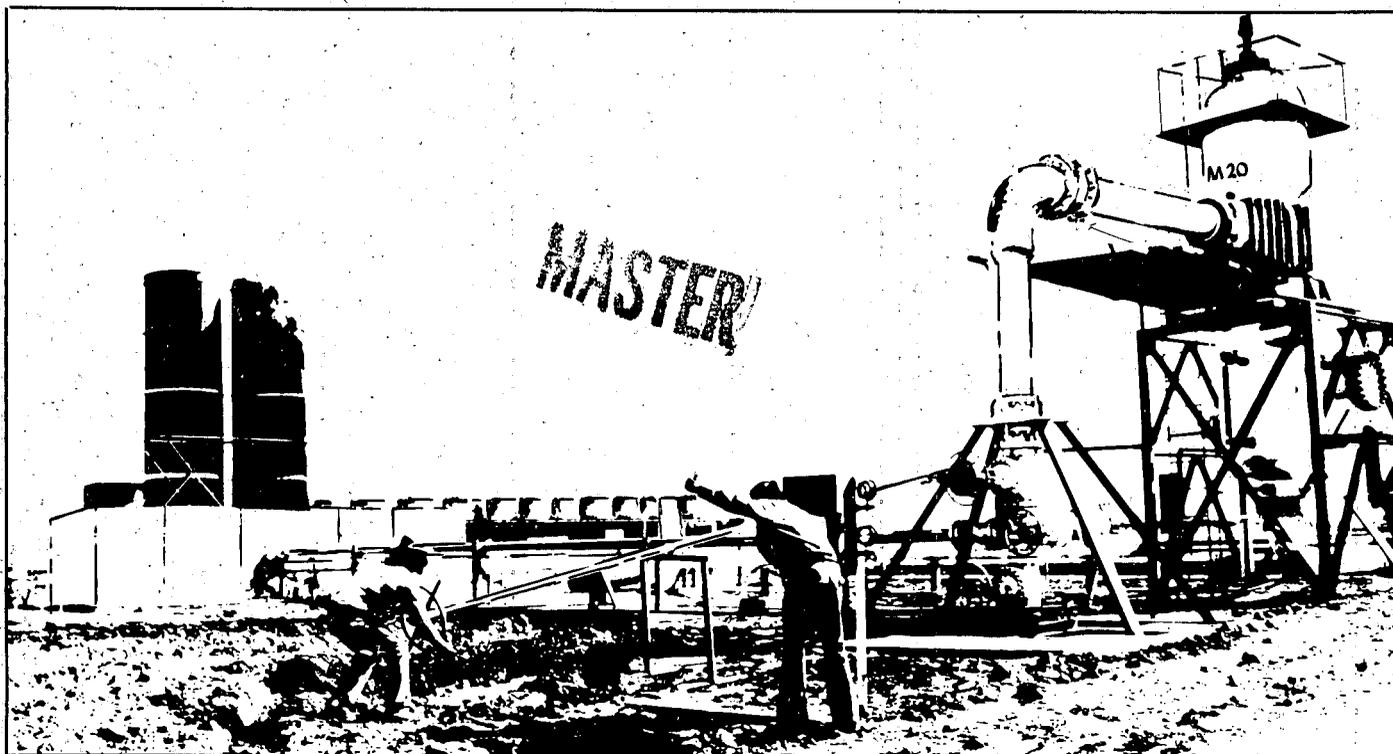


MEXICAN-AMERICAN COOPERATIVE PROGRAM AT THE CERRO PRIETO GEOTHERMAL FIELD



SIMULATION OF REINJECTION AT CERRO PRIETO USING AN IDEALIZED TWO-RESERVOIR MODEL

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INTRODUCTION

Most of the papers published on the hydrodynamic and thermal effects of reinjection in geothermal fields assume a single reservoir with uniform transmissivity and storativity. However, there is evidence that the Cerro Prieto geothermal field is a two-reservoir system and that each reservoir has different hydraulic properties (Abril and Noble, 1979). Because two-reservoir fields have not been adequately studied, we will analyze the thermohydrological response of this kind of geothermal system to various alternative schemes of reinjection. We use parameters relevant to the Cerro Prieto system so that the results will be useful in planning future reinjection operations at this field.

