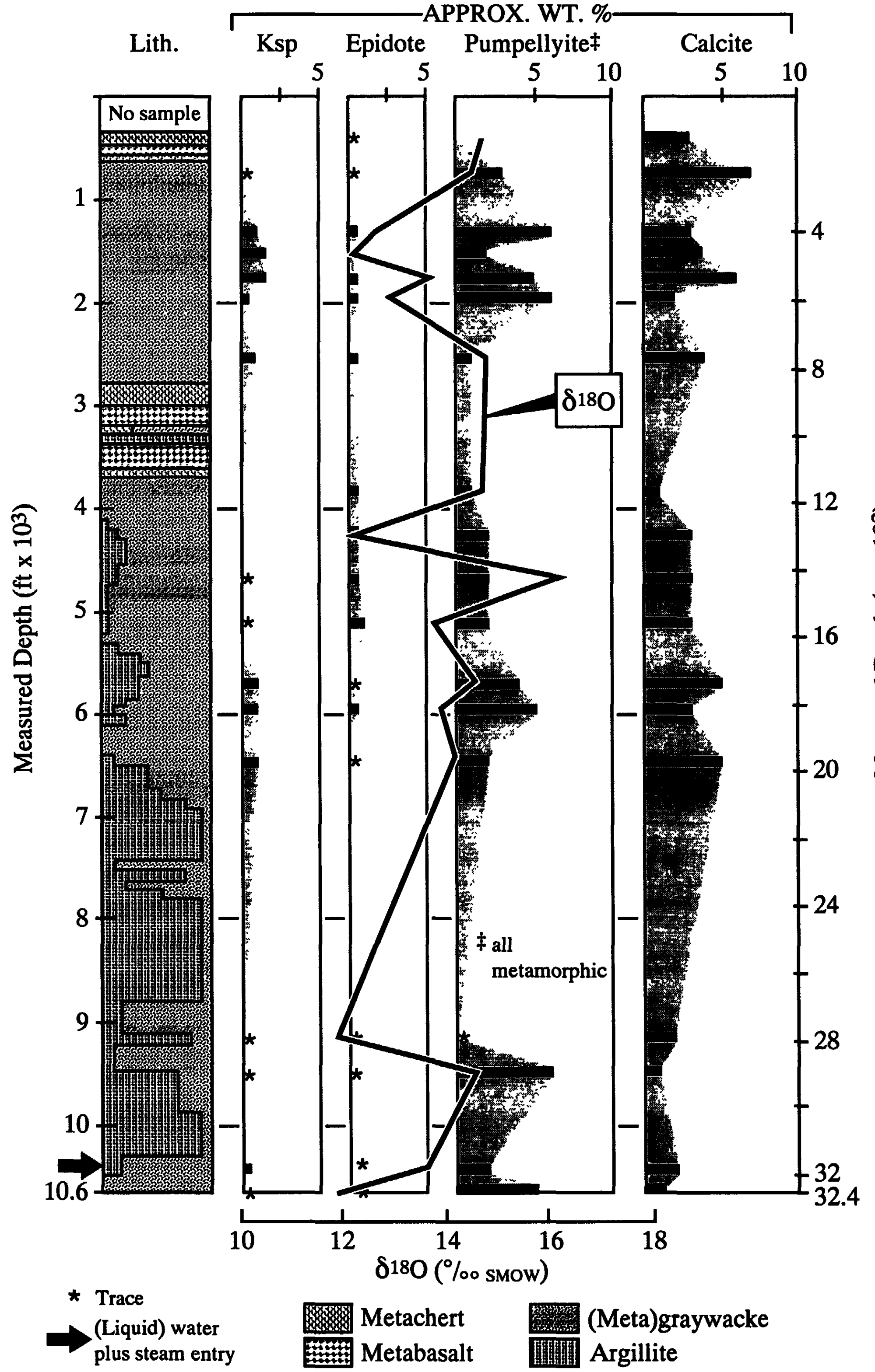

Figure 2 . Well Bud Taylor No. 3: Whole-rock $\delta^{18}O$ values vs. downhole distributions of various secondary minerals. Lith. = Lithology. Ksp = Potassium feldspar.

