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AN INTEGRATED MODEL FOR THE ORIGIN OF THE GEYSERS GEOTHERMAL FIELD

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ABSTRACT

Published information on the physical and geochemical characteristics of the Southeastern, Central and Northwestern Geysers reservoirs is examined. A model for the origin of the entire vapor-dominated geothermal system, based on its geological, geochemical and reservoir engineering characteristics, is proposed that agrees satisfactorily with the observed field data.

EXISTING CONCEPTUAL MODELS

Two appealing conceptual models (White et al., 1971; Truesdell, 1991) have been suggested for the pre-exploitation state of the Southern and Northern[1] Geysers but these models have not been integrated and do not explain the origin of The Geysers as a whole.

The model of White et al. (1971) presents many (but not all) of the features observed in the Southern Geysers. The model consists of three parts: 1) a vapor-dominated main reservoir containing steam in large, through-going fractures and liquid water in the rock matrix and small fractures, 2) an underlying zone of boiling saturated liquid, assumed to be brine, and 3) a zone of condensation at the top of the vapor-dominated reservoir. Steam boiled from the brine flows up through the vapor-dominated reservoir and condenses at the top, releasing heat which is conducted to the surface, and forming condensate which drains back to the brine layer. The counterflow of steam and condensate acts as a heat pipe, moving heat through the reservoir with little gradient in temperature. This conceptual model is supported by mathematical models and by observed changes of steam chemistry with time.

In the Southern Geysers major convection is indicated by the patterns of chemical and isotopic compositions of steam (Truesdell et al., 1987; Gunderson, 1989). It is observed that gas concentrations increase from central zones toward field margins (Figure 1), that oxygen-18 concentrations decrease in that direction (Figure 2) and that gas concentrations increase upwards in the reservoir (Figure 3). More detailed patterns in Larderello and

[1]For convenience, "Southern" and "South" may be used here to refer collectively to the Southeast and Central Geysers and similarly "Northern" and "North", to refer to the Northwest Geysers.

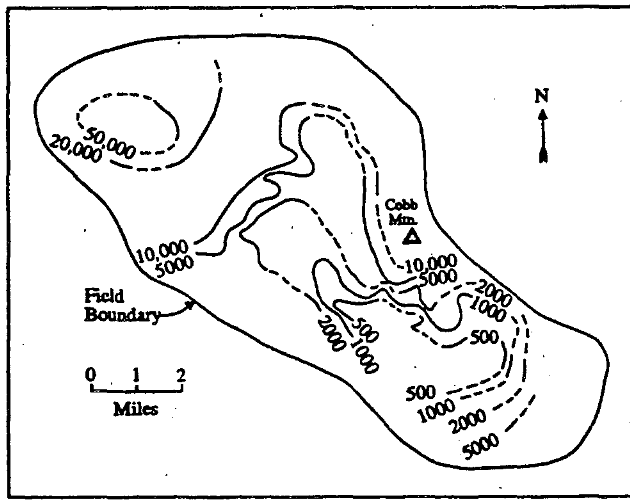

Figure 1. Initial (early-production) distribution of noncondensable gas in steam from The Geysers reservoir (in parts per million by weight) after Gunderson (1989) with some additional estimated contours.

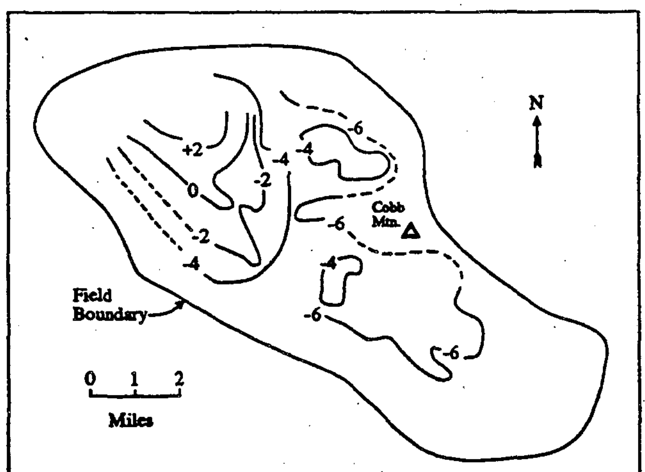

Figure 2. Initial (early-production) distribution of oxygen-18 in steam from The Geysers reservoir (in permil SMOW) after Gunderson (1989).