In our present analysis, we use the LBL integrated finite-difference computer program CCC (Lippmann et al., 1977), which is capable of modeling the complex geological and boundary conditions of a geothermal system. CCC also simulates the major physical factors involved in the movement of the injected waters: (1) forced convective flow between the production and injection areas; (2) heat exchange among injected water, rock matrix, and native waters; (3) density-buoyancy effects; and (4) influence of temperature-dependent viscosity on fluid flow. The problems associated with the chemistry of the fluids and the porous media--such as injectivity of the wells, injected/native groundwater compatibility, and water-rock interactions--will not be covered here. These matters are discussed in a number of other papers at this symposium.

Instead, we show the results of computations for the response of a two-reservoir geothermal system to injection at various depths and positions within the field. The influence of differences in thermal, hydraulic, and geometric properties between the reservoirs are discussed. The results indicate that it is possible to stabilize or increase reservoir pressures and maintain production temperature in a two-reservoir geothermal field by using an appropriate fluid reinjection scheme.

REINJECTION MODELING

In any type of modeling study, we may distinguish two broad categories: special studies and detailed simulations. In the case of reinjection, special studies include optimal injection well patterns and the effects of temperature-dependent properties on the reservoir (Tsang et al., 1979). On the other hand, detailed simulation studies are appropriate only after developing a realistic

geologic model of the system including its geometry, physical properties, and boundary and initial conditions.

In this general framework, we address a special study of reinjection operations in a geothermal field. We are concerned with the peculiarities of carrying out this type of operation in a system consisting of two separate reservoirs. Efforts are being made to develop a realistic geologic model for the Cerro Prieto field, as shown by a number of papers in this volume. In the future, this model will be useful for simulating the behavior of the field and for exploring different reinjection scenarios. By employing a simpler, idealized model in this paper, we can begin to determine the best strategies for reinjection so that they can be tested later in more realistic simulations.

TWO-RESERVOIR SYSTEMS

Model without Intervening Layer

When there is no intervening layer and no difference in properties between the two reservoirs, the injection of cold water corresponds to the case of a well partially penetrating the geothermal reservoir. Figure 1 shows three cases taken from an earlier study (Lippmann et al., 1977): (A) injecting 100°C water into a 250°C aquifer in the upper part; (B) injecting 100°C water in the lower part of the reservoir; and (C) injecting beneath a relatively less permeable lens. In all three cases the effect of the lower density of the warmer waters (buoyancy) can be seen; there is a noticeable dispersion of the cold temperature fronts, even when the injected water is restricted for some distance by a lens in the aquifer (case C). These results will be useful later when considering the behavior of the system in which a continuous layer separates these reservoirs.

Single Well Model

Figure 2 shows a simplified radially symmetric two-reservoir model used for this case, with its initial temperature distribution. The reservoir hydraulic and thermal properties are displayed in Table 1. These data are all taken from an earlier simulation study of Cerro Prieto (Lippmann et al., 1979). Note from the table that the permeability in the lower aquifer is 80 md while in the upper aquifer it is 50 md. The intervening layer has a permeability of 0.5 md, which is two orders of magnitude smaller than in the upper reservoir, but still not negligible. For simplicity, we

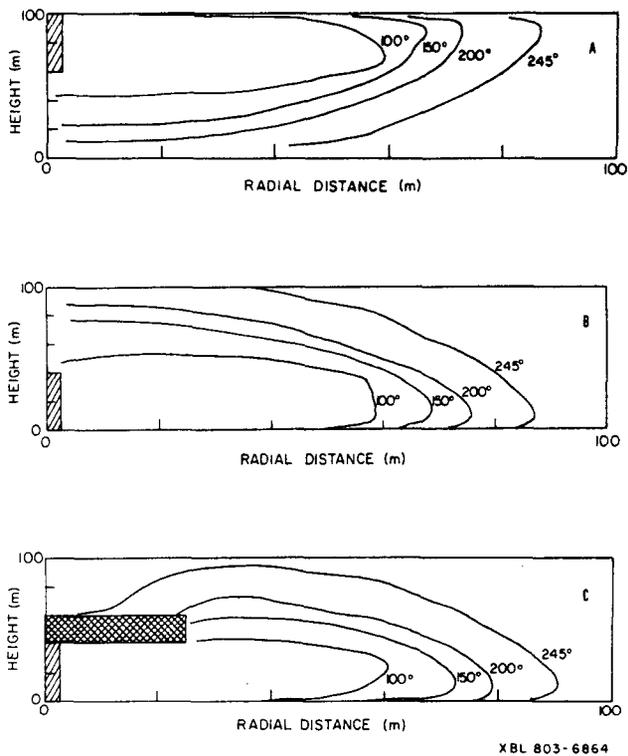
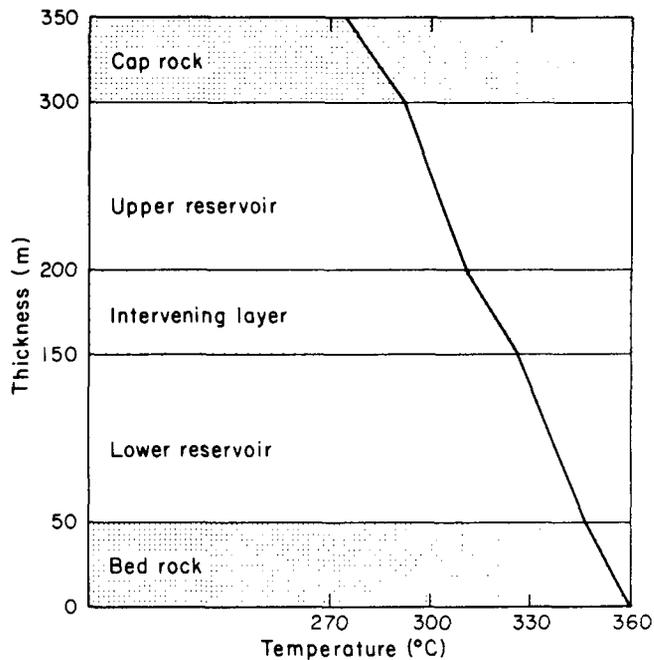


