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THE RECOVERY OF INJECTED WATER AS STEAM AT THE GEYSERS

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ABSTRACT

The stable isotopes of hydrogen and oxygen have been used as tracers to track the movement of injected water within UNOCAL-NEC-Thermal leases at The Geysers, and also used to estimate the mass of injectate recovered for the period 1983 - 1988. Cooling tower condensate has been injected into The Geysers reservoir since 1969 and that has been supplemented by river water since 1980. To estimate the contribution of flashed injectate in the produced steam, two methods of calculation were employed: one (R-C) assumed that the produced steam was a mixture of original reservoir steam and flashed condensate only and the other (R-C-M) assumed that a third component, meteoric water, was also present. In 1988 the mass of injectate produced as steam was equivalent to 65 percent by the R-C method, and 80 percent by the R-C-M method, of the total mass of water injected that year.

INTRODUCTION

The Geysers geothermal field is the world's largest producing geothermal field with a gross installed capacity of 2,043 MW. The reservoir was formed in Franciscan rocks of the California Coast Ranges. Geysers wells have produced dry steam for electrical generation since 1960, and steam from UNOCAL-NEC-Thermal (U-N-T) leases supplies 1,103 MW of installed generating capacity built by PG&E. The location of U-N-T leases and PG&E's power plants are shown in Figure 1 and the plants supplied from U-N-T leases (Units 1 - 8, 9 & 10, 11, 12, 14, 17, 18, 20) are used as points of reference in this paper. Steam condensate has been injected back into The Geysers reservoir since 1969 and by the end of 1988 407 Glbs of condensate had been returned to the reservoir. In 1980 Unocal began injecting water extracted from Big Sulphur Creek (BSC) during periods of high runoff and by the end of 1988, 55 Glbs of BSC water had been injected.

Condensate and BSC meteoric water have different isotopic compositions from the initial reservoir steam (Figure 2) and when these fluids interact, the isotopes combine in a simple mixing process. The isotopic differences between injected water and the predevelopment reservoir fluid allow the fraction of flashed injectate being produced in a Geysers steam well to be estimated.

DATA

Stable isotope data for water are reported as the per mil difference between the ratio of heavy to light isotopes in the sample and the ratio of Standard Mean Ocean Water (SMOW), divided by the SMOW ratio. The data for this study include values from the 1960s and 1970s used to determine initial reservoir composition, and data from surveys conducted annually since 1983 used to estimate the injectate contribution. In the annual surveys every producing well on U-N-T leases was sampled, and samples were analyzed by Southern Methodist University. The data were normalized to the 1986 survey values using standards.

Three isotopically distinct fluid components are produced at The Geysers: initial reservoir fluid, power plant condensate, and meteoric water, which includes injected river water (BSC) and naturally recharging groundwater. Initial reservoir steam compositions become heavier