part of the Southeast Geysers show a chemical sequence depending on solubility in steam (D'Amore and Truesdell, 1979; Truesdell et al., 1987). With distance from the center Cl, B and ^{18}O decrease, while NH_3 and CO_2 increase. These concentration changes were shown by D'Amore and Truesdell (1979) to be a Rayleigh-type function of the fraction of steam condensed (Figure 4). Steam flowing laterally away from a zone of upflow partially condenses as heat is conducted to the surface. Condensate drains downward removing steam-insoluble constituents and residual steam becomes enriched in steam-soluble gases. The chemical patterns indicating lateral steam flow and condensation support the existence of a deep liquid-saturated layer in which condensate flows back to central boiling zones. With low liquid saturation this inward flow would be very slow (possibly blocked by vapor-filled fractures) and probably could not maintain convection. These liquid-saturated zones have been observed in drillholes near reservoir margins (Calore et al., 1980; Enedy et al., 1990).

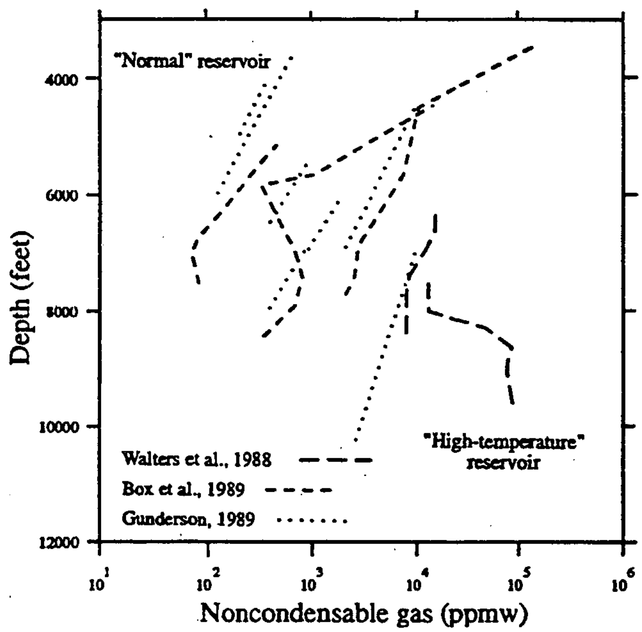

Figure 3. Variations with depth of gas concentrations (in parts per million by weight) in steam from The Geysers "normal" and "high-temperature" reservoirs.

The original White et al. (1971) model assumed diffuse boiling over the entire area of the deep liquid, supplying steam that flowed vertically upwards to condense at the top of the reservoir and produce downward-draining condensate to constitute a heat pipe. The observations of lateral flow and partial condensation suggest that boiling occurs mainly in upflow centers and that liquid at the bottom of much of the reservoir may be condensate, at lower than boiling temperatures, flowing back to the centers of boiling. This does not negate the concept of heat pipe behavior but enlarges the size of individual heat pipe units to include large cells within the reservoir or the entire reservoir. Thus boiling and steam upflow is localized and condensation at the top and condensate downflow is diffuse. An observer measuring heat flow at the surface or pressure within the reservoir would see little difference from a reservoir with many individual heat pipes.

