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Gas Geochemistry of The Geysers Geothermal Field

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GAS GEOCHEMISTRY OF THE GEYSERS GEOTHERMAL FIELD

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ABSTRACT

Increases in gas concentrations in Central and Southeast Geysers steam are related to the decreases in pressure caused by heavy exploitation in the 1980s. When reservoir pressures in the central parts of the field decreased, high-gas steam from undrilled reservoir margins (and possibly from underlying high-temperature zones) flowed into exploited central areas. The Northwest Geysers reservoir probably lacks high-gas marginal steam and a decline in pressure may not cause a significant increase of gas concentrations in produced steam.

BACKGROUND

A nearly-fieldwide accelerated decline in pressure and steam production occurred at The Geysers in the late 1980s. As a result of this crisis, the U. S. Dept. of Energy has begun a program to examine the reservoir processes at The Geysers in greater detail with particular attention to understanding the sources of steam and noncondensable gas, and predicting changes in pressure, steam flow and gas content. As part of that program the Lawrence Berkeley Laboratory is studying the chemical composition of steam and mathematically simulating processes that affect steam composition as well as its temperature, pressure and flow.

In this study the aspect of greatest near-term importance is the prediction of changes in noncondensable gas concentrations in steam. Removal of gas is necessary to achieve low pressures at the turbine exhaust and high conversion efficiency. As part of the field management program recommended by the California Energy Commission Geysers Technical Advisory Committee, some power plants are being shut down and steam directed to other more-efficient plants and older ones are being refurbished. In addition, plans are being made to build new plants in the Northwest Geysers where some drilled areas are presently shut-in because of excessive gas concentrations. It is of great concern to the producers whether existing gas-handling equipment will be adequate for future gas concentrations and how much gas-handling capacity to provide in new and refurbished plants. Inadequate capacity may cause plant shutdown, while an excess costs money. For a 100 MW plant each percent of gas increase costs about a million dollars in gas-handling equipment.

CHANGES IN GAS CONCENTRATIONS

Noncondensable gas concentrations at The Geysers have risen sharply since the late 1980s. Examples of these changes are taken from the Northern California Power Agency (NCPA) field in the Southwest Geysers (Figure 1). Wells at the center of the field (Figures 2 and 3) have relatively low gas, in part because of the effect of injection (particularly N wells, Figure 3). Wells at the field margins have much higher gas concentrations (Figure 4). Steam from most wells showed decreases in gas concentrations from start of production to 1987 and large increases afterwards. Exceptions to this increase include some N and Q wells affected by routine injection operations and, after 1990, some F and C wells affected by increased injection in well C-11 during injection experiments in the low-pressure area of the Southwest Geysers (Enedy et al., 1992). In addition to maintaining reservoir pressures, vaporization of injected liquid causes dilution of gas in existing vapor and decreases wellhead gas concentrations. The long-term effect is an overall reduction in gas concentrations with detailed effects due to the amounts and location of injection and production. Similar increases in gas concentrations are observed in other parts of the Southeast and Central Geysers (PG&E engineers, pers. commun., 1993). These changes in gas concentrations seem to be related to decreases in reservoir pressure.

Pressure cross-sections of UNOCAL leases from Barker et al. (1992) show that by 1984 initial pressures near 500 psig had declined to 250 psig in the central ("Big Geysers") area, to 330 psig in the south-central (Unit 9-10) area, and to 440 psig in the southeast. By 1986 pressures dropped to 220 - 230 psig in the central and south-central areas and to 340 psig in the southeast. From 1986 to 1988 the rate of pressure change decreased in the central and south-central areas (180 and 200 psig in 1988) but continued in the southeast (250 psig in 1988). The rate of decline was greatest in the central area in 1970-1978, in the south-central area in 1980-1986 and in the southeast between 1984 and 1988. A separate cross section at right angles shows 1988 pressures at the southwest edge of the field near 400 psig and at the northeast edge near 500 psig, close to original values. Enedy et al. (1990) show average pressure in the NCPA field decreasing from 420 psig in January 1985 to 270 psig in July 1987 and to 200 psig in February 1990. Thus, in the 1980s a large and increasing pressure gradient developed between the margins of the field and the central, highly exploited areas.

