GEOCHEMISTRY AND REINJECTION OF WASTE WATERS IN VAPOR DOMINATED FIELDS

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INTRODUCTION

The geothermal power-plants in vapor dominated fields produce large quantities of condensate. These waters have high concentrations of ammonia, boric acid and sulphides and are therefore potential polluttants of ground-water. Reinjecting the condensate in selected wells of the field gets rid of industrial waste waters (Einarsson et al. ,1975) and may compensate in part for the natural fall in reservoir pressure caused by the negative hydrological balance between exploitation and the limited natural field recharge (Celati et al. ,1973).

Nuti et al. (1981) first demonstrated the use of stable isotopes of oxygen and hydrogen as natural tracers in reinjection processes, and in tracing the underground pathways and defining the amount of reinjected water recovered in the wells. These techniques were then applied by Giovannoni et al. (1981), Cappetti et al. (1982), Bertrami et al. (1985) at Larderello. In the cooling towers a large fraction of condensate water is discharged into the atmosphere in the form of steam at low temperature. As a result of this evaporation, the residual water, which will be reinjected, is greatly enriched in the heavy isotopes Oxygen-18 and Deuterium. This paper describes how stable isotopes and well-head gas/steam ratios can be used to investigate reinjection induced phenomena in the reservoir at Larderello and The Geysers geothermal fields.

The following phenomena in the reservoir induced by reinjection will be described:

a) mixing of original deep steam and reinjection-originated steam;
b) isotope fractionation of steam produced from reinjected water;
c) effects of fluid redistribution (displacement), where areal gradients of isotopic composition and gas/steam ratio are present.
d) possible cooling of rock matrix.

REINJECTION AT LARDERELLO

Reinjection of spent steam condensate at Larderello began in 1979, several years after the start of field exploitation.

Two different cases will be described. Firstly reinjection in the oldest central zone, where pressure dropped to about 5-6 bar in the fractured media. This zone is characterized by a high fractured-derived permeability in the dolomitic limestone rocks (Celati et al., 1977). Reservoir temperature is about 250°C, and the wells, including the reinjector, are shallow (about 600 m). In the second case reinjection was carried out in an area four km southwest of the central area. The reservoir is far less permeable than in the first zone and temperature is equal or less than 220°C, with the same pressure in the fractured media. An extensive study of the effects of reinjection in both zones is reported in D'Amore et al. (1987). For both zones the fluid from the monitored wells surrounding the reinjector is formed by steam from at least two sources that have undergone various mixing processes. For each well, one component is deep steam with its own local isotopic composition and gas /steam ratio. A second component is the steam derived from the injected water with very positive isotopic composition and no gas. If this water vaporizes completely in contact with hot reservoir rocks, then the fluid at the discharge point is the result of a simple mixing, in different proportion for different wells, of the previous two end members (points B and J in Fig. 1). This will usually happen in the early stages of reinjection and at low injection rates. As the amount of reinjected water increases a shift occurs in the isotopic composition of the generated steam. This is due to partial boiling of the injected water, which produces a fractionation in the newly formed steam. Figure 1 shows 2 lines of fractionation at 200° and 220°C, starting from the composition of reinjected water, J, and showing the composition of steam for $f_v = 0.2, 0.4, 0.6$ (f_v = fraction of vaporized water). During injection a liquid plume forms beneath the injector, due to gravitative effects, despite injection into a superheated zone. Isotopic composition reveals with time a decrease in f_v, indicating that the volume of the plume increases with time (D'Amore et al., 1987). Because of fractionation, mass balance based on Oxygen-18 may produce serious underestimates of the recovered injected water. In the central zone wellhead temperatures remained constant at about 230°C despite the close spacing of wells, suggesting that the high vertical permeability existing in this part of the reservoir allows deep penetration of water and efficient fluid-rock heat exchange. At the end of the injection test in this zone, it was calculated that all the injected water had been recovered in less than two years.

In the peripheral zone, where reservoir temperature and permeability are lower, a decrease in the contribution of steam from injected water was observed when the injection rate was more than doubled. Gas/steam ratio remained constant and Oxygen-18 and Deuterium became more negative. Wellhead temperatures decreased by about 20°C. All these phenomena would suggest that the presence of a liquid plume at high flow rates tends to cool the system (regression along B'-B in Fig. 1).