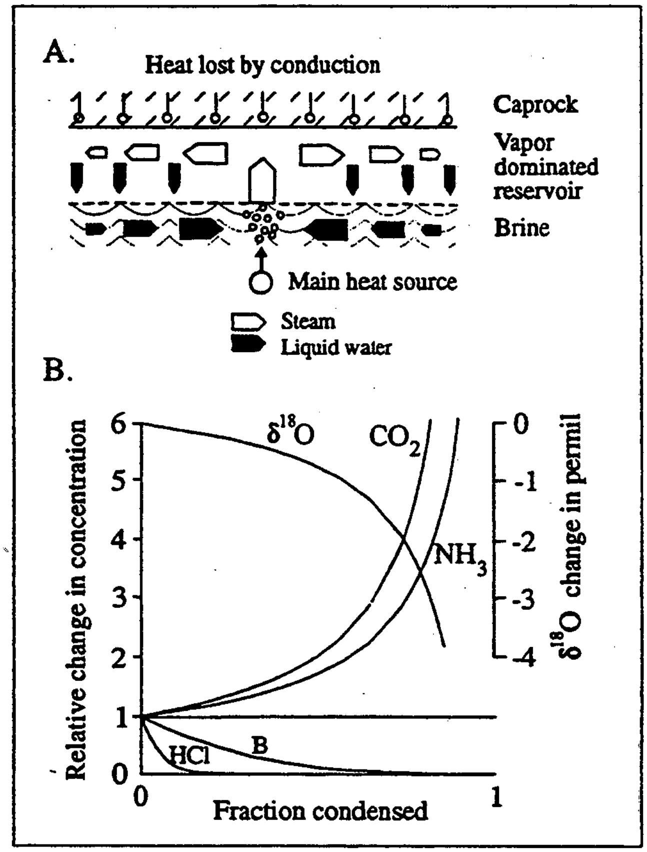

Figure 4. (A) Schematic fluid flow, boiling and condensation in a vapor-dominated geothermal reservoir and (B) effects on gas concentrations and $\delta^{18}O$ values in steam due to partial condensation in a Rayleigh process during lateral flow (after D'Amore and Truesdell, 1979).

The elevations of first steam entries (Figure 5) and the patterns of gas and oxygen-18 concentrations (Figures 1 and 2) show remarkable similarities for the southern two-thirds of The Geysers field. These maps suggest that there are three upflow zones in the Southern Geysers, one in the southeast area and two others, perhaps less distinct, in the central area. Each of these possible upflow zones has a local maximum in the elevation of first steam and in $\delta^{18}O$ value, and a local minimum in noncondensable gas concentration. D'Amore and Truesdell (1979) discussed the relation of upflow to chemical and isotopic patterns; Thomas (1981) suggested that the three reservoir highs in the Southern Geysers represented upflow zones.

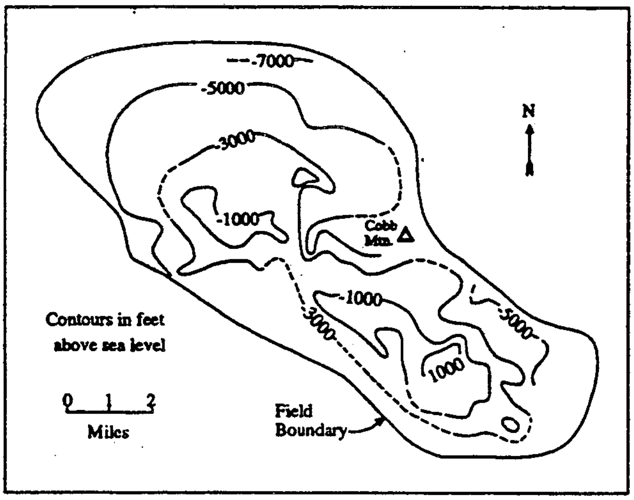

Figure 5. Elevation of the top (first steam entries) of The Geysers reservoir (after Field Operators, 1992).

THE NORTHERN GEYSERS

In the Northern Geysers, a vapor-saturated, high-temperature (to 350°C) reservoir underlying a relatively thin vapor-dominated "normal" (250°C) reservoir has been found (Walters et al., 1988) with much higher gas, $\delta^{18}O$ and chloride concentrations in steam than elsewhere in The Geysers. Steam composition patterns differ significantly from the rest of the field in that gas concentrations decrease away from central locations rather than increasing (Figure 1). The temperature gradient between the high-temperature zone and the normal reservoir is steep, with a difference of up to 100°C occurring over a 100 to 200 m depth interval. The pressures in the reservoirs were observed to be similar and there is no observed low-permeability zone between them.