GAS CONCENTRATION PATTERNS

At The Geysers the composition of steam varies with position in the reservoir. Initial variations of total noncondensable gases and in oxygen isotopes are shown in Figure 5 (after Gunderson, 1989). In the Central and Southeast Geysers (and in Larderello, Italy) there is a characteristic pattern of steam composition in which water-soluble salts and isotopes (e.g., boron and ^{18}O) are more concentrated in steam at the center of the field, and gases and isotopes less soluble in water (e.g., CO_2, NH_3, ^{16}O) are more concentrated at the margins (D'Amore and Truesdell, 1979; Truesdell et al., 1987). These patterns are produced by natural-state (pre-exploitation) lateral steam flow with partial steam condensation as heat is lost by conduction to the surface (Figure 6). This can be described as a Rayleigh or open-system process where the concentration of a component is a function of the amount of steam condensed and the relative solubility of the component in steam and water. Similar vertical variations in gas composition are caused by partial condensation of steam at the top of the reservoir (Figure 7).

Steam reservoirs may continue laterally (and vertically) beyond the margins of production zones. These areas tend to be initially rejected because of their high gas or low productivity, but they are connected to the central reservoir and can contribute to the total steam produced. Flow of marginal steam to central production areas depends on the pressure gradient. As discussed earlier, Barker et al. (1992) show that pressure gradients between field margins and central production areas doubled in the north-central area from 1984 to 1988, and in the southeast, from 1986 to 1988. Changes in the NCPA field were even greater where, with assumed marginal pressures near 500 psig, the gradient increased more than three times from 1985 to 1990.

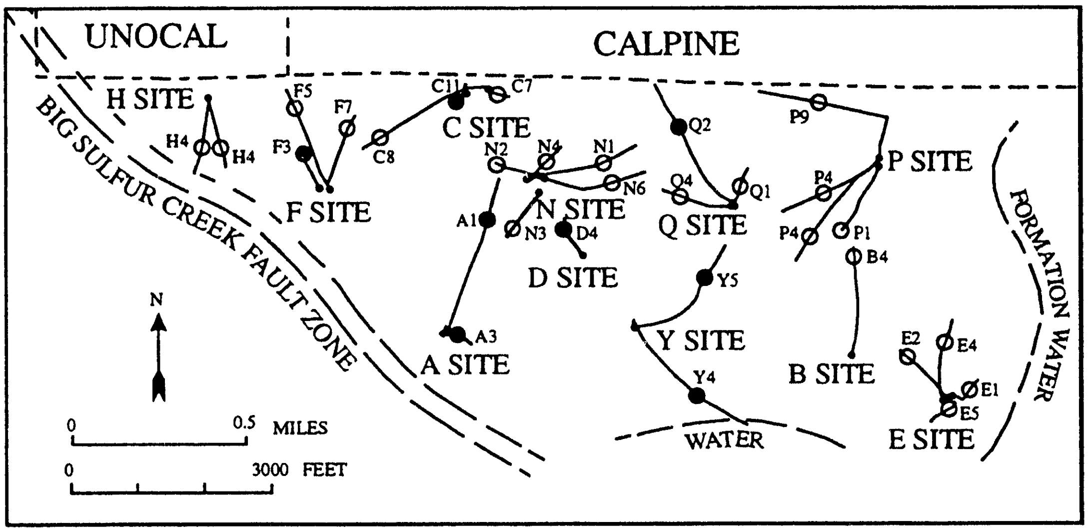

Figure 1. Map of the NCPA field at The Geysers (modified from a NCPA unpublished map) showing locations of selected well sites, mean steam entries (open circles) and mean injection points (solid circles).

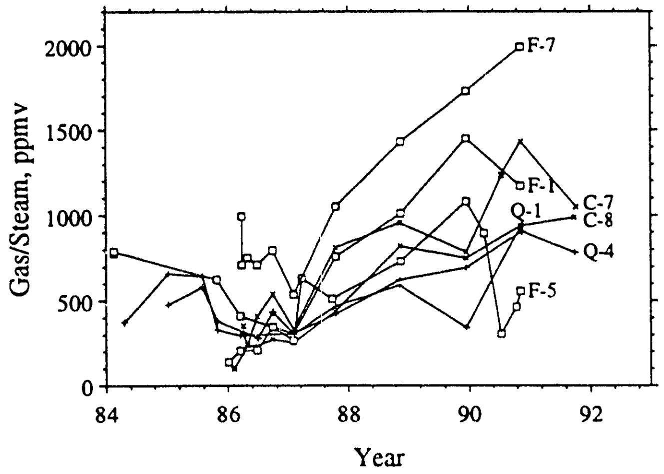

Figure 2. Changes with time of noncondensable gas concentrations (parts per million by volume) in steam from representative wells in the central part of the NCPA field that are not strongly affected by injection.