Figure 1. Temperature distribution in the reservoir for the partial penetration case: A, injection at the top; B, injection at the bottom; and C, injection below a lens of low permeability material.



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Figure 2. Cross section of the two-reservoir model used and its initial temperature profile.

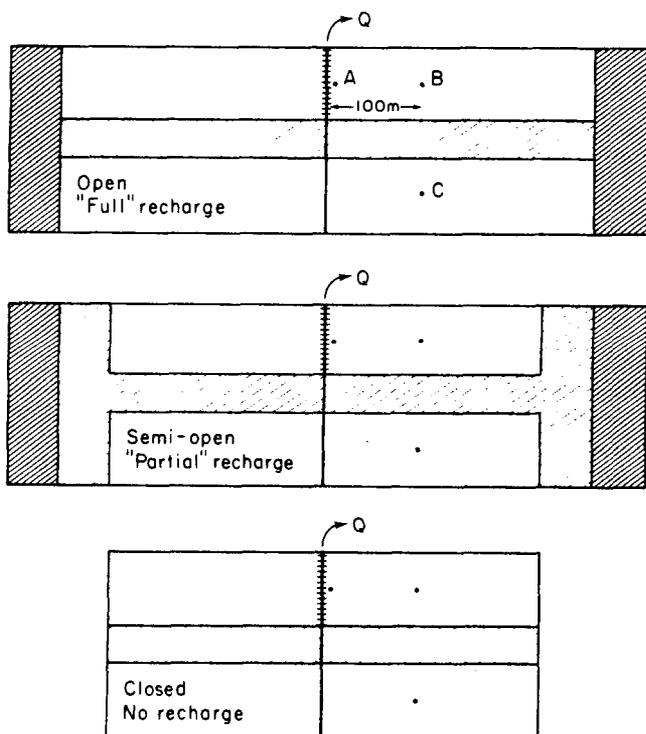
TABLE 1. MATERIAL PROPERTIES USED IN THE SINGLE-WELL AND DOUBLET SIMULATIONS

Property	Lower reservoir	Intervening layer	Upper reservoir	Bedrock/Caprock
Intrinsic permeability (md)	80	0.5	50	0.005
Porosity	0.22	0.40	0.20	0.40
Specific storage (m^{-1})	10^{-4}	1.6×10^{-3}	10^{-4}	1.6×10^{-3}
Thermal conductivity (cal/sec \cdot cm $^{\circ}$ C)	10×10^{-3}	7.5×10^{-3}	10×10^{-3}	6.0×10^{-3}
Heat capacity (cal/g $^{\circ}$ C)	0.250	0.230	0.250	0.230

assume the aquifers are uniformly 100 m thick and the intervening layer is 50 m thick. In the mesh there are 38 radial steps from the well to the boundary 2.3 km away; for seven layers (including caprock and bedrock) this means there are 278 elements employed.

