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GEOLOGY AND OXYGEN-ISOTOPE GEOCHEMISTRY -- AUDREY A-1 GEOTHERMAL WELL, SULPHUR BANK MINE AREA, LAKE COUNTY, CALIFORNIA

Mark A. Walters[1], Jeffrey B. Hulen[2] and Joseph N. Moore[2]

1. Geothermal Consultant, Santa Rosa, CA 95404
2. Energy & Geoscience Institute, University of Utah, Salt Lake City, UT 84108

ABSTRACT

Results of new whole-rock oxygen-isotopic and mineralogic analyses of drill cuttings, combined with prior exploration data, suggest that deep (true vertical depth 2.9 km) exploratory well Audrey A-1 penetrated the fringes of a small, high-temperature (up to 300°C), but fault-restricted and sparingly permeable hydrothermal system beneath a soil mercury anomaly surrounding the historic Sulphur Bank mercury mine. Although this is an area of very high heat flow (up to more than 420 mW/m^2), the new data strongly suggest that the hydrothermal system is unlikely to yield thermal fluids at the rates currently required for commercial viability.

Audrey A-1 was completed almost entirely in a thick sequence of Franciscan-Assemblage (late Mesozoic) argillites (metashales) and metagraywackes similar to those of the nearby Geysers steam field. A few thin dikes or sills of mafic-rich, probable late Cenozoic micromonzodiorite (intrusive andesite) occur in the Franciscan rocks in the bottom 300 m of the well. In this interval, the rocks are also partially recrystallized to brownish phengite, developed at the expense of original chlorite and illite. Above this zone, the rocks retain their original low-grade metamorphic compositions, locally containing abundant pumpellyite. Unambiguous hydrothermal effects are minimal, confined to the deeper reaches of the well (where two small thermal-fluid entries were encountered), and limited to traces of disseminated pyrite and vein adularia.

Oxygen-isotopic values reflect this lack of hydrothermal overprinting, ranging narrowly through the entire penetrated interval from $\delta^{18}O = +13.5$ to $+16.7°/oo$. In comparison, similar rocks altered by a copious flux of Cenozoic thermal waters at The Geysers are commonly as light as $\delta^{18}O = +4$ to $+8°/oo$. The high values of the Audrey rocks are typical for the Franciscan Assemblage on a regional basis, and indicate very low integrated water-rock ratios (near 0.1).

Audrey A-1 and other high-temperature, greater Geysers area wells which penetrate isotopically "heavy" and minimally exchanged Franciscan rocks tend to produce steam enriched in noncondensible gases (NCG) such as carbon dioxide and methane. In contrast, wells producing from similar but highly-exchanged and isotopically depleted rocks yield very little NCG. This relationship strongly suggests that: (1) the locally organic-rich Franciscan lithologies themselves can be important NCG sources; and (2) their capacity to generate these gases is significantly lessened by extensive interaction with convecting, high-temperature hydrothermal fluids.

INTRODUCTION

None of the deep exploratory wells drilled outside the currently defined margins of The Geysers steam field **(Fig. 1)** have been commercially producible. Although many of these wells are hotter than 250°C, the penetrated rocks invariably have very low permeabilities. Moreover, wells drilled through organic-rich Franciscan metaclastic rocks commonly produce high quantities of NCG. Walters and Combs (1992) noted that many of these nonproductive wells encountered principally ductile lithologies such as serpentinite and argillite-melange -- rocks which they suggested inhibited the brittle fracturing necessary to create open fluid conduits. In others, such as Bud Taylor No. 3 just northwest of The Geysers **(Fig. 1)**, the near-absence of hydrothermal veins indicates that even the penetrated metagraywackes -- relatively brittle rocks -