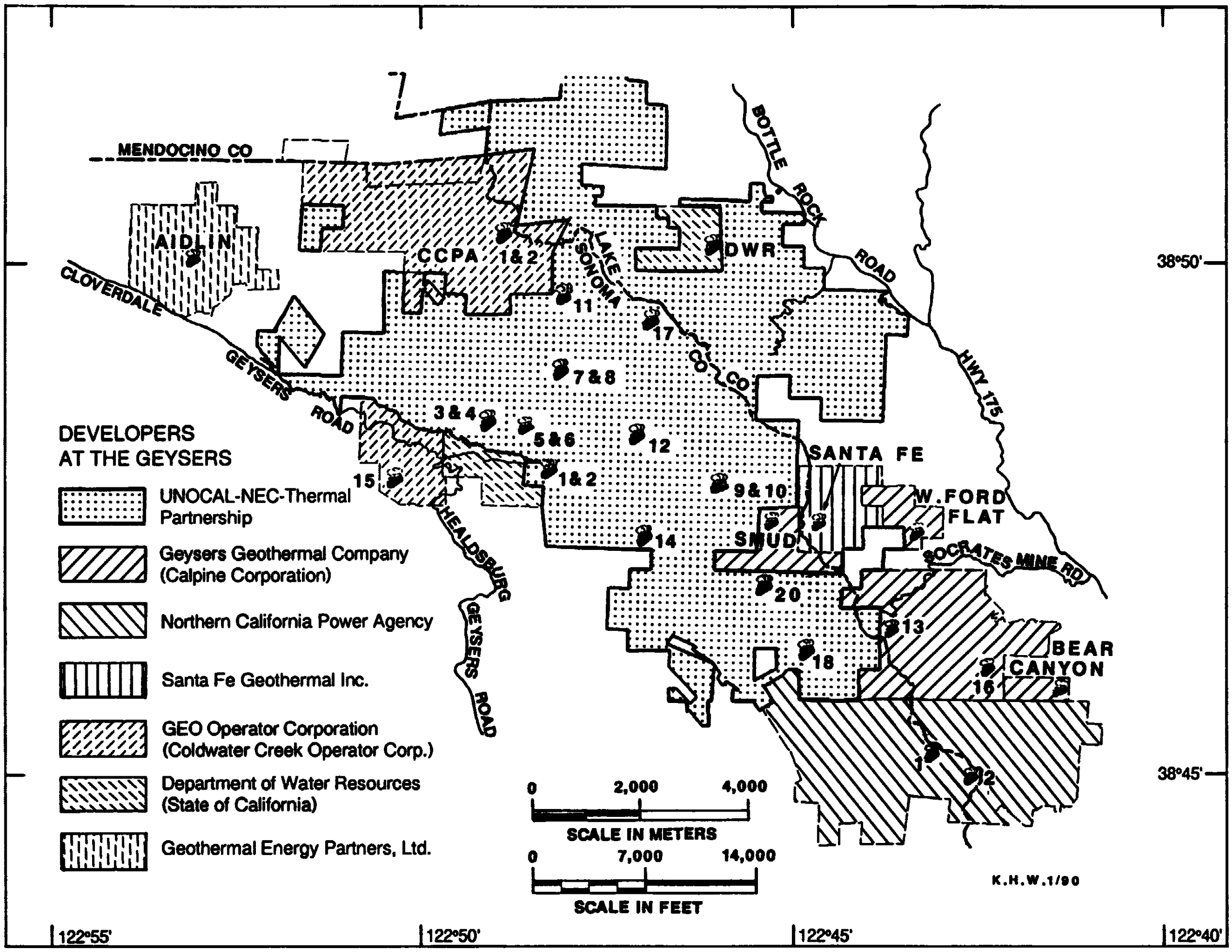

Figure 1. Power plants and leases at The Geysers.

southeast to northwest throughout the reservoir, with average values of $\delta^{18}O$ = -5.5 per mil and δD = -55 per mil in the southeast and $\delta^{18}O$ = 2 per mil and δD = -45 per mil in the northwest (Figure 2). The approximate ranges for condensate throughout the field are between 1 and 9 per mil for $\delta^{18}O$ and between -20 and 10 per mil for δD,

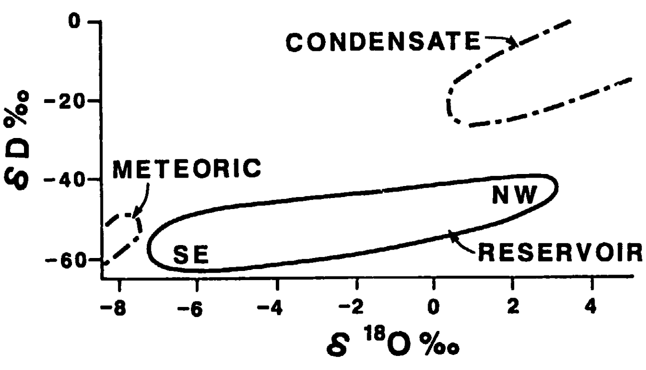

Figure 2. Range of isotopic content of fluid sources at The Geysers. Values given in per mil relative to SMOW. Data from northwest Geysers from Haizlip (1985).

although each individual injector has a smaller variation. Meteoric water isotopes from local surface waters fall in a narrow range with an average of -8 per mil for $\delta^{18}O$ and -55 per mil for δD. In Figure 3 the ÇMdD variation in the U-N-T part of the reservoir is shown for the years 1983 and 1988, and the association between areas of positively shifted δD and the location of injection wells is clear. The $\delta^{18}O$ variation for the same years is shown in Figure 4 and an association between positively shifted $\delta^{18}O$ and injector locations is also present but is less distinct because of the relatively large natural variation in the reservoir.