Pressure effects (production only). In this series of simulations, a constant production rate of 1000 m³/hr is assumed (approximately 40% of the 1978 production rate at Cerro Prieto). The injection rate is at 500 m³/hr, one-half of the production rate. The three different boundary conditions employed to study pressure effects during production are shown in Figure 3.

The open boundary case corresponds to an aquifer of large radial extent, with a constant potential boundary simulating "full" recharge conditions 2.3 km away from the well. The semi-open boundary case had a leaky flow barrier at the same distance to simulate "partial" recharge. The closed boundary case was used as a limiting case, with no recharge through the barrier. The letters A, B and C on the open boundary case are the points where temperature and pressure were determined as the upper aquifer was produced. A is near the well in the upper aquifer and B and C are 100 m away from the well in the upper and lower aquifers, respectively.



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Figure 3. Sketch of the open, semi-open, and closed systems used in the simulation of production from a single well. Darkest areas are the constant pressure and temperature boundaries.

TABLE 2. PRESSURE DRAWDOWNS FOR THE SINGLE WELL PRODUCTION SIMULATIONS

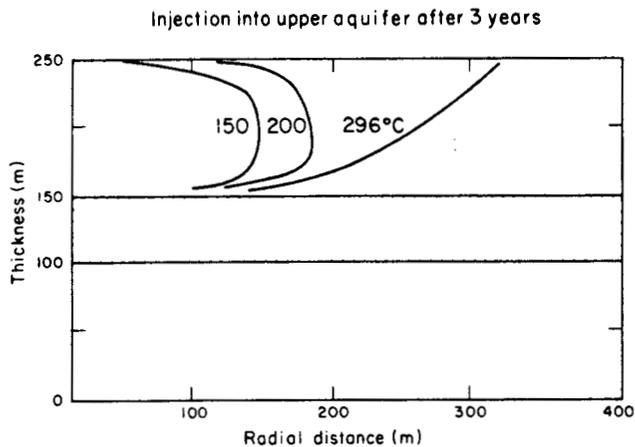
Case	Pressure drawdowns (psi)	
	1 to 5 yrs	1 to 10 yrs
At Point A		
Open	36	40
Semi-open	38	61
Closed	39	64
At Point B		
Open	36	40
Semi-open	38	61
Closed	39	64
At Point C		
Open	32	36
Semi-open	33	58
Closed	35	61

Table 2 gives the results of the simulations for 5 and 10 years of production. In comparing pressure reductions for the upper and lower aquifers at either 5 or 10 years, the results show maximum differences of only 13% after 5 years, and 10% after 10 years. This demonstrates considerable hydraulic communication through the intervening layer. The results also show the effect of boundary conditions: the open boundary case always has significantly less drawdown after 10 years due to the "full" recharge condition. There is a slightly smaller drawdown due to the "partial" recharge condition for the semi-open boundary case compared with the closed boundary case. The differences among the boundary conditions are not so apparent at 5 years as at 10 years, however.

Temperature effects (injection). Figures 4 and 5 show the temperature fronts after injection of 150°C water into the upper aquifer for 3 and 10 years, respectively. Here we assumed an open boundary or "full" recharge condition. After 3 years there is some dispersion of the thermal front at the top of the upper aquifer, but little effect in the intervening layer. However, after 10 years the thermal fronts begin to penetrate through the intervening layer into the lower aquifer. This is partly due to the downward flow of the higher density injected cold water.

Figures 6 and 7 show the temperature fronts in the lower aquifer after 3 and 10 years of injection, respectively. Again, there is some dispersion of the thermal front within the aquifer, but little effect on the intervening layer. This is encouraging, because it shows that thermal fronts do not easily migrate through the intervening layer.

The boxes below the thermal front diagrams in Figures 4 through 7 indicate pressure changes in

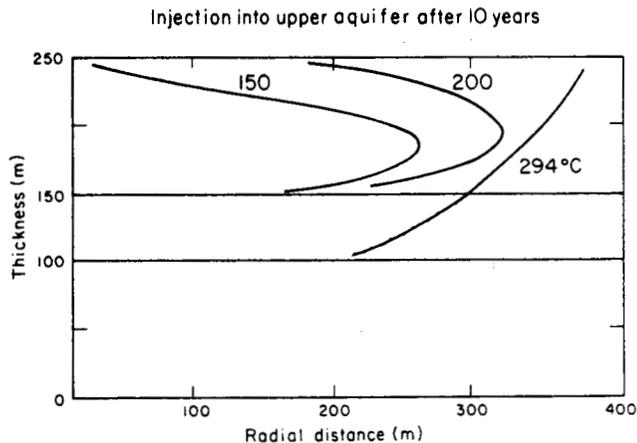


Pressure increase (psi) measured at

Aquifer	500m	1000m
Upper	42	10
Lower	22	14

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Figure 4. Isotherms and pressure changes simulated for 3 years of single-well injection into the upper reservoir.