A third possible steam source for each well could be the fluid displaced from nearby wells. This process is triggered by a modification of the local original steam flow patterns due to the pressure increase caused by the plume and its steam. When the wells are located in an area with a large gas/steam ratio or Oxygen-18 content areal distribution (not constant values), this phenomenon can produce an appreciable variation of the composition of the fluid derived by simple mixing. In the Larderello field the gas content observed in each well before reinjection usually cannot be assumed representative of the gas content supplying the well during reinjection. Mass balance, using gas/steam ratios to calculate the recovery of injected water, could give then quite different results from those computed using Deuterium. Deuterium is not affected by fluid redistribution phenomena, due to its homogeneity in most parts of the field.

REINJECTION AT THE GEYSERS

An area was selected in the south-eastern part of this field, where reinjection started at the same time as production in 1980. Reservoir temperatures are close to those measured at Larderello, 235-255°C, but with a higher operating pressure of the order of 15 bar (20-30 bar in the fractured media of the reservoir). Depth of the reinjectors is much higher than at Larderello, of the order of two to three km. A recently drilled well in this area pierced the liquid plume of reinjected water. The plume had a temperature of about 205°C and was highly enriched in silica and boron, showing strong water-rock interaction effects. The steam produced at this temperature does not have a large fractionation factor for Deuterium. After about 8 years of reinjection the isotopic composition of the liquid plume shows isotopic values that are practically the same as the annual average of isotopic composition of the reinjected water. The temporal variations in isotopic and chemical parameters induced by reinjection in this area, can be better understood by describing the conceptual model of this part of the field. Steam delivered from geothermal wells shows to be produced substantially from three different sources located in different areas and depths. Two of them are constituted by an upper condensate layer (source 1) and a deeper two-phase layer, source 2, having different tickness (D'Amore and Truesdell, 1979; Box et al., 1987). A third source, affecting some wells, is constituted by fluid resulting from the reinjection of condensate from the power plants (source 3). The fluid produced from each source has different physical and chemical characteristics. The different contributions to fluid production from these sources induces variations in the observed physical, chemical and isotopic parameters in wells located in different areas and depths. The relative contributions from each source vary with time. Steam from source 1 has the following charachteristics: high liquid saturation values correlated to high flow rates; low gas/steam ratio values; deuterium content is close to the average composition of the local recharge water because the condensate originated at temperatures which result in no-fractionation of deuterium between the two-phase source and condensate. The Oxygen isotopic composition is less negative (about 2 per mil) than the underlying two-phase source from which the condensate originated because of the fractionation process during condensation at temperatures between 220° and 250°C. Oxygen-18 absolute values in the condensate layer are different depending upon the geographic location relative to source 2.

Steam from source 2 has the following characteristics: low liquid saturations correlated to low flowrates; high gas/steam ratio values; deuterium content close to the composition of the meteoric water. Oxygen isotopic composition more negative than source 1 and with absolute values differing according to the geographic location. Close to the recharge area, we can observe Oxygen-18 concentrations close to those of the recharge water (Truesdell et al., 1987), along the pathway toward the central parts of the field. Oxygen isotopic composition becomes the more and more positive from east to west as consequence of the "Oxygen shift" observed in all geothermal fields. The larger shift corresponds to water which is more "mature", that is older and more interacted with rocks. Steam delivered from wells located close to the recharge area will show then the more negative Oxygen isotopic compositions, lower gas/steam ratios and lower computed and measured reservoir temperature.