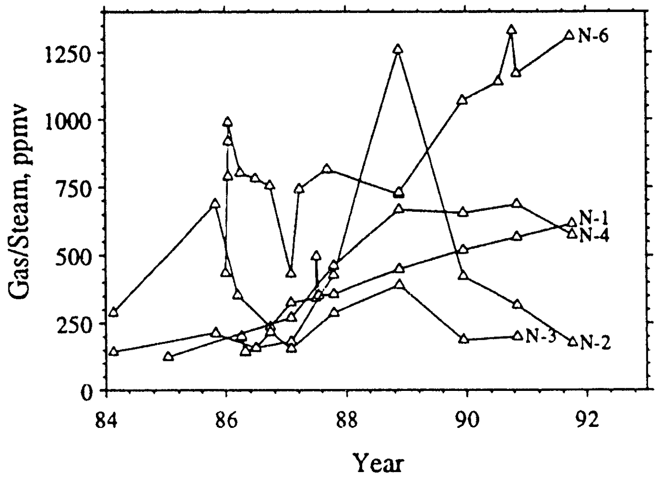

Figure 3. Changes in gas concentrations in steam from N wells in the central NCPA field which are strongly affected by injection.

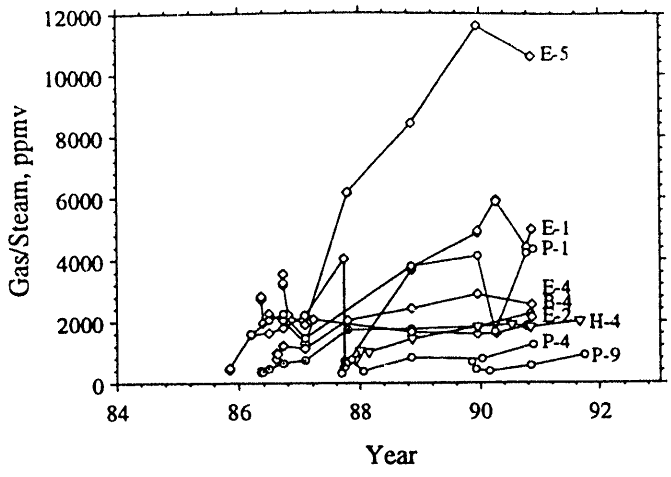

Figure 4. Changes in gas concentration in steam from representative wells at the margin of the field.