In explaining these observations, Truesdell (1991) suggested that heat transfer by the heat pipe mechanism operated in the absence of a zone of liquid saturation with evaporation of condensate on hot rock substituting for the boiling liquid. According to this model the high-temperature, vapor-saturated zone was produced by conductive heating from an igneous intrusion. With a supply of water from above, the vapor-dominated reservoir "migrated" downward into the high-temperature dry rock with heat transported by the heat pipe to the base of the caprock and then by conduction to the surface. Thus the steep temperature gradient between the normal and high-temperature reservoirs results from heat transfer in the normal reservoir (by heat pipe) that is much more efficient than the conductive heat transfer in the high-temperature reservoir. This model has been simulated mathematically and showed the expected sharp thermal gradient (Bodvarsson et al., 1992).

PROPOSED MODEL FOR THE ORIGIN OF THE ENTIRE GEYSERS

A satisfactory model for the origin of The Geysers should consider the character of the rocks, the heat and mass recharge and discharge, as well as events influencing the evolution of the field. The great size and the vapor-dominated character of the reservoir suggests that a very special combination of these factors was required to form The Geysers field. Because parts of the northern and southern reservoirs are so different in their present temperature and fluid circulation, this review will emphasize the differences that may have influenced their separate evolution.

THE CHARACTER OF THE ROCKS

At The Geysers, the Franciscan Assemblage is a sequence of tabular, stratigraphically continuous slabs bounded by thrust faults (McLaughlin, 1981; Thompson, 1989). These were intruded by shallow, silicic magmas during the Pleistocene to form a composite batholith-sized intrusion collectively known as "felsite" (Schriener and Suemnicht, 1980). Simultaneously, related magmas of the Clear Lake volcanic field were erupted adjacent to, and to the northeast of The Geysers; Cobb Mountain being the most significant volcanic edifice.

A large portion of The Geysers geothermal reservoir is within a thick, areally extensive body of graywacke sandstone. The graywacke reservoir is interrupted by tectonically mixed units of rocks known as "melange" in the Northwest Geysers and as greenstone in the Southeast. The vast majority of the steam entries, however, occur in the graywacke. In the Southern Geysers, sequences of Franciscan greenstone, chert and serpentinized peridotite outcrop and form the caprock to much of the reservoir. In the Northwest Geysers, graywacke both outcrops and forms the entire reservoir section; the important difference being that the graywacke "caprock" does not have an open fracture system and the reservoir graywacke does. In the Northwest Geysers the graywacke section above the postulated felsite body is believed to be at least 3300 m thick. In the Southeast Geysers where the felsite is shallowest, the graywacke section is as thin as 1100 m and in several locations the felsite was intruded at a sufficiently shallow depth that the associated fracture system reached the surface causing venting and alteration (Walters et al., 1988).

The intrusion of the felsite is believed to have created an earlier hydrothermal system and also prepared the present vapor-dominated graywacke reservoir rock by silicification and fracturing (Sternfeld, 1989). The felsite therefore is the primary structural feature related to the formation of the fluid-flow characteristics of The Geysers reservoir host rock. It is observed that the top of the steam reservoir is a reflection of the shape of the top of the felsite (Figures 5 and 6). In some areas of the Central and Southeast Geysers, the felsite constitutes the reservoir basement and does not produce steam; and in other areas felsite produces commercially significant quantities. It is our belief that the intrusive processes that lead to the formation of the felsite batholith, also created both the vertical and horizontal fracture permeability needed to unify The Geysers reservoir.