Steam from source 3 produces the following effects: contribution of steam from this source induces increasing liquid saturation values with respect to the simple two-phase; arrival of reinjected water slows flowrate and pressure decline due to exploitation (as at Larderello); the gas/steam ratio rate of increase is also lowered by contribution of this source; the injection water is initially at a temperature lower than reservoir temperatures. Boiling occurs at a temperature consistent with the local pressure in the fractures. The produced steam will increase enthalpy due to heat exchange from hot rocks (as observed at Larderello); Hydrogen and Oxygen isotopic composition of this source will be more positive with respect to the other sources due to the concentration of Deuterium and Oxygen-18 in condensate from the cooling towers. Depending on the variable composition of the reinjected waters, isotopic composition of the contribution from this source may vary with time. A cooling and induced low temperature condensation process will produce large negativization of Oxygen-18 content and Deuterium as function of local steam condensation temperature. This has been observed at The Geysers for negative thermal balance.

The fluid at wellhead represents a mixture of fluid coming from these sources in different proportions throughout the drainage volume of the well. As shown in Fig. 2 in the early stages of exploitation in this area fluid comes mainly from sources 1 and 2. With time the relative contribution of source 2 will increase. Increasing contribution of source 2 will produce an increase in gas/steam ratio, decrease in liquid saturation and negativization of Oxygen-18. Contribution from source 3 will then start for wells better connected

Figure 1. Temporal and reinjection-induced variations in isotopic composition of steam from geothermal wells.
A = composition in the early stages of production, strong contribution from the condensate layer.
B = composition of the two-phase layer.
J = composition of reinjected water.
line AB-J = mixing of deep steam and steam from reinjected water (no fractionation).
line B-B′ = mixing of deep steam and steam from reinjected water (fractionation).