METHOD

Two methods were used to calculate the amount of injection fluid recovered using steam isotope data. The first (R-C) method assumes that each sample is a mixture of reservoir fluid and condensate only. The second (R-C-M) method calculates each sample composition as a mixture of reservoir steam, condensate, and meteoric water. In the reservoir-condensate method (R-C), each sample composition is simply projected onto the tie line between pre-exploitation reservoir values and condensate values

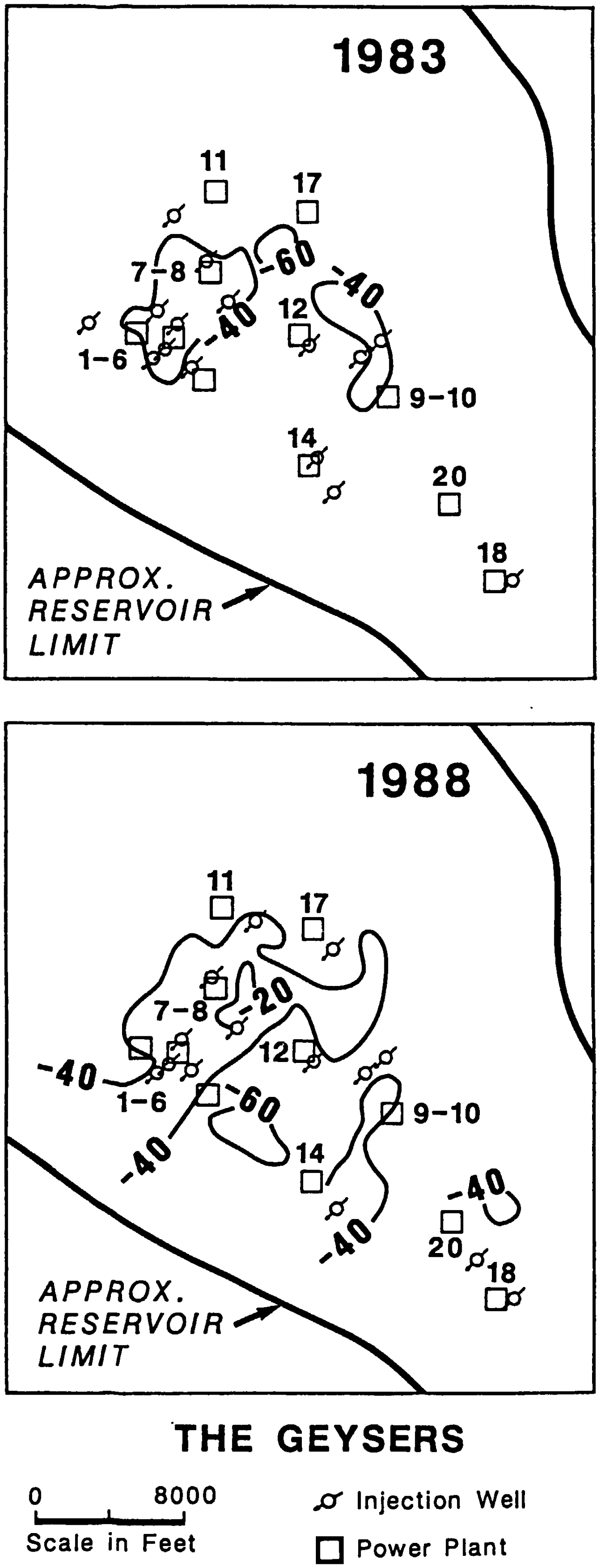

Figure 3. δD in produced steam for 1983 and 1988. Contours are in per mil relative to SMOW.