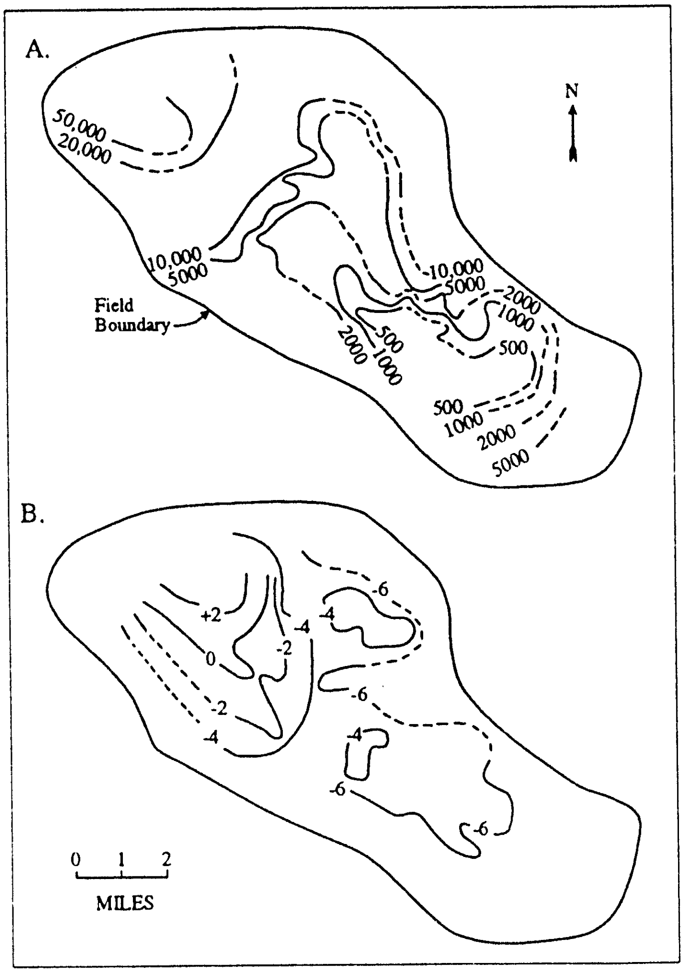

Figure 5. Initial (early production) variations in (A) noncondensable gas (parts per million by weight) and (B) $\delta^{18}O$ values (permil SMOW) in steam from The Geysers (after Gunderson, 1989).

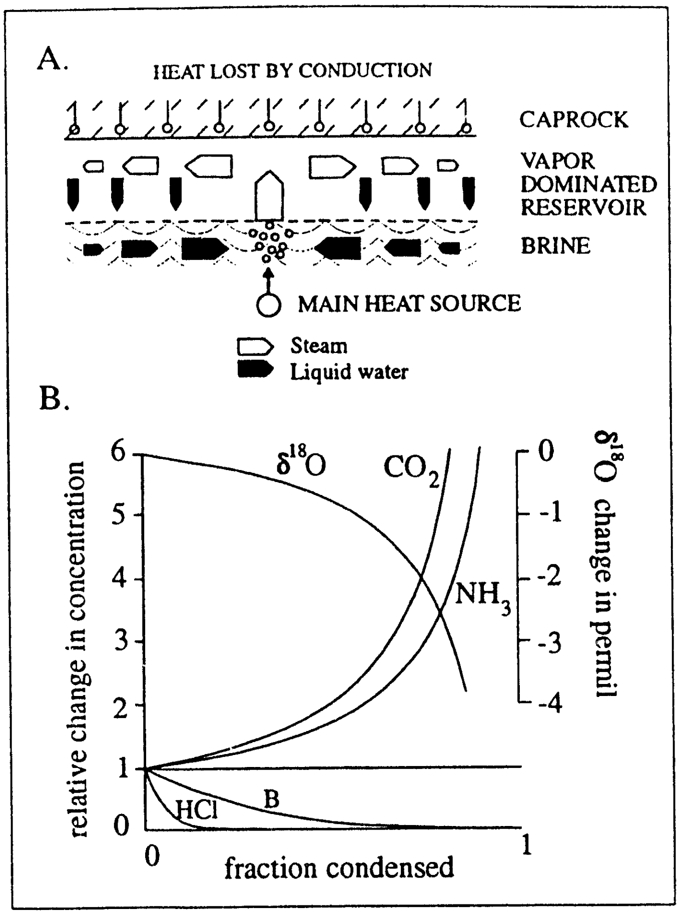

Figure 6. (A) Lateral flow and condensation in a vapor-dominated geothermal reservoir and (B) effects on gas concentrations and $\delta^{18}O$ values in steam undergoing partial condensation in a Rayleigh process during lateral flow (after D'Amore and Truesdell, 1977).