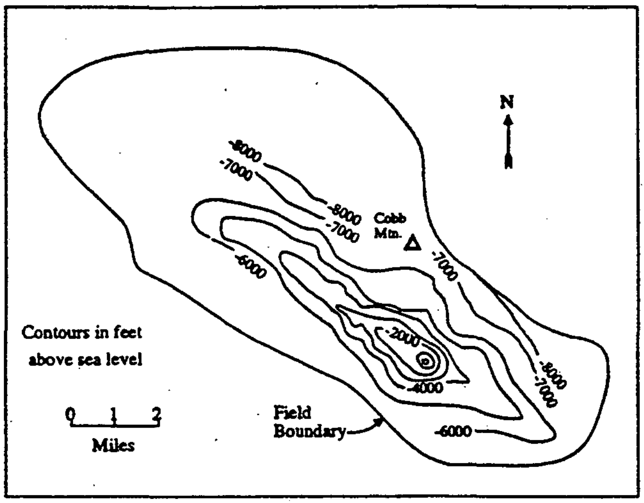

Figure 6. Elevation of the top of the felsite in The Geysers reservoir (after Field Operators, 1992).

THE HEAT SOURCE

The age of the drilled felsite batholith is too great (1.3 to 1.4 Ma; Dalrymple, 1992), to be the heat source for the present day geothermal system. This of course does not preclude the presence of much younger intrusive bodies. There are several indications, in fact, that magma is the heat source for the present Geysers geothermal system:

- A heat flow maximum of >12 HFU or 0.50 Wm^{-2} over The Geysers compared with regional Coast Range heat flow near 2 HFU or 0.08 Wm^{-2} (Walters and Combs, 1989),
- Close association with the Clear Lake volcanic field in which eruptive rocks are as young as 0.03 Ma (Donnelly-Nolan et al., 1981),
- A probable magma body associated with the area of nearby Mt. Hannah and beneath The Geysers itself (Chapman, 1975; Isherwood, 1981), apparently centered in the vicinity of Caldwell Pines (Northern Geysers) where teleseismic P-wave delays exceed 1 second (Iyer et al., 1981),
- The high-temperature (350°C) reservoir (Walters et al., 1988) containing steam with high (6 to 9 wt%) noncondensible gases and enriched heavy oxygen and hydrogen isotope compositions trending toward the "andesite" water of Giggenbach (1991), and
- Steam from southern areas with high $^3He/^4He$ (5.3 to 9.5 times that of air), similar to ratios at active oceanic ridge spreading centers, indicating a magmatic component (Torgersen and Jenkins, 1982).

We believe that The Geysers reservoir is "mining" heat from buried, still-hot, 0.1 Ma (or younger) igneous rock and possibly magma, and moving it to the near surface. This process occurs when the reservoir extends downward into hot rocks, enhancing upwards heat transfer by convection. This was suggested for the Northwest Geysers by Truesdell (1991), and is even more likely to have occurred in the South Geysers where recharge water is more available. The downward extension of the two-phase, vapor-dominated reservoir into hot rock rapidly cools the rock to normal reservoir temperature and, through the heat pipe mechanism, moves the heat to the top of the reservoir where it is conducted to the surface. This process is similar to that suggested by Lister (1976) for a penetrating convective system, but more effective because the high-temperature rock is already fractured and the vapor-dominated heat pipe removes heat more rapidly than does convecting liquid. The heat flows measured over The Geysers production area (Walters and Combs, 1989) refer to the caprock and not to the "basement" below the reservoir. It is probable that conductive heat flow upwards into the reservoir is similar to that in other parts of the Clear Lake volcanic field.

SOURCES OF RECHARGE WATER

A key difference between the northern and the southern areas of The Geysers is the initial amount of liquid water in the fractured reservoir. Production in the Central Geysers has taken place over more than 30 years and during that time the main source of steam has almost certainly been liquid water. In the south the two-phase liquid-vapor reservoir extends in part to 5 km depth (Eberhart-Phillips and Oppenheimer, 1984) and the original quantity of liquid in the reservoir was undoubtedly large. In the Northern Geysers, however, the two-phase reservoir is thin and conditions of temperature and pressure in the high-temperature reservoir suggest that fractures hold only vapor. Obviously there has been more recharge in the south than in the north. The isotopic compositions of steam (Figure 7) also indicate strong recharge in the south where some steam and local meteoric water isotopes are nearly identical, while steam from the north is most similar to metamorphic or magmatic water (Truesdell et al., 1987). This difference in recharge is the key to much of the contrast between the north and south reservoirs.