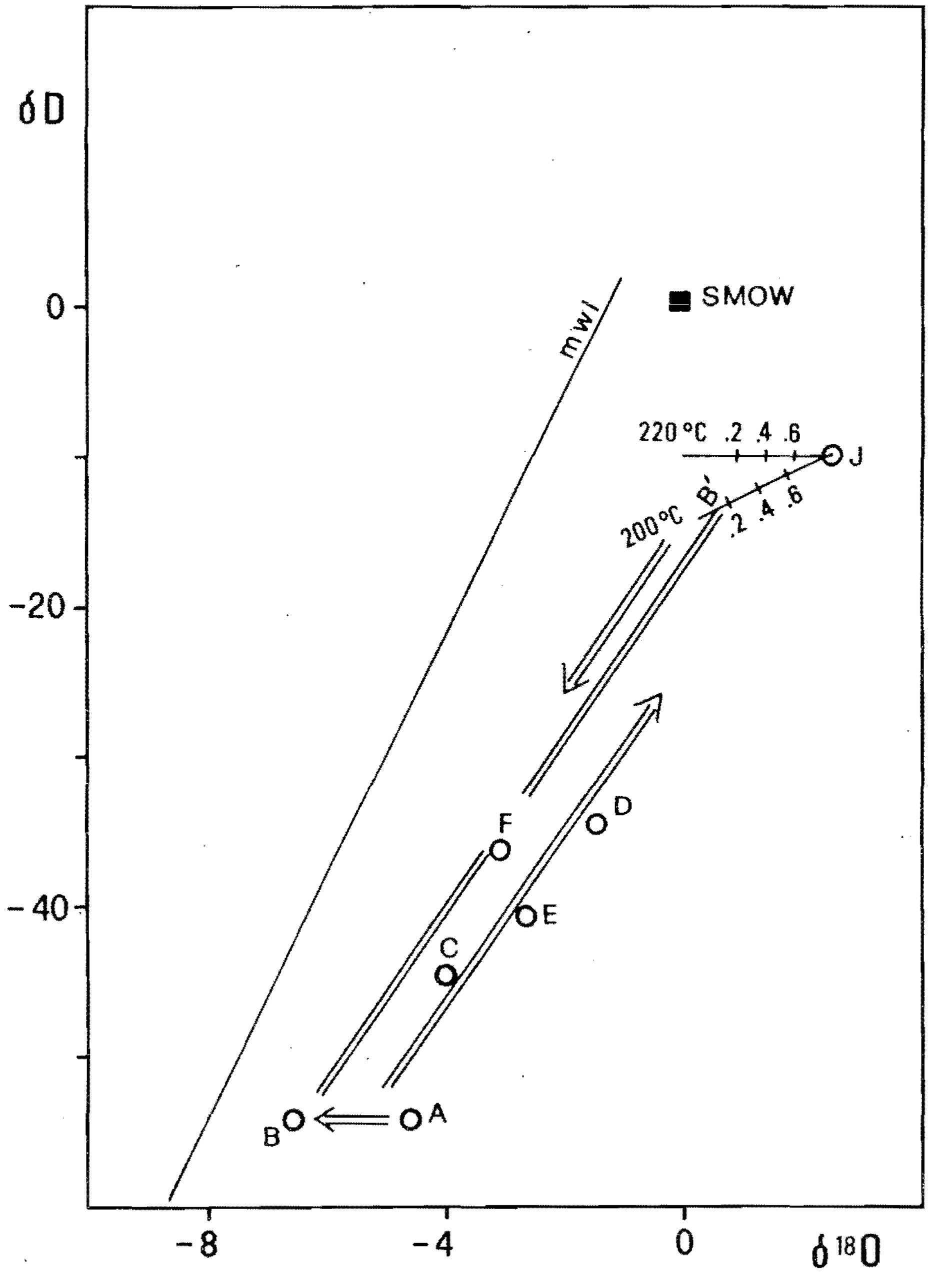
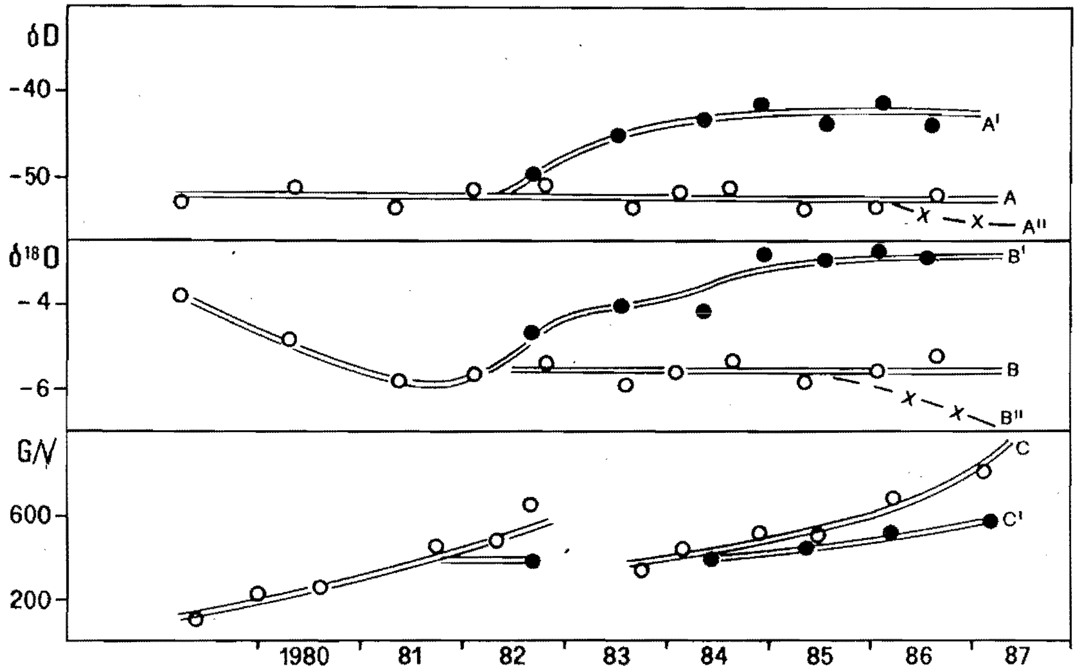


Figure 2. Temporal and reinjection induced variations in Oxygen-18, Deuterium and G/V ratios.
Lines A, B and C (open circles) represent variations in wells not affected by reinjection.
Lines A′, B′ and C′ (full circles) represent variations in wells affected by reinjection.
Lines A″ and B″ represent variations induced by cooling.



structurally with the plume around the injection well. With time the number of wells affected by source 3 will increase as a consequence of the increase in size of the liquid plume and the local decrease in pressure.