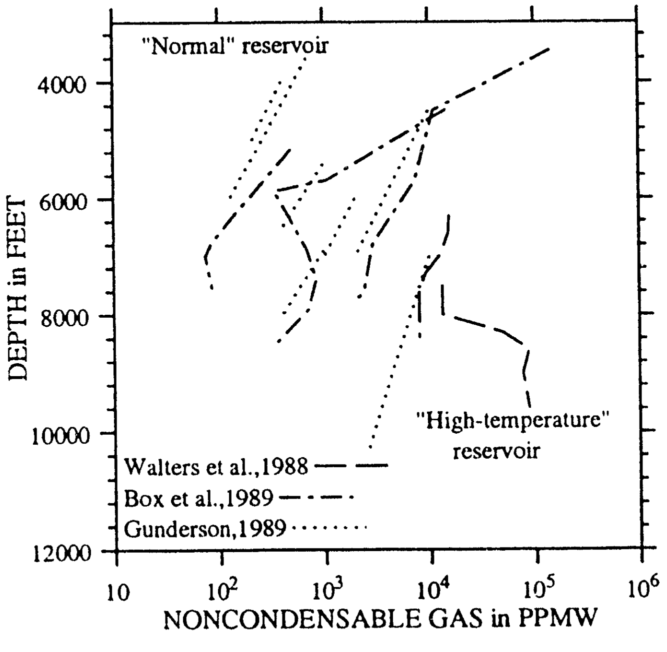

Figure 7. Variations with depth of gas concentrations (parts per million by weight) in The Geysers reservoir.

OTHER SOURCES OF GAS

In addition to noncondensable gas from reservoir margins, there may be other sources of increased gas at The Geysers. It is possible that gas pressures are maintained by mineral reactions. This process requires a reaction with gas as a product and a mineral or minerals as reactant(s). When the gas pressure decreases, more of the mineral reacts to raise gas pressure to equilibrium values until the mineral is exhausted. The mineral is said to "buffer" the gas pressure. Mineral buffer reactions are probably responsible for the increase of CO_2 with temperature in many geothermal reservoirs (Giggenbach, 1981; Arnorsson et al., 1983). For Larderello, this process has been suggested to account for the apparent excess production of CO_2 beyond that originally contained in the reservoir fluid (Pruess et al., 1985). Application of this process to The Geysers is limited by the lack of carbonate minerals in the reservoir. Other sources of carbon (coaly material, black shales) require oxidizing conditions to produce CO_2. These conditions are ruled out by the high concentrations of H_2 observed in Geysers steam (Truesdell et al., 1987). For this reason mineral buffering is considered an unlikely source of increased gas at The Geysers.

A more likely source of gas is a high-temperature reservoir that may exist below the "normal" reservoir in parts of the field. In the Northwest Geysers a relatively thin normal (240°C) reservoir is underlain by a high-temperature (to 350°C) reservoir with up to 9% noncondensable gas and high $\delta^{18}O$ and HCl (Walters et al., 1988). Thus the appearance of HCl and high gas concentrations in steam from part of the Central Geysers (Unit 15 area) was interpreted to indicate the presence of a high-temperature reservoir below the exploited reservoir in this area (Haizlip and Truesdell, 1989). The high HCl and high $\delta^{18}O$ of the Northwest Geysers steam suggests that a magmatic component may be present. This is consistent with high $^3He/^4He$ in steam (7 to 9 times that in air) from the Central and Southeast Geysers reported by Torgersen and Jenkins (1982). A program of sampling and analysis of steam from all parts of The Geysers is proposed to examine this possibility.

THE NORTHWEST GEYSERS

Gas (and ^{18}O) in Northwest Geysers steam has a different pattern from that in the center and southeast (Figure 5). This results from the lack of Rayleigh condensation of laterally flowing steam. Condensate percolating downward from the normal reservoir into the high-temperature reservoir is immediately vaporized, so steam and condensate flow only up and down. The relation of the high-temperature reservoir to the "normal" reservoir in a schematic cross-section of The Geysers is shown in Figure 8. In the Northwest Geysers wells are completed in both reservoirs, with most production from the high-temperature one. The variation in wellhead gas concentrations depends mainly on the proportion of steam produced from each reservoir. Because of the lack of lateral flow and condensation in this area, there is no equivalent of the marginal high-gas steam found in the central and southeast areas. Changes in gas in the Northwest Geysers will depend on changes in pressure in the production area and on the variation of gas concentrations in the interconnected normal and high-temperature reservoirs which may contain zones with lower gas concentrations than now produced (Mark Walters, pers. commun., 1992).

INJECTION OF LIQUID

Injection of liquid water into The Geysers reservoir produces rapid decreases in gas concentrations in steam both from increasing reservoir pressures and from dilution of existing gassy vapor with nearly gas-free vaporized liquid. The greatest benefit of injection are realized in underpressured, superheated areas of the reservoir in which original liquid has disappeared. These areas have been used in experiments in which almost all injected water was recovered in production. In the NCPA field the main injection wells are clustered in the center (Figure 1), with most injectate return produced from N and Q wells.