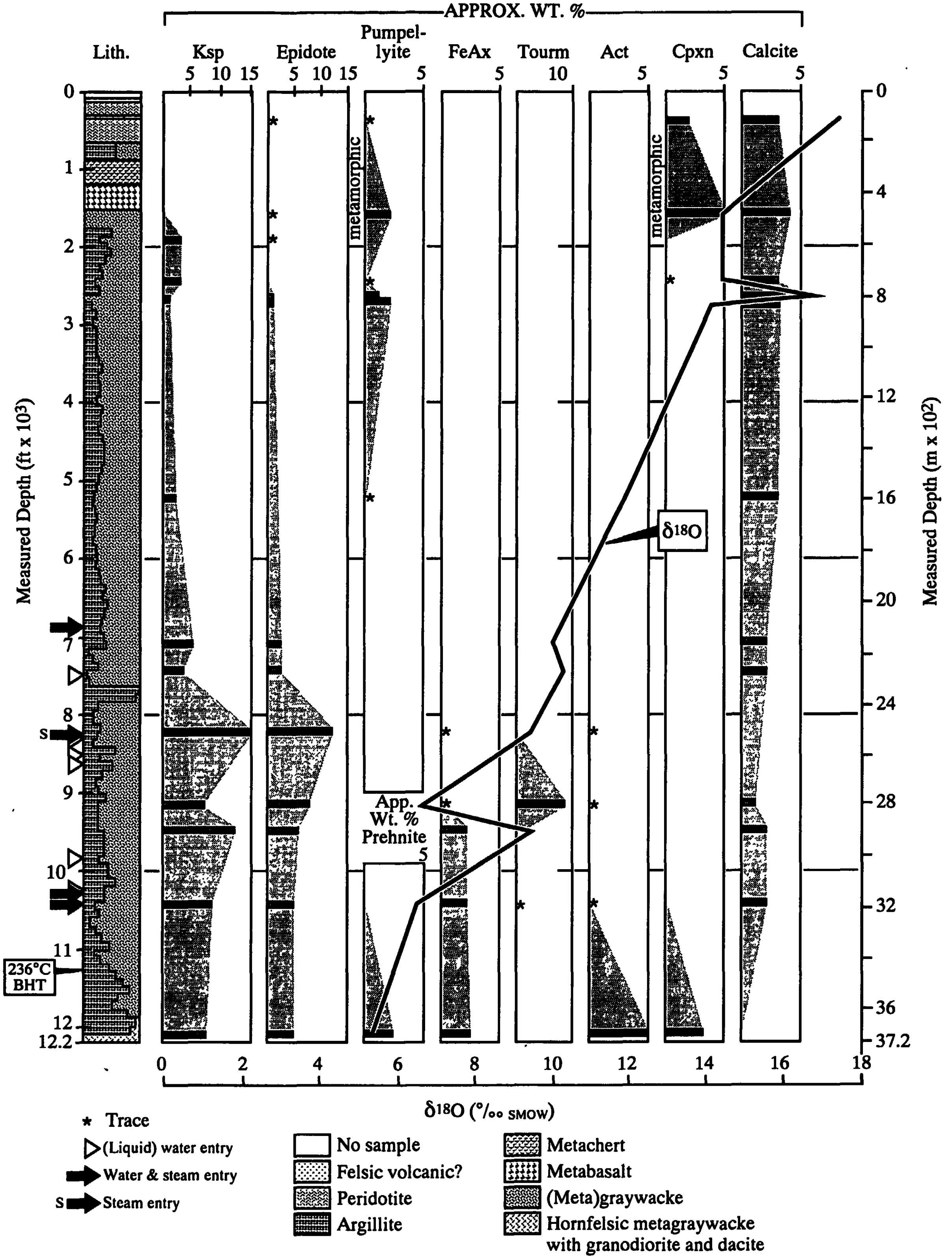

Figure 3 . Well Tellyer 1-24: Whole-rock $\delta^{18}O$ values vs downhole distributions of various secondary minerals. Lith. = Lithology. Ksp = Potassium feldspar. FeAx = Ferroaxinite. Tourm = Tourmaline. Act = Actinolite. Cpx = Clinopyroxene. BHT = Bottom-hole temperature.

chips of borehole cement (this also had the effect of removing indigenous calcite). For petrographic analyses, grain-mount thin-sections were prepared from the washed drill cuttings, with one-half of each section stained with sodium cobaltinitrite to facilitate recognition of potassium feldspar. Each of the sections was point-counted (nominally 300 points per section) to quantify approximately the primary and secondary mineralogies of the rocks.