Lower recharge to the northern reservoir can be due to either its greater depth, the character of the adjacent rocks or, most likely, both. Studies by Johnson and Treleaven (1990) show that "non-reservoir" Franciscan rocks are "essentially non water bearing" with intrinsic porosity about 1%, permeability of the order of microdarcies ($10^{-18}m^2$) and mostly sealed fractures. Most rain falling on Franciscan rocks runs off and little infiltrates. In contrast the dacite and rhyodacite of Cobb Mountain are highly permeable, weather slowly and maintain open fractures. Little runoff is observed from Cobb Mountain and it has been estimated that 95% of the 200 cm average annual precipitation infiltrates into the volcanics. Part of this water forms springs which emerge at the contact of the volcanic rocks with Franciscan rocks, but some fraction may flow to greater depths down the neck of the volcano. Although the subsurface connections are not known, it is possible that the Cobb Mountain volcanic rocks communicate with the graywacke reservoir directly or through the felsite. Recharge through volcanic edifices such as Cobb Mountain was also suggested by Goff et al. (1977). Some additional recharge could flow into the reservoir from directly above as the steam reservoir in the south is relatively near the surface (Figure 5) and has significant vents.

In the north the great thickness of low-permeability Franciscan rocks above the reservoir makes it unlikely that any large amount of surface recharge reaches the Geysers reservoir from above. In the south, recharge is likely to have occurred from rainwater infiltrating the fractured Cobb Mountain volcanics and entering the reservoir from the side. The oxygen isotope data show that the composition of nearby steam is similar to that of meteoric water suggesting direct recharge (Figure 7). The process is probably not that simple because the pattern of gas concentrations (isotope data is less complete) indicate movement

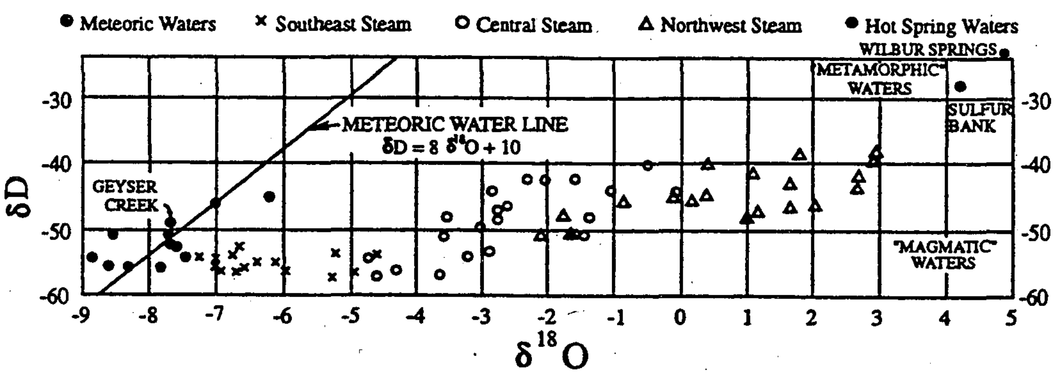

Figure 7. Isotopic composition of initial (early-production) steam from The Geysers reservoir in permil SMOW. After Truesdell et al. (1987) with some additional data (F. D'Amore, pers. commun., 1993).