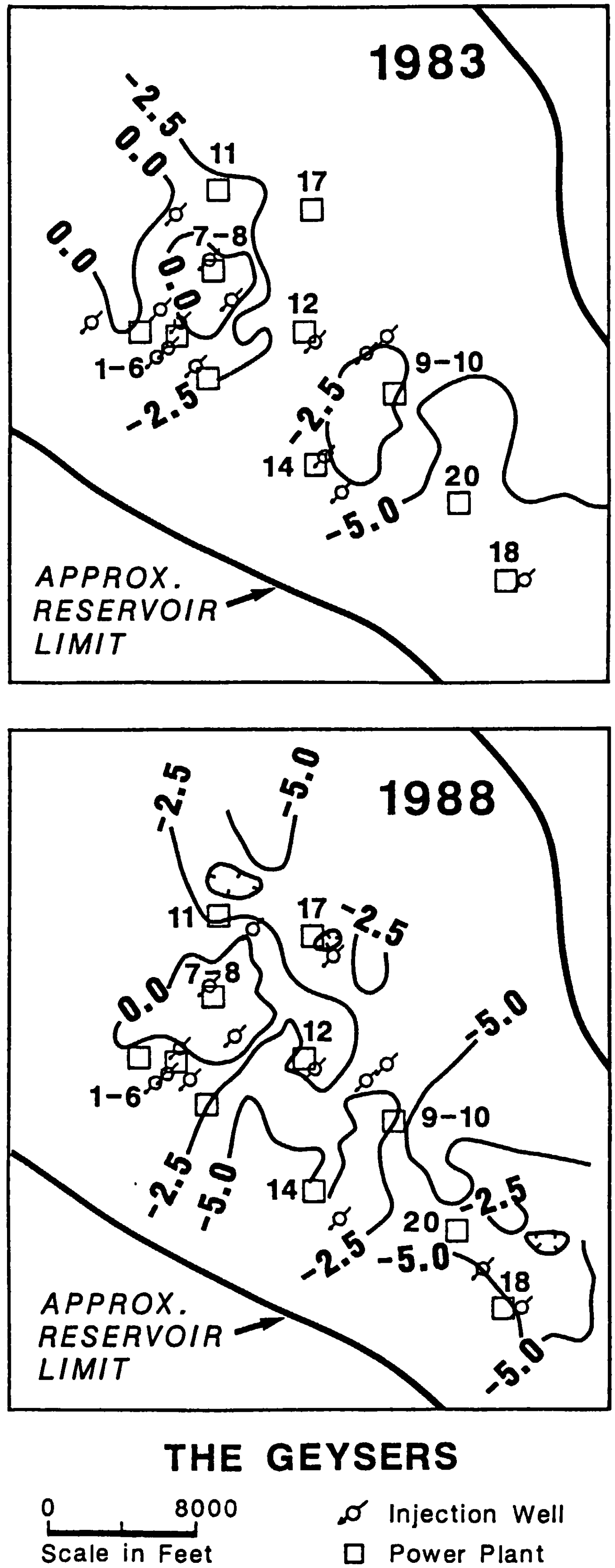

Figure 4. $\delta^{18}D$ in produced steam for 1983 and 1988. Values are per mil relative to SMOW.

as shown in Figure 5. For each producing well, the condensate compositions from nearby injectors were averaged to estimate an appropriate condensate endmember.

The principal simplifying assumption in the R-C method is that any meteoric component in the sample is ignored. The effect of meteoric water is to add lighter isotopes, and where meteoric water is present, as in parts of Units 1 through 8, 9 & 10, 14, 18, and 20, the R-C method tends to underestimate the amount of condensate in a sample. The R-C method is more appropriate for most of Units 11, 12, 17 which do not appear to be affected by meteoric water.

In the R-C-M method, each sample is considered to be a mixture of reservoir steam, flashed condensate, and flashed meteoric water (Figure 5) and the fraction of each component is calculated algebraically.

Uncertainty in both methods is due largely to natural variations in the pre-exploitation reservoir steam, temporal variations in the isotopic content of cooling tower condensate, and the effects of fractionation during boiling of the injected liquid. Boiling and fractionation at Geysers reservoir temperatures (typically around 240°C) cause a negative isotopic shift in the vapor roughly parallel to the $\delta^{18}O$ axis, and have the greatest effect on the apparent meteoric component of the sample.

Figure 6 shows the extremes of the differences possible in the application of the R-C-M and R-C methods applied to individual wells over the time interval 1983 to 1988. Well DV-1 has small differences in estimated injectate recovery, typically less than 10 percent, whereas well SB-27 has large differences, as much as 70 percent, between the two calculation methods.

