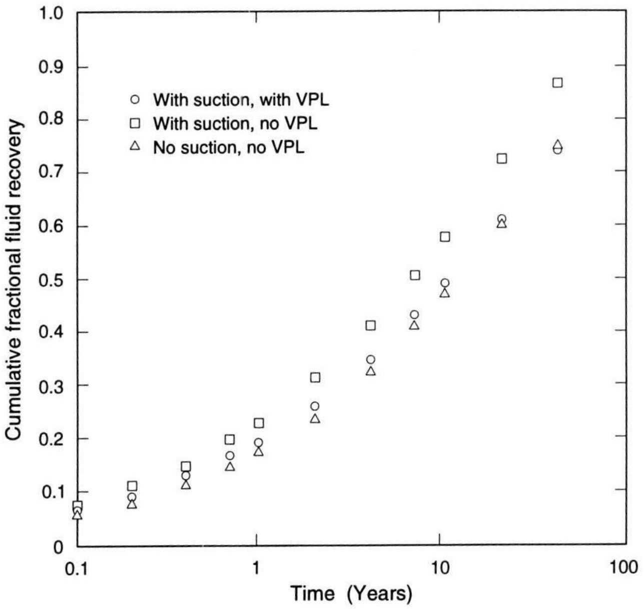

Figure 3. Cumulative fluid recovery in block depletion problem for matrix permeability of 10^{-18} m^2. [XBL 9112-7104]

for most of the productive life of vapor-dominated systems, playing a role only in the final stages of reservoir dry-out.

Depending on the relative permeability behavior of vapor-dominated systems, which has not yet been well characterized, it is possible that the suction effects from capillarity and vapor adsorption may significantly affect liquid flow in the matrix blocks. Although of minor importance for pressure and flow-rate behavior of vapor-dominated systems, the presence of adsorbed and capillary water at pressures below saturated values may play a crucial role in rock-fluid reactions and in the release and transport of noncondensable gases. A more detailed analysis of vapor pressure lowering effects has been given in Pruess and O'Sullivan (1992).

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Geochemical Studies of Reservoir Processes in the Southeast Geysers

A. H. Truesdell, S. Enedy,† J. L. Smith,† and M. J. Lippmann*

A nearly field-wide accelerated decline in pressure and steam production occurred at The Geysers in the late 1980s. As a result of this crisis, the U.S. Department 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 gas and predicting changes in pressure, steam flow, and gas content. The chemistry of steam has been used to indicate the distribution of liquid and gases in the reservoir and the sources of produced steam. These studies involve calculating temperature and fraction of steam in the feed to wells and tracing steam compositions that originate from partial condensation, evaporation of liquid, and mixing of steam sources. Steam sources now exploited include steam from the open fractures of the system, vaporized liquid from small fractures and the rock matrix, and fluids entering the reservoir from outside, including injected condensate and fluids from undrilled areas.

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* Consultant, Menlo Park, California.

† No. California Power Agency, Middletown, California.

This study concentrated on the Northern California Power Agency (NCPA) field, located in the southeastern part of The Geysers (Figure 1). The field is bounded to the north by Unocal and Calpine leases, to the southwest by the Big Sulfur Creek fault zone, in which low permeability limits steam production, and partially to the south and east by liquid-saturated boundaries. Geochemical methods of tracing reservoir processes have been applied to steam analyses provided by NCPA.

GAS EQUILIBRIA

At equilibrium, concentrations of gases in reservoir steam and liquid differ because gases partition strongly into the steam. If reservoir liquid vaporizes during production and this steam mixes with original reservoir steam, gas concentrations in the mixture will not correspond to equilibrium in either liquid or steam. By combining gas solubilities and equilibria for two reactions, both reservoir temperature and steam fraction, "*y*," which is equal to the fraction of original reservoir steam in the produced mixture (also called effective reservoir steam saturation), can be calculated. Methods for this calculation were first described by Giggenbach (1980) and D'Amore et al. (1982).