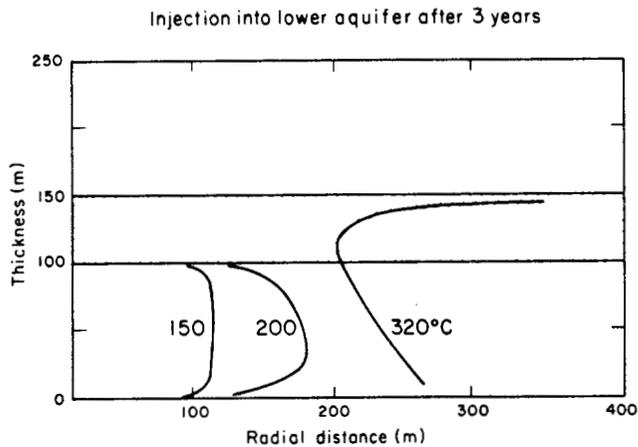


Pressure increase (psi) measured at

Aquifer	500m	1000m
Upper	54	19
Lower	33	22

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Figure 5. Isotherms and pressure changes simulated for 10 years of single-well injection into the upper reservoir.

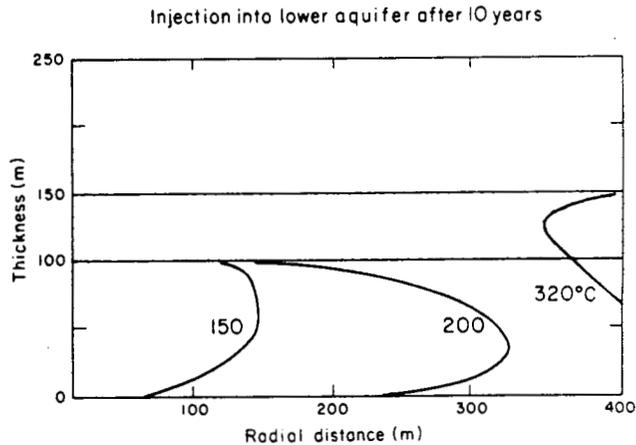


Pressure increase (psi) measured at

Aquifer	500m	1000m
Upper	7	1
Lower	45	22

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Figure 6. Isotherms and pressure changes simulated for 3 years of single-well injection into the lower reservoir.



Pressure increase (psi) measured at

Aquifer	500m	1000m
Upper	16	9
Lower	54	28

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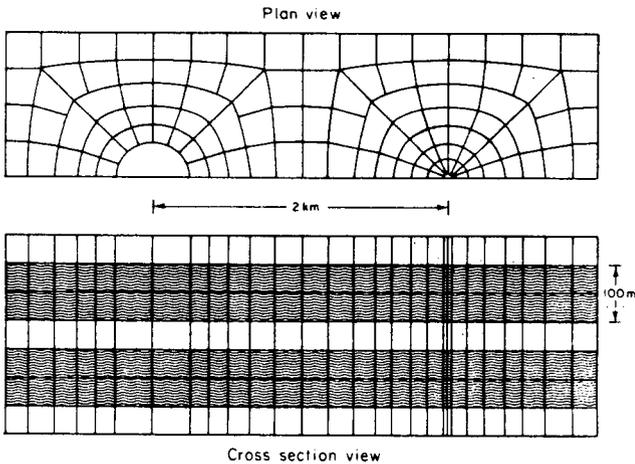
Figure 7. Isotherms and pressure changes simulated for 10 years of single-well injection into the lower reservoir.

the upper and lower aquifers, respectively, at radial distances of 500 m and 1000 m. These pressures agree with the results of the production tests mentioned above. Despite the much lower permeability of the intervening layer, pressures are readily transmitted through it from the injected reservoir to the other reservoir over the 3- to 10-year time span. This indicates that reinjection may be useful for maintaining overall reservoir pressures, even through an intervening layer that inhibits thermal fronts, thereby prolonging the useful life of a geothermal field.