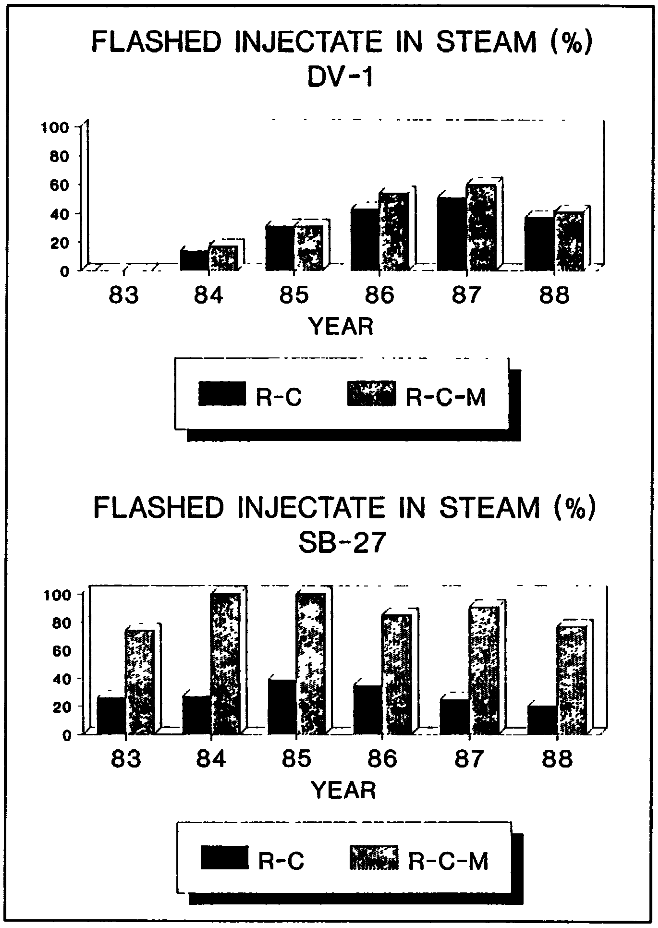

Figure 6. Examples of injectate recovery for two wells, DV-1 and SB-27.

DISCUSSION

The estimated percentage of total injectate produced in the steam from U-N-T leases, i.e. condensate plus injected meteoric water, calculated by the R-C-M method, is shown in Figure 7 for 1983 and 1988 "water years" (water years span the interval October through September). By 1988, flashed injectate was being produced through U-N-T leases, except to the west of Units 1 through 6 and 7 & 8, east of Units 9 & 10, northeast of Unit 11, and in the vicinity of Unit 17 (Figure 7).

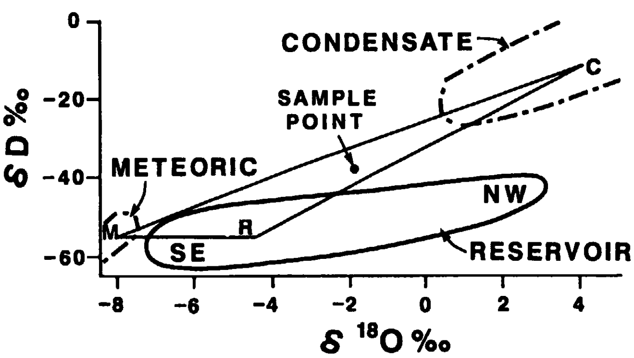

Figure 5. R,C&M endmembers for a sample calculation. Values are per mil relative to SMOW.

The western limit of injectate recovery west of Units 1-6 has not changed since at least 1983 (Figure 7). In an attempt to examine the possibility of a structural barrier the well logs of the wells penetrating the reservoir were studied in detail, but the fine size of drill cuttings from air-drilling made it difficult to distinguish subtle changes in lithology within the reservoir graywacke. However, a northeast-southwest trending structure offsetting the top of the reservoir graywacke was evident on the lithologic logs of wells drilled along this same zone, and it is therefore possible that the western limit of injectate recovery is fault controlled.

Wells east of Unit 11 have been affected since the early 1980s by injectors east of Units 7 & 8. The amount of injectate recovered north of Unit 11 has increased steadily since injection began in well DX-61 in 1986 until by 1988, one well in the area produced up to 40 percent flashed injectate. Wells in the vicinity of Units 1 - 6 and 7 - 8 have produced the greatest fraction of injectate since 1983. Indeed, the isotopes suggest that a few wells produced 100 percent flashed injectate by 1988. The recovery of injected