Methane breakdown and pyrite-H_2S reactions were chosen for the calculation. These reactions are

$$CH_4 + 2H_2O = CO_2 + 4H_2$$

and

$$3FeS_2 + 4H_2O + 2H_2 = Fe_3O_4 + 6H_2S \ .$$

Equilibrium expressions for these reactions can be written as

$$\begin{aligned} 4\log(H_2/H_2O)WH + \log(CO_2/CH_4)WH = \\ -15.35 - 3952/T + 4.635\log T \\ +4\log AH_2 + \log(ACO_2/ACH_4) \end{aligned}$$

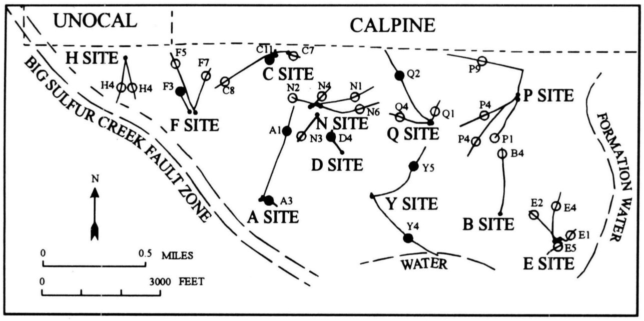

Figure 1. Map of the NCPA field showing locations of field boundaries, and selected well sites, well courses, mean steam entries, and mean injection points (solid circles). [XBL 936-888]

and

$$\begin{aligned} 3\log(H_2S/H_2O)WH - \log(H_2/H_2O)WH = \\ 6.23 - 6222/T - 0.412\log T \\ +3\log A_{H_2S} - \log A_{H_2} \ , \end{aligned}$$

where *WH* refers to wellhead analyses in molal units, *T* is in degrees kelvin, $A_i = y + (1 - y)/B_i$, and B_i is the gas distribution constant, C_{vapor}/C_{liquid} (given in Giggenbach, 1980).

On a grid drawn using these equations (Figure 2), the NCPA steam analyses indicate temperatures from about 210 to 265°C and steam fractions (*y* values) from about 0.005 to 0.25. Most steam analyses are between 225 and 250°C, and 0.05 and 0.2*y*. The indicated temperatures are reasonable. The original temperate at 2000 m depth was probably near 245°C (Truesdell and White, 1973), with somewhat lower temperatures expected as a result of exploitation. The calculated steam fraction values (5 to 20 wt% steam) indicate substantial liquid reserves.

GAS CONCENTRATIONS

Total gas concentrations (as mole fractions) are shown for a cross section of the NCPA field in Figure 3. These values vary with time and position in the field. Large increases occurred at the field margins after 1985, with smaller increases in the center of the field after 1987. These changes can be better seen in Figures 4 and 5, which show changes with time of the gas concentration of wells at the margins and center (except N wells) of the field. Gas concentrations in steam from N wells are lower and more variable as a result of intense nearby injection (Figure 6). (In-

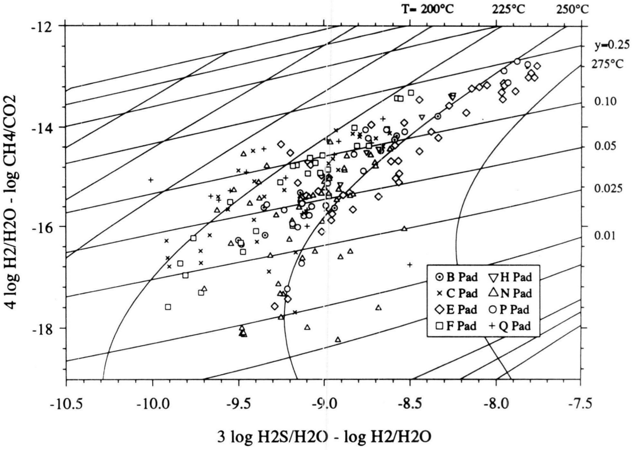

Figure 2. Part of the *y-t* "grid" diagram for CH_4-CO_2-H_2 and pyrite-magnetite-H_2S reactions showing effective vapor saturation, *y*, and temperature for selected NCPA steam samples collected from 1985 to 1990. [XBL 936-889]

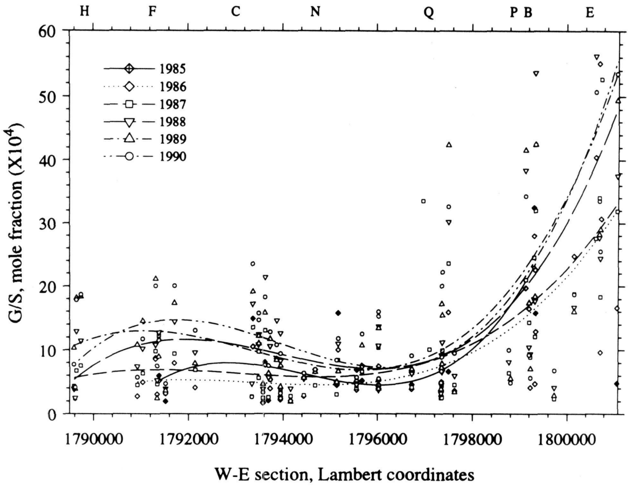

Figure 3. W-E cross section of the NCPA field showing gas to steam mole fractions for yearly steam samples and curves fitted to each year's data. [XBL 936-890]

jection well locations are shown as filled circles in Figure 1.) These figures show that gas concentrations in almost all steam analyses decreased or were constant until mid-1987 and increased markedly from 1987 to late 1989 or 1990.