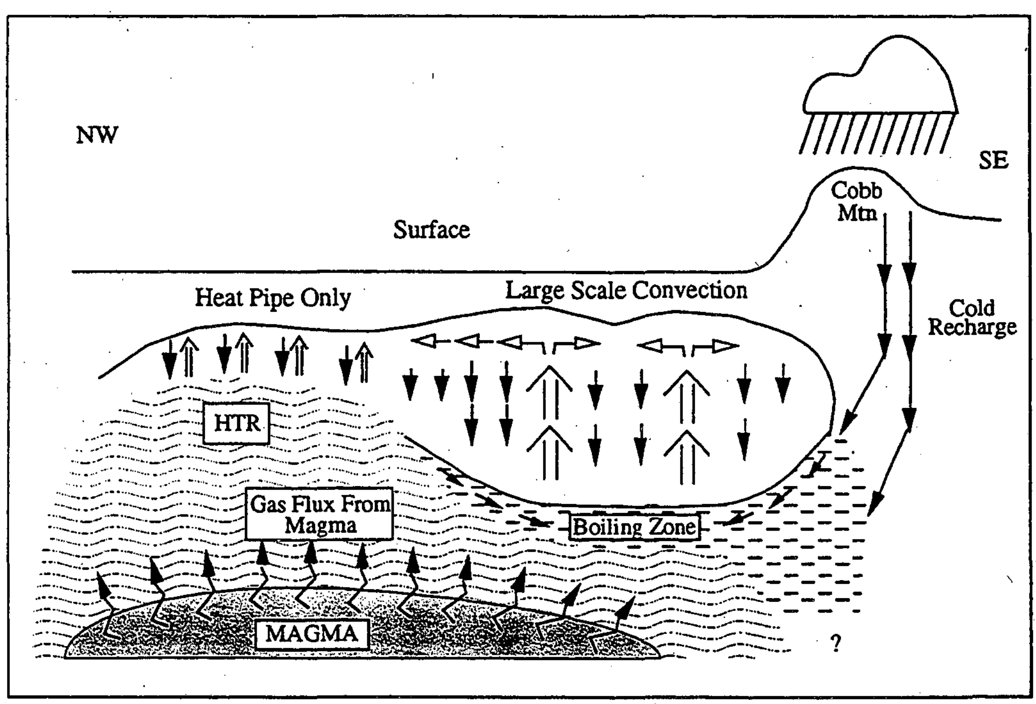

Figure 8. Schematic conceptual model of The Geysers geothermal system showing flow of steam (open arrows) and liquid (condensate and recharge water; solid arrows). HTR denotes the high-temperature reservoir.

from the upflow zone toward Cobb Mountain, not the reverse. Therefore it is likely that recharge from Cobb enters the deep liquid zone rather than being directly connected to the steam reservoir.

THE SOUTHERN AND NORTHERN RESERVOIRS

We believe that the greater reservoir thickness and greater initial liquid saturation in the Southern Geysers reservoir is due to a greater access to recharge water rather than to differences between the north and south in availability of heat or rock character. It seems reasonable to assume further that the source of recharge in the south is Cobb Mountain which has the required high infiltration and is nearly equidistant (1.6 km) from each of the three major upflow zones. What then is the possible fluid recharge source for the Northern Geysers reservoir? Recharge must have been sparse compared to the Southern Geysers; in the north, the normal reservoir above the high-temperature reservoir is 600 to 1000 m thick, while in the south it is at least 1500 m and possibly as much as 5 km thick (Eberhart-Phillips and Oppenheimer, 1984). Possible sources of recharge in the north include, as discussed above, limited infiltration through pores and fractures in the overlying Franciscan rock and fluid transferred from the southern reservoir. The latter possibility is shown in the schematic diagram of The Geysers reservoir in its pre-exploitation state (Figure 8).

Figure 8, without scale and with certain geographic rearrangments, shows from right to left (or southeast to northwest) that rain falling on Cobb Mountain recharges a liquid-saturated aquifer in fractured Franciscan and igneous (volcanics and felsite) rocks. At the top the groundwater is cold, but as it moves downward it is heated conductively and feeds the boiling liquid beneath upflow zones of the southern reservoir. Only two of the three upflow centers are shown. The base of the boiling liquid reservoir may be located at the rapid decrease in fracture density that marks the brittle-ductile transition of the last intrusion (0.1 Ma or younger). The top of the liquid-saturated reservoir is not planar, but tilted up toward the sides where it receives condensate trickling from above. The boiling liquid, steam upflow, condensation near the top, and condensate percolating downward to join the liquid constitute a closed convection loop. In some ways this diagram resembles figure 1 of Hebein (1986) but the interpretation is different.