Doublet Model

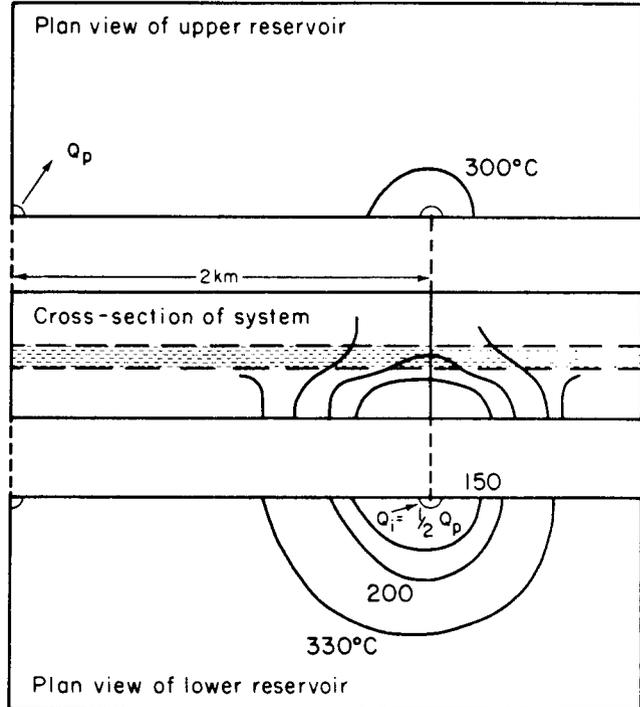
As a further development in modeling reinjection, we simulated the slightly more realistic case of a simultaneous system of production and injection. Figure 8 illustrates the mesh for a two-layer doublet system, which is produced from the upper reservoir at the rate of 2000 m³/hr and is injected into either the upper or lower reservoir with 150°C water at the rate of 1000 m³/hr. The three-dimensional mesh makes use of symmetry along the line connecting the production and injection wells, but otherwise it is similar to the single-well model, with the same seven layers, thickness and reservoir properties. The simulated area is 4 km long by 1 km wide at the surface, with a 2 km spacing between production and injection wells, surrounded by a closed boundary. There are 828 elements in the mesh.

The outcome of the simulation at 10 years is displayed in Figures 9 and 10 for injection into the upper and lower reservoirs, respectively. The upper panel shows the temperature fronts for the upper reservoir, the middle one is a cross-section view with the intervening layer shaded, and the lower panel shows the temperature fronts for the lower reservoir. (Recall that the upper and lower reservoirs are at different temperatures initially.) The results are similar to the single-



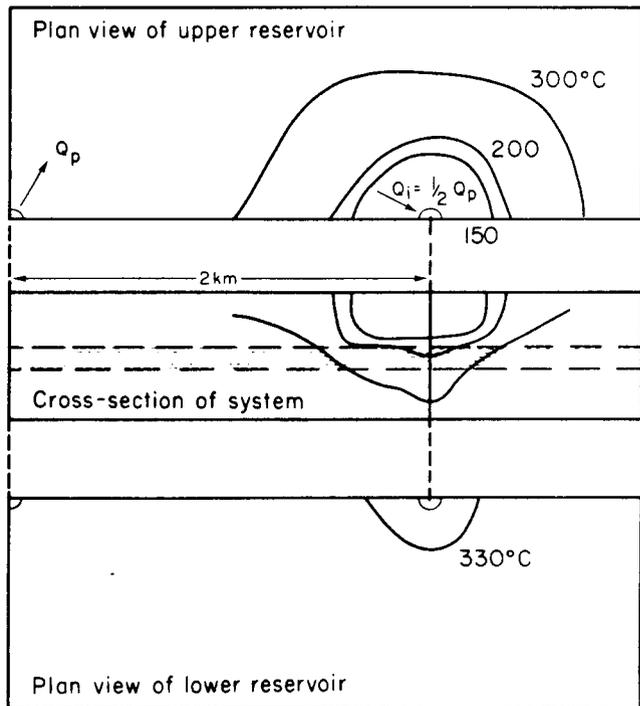
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Figure 8. Plan and cross section views of the doublet mesh.



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Figure 9. Isotherms simulated for 10 years of doublet injection into the upper reservoir.