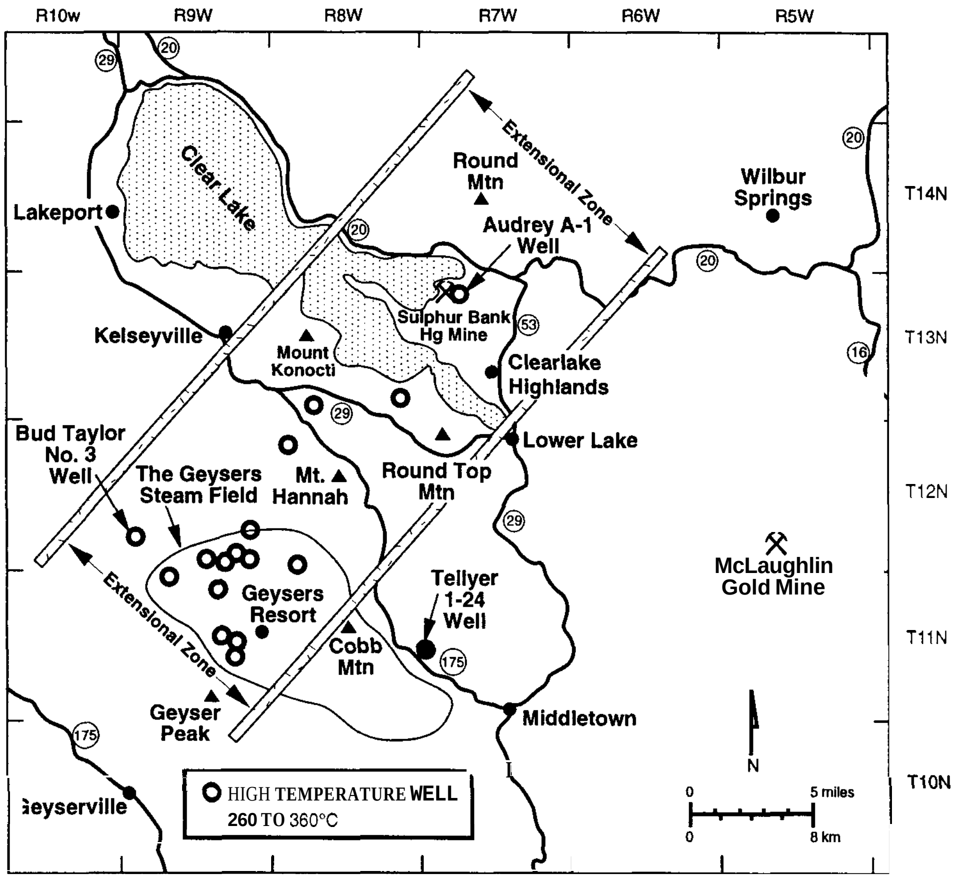


Figure 1. Location map for geothermal exploratory well Audrey **A**-1 in The Geysers-Clear Lake area of northwestern California. The well is in an extensional tectonic zone, documented by Stanley et al. **(1997),** which extends northeastward from The Geysers steam field to several km northeast of the Sulphur Bank mine area.

- were never highly fractured and therefore experienced only minimal invasion by the thermal waters which circulated extensively in the adjacent Geysers geothermal system. Accordingly, the Bud Taylor No. **3** and similar metagraywackes retain their original "heavy" oxygen-isotopic values, as high as $\delta^{18}O = 17^{o}/oo$ (Hulen and Moore, **1995).** In contrast, the similar rocks of another deep hot well near The Geysers, Tellyer **1-24** to the east **(Fig. 1**), are contact-metamorphosed and intensely veined with hydrothermal minerals such as epidote and ferroaxinite. As a result, these rocks show the same isotopic "lightening" as their counterparts in the nearby steam field, with $\delta^{18}O$ values as low as **+4** to $+6^{o}/oo$ (Moore and Gunderson, **1995;** Hulen and Moore, **1995).** However, unlike The Geysers rocks, those in Tellyer **1-24** are also veined with late-stage calcite, rendering nearly impermeable what would otherwise likely have been effective thermal-fluid channels.

These relationships suggest that whole-rock oxygen-isotope data combined with detailed study **of** hydrothermal alteration and vein mineralogy can be used to determine: (1) if a convecting hydrothermal system ever developed in the host rocks, and potentially enhanced their permeability; (2) if the rocks are likely to be permeable enough for commercial thermal-fluid production; and **(3)** if steam from these rocks will be enriched or depleted in NCG. To further test these ideas, we have completed mineralogic and whole-rock oxygen-isotopic analyses of Franciscan metagraywacke from the Audrey **A-1** exploratory geothermal well, drilled **1.1** km southeast of the Sulphur Bank mercury mine in the Geysers-Clear Lake region of northwestern California **(Fig. 1).**

Audrey A-**1** was drilled to a measured depth of **10,042** feet (3.06 km) in February **1981** by Phillips Petroleum Company. Heat flow is high in the area, up to more than 420 mW/m^2, and the well's bottom-hole temperature was close to 300°C. Audrey A-1 encountered sub-commercial flows of steam and hot water from a section of metagraywacke and argillite near its total depth, and these deep thermal fluids were enriched in NCG. The well was not redrilled, even though in The Geysers many redrills encountered commercial quantities of steam as little as 10-20 m away from sub-commercial initial penetrations. Would an Audrey redrill have been equally successful? Was drilling of the original hole prematurely terminated? Were the high NCG contents representative of the entire Sulphur Bank hydrothermal system? Results of the present study allow us to answer these questions with a reasonable degree of confidence.