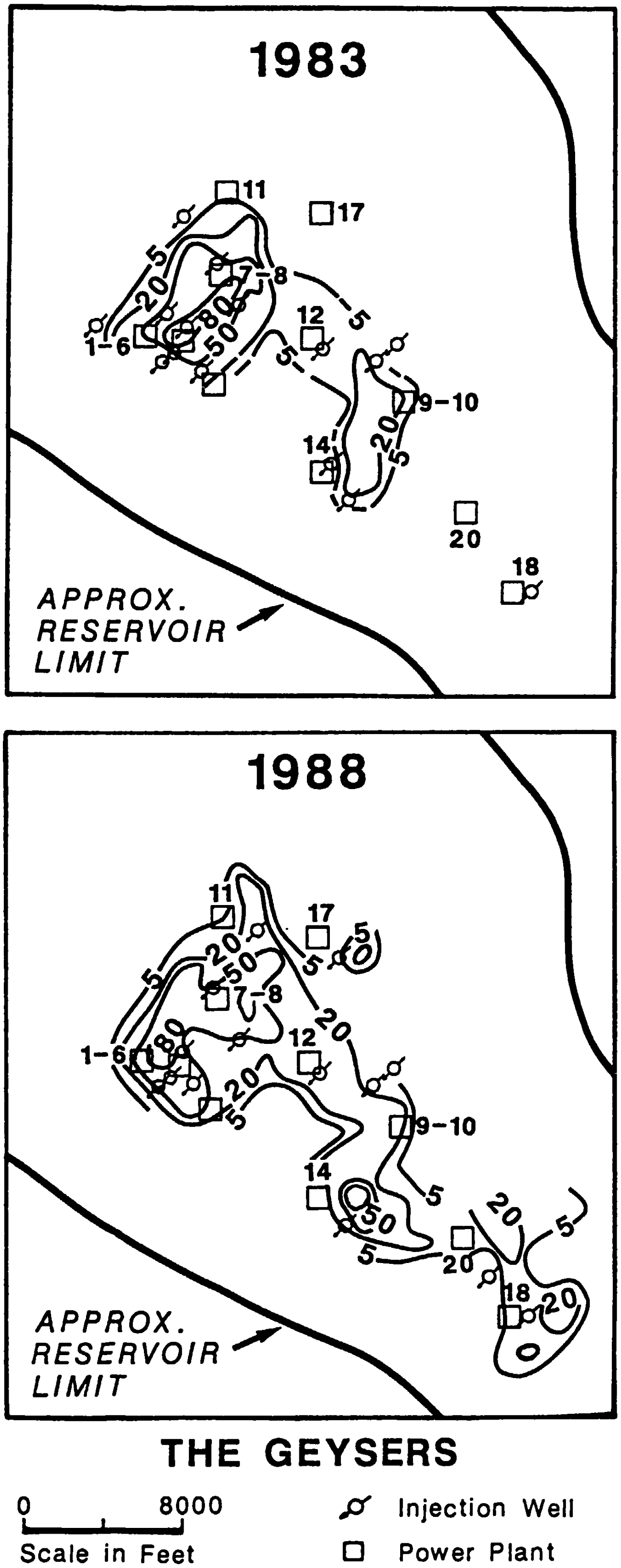

Figure 7. Injectate recovered in produced steam for 1983 and 1988. Contours shown are percent injectate in steam.

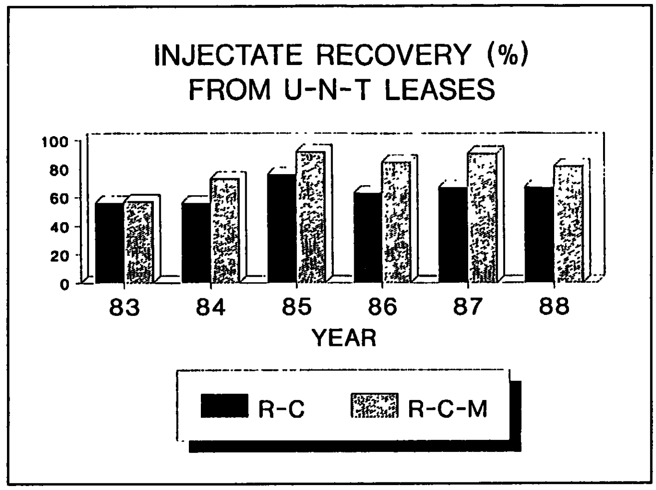

Figure 8. Ratio of mass of flashed injectate recovered as steam to mass of injected water for 1983-88. Results of R-C and R-C-M methods are shown.

water as steam from all producing wells on U-N-T leases is shown for the years 1983 to 1988 in Figure 8. The parameter plotted on the bar chart is the ratio of the mass of flashed injectate produced by all wells on U-N-T leases to the mass of fluid injected into U-N-T leases for a given year. The mass of injectate produced by a well for a year is the fraction of produced injectate, based on a single determination of the isotopic composition for the year, multiplied by the year's cumulative steam production for that well. All U-N-T wells were then summed to generate the results shown in Figure 8. The results of both the R-C and R-C-M methods of calculation are shown. On a field-wide basis, the two methods of calculation indicate that the mass of injectate produced as steam in 1988 was roughly equivalent to 65 to 80 percent of the mass of liquid injected during that year. This technique cannot determine when the injectate produced as steam was actually injected.

ACKNOWLEDGEMENTS

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REFERENCE

Haizlip, J.R., 1985. Stable Isotopic Composition of Steam from Wells in the Northwest Geysers, Sonoma County, California GRC 1985 International Symposium on Geothermal Energy, p. 311-316.