The southern reservoir represents an advanced or possibly mature vapor-dominated reservoir in which the edges of the reservoir are close to the limits of the zone of fracturing created during the emplacement of the felsite. In particular, if the bottom of the reservoir coincides with the maximum downward extent of fractures, then the heat transfer mechanism should change from rapid heat removal by heat pipes through existing permeability to slower transfer through cracks formed by thermal stress cracking (Lister, 1976) or even to conduction. At an earlier stage, the southern reservoir may have been more like the northern reservoir as represented in Figure 8. The liquid-saturated zone and the major convection cells would not be present and fluid circulation would be limited to vertical transport of steam and condensate. The lateral recharge of liquid would add to the total fluid and allow the reservoir to grow rapidly downward into the fractured hot rock. During this period of intense downward expansion the heat and fluid flow out of the reservoir may have been greater, with widespread steam venting and hydrothermal alteration.

When convection was established in the southern reservoir (and perhaps earlier), some steam could migrate into the northern reservoir to add to the limited recharge from above and initiate local convection. There is evidence that convection and cooling in the Northern Geysers started much later than in the south. Williams et al. (1993) have found that temperatures in the caprock above the high-temperature reservoir in this area have not attained steady state and that heat flow at the top of the caprock is higher than at the bottom indicating cooling in the lower portion of the caprock within the last 5000 to 10,000 years. Earlier published studies in the Central Geysers showed that caprock temperatures had reached steady state indicating no recent temperature changes in the reservoir (Urban et al., 1976). The cooling and relatively-thin normal reservoir in the north may reflect recent recharge and initiation of convection. In the northern reservoir heat mining would be limited by the rate of heat loss through the caprock as well as by the limited recharge from the reservoir to the south and through the caprock.

Some transitional areas of the southern reservoir (e.g., near Unit 15), initially produced low-gas, chloride-free steam from a normal reservoir and later steam high in gas and chloride suggesting a high-temperature reservoir source (Haizlip and Truesdell, 1989). Whether more of the southern reservoir will produce this type of steam probably depends on whether the inferred deep high-temperature reservoir in that part of the field is fractured and contains vapor which can move upwards. Alternatively it could be unfractured and not contribute vapor to the overlying exploited reservoir. As pressures in the producing volumes drop, steam from both marginal zones and underlying hot zones (where they exist) will be drawn in carrying higher gas to wells. These gas sources can probably be distinguished by their content of ^3He and other characteristic magmatic components. HCl may be such a component, although other origins for HCl at temperatures above 300°C are possible (D'Amore et al., 1990).

In the southern reservoir the initial presence of liquid water in matrix pores and small fractures provided a plentiful supply of low-gas steam to dilute the gas contained in the original vapor. The loss of this liquid in the late 1980s caused rapid declines in reservoir pressures and steam flow along with increases in gas concentrations (Truesdell et al., 1993). The northern reservoir, which at present produces from both a normal, vapor-dominated reservoir and a high-temperature reservoir, may not undergo these unfavorable changes to the same extent. Gas concentrations in the produced steam may be near the maximum in the area. Without lateral steam flow and condensation, gas would not have accumulated at reservoir margins, and the initial contribution from readily-available liquid water in the thin normal reservoir is probably less (certainly there was no pool of liquid at the bottom). Continued production from the high-temperature reservoir and pressure decrease may indeed pull lower-gas steam into the exploited zone.

CONCLUSIONS

We present a model for the origin of distinct but connected reservoirs in the North and South Geysers based on differences in depth, access to recharge water and rock types. The high heat flow over the Southern Geysers is attributed to active mining of heat from hot fractured rock associated with at least two intrusive events. Less energetic heat mining in the north is attributed to lower capacity for heat loss to the surface through a thicker cap rock and less recharge (mostly by transfer of steam from the south). Plentiful recharge in the south produced a saturated zone (of unknown thickness) and allowed the establishment of large convective cells with characteristic chemical and isotopic patterns in produced steam. The high overall liquid saturation of this reservoir resulted in low gas steam as long as liquid was available, but liquid has declined recently and gas concentrations are rising. The northern reservoir with less recharge has steam with higher gas, which is unlikely to increase significantly.

ACKNOWLEDGMENTS

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