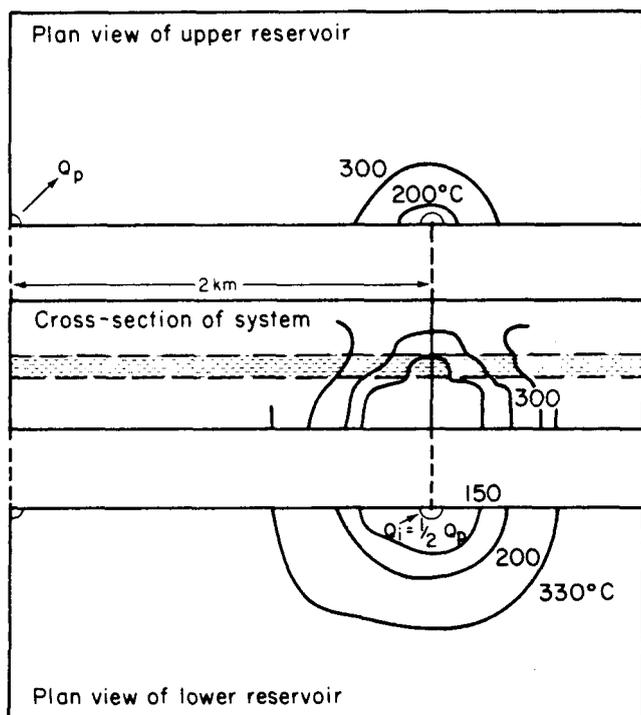
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Figure 10. Isotherms simulated for 10 years of doublet injection into the lower reservoir.

well case. Due to its greater density, the colder water, which has been injected into the upper reservoir, penetrates the intervening layer and cools the lower reservoir as before. Injection into the lower reservoir has almost no effect on the upper reservoir, even after 10 years, although the thermal front has penetrated into the intervening layer. These results confirm that injection into the lower reservoir localizes thermal effects to that reservoir for a long time.

A further case of injection into the lower reservoir was run with the permeability of the intervening layer increased by one order of magnitude to 5 md. The results are shown in Figure 11 for a 10-year simulation. The thermal fronts have spread into the upper aquifer more than in the previous case (Fig. 10), but the effects are still limited to a region that is within 0.37 km of the injection well in the upper aquifer, compared with 0.30 km for the same case with the lower permeability.

The pressure response is given in Table 3. Pressures are shown there as the differences between the pressure changes resulting from simultaneous production and injection ($\Delta P_{i,p}$), and those due to production only (ΔP_p). The results indicate that the overall increase in pressure from injection is on the order of 100 psi at 1 km from the production well. Again, as in the single-well model, there appears to be very good pressure communication through the intervening layer, because the reservoirs without



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Figure 11. Isotherms simulated for 10 years of doublet injection into the lower reservoir (permeability of intervening layer is 5 md).

TABLE 3. PRESSURE CHANGES FOR DOUBLET INJECTION SIMULATIONS AFTER 10 YEARS*

	At production well		1 km from prod. well	
	Upper Reservoir	Lower Reservoir	Upper Reservoir	Lower Reservoir
Upper injection	78	80	132	120
Lower injection	81	88	120	138
Lower injection (intervening layer permeability = 5 md)	226	-3	148	116

* $\Delta P_{i,p} - \Delta P_p$ (psi), where $\Delta P_{i,p}$ = change in pressure in the case of simultaneous injection and production; and ΔP_p = change in pressure in the case of production only.

injection have pressures that are within 10 to 15% of those of reservoirs with injection. The lower pressure at the producing well for the upper injection case appears to be caused by the thermal effects described below.

The pressures for the higher permeability case for the intervening layer are much higher near the production well. If the same "production only" pressures are used for the pressure differences in this case, the results show an increase of 145 psi in the production area (Table 3, last line).

The pressure response for the upper injection case over the 10-year period is shown in Figure 12 (with the usual 0.5 md for the permeability of the intervening layer). The pressure profile between the production area and the injection well displays a transition region between the injected 150°C water and the surrounding 302°C water. In this region, the viscosity changes significantly due to fluid temperature differences (a ratio of nearly 2:1), producing a moving thermal barrier which can be responsible for larger-than-usual pressure declines in well test analysis (Mangold et al., 1979). Figure 13 suggests the influence of this effect on pressure response in a comparison between the cases of upper and lower injection. After 10 years of upper injection, the production well area actually has a lower pressure than the lower injection case, probably due to the thermally produced viscosity barrier in the upper aquifer. For the lower injection case, the pressures in the upper aquifer are not as affected by such a barrier since it is restricted to the lower aquifer. Such results indicate that a combination of viscosity and buoyancy effects are needed in order to adequately describe the physical processes of reinjection, especially in a two-reservoir system. These matters will be the subject of a further investigation.