GEOLOGIC SETTING

Audrey A-1 is inclined northwestward so that its base, at an elevation of -2835 m (subsea), is within 400 m (horizontally) of the historic Sulphur Bank mine workings. The mine exploited the fifth largest known mercury deposit in the U.S.A., and contributed about 4% of the cumulative domestic mercury production. An andesite flow associated with the mercury mineralization has been dated at 45 ka (Sims and White, 1981). Hot springs at Sulphur Bank are actively depositing mercury, and have been the object of numerous investigations for more than fifty years. White and others (1973) concluded that the isotopic composition of these hot-spring waters ($\delta^{18}O$ = +5.62‰ and δD = -24.1‰) indicated a probable connate/metamorphic origin. As noted by Beall (1985), the Sulphur Bank mine is a notable exception to Craig's (1963) observation that most high-temperature geothermal systems derive their water from local meteoric recharge. More recent isotopic studies report $\delta^{18}O$ values of +3 to +6‰, δD values of -25 to -30‰, and R/Ra ($^3He/^4He$) values of 7.5 to 7.9 (Goff and others, 1993). These R/Ra values are very similar to the 8.3 value of steam from the Northwest Geysers, where high-temperature conditions are believed to be related to the cooling of a Recent intrusion (Truesdell et al., 1994).

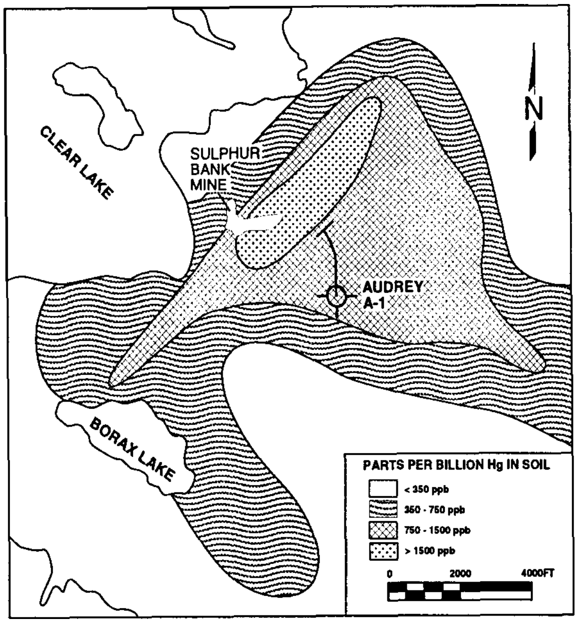
Geophysical studies by the U.S. Geological Survey indicate that the Sulphur Bank mine is within a northeast-trending extensional zone that continues from the Northwest Geysers across the northern half of the Clear Lake volcanic field to Wilbur Springs (Stanley and others, 1997; **Fig. 1).** It is within this zone that the most recent injection of magma into the upper crust has apparently occurred, creating localized, high-temperature (>260°C to 360°C) hydrothermal systems.

The temperature gradient in an intermediate-depth drill hole (TD = 985 ft/300 m) adjacent to Audrey A-1 is 7°F/100 ft (128°C/km). This gradient agrees well with a deep static-temperature gradient of 7.6°F/100 ft (139°C/km) extending to a depth of at least 5800 ft (1768 m) in Audrey A-1 (Walters and Combs, 1992). Between 6,000 and 8,000 ft (1829 and 2439 m) a gas-flow zone lowers the apparent temperature gradient in the well. This gas flow is interpreted to occur where Audrey A-1 intersects a northeast-trending fault exposed adjacent to the Sulphur Bank mine. The measured thermal conductivity of metagraywacke-argillite samples from Audrey A-1 averages 7.5 TCU (3.14 W/m°K), and is within the reported range for metagraywacke-argillite sequences throughout The Geysers-Clear Lake area (Walters and Combs, 1992). The calculated heat flow in Audrey A-1 is 10.4 HFU (436 mW/m^2).