At a constant injected water flowrate, it is possible, after some years of production, to achieve a stationary state in the contribution of steam from the reinjected water which will be shown by constancy in deuterium composition at values intermediate between those of steam produced by sources 1 and 2 and steam produced by source 3. Steam originating from source 3 may show Oxygen isotopic fractionation to values more negative than the reinjected water. Change in the gas/steam ratio of wells affected by reinjection results from the contribution of injection derived steam with a very low concentration of gas and the simultaneous increase of contribution of source 2.

CONCLUSIONS

All the considered processes must be taken into account when evaluating the amount of injected water re-entering the surrounding wells. From all the work available on vapor dominated systems, it can be deduced that Deuterium is the parameter less affected by fractionation (at boiling temperatures between 200 and 240°C), by any kind of water interaction (for long residence times of the liquid water plume at high temperature) and by fluid displacement. This parameter alone may thus be used to detect both the flow paths of steam produced by the injected water and the relative contribution to the steam produced from this water. For previously unexploited areas, the effects of reinjection are overlapped by the natural temporal evolution of Oxygen-18 content towards more negative values, and of the gas/steam ratio (as steam saturation) towards higher values. Effects induced by fluid redistribution can also create serious problems in the practical use of these parameters alone as tracers. To assess all the effects induced by injection and natural temporal evolution, numerous homogeneous values of the isotopic (and chemical) parameters should be monitored for the fluid of both producing wells and the injector (in the latter case large daily variations of Oxygen-18 and Deuterium are due to seasonal evaporations conditions and operations in the power-plants). In spite of these limitations Oxygen-18-Deuterium and gas/steam Deuterium diagrams may, depending on the number of measurements available, permit a quantitative computation of the contribution of steam from the different sources and an assessment of eventual cooling effects in the reservoir matrix.

REFERENCES

Bertrami R., Calore C., Cappetti G., Celati R. and D'Amore F.(1985)A three-year recharge test by reinjection in the central area of Larderello field: analysis of production rate. Geothermal Resources Council, Trans.9,pt.2,293-298.

Cappetti G., Giovannoni A., Ruffilli C., Calore C. and Celati R.(1982)Reinjection in the Larderello geothermal field. Proc. Inter. Conf. Geothermal Energy, BHRA Fluid Engineering, Vol.I,395-407.

Celati R., Noto P., Panichi C., Squarci P. and Taffi L.(1973)Interaction between the steam reservoir and surrounding aquifers in the Larderello geothermal field. Geothermics,2,174-185.

Celati R., Neri G., Perusini P. and Squarci P.(1975)An attempt to correlate Kh distribution with geological structure of Larderello geothermal field.Proc. 1st Stanford Geothermal Reservoir Engineering Workshop,37-41.

Celati R., Squarci P., Stefani G.C. and Taffi L.(1977)Study of water-levels in Larderello region geothermal wells for reconstruction of reservoir pressure trend. Proc. Simposio Inter. sobre Energia Geotermica en America Latina, 501-526.

D'Amore F. and Truesdell A.H.(1979)Models for steam chemistry at Larderello and The Geysers. Proc. 5th Stanford Geothermal Reservoir Engineering Workshop,283-297.

D'Amore F.,Fancelli R. and Panichi C.(1987)Stable isotope study of reinjection processes in the Larderello geothermal field.Geochim. et Cosmochim. Acta,Vol.55,857-867.

Einarsson S.S., Vides A. and Cuellar G.(1975)Disposal of geothermal waste waters by reinjection.Proc.2nd U.N. Symposium, S.Francisco,2,1349-1363.

Giovannoni A.,Allegrini G., Cappetti G.and Celati R.(1981)First results of reinjection experiment at Larderello.Proc.7th Stanford Geothermal Reservoir Engineering Workshop,77-83.

Nuti S., Calore C. and Noto P.(1981)Use of environmental isotopes as natural tracers in a reinjection experiment at Larderello. Proc. 7th Stanford Geothermal Reservoir Engeneering Workshop,85-89.

Truesdell A.H., Haizlip J.R., Box W.T. and D'Amore F.(1987) Fieldwide chemical and isotopic gradients in steam from The Geysers. Proc. 12th Stanford Geothermal Reservoir Engeneering Workshop,241-246.