The fraction of injectate return can be calculated from changes in steam isotopic composition (e.g., Beall and Box, 1992), but the effects of injection are also shown in gas equilibrium calculations using "grid" diagrams (D'Amore et al., 1982). In these diagrams the temperature and steam fraction are calculated assuming that steam and water are in equilibrium in the reservoir, and that during production water vaporizes and mixes with in-situ steam without further equilibration. Figure 9 shows part of a grid for the equilibrium of CO_2, CH_4, H_2 and H_2O (y-axis) and of pyrite, magnetite (or other Fe oxide), H_2S, H_2 and H_2O (x-axis). Changes in temperature and steam fraction ("y" value) are shown for steam from well E-1 at the NCPA field margin, and well N-3 in the center, which is strongly affected by injection. Temperatures indicated are in the range of 230 to 265°C for both wells, and initial y values are the same (0.01), but steam from well E-1 at the margin evolves toward higher temperatures and much higher y values (near 0.25), while well N-3 changes temperature and y value within a small range.

These differences in behavior are interpreted as showing that well E-1 changed its steam source from local steam with low gas and moderate temperature (partly from vaporization of initial water) to high-gas, somewhat higher-temperature steam from the reservoir margin, while well N-3 produced low-gas steam largely from vaporized injectate. Pressures at field margins are near original values, so the amount of vaporization of liquid is less, resulting in larger y values. Variations in source temperatures calculated for N-3 steam are probably related to the variation of gas concentrations (Figure 3).