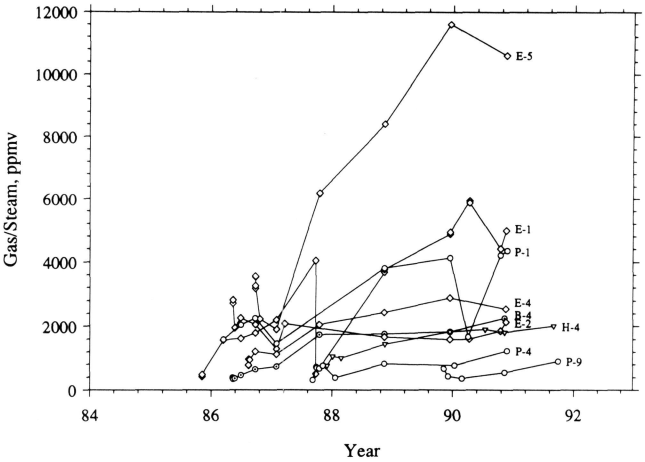

Figure 4. Changes with time of gas concentrations (in ppm by volume) for steam at the margins of the NCPA field (H, P, B, and E wells). [XBL 936-891]

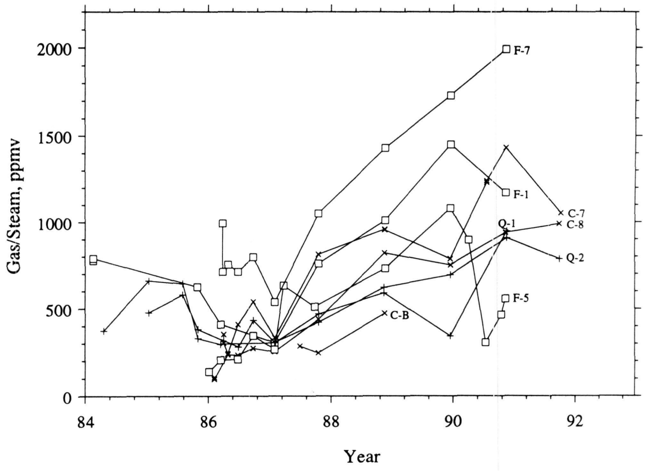

Figure 5. Changes in gas concentrations for steam from wells in the central NCPA field (except N wells). [XBL 936-892]

Steam may exist in areas beyond the margins of the drilled field. These areas, initially rejected because of high gas or low productivity, eventually contribute to the total steam produced in neighboring wells. Steam at the reservoir margins is distinct chemically from steam in the center. In the Southeast Geysers and in several areas of Larderello, water-soluble salts are more concentrated in steam from the center of the field and water-insoluble gases more concentrated at the margins (D'Amore and Truesdell, 1979; Truesdell et al., 1987). Oxygen-18 is depleted in marginal steam. These patterns are produced by natural-state (pre-exploitation) lateral steam flow with partial condensation as heat is lost by conduction to the surface.

Steam from E and P wells clearly shows the effect of mixture with marginal steam (Figure 4). These wells generally produce the highest initial gas contents and have increased in gas with time starting in 1987. Wells E-5, E-1, and P-1 produce the highest gas of the field (to 12000 ppmv) and are nearest to the field margin. Steam from well H-4 on the western margin, which (along with E well steam) was originally low in ^{18}O, has moderately high gas relative to most wells but much lower than for E wells.

Steam from C, F, and Q wells (Figure 5) has somewhat higher gas contents than those from N wells and much lower gas than steam from field margins. This group shows a small decrease in gas before 1987 and a large increase in