Audrey A-1 is at the approximate center of a soil mercury anomaly of 350 to >1500 ppb which covers an area exceeding 10 km^2 and includes the Sulphur Bank mine **(Fig. 2;** Beall, 1985). A micrometeorological model showed that this anomaly could not have been formed by a wind-driven plume from the retort which serviced the mine (W. Goddard, oral communication). Drill cuttings from Audrey A-1 are enriched in mercury (commonly 500 to 3000 ppb) to a depth of 4200 ft (1280 m), below which the mercury values diminish to 100 to 400 ppb **(Fig. 3).**

In 1964, two geothermal wells, Bradley 1 and 2, were drilled at the Sulphur Bank mine to a maximum depth of 1.2 km. They encountered a small, highly fault-localized, nonmeteoric hydrothermal system (Beall, 1985) with a maximum temperature of 218°C. Sodium-bicarbonate-sulfate fluid charged with ammonia and boron was produced from one of the wells at a rate of 680,000 kg/hr. The fluid had an estimated NCG content of 7 wt% (CADOGGR*, open-file records). To further explore this potential geothermal resource, the Borax Lake 7-1 well was drilled 1.7 km south of the Sulphur Bank mine to a measured

* California Division of Oil, Gas, **and** Geothermal Resources



gure 2. Soil mercury concentration map of the ılphur Bank mine area, showing relationship of ıomalous mercury geochemistry to well Audrey **A-1** fter Beall, 1985).

ɜpth of 2.4 km in 1978. The well did not flow. hermal waters recovered from a depth of 1.1 km in orax Lake 7-1 contained 700 ppm boron and 400 ɔm ammonia, and had a $\delta^{18}O$ value of +6.4‰ and δD value of - 29‰. The fluids were interpreted ; having the same origin as the connate/metamorphic aters of the Sulphur Bank mine (Johnson, 1979). ^{18}O values of +6‰ indicate that meteoric water as not significantly diluted the Sulphur Bank ydrothermal system, as typical $\delta^{18}O$ meteoric val- es for this region are near -7.7‰.

ntries of steam and hot water were encountered in ɩudrey A-1 at measured depths of 9930 ft (3027 m) nd 10,002 ft (3049 m) **(Fig. 3).** The well produced 1,000 lb/hr (9526 kg/hr) during flow tests, with a alculated permeability-thickness factor **(kh)** of 7903 id-ft (Thermasource, 1982). This permeability fac- ɔr is less than 20% of the "average" kh (50,000 md- .) of commercially viable wells at The Geysers. The ɩudrey A-1 flow rate is also much less than the 40,000 lb/hr (63,505 kg/hr) typical rate for xploratory wells in the Northwest Geysers. A skin ıctor of -1.6 calculated for Audrey **A-1** by 'hermasource (1982) indicates only a modest degree f fracturing in the borehole. Pressure did not limit flow in Audrey A-1, as the static wellhead pressure was 1200 psig.

The water chemistry of thermal fluids produced from Audrey A-1 is very similar to that of the connate/metamorphic fluids from both the Borax Lake 7-1 well and the Sulphur Bank mine (sodium bicarbonate -- 5960 ppm; sulfate -- 46 ppm; and boron -- 645 ppm; Beall, 1985). The NCG content of the steam at the conclusion of the Audrey A-1 production test exceeded 2%, and was rising as the steam flow decreased to a "steady" value. At the conclusion of the flow test, the fluid contained 1250 ppmw hydrogen sulfide, 750 ppmw ammonia, 3200 ppmw methane, 24 ppmw hydrogen, and more than 1150 ppmw nitrogen (Thermasource Inc., 1982).