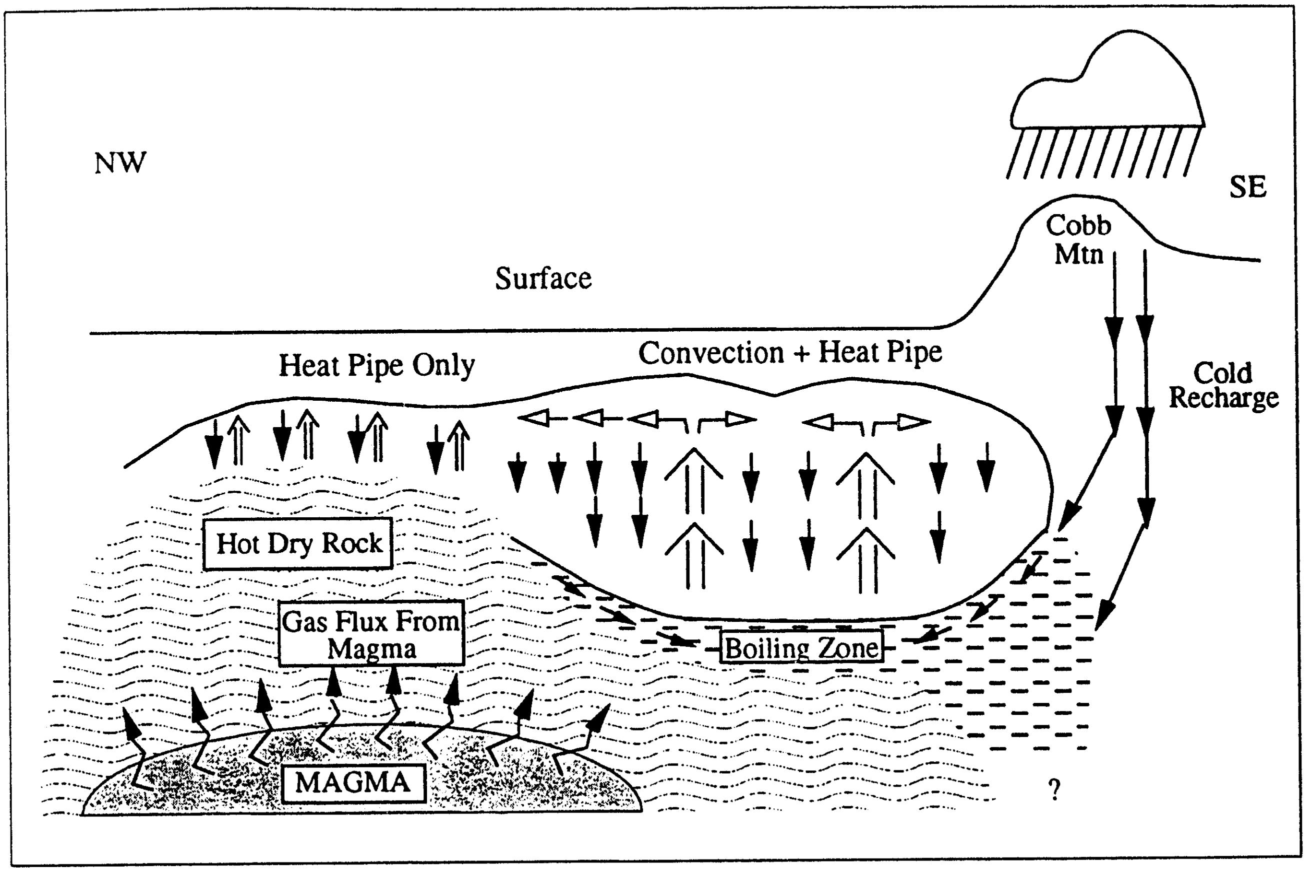

Figure 8. Schematic cross section of The Geysers geothermal system showing flow of steam (open arrows) and condensate (closed arrows) for convection in the northwest and central/southeast parts of The Geysers.

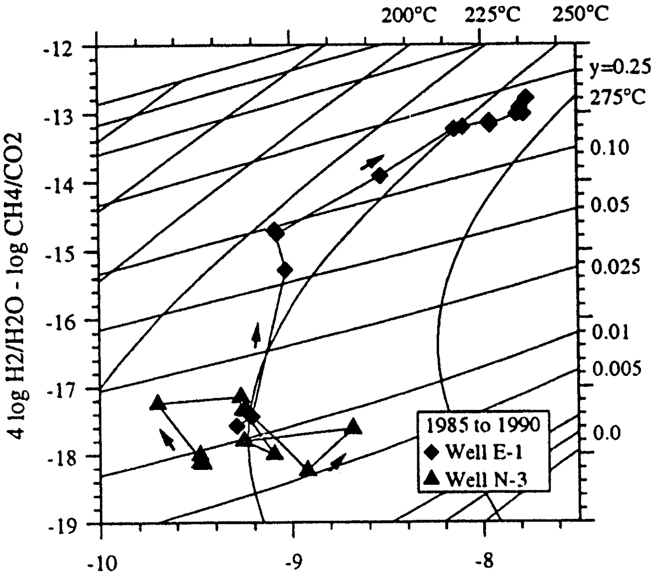

Figure 9. Temperature-steam fraction ("y") grid diagram showing changes with time for steam from a NCPA central well (N-3) affected by condensate injection, and for steam from a well on the field margin (E-1) affected by inflow of marginal steam.

SUMMARY

The decrease of pressure that occurred in the Central and Southeast Geysers reservoir in the late 1980s also caused an increase in noncondensable gas concentrations in the produced steam. The link between lower pressure and higher gas concentrations is due to the existence of high-gas marginal (and possibly overlying) zones connected to the exploited reservoir. Gas in these distal zones resulted from condensation of steam flowing laterally (and upward) under natural state conditions. When pressures in central zones decreased, higher-pressure steam richer in gas flowed in from the margins. This effect was greatest in the Southeast Geysers where the increase of exploitation was the most rapid. Other sources of gas include underlying high-temperature, high-gas steam reservoirs and less probably, mineral buffering reactions. Thus the reservoir first exploited in the center and southeast Geysers contained low gas but was connected to marginal zones with much higher gas. When central pressures declined strongly, marginal, high-gas steam flowed into the exploited zone. Deep, high-temperature reservoirs may also contribute high-gas steam to pressure-depleted production areas.

The Northwest Geysers reservoir is significantly different because the high-gas, high-temperature reservoir contains most of the steam resources and was exploited first. In the northwest the lack of large scale convection prevented the formation of high-gas zones at reservoir margins and the steam produced now may contain close to the highest concentrations of gas in the reservoir. As a result the produced steam may not evolve toward significantly higher gas concentrations.

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