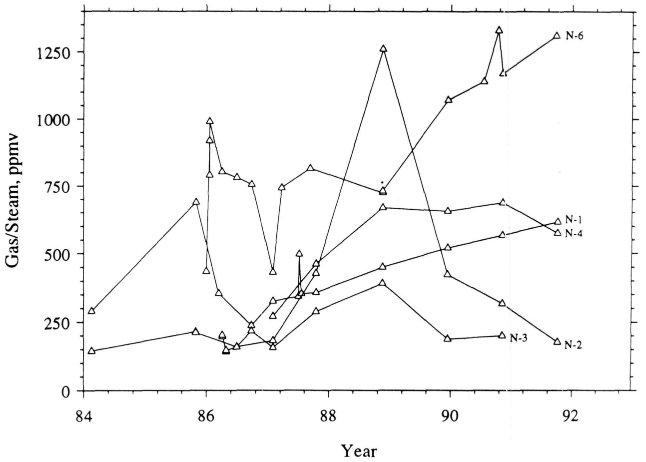

Figure 6. Changes in gas concentrations for steam from N wells. [XBL 936-893]

gas afterwards. The decrease in gas content before 1987 is due to dilution of reservoir steam by the continued vaporization of reservoir liquid. In 1987 this process stopped or slowed markedly and the gas contents of steam increased.

N well steam has the lowest gas of the NCPA field (Figure 6). This is probably due both to the position of N wells at the center of the field and to gas dilution from vaporization of injectate. Steam from wells N-1 through N-4 generally has gas contents below 750 ppmv and has not shown rapid increase in gas. These wells are evidently receiving enough injectate to stabilize gas contents of the produced steam.

ISOTOPES

Isotopes have been frequently used in tracing injection return in steam fields (Nuti et al., 1981; Beall and Box, 1992). Studies of injection in a low-pressure area (LPA) of the Southeast Geysers shared by NCPA, Calpine, and Unocal have demonstrated substantial increases in steam flow and reservoir pressure (Enedy et al., 1992). Isotopic data were used as tracers in this and other studies to estimate the quantity of steam generated from evaporation of injected condensate.

The effects of evaporation on the injected condensate and the results of mixing steam from vaporized condensate with reservoir steam are shown in Figures 7 and 8, in which steam isotope compositions for 1985–1986 are compared with those for 1990. In 1985–1986 some N and A wells were affected by condensate injection, whereas in 1990 this effect was felt strongly by F, C, and N wells, with some effect for most other wells. The effects of intense injection in the LPA near F and C wells is seen in Figure 8. In 1990 only wells far from injection wells (some E and H wells) retained their original isotope compositions.

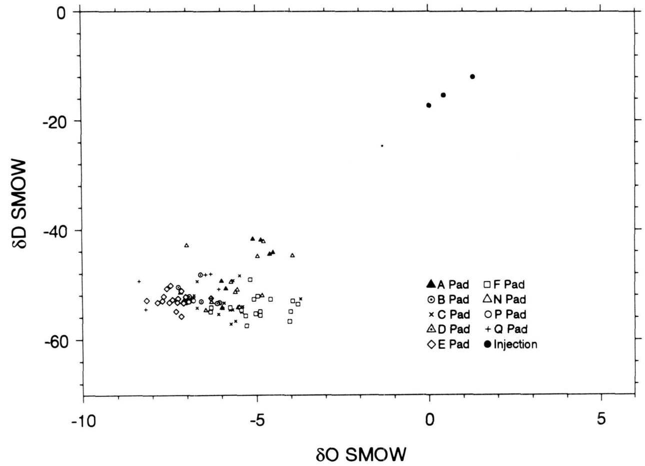

Figure 7. Isotope diagram showing values of $\delta^{18}O$ and δD (in permil SMOW) for 1985–1986 NCPA steam samples. [XBL 936-894]

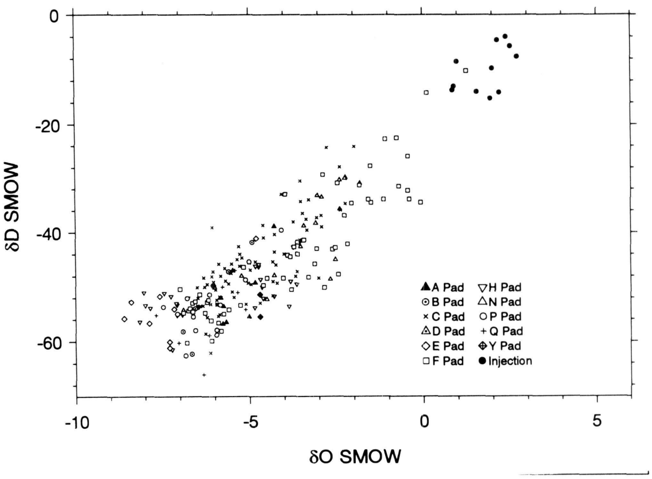

Figure 8. Isotope diagram (like Figure 7) for 1990 NCPA steam samples. [XBL 936-895]

DISCUSSION

The main influences on the gas and isotope compositions of steam from the NCPA field include: (1) original (pre-exploitation) gradients produced by the lateral movement of steam, resulting in the presence of high-gas steam at field margins; (2) injection of steam condensate, which vaporizes and mixes with reservoir steam to dilute gases and increase heavy isotope contents; and (3) a decrease in the availability of liquid in the reservoir, which has decreased pressures and flows and increased gas concentrations.