PETROLOGY AND VEIN MINERALOGY

Franciscan Metaclastic Rocks -- Audrey A-1 penetrated a thick sequence of Franciscan Assemblage metaclastic rocks not unlike those which host the Northwest Geysers steam field (e.g. Walters and others, 1988; Sternfeld, 1989; **Fig. 3).** At both sites, the Franciscan rocks are argillites and subordinate metagraywackes regionally metamorphosed to greenschist or glaucophane-schist grade. The argillites are dark gray, massive to well-foliated rocks which commonly contain abundant terrigenous organic debris. They consist of varying amounts of silt-size clastic quartz, chert, albite, and volcanic rock fragments embedded in a microcrystalline matrix of chlorite, illite, and "rock flour" compositionally equivalent to the silt grains. Interstratified metagraywackes are essentially coarser-grained, more poorly-sorted versions of the argillites, with correspondingly less matrix illite and chlorite. Also locally present in the Audrey A-1 cuttings are minor amounts of serpentinite, metachert, metabasalt (greenstone), and "silica-carbonate" rock (fine-crystalline quartz and probable dolomite), but together these rock types account for <5% of the entire penetrated Franciscan sequence.

Eighteen metagraywacke samples, the same as utilized for oxygen-isotopic analysis (discussed later in this report), were examined in detail petrographically. Most of these rocks retain their original Franciscan metamorphic textures and compositions. The metagraywackes have been metamorphosed to lower greenschist and glaucophane-schist grade. Many contain pumpellyite, locally accompanied by the allied