The washed and acid-treated metagraywacke cuttings were reacted with bromine pentafluoride to extract oxygen from silicate minerals (Clayton and Mayeda, 1963) for the isotopic analyses. The evolved oxygen was converted to CO_2 by combustion with graphite. The results are reported in parts per mil relative to Standard Mean Ocean Water (SMOW). Analytical precision was + 0.2‰.

BOREHOLE GEOLOGY, ALTERATION, AND VEIN MINERALOGY

The two study boreholes penetrated broadly similar Franciscan rock sequences, consisting of an upper zone in which generally fine- to medium-grained metagraywackes and argillites occur interstratified with greenstones (metabasalts) and metacherts and a deeper, much more extensive sequence in which metagraywackes and argillites are the overwhelmingly dominant rock types (Figs. 2 and 3). The metagraywackes consist of subrounded to subangular clastic grains of (in decreasing order of abundance) quartz, albite, intermediate-composition volcanic rocks, chert, and felsic- to intermediate-composition plutonic rocks embedded in a microcrystalline matrix of illite and chlorite with rock flour compositionally similar to the clastic grains. The argillites are essentially finer-grained, layer-silicate-enriched versions of the metagraywackes, ranging from illite- and chlorite-dominated metashales to coarse-grained argillaceous metasiltstones.

The upper metagraywacke/argillite sequence in Tellyer 1-24, according to "mud logs" prepared during drilling, is apparently overlain by a veneer of felsic volcanic rock (Fig. 3). This upper sequence also contains a thin, serpentinized peridotite interval. The deeper metagraywacke/argillite sequence in this borehole contains relatively more metagraywacke and less argillite than the corresponding sequence in Bud Taylor No. 3. Moreover, below about 3600 m, the Tellyer metagraywacke is hornfelsic — recrystallized to a brownish, biotite-bearing, flinty-appearing rock — and contains some biotite-, hornblende-, and orthopyroxene-bearing dacite and granodiorite. These intrusive rock types are similar to those recognized in the batholith-sized, hypabyssal plutonic body (the felsite) which underlies much of The Geysers and which actually hosts a large portion of the steam field itself (Schriener and Suemnicht, 1982; Hulen and Nielson, 1993; Hulen and Walters, 1993). The felsite within the field is enveloped by a contact-metamorphic halo with a typical thickness of about 300 to 600 m (Walters et al., 1988; Hulen and Walters, 1993; Gunderson and Moore, 1994). Since felsite chips apparently appear in cuttings from Tellyer 1-24 only in the lower 100 m, we suspect that the main mass of the felsite probably underlies the bottom of this borehole by at least another 200 m. Alternatively, the recrystallization of metagraywacke to hornfels toward the bottom of this hole has taken place around dikes or sills extending outward to the east from the main felsite body.

There is a notable difference in the extent and type of vein mineralization and alteration between the two boreholes. In Bud Taylor No. 3, metamorphic veining predominates. Quartz and calcite are the dominant metamorphic minerals, but the bright green, metamorphic calcium-iron silicate pumpellyite is common in even the deepest drill chips from this borehole. Later-stage hydrothermal veining and alteration are relatively sparse, but trace to minor amounts of hydrothermal quartz, calcite, epidote, and potassium feldspar record at least some circulation of high-temperature hydrothermal waters through these rocks. Hydrothermal borosilicates like tourmaline and ferroaxinite, so common throughout much of The Geysers steam reservoir, are completely lacking in Bud Taylor No. 3.