Thus the doublet model further confirms that in a more realistic model of a two-reservoir system, reinjection will be useful in maintaining reservoir pressure while restricting the thermal front to the neighborhood of the injection area.

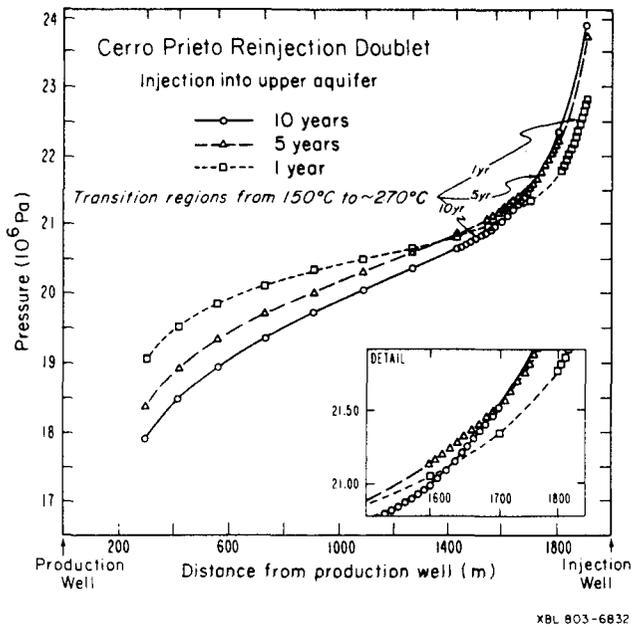


Figure 12. Radial pressure distribution simulated for 1, 5, and 10 years of doublet injection into the upper reservoir, showing the transition region between hot and cold waters.

CONCLUSION

In this paper we have introduced an idealized two-reservoir model to explore some of the effects of reinjection in a geothermal field. For both the single-well model and the doublet model, the results indicate that reservoir pressures will be adequately maintained even when an intervening layer of low permeability is present. The same intervening layer may nevertheless be an effective barrier to the movement of cold fronts, due to the effect of gravity and viscosity on the flow of denser colder waters. This shows promise for developing reinjection strategies that can be tested on more detailed simulation models for specific sites such as the Cerro Prieto field.

In further research we hope to conduct a sensitivity analysis on some of the main parameters used in this study, especially permeability. Clearly, there is also a need to study the flow of the colder water toward the production well for a longer period of time than 10 years. Simulations of permeability anisotropy and optimum well spacing for injection may have to wait until detailed geological models become available. Idealized models like the ones employed in this study, however, are useful for suggesting practical reinjection operation strategies for optimizing the development of geothermal energy resources.

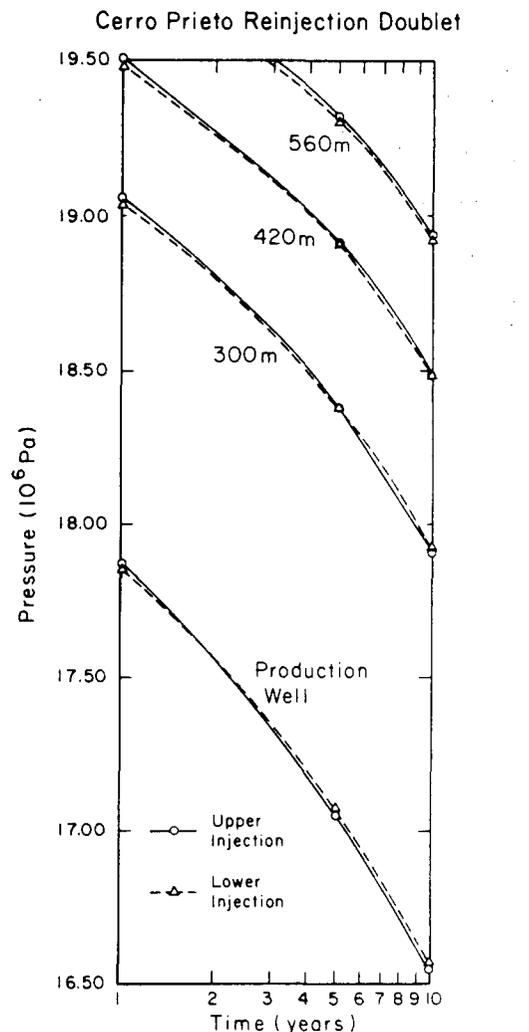


Figure 13. Pressure changes near the production area simulated for 1, 5, and 10 years of doublet injection into the upper and lower reservoirs.

ACKNOWLEDGMENTS

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