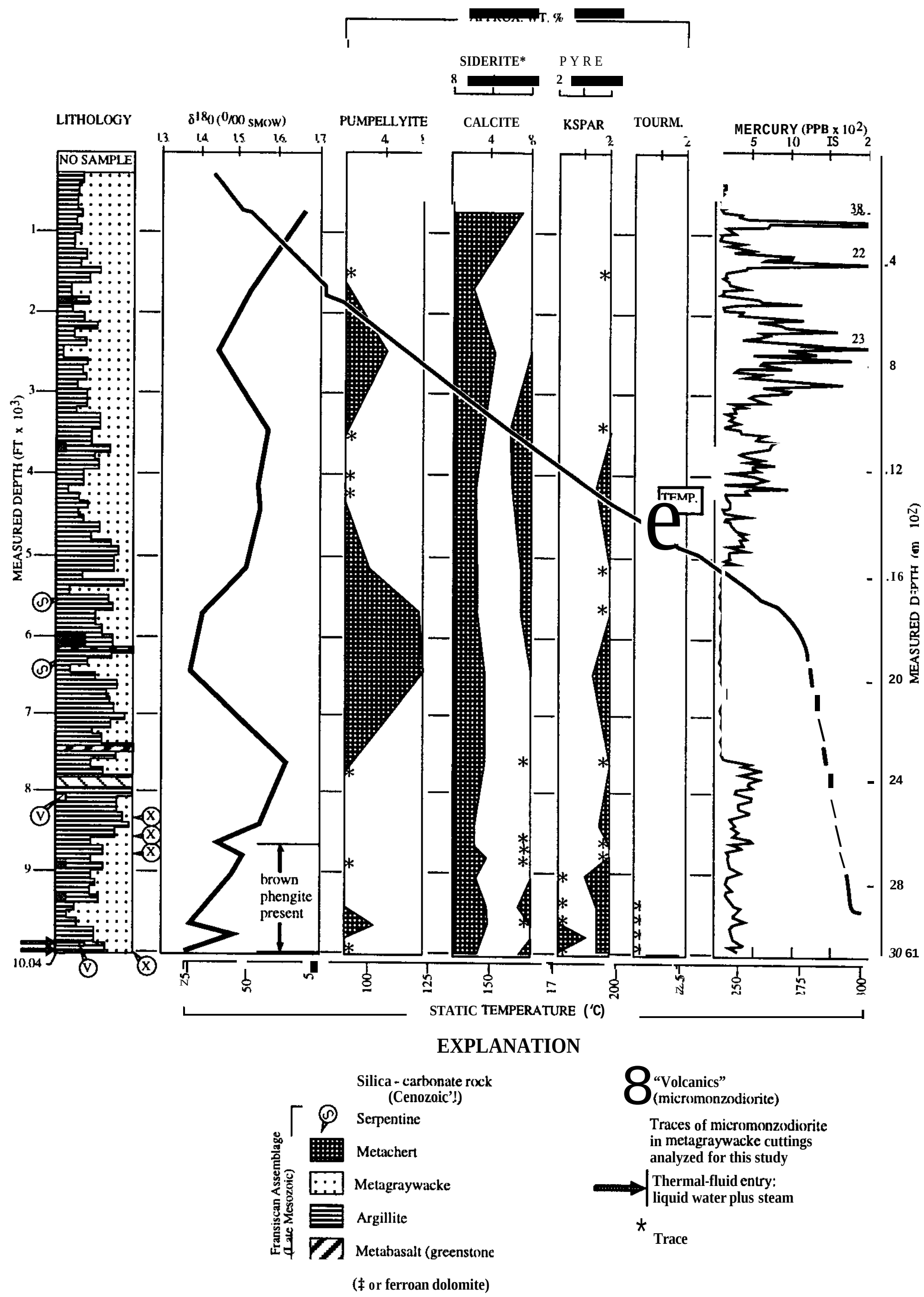


Figure 3. Composite log for well Audrey A-1, showing generalized lithology, mercury geochemistry, and static temperature relative to selected mineral abundances and corresponding oxygen-isotope compositions for eighteen representative Franciscan Assemblage metagraywacke cuttings samples.

calc-silicate lawsonite. In several samples, the pumpellyite accounts for a significant proportion of the total rock volume -- up to 8% **(Fig. 3).** Metamorphic quartz and calcite are ubiquitously present, principally as elongate-lensoid, discontinuous, and turbid-appearing veins. The Audrey A-1 metagraywackes also contain up to **3%** pale to medium brown carbonate, probably either siderite or ferroan dolomite. This carbonate forms thin veinlets and irregular replacement patches in clastic plagioclase and mafic phases as well as in the microcrystalline matrix.

Late Cenozoic (?) **Intrusive Rocks --** Below a depth of 8000 ft (2439 m) in Audrey A-1, there are two intervals initially logged as "volcanics" **(Fig. 3;** ExLog Smith, 1981). Thin sections reveal that these igneous rocks are mafic-rich micromonzodiorites (intrusive andesites). They are medium greenish-gray, microdiabasic-textured rocks consisting of subhedral plagioclase laths, orthopyroxene (and its alteration products chlorite, sphene, and calcite), as well as minor biotite, potassium feldspar, quartz, and traces of acicular apatite.

The age of the micromonzodiorite is unknown, but almost certainly it is affiliated with the late Cenozoic Clear Lake Volcanics (Hearn et al., 1981). It could be related to the 45 ka andesite flow documented at the Sulphur Bank mine by Sims and White (1981), but confirmation of this association must await radiometric dating.

Post-Franciscan Metamorphism -- Metagraywacke samples from 8650 ft (2637 m) and below **(Fig. 3)** show evidence of incipient metamorphic recrystallization. The principal evidence of this recrystallization is scattered, brownish phengite, an iron-rich illite analogue. The phengite appears to have been created at the expense of original chlorite and illite in the metagraywacke matrix. Some of the detrital micas in these deep samples are also pale brown and pleochroic, and could represent phengitic replacement of the original detrital chlorite (after biotite) and muscovite. In the four deepest samples analyzed, the phengite is accompanied by traces of finely-crystalline, porphyroblastic brown tourmaline.

Alteration and Mineralization -- The Franciscan rocks in Audrey A-1 have undergone only minimal hydrothermal alteration and mineralization. There are no obvious secondary minerals related to the prominent mercury anomaly in the upper part of the hole **(Fig. 3),** and apart from a possible "silica- carbonate" horizon at about 8000 ft (2439 m) (ExLog-Smith, 1981), the only other hydrothermal effects in the Franciscan rocks are trace to minor amounts of adularia and pyrite. The adularia forms thin, discontinuous microveinlets as well as local replacement patches in clastic plagioclase. It is confined to samples from the lower 1000 ft (305 m) of the well, where it is accompanied by minor amounts of disseminated, fine-grained pyrite **(Fig. 3).**

The micromonzodiorite in Audrey A-1 is moderately altered, perhaps deuterically. Orthopyroxene is partially to completely altered to chlorite and calcite; plagioclase is partially replaced by calcite; and biotite is weakly altered to chlorite and sphene. An unidentified mafic mineral, occurring as an interstitial phase between plagioclase laths, has been totally altered to microcrystalline chlorite-sphene aggregates.