In striking contrast to with the Bud Taylor borehole, hydrothermal phases dominate among the secondary minerals of Tellyer 1-24. Whereas, for example, pumpellyite occurs throughout the former borehole, in the latter this metamorphic mineral, along with local glaucophane and a jadeitic clinopyroxene, is confined principally to the upper 800 m (Fig. 3). Tourmaline and ferroaxinite occur commonly in the lower 700 m of Tellyer 1-24, and hydrothermal potassium feldspar, epidote, and calcite, in various combinations, are nearly ubiquitous in the lower 3000 m; minor hydrothermal prehnite occurs only in the deepest sample (Fig. 3). Epidote and potassium feldspar are found not only in late-stage veinlets, but replace the metagraywacke matrix to a greater or lesser extent; the same relationships prevail in the deep igneous-rock chips, but in general the dacite and granodiorite are much less altered than the metagraywackes they intrude.

The main difference between the hydrothermal veins of Tellyer 1-24 and those in so-called "reservoir" metagraywacke within the steam field (Walters et al., 1988; Gunderson, 1990; Hulen et al., 1991, 1992) is that the Tellyer veins contain calcite. It appears to be a late-stage mineral, filling available voids, but is not the bladed variety so common at high levels of the steam reservoir and its caprock (Hulen et al., 1991, 1992; Moore, 1992). As in the reservoir metagraywacke, in the Tellyer rocks metamorphic calcite appears to have been hydrothermally dissolved. Unlike the reservoir metagraywacke, however, the resulting open spaces (along with newly formed ones) in the Tellyer rocks appear to have been infilled with hydrothermal calcite.

OXYGEN-ISOTOPIC GEOCHEMISTRY

Downhole, bulk, oxygen-isotopic-ratio distributions of representative metagraywacke cuttings samples differ strongly between Tellyer 1-24 and Bud Taylor No. 3. $\delta^{18}O$ values for the Bud Taylor samples range from about +12 to slightly more than +14‰ throughout the hole, displaying no systematic vertical variations. These values are typical of "fresh" Franciscan rocks outside The Geysers (Lambert and Epstein, 1992). The elevated $\delta^{18}O$ values for these samples, despite the sparse presence of vein-hosted potassium feldspar and epidote (Fig. 2) would suggest minimal interaction of the Bud Taylor rocks with hydrothermal fluids of The Geysers hydrothermal system.

On the other hand, the metagraywackes of Tellyer 1-24 show evidence of thorough interaction with high-temperature hydrothermal fluids (Fig. 3). Samples from the upper portion of this borehole display the relatively elevated $\delta^{18}O$ signatures of the Bud Taylor cuttings, but below about 800 m depth they show a systematic decrease, with increasing depth, to about +5‰ in the deepest sample analyzed. It should be noted that this sample also includes a significant component of felsic intrusive rock, which is isotopically much lighter to begin with than the graywacke (+8 to +10‰ vs +12 to +17‰; Lambert and Epstein, 1992; Gunderson and Moore, 1994). However, even the next-to-deepest sample of the Tellyer metagraywacke (at about 3200 m depth) yields a $\delta^{18}O$ value only slightly above +6‰ (Fig. 3).

DISCUSSION AND CONCLUSIONS

Both Bud Taylor No. 3 and Tellyer 1-24 penetrated the same thick, Franciscan, metaclastic sequence which elsewhere hosts the bulk of The Geysers steam field, yet neither borehole encountered commercially productive steam entries. The reasons for this discrepancy are undoubtedly complex but in part appear to be related to the nature and intensity of hydrothermal fluid-rock interactions. As evidenced by distinctive secondary-mineral assemblages, the rocks of both boreholes were invaded by late Cenozoic hydrothermal fluids circulating in the high-temperature, liquid-dominated system which immediately preceded development of the modern steam field. However, the Bud Taylor rocks were only minimally mineralized. Although obvious trace to minor amounts of hydrothermal epidote and K-feldspar occur throughout the hole, pumpellyite and other Franciscan metamorphic phases — including calcite — occur to total depth. The persistence of the regional metamorphic assemblage throughout the well is mirrored by the downhole whole-rock $\delta^{18}O$ profile, which changes little from top to bottom. Since hydrothermal dissolution of Franciscan calcite appears to have been an important product of the overall ground preparation of the steam reservoir, we conclude that its presence in the Bud Taylor rocks, and the lack of a strong hydrothermal signature, is directly related to the absence of steam entries.