Natural-state gradients in gas and isotope chemistry result from lateral movement of steam from an upflow zone in the west-central part toward zones of condensation mainly to the south and east, with a smaller flow to the west. This movement was accompanied by partial condensation of steam along the flow path, causing the residual steam to be enriched in gas and depleted in ^{18}O. The resulting zones of condensation at the field margins contain subcommercial quantities of high-gas steam. As pressures decrease during production, the marginal steam is drawn into producing zones, causing an increase in gas concentrations. This effect may produce results similar to the general decrease of steam from vaporized liquid.

Injection of steam condensate has influenced steam compositions in the center of the field. Injection greatly increases heavy isotope (D and ^{18}O) contents of steam fed in part from vaporization of the injectate and lowers gas concentrations by dilution. Injection has affected the gas contents of some steam in the center of the field, but this effect has been overshadowed by the general change in steam origins discussed next.

The most important influence on steam compositions is the sudden decrease in 1987 of the amount of steam formed by vaporization of liquid water in the reservoir. This is clearly seen in the change in the gas concentration of steam from individual wells (Figures 4 and 5). Before 1987 steam from most central wells contained less than 1000 ppmv, and wells at the eastern margin contained less than 3000 ppmv. In early 1987 gas contents increased rapidly from minimum values to maxima in 1990 (2 to 6 times greater). The decrease in vaporization of easily available liquid in the reservoir has caused rapid decreases in pressure and steam flow throughout most of The Geysers field. This has important consequences for the continued productivity of the entire field.

Numerous modeling studies of mass and heat transfer in vapor-dominated reservoirs have demonstrated steam-water counterflow, but only Pruess and Narasimhan (1982) indicate the location of liquid in the reservoir. These authors state that liquid is confined to matrix blocks because it will vaporize if it enters vertical fractures and cannot exist on fracture surfaces. This argument appears limited to very low permeability rocks in which conductive heat flow is as rapid as fluid flow. For a natural system at equilibrium, thermodynamic arguments indicate that water in rock pores, water on fracture surfaces, and steam can coexist.

It seems likely that the 1987 increase in gas and decline in pressure and flow was due to a decrease in the availability of liquid water in the reservoir. Pressure could be maintained by producing steam from a large volume of interconnected fractures with minimal vaporization of liquid in each unit volume or from a smaller production volume with extensive vaporization. Similarly, declining pressure could result from an increasing distance to the source of steam or from decreasing availability of nearby liquid.

The existence of well-defined chemical patterns inherited from the natural state in the long-exploited Larderello field (D'Amore and Truesdell, 1979) and in the geochemical results presented here suggest a local source of steam. In this view, rather than the exhaustion of a distant homogeneous source, the recent accelerated decline in pressure and flow at The Geysers resulted from the local disappearance of liquid held in easily accessible sites—liquid on surfaces of major fractures, in minor fractures opening upward, and perched liquid in structural traps. Continued production is from existing steam and vaporization of less-accessible reservoir liquid as well as from injected water and possibly from underexploited areas at the reservoir margins.

Before 1987 much of the steam produced from The Geysers probably originated from vaporization of easily accessible liquid. The field-wide pressure decline after 1987 indicated that the amount of easily accessible liquid had declined rapidly throughout the interconnected reservoir. Continued production is largely from existing steam and less-accessible liquid. This liquid is probably contained in limited matrix porosity (< 2% in Geysers graywacke; G.S. Bodvarsson, personal communication, 1992) and in small fractures of matrix blocks. The amount that this "matrix" liquid contributes to steam flow is indicated at least semiquantitatively by the gas equilibria calculations (Figure 2). At the NCPA field, vaporization of matrix liquid may still provide more than 75 or 80% of production from most wells. The rate at which the steam produced by vaporization of liquid within the matrix blocks can move to large fractures connecting to wells is limited by permeability. The Geysers cannot boil dry immediately (unlike a teakettle), but the rate of boiling may be limited. If the indication from gas geothermometry that most of present steam is from matrix blocks, then the amount of liquid water in the reservoir may be large but the production rate limited. This suggests that The Geysers will continue to be productive for a long time but at a lower rate.

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