OXYGEN-ISOTOPIC ANALYSIS

Methods and Procedures -- The eighteen Audrey A-1 metagraywacke samples described above were also analyzed for their oxygen-isotopic compositions, Only metagraywackes were analyzed, because this is the dominant host rock for The Geysers geothermal reservoir. The cuttings were prepared for analysis in the same fashion as for previous Geysers oxygen-isotopic studies to remove contaminants and carbonate minerals (Gunderson and Moore, 1994; Hulen and Moore, 1995; Walters and others, 1996). Each sample, 10-15 mg in size, was then digested in bromine pentaflouride to extract oxygen from silicate minerals. Analytical results are reported in the standard del notation relative to Standard Mean Ocean Water (SMOW). The variance for the $\delta^{18}O$ determinations was found to be ±0.21 $^{o}/oo$ based on repeat analyses of "splits" from samples representing 10 ft (3.1 m) intervals of drilled rock. This compares favorably to the ±0.20 $^{o}/oo$ variance reported for field-scale isotopic studies of The Geysers metagraywacke (Gunderson and Moore, 1994).

Results -- Whole-rock $\delta^{18}O$ values for the eighteen Audrey A-1 metagraywacke samples range narrowly from +13.5 to +16.7 $^{o}/oo$ **(Fig. 3).** These values are typical for Franciscan metaclastic rocks on a regional basis (e.g. Walters et al., 1996), and are consistent with the lack of obvious hydrothermal effects in the well. By contrast, similar but hydrothermally altered and mineralized metagraywackes in The Geysers steam field are significantly depleted in ^{18}O, commonly to values of <10 $^{o}/oo$ (Moore and Gunderson, 1995). The relatively small variations in $\delta^{18}O$ for the Audrey A-1 samples reflect in part the abundance of metamorphic pumpellyite -- many samples enriched in this mineral are slightly lighter isotopically **(Fig. 3)** than their counterparts which are free of the phase. Similar slight isotopic "lightening" is observed for samples from the phengite zone in the well's deepest reaches.

DISCUSSION

The Sulphur Bank mine area was a very favorable geothermal prospect because of its similarity to The Geysers. Both areas are characterized by high heat flow -- 8-12 HFU (335-500 mW/m^2) and anomalous mercury geochemistry (Walters and Combs, 1992; Hulen and Walters, 1993). The mercury anomaly at Sulphur Bank is areally extensive, and was believed to be a permissive indicator of a concealed, high-temperature hydrothermal system at least 10 km^2 in area. Audrey A-1 was drilled to test this attractive target.

It is likely that the failure of the well to meet expectations fundamentally reflects the lack of prior hydrothermal fluid-rock interaction, so much in evidence in otherwise similar Franciscan steam-reservoir rocks at The Geysers. Much of the porosity in The Geysers, for example, has been created by high-temperature hydrothermal dissolution of original metamorphic calcite and aragonite (Hulen and others, 1992). By contrast, metamorphic calcite is common from top to total depth in Audrey A-1, occluding what might otherwise be fluid-transmitting or -storing open spaces. The two small thermal-fluid entries of Audrey A-1 do occur in the sole region of the well with unambiguous evidence of at least minor hydrothermal fluid circulation (adularia below 9000 ft/ 2740 m). The entries are also localized in relatively brittle metagraywacke rather than argillite, which tends to deform in a ductile mode, thereby inhibiting fracture development (Sternfeld, 1989; Nielson and others, 1991; Hulen and Nielson, 1995).

The $\delta^{18}O$ values measured for the Audrey A-1 rocks not only fall within the reported regional range for Franciscan metagraywackes, but are similar to those prevalent in the same rocks capping The Geysers steam reservoir -- generally +13 to +16‰ (Lambert and Epstein, 1992; Gunderson and Moore, 1994; Walters and others, 1996). Beneath The Geysers caprock, in the steam reservoir itself, whole-metagraywacke $\delta^{18}O$ decreases systematically downward to a minimum of about +4‰ immediately above the deep "felsite" pluton which underlies much of the field (Gunderson and Moore, 1995). These authors concluded that temperature of the hydrothermal system was the dominant control on this downward isotopic lightening.

Integrated water/rock ratios calculated for The Geysers and for Audrey A-1 at 300°C are shown in **Figure 4.** An initial $\delta^{18}O$ value of 15‰ was assumed for the metagraywacke; and 0‰ for the water. Data for the reservoir section of Audrey A-1 yield a waterhock ratio of about 0.1, compared to 2.5 for The Geysers reservoir rocks. Estimated bulk porosities are 1% for the Audrey A-1 rocks, and 3% for those from The Geysers (see also Gunderson, 1992). There is clearly a much greater discrepancy between the calculated water/rock ratios at the two sites than between the corresponding bulk porosities -- in the first case by a factor of 3; in the second by a factor of *25*. The throughput of water in the Audrey A-1 rocks is estimated to have been about one order of magnitude less than for the analogous Geysers rocks. This difference is even reflected in modern permeability-thickness products -- 7903 md-ft for Audrey A-1 vs >50,000 md-ft for The Geysers (Thermasource Inc., 1982).