Hydrothermal alteration and mineralization as well as vertical zonation of vein minerals and oxygen-isotopic values in borehole Tellyer 1-24 are very similar to those for wells within the steam field (Walters et al., 1988; Hulen et al., 1991, 1992; Moore, 1992; Gunderson and Moore, 1994). In particular, much of the Franciscan calcite initially present in the Tellyer rocks appears to have been hydrothermally dissolved below a depth of about 800 m, This observation may help explain the greater fluid-entry frequency in this borehole relative to Bud Taylor No. 3; these entries (none of which were commercial) may occur in part along Franciscan veins from which calcite has been selectively leached. It is noteworthy, however, that although metamorphic calcite is absent from the deeper veins, hydrothermal vein calcite occurs to total depth. Such calcite is lacking from deep hydrothermal veins within the steam reservoir. We suggest that this hydrothermal carbonate may have plugged much of the fracture and vug porosity which otherwise would have contributed to formation of a productive steam reservoir.

At this stage of our investigation, however, and working only with small-diameter drill cuttings, we cannot determine with confidence whether the hydrothermal vein calcite was: (1) coprecipitated with spatially related calc-silicate and other vein minerals; (2) deposited shortly after these other phases in remaining open space; or (3) precipitated in this open space long after the other minerals by wholly unrelated hydrothermal fluids. Thus, the calcite could have been deposited by inflowing waters as they warmed with approach to The Geysers' high-temperature heat center, in a lateral-sealing process first postulated for The Geysers by White et al. (1971). The presence of hot-water entries in Tellyer 1-24 (features extremely rare within the steam reservoir) suggests the possibility that this process could be ongoing today.

The dominant feature of the isotopic data from Tellyer 1-24 is the progressive and systematic decrease in whole-rock $\delta^{18}O$ values with depth. Gunderson and Moore (1994) observed similar isotopic trends within the productive portions of The Geysers field. As in Tellyer 1-24, no clear relationship was observed between the intensity of mineralization — as indicated by the types and abundances of hydrothermal alteration and vein minerals — and the extent of isotopic enrichments or depletions. These relationships suggest that other factors control the isotopic compositions of these rocks. Gunderson and Moore (1994) examined the importance of one such factor, temperature, by determining water-rock fractionation factors based on: (1) the average compositions of the metagraywackes; and (2) fluid-inclusion trapping temperatures. From these data, they calculated a fractionation factor of 2.4 for rocks altered at a distance of 450 m from the underlying felsic pluton (maximum temperature of 425°C) and 9.5 for rocks altered at distances of 2750 m from this igneous body — distances at which maximum rock temperatures were estimated to be approximately 200°C. These data indicate that the temperature gradient established at the peak of alteration could account for a 7‰ difference in the isotopic composition of these rocks (assuming that they fully equilibrated with waters that remained through high water-rock ratios at a uniform isotopic composition). The water in equilibrium with the rocks, based on the calculated fractionation factors, would have had a $\delta^{18}O$ value of +4.5‰ at shallow depths, and a value between +2.5 and +5.5‰ at the top of the hornfels. Similar values of +5.3 to +6.7‰ were determined by Lambert and Epstein (1992) from the isotopic compositions of vein quartz and calcite in the upper 800 m of steam well Lakoma Fame 19 in the central part of The Geysers.

Although paleotemperatures were not determined by fluid-inclusion measurements for the Tellyer 1-24 samples, hydrothermal minerals in cuttings from this borehole are similar to those found in wells penetrating the same rock sequence within the steam reservoir. Thus, these minerals are likely to have formed under similar thermal and chemical conditions. The first appearance of secondary potassium feldspar suggests that the 200°C isotherm at the time of mineralization would have been located at a depth of about 600 m below the wellhead. $\delta^{18}O$ values at this depth would have been near +15‰. The corresponding 450°C paleo-isotherm in Tellyer 1-24 would have been located in hornfels near the bottom of the well, where $\delta^{18}O$ values are about +5‰.

These relationships indicate that temperature was largely responsible for the bulk of the isotopic variation (approximately 7‰) observed in Tellyer 1-24.

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