We believe that the high and relatively unexchanged whole-rock $\delta^{18}O$ values for the Audrey A-1 metagraywackes are a clear indication that redrills of the well would not be likely to encounter commercially productive thermal-fluid channels. This asser-

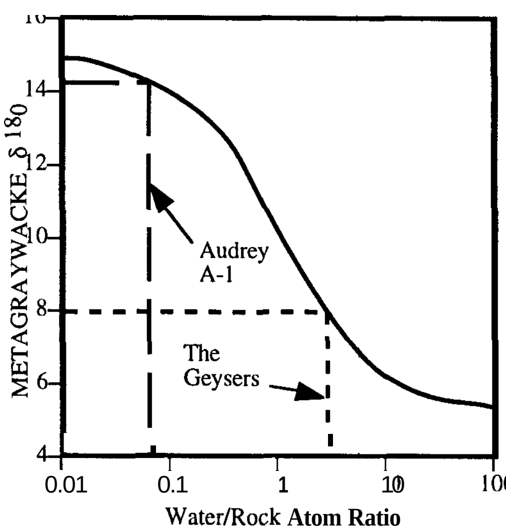


Figure 4. Water/rock atom ratio far 0 ‰ water in equilibrium with metagraywacke at 300°C.

tion is based on the following observations: (1) Whole-rock oxygen-isotopic compositions of both caprock and steam-reservoir metagraywacke cuttings and cores from wells at The Geysers vary little over vertical and lateral distances of hundreds of meters (Gunderson and Moore, 1994). (2) Numerous repeat analyses of metagraywacke sample splits from 3.1 m drilled intervals in the steam field (and in Audrey A-1) vary by only ±0.2°/oo, even though each split is a miniscule fraction of the total sample volume (<0.5 cm^3 vs roughly 112,000 cm^3). In combination, these findings suggest that: (A) The isotopically heavy Audrey A-1 metagraywacke cuttings accurately samplet a much larger rock volume than the wellbore -- conceptually a cylinder of stone coaxial with the well and several hundred meters in diameter; and (B) With local exceptions (for example the Audrey A-1 fluid entries), this large rock volume is essentially impermeable.

CONCLUSIONS

Audrey A-1 did not find a commercial geothermal resource because of inadequate permeability in the penetrated rocks. Not only are the rocks currently "tight", they appear always to have been relatively impermeable. Despite deep temperatures near 300°C, the oxygen-isotopic compositions of the Audrey A-1 metagraywackes have been "lightened" by a few per mil at most (if in fact at all). It is unlikely that commercially producible thermal-fluid conduits will be found within several hundred meters of this well.

Even if productive steam channels did occur in the immediate vicinity of Audrey A-I, it is likely that the NCG content of the steam would be unfavorably high. In the Northwest Geysers, some high-temperature wells producing from relatively little-exchanged Franciscan rocks furnish steam enriched in NCG, which are apparently derived from evolved, remobilized, connate/metamorphic thermal waters (Walters et al., 1996). In contrast, the typical Geysers metagraywacke steam-reservoir rock is highly exchanged and isotopically light, yielding steam from waters largely of meteoric origin. Because the Audrey A-1 rocks are little-exchanged, and because produced waters from the well are the heavy, presumed connate/metamorphic variety, it seems clear that the host rocks have not been significantly invaded by meteoric waters. Beall (1985) suggested, and we concur, that recharge of voluminous fracture systems by meteoric waters may be essential for the formation of most large, commercially-viable geothermal reservoirs.

On the basis of this and prior related Geysers isotopic/petrologic investigations, we recommend strongly that future geothermal exploration drilling in The Geysers-Clear Lake area be supplemented by whole-rock oxygen-isotopic analyses in conjunction with detailed petrologic and petrographic characterization of the penetrated rock sequences. We believe that these tools, at comparatively minor expense, will permit effective screening of unfavorable from potentially productive geothermal prospects.

ACKNOWLEDGEMENTS

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