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Authors
Tsang, C.F.
Mangold, D.C.
Doughty, C.
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Publication Date
1982-10-01

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LBL-14895
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Conf-8208109--5

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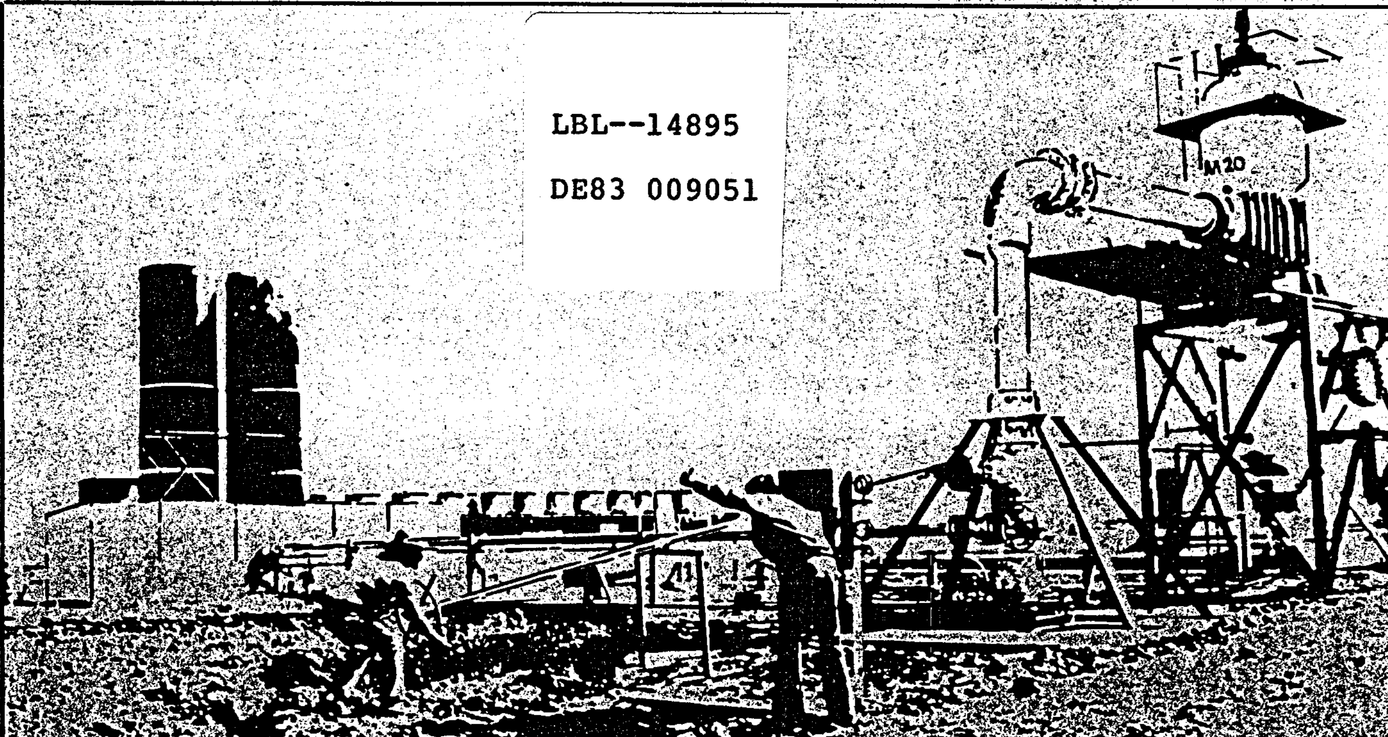

LBL--14895

DE83 009051

Presented at the 4th Symposium on the Cerro Prieto Geothermal Field, Guadalajara, Mexico, August 10-12, 1982

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C.F. Tsang, D.C. Mangold, C. Doughty, and M.J. Lippmann

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October 1982

A Joint Project of

COMISION FEDERAL DE ELECTRICIDAD
Mèxico

DEPARTMENT OF ENERGY
Division of Geothermal Energy
United States of America

Coordinated by

Coordinadora Ejecutiva
de Cerro Prieto
Apdo. Postal No. 3-636
Mexicali, Bja. Cfa., México
and P. O. Box 248
Calexico, Ca. 92231

Lawrence Berkeley Laboratory
Earth Sciences Division
University of California
Berkeley, California 94720

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DE-AC03-76SF00098

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LBL-14895
CP-23

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C.F. Tsang, D.C. Mangold, C. Doughty, and M.J. Lippmann

Earth Sciences Division
Lawrence Berkeley Laboratory
University of California
Berkeley, California 94720

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PREDICTION OF REINJECTION EFFECTS IN THE CERRO PRIETO GEOTHERMAL SYSTEM

C. F. Tsang, D. C. Mangold, C. Doughty, and M. J. Lippmann
Lawrence Berkeley Laboratory, University of California
Berkeley, California 94720

ABSTRACT

The response of the Cerro Prieto geothermal field to different reinjection schemes is predicted using a two-dimensional vertical reservoir model with single- or two-phase flow. The advance of cold fronts and pressure changes in the system associated with the injection operations are computed, taking into consideration the geologic characteristics of the field. The effects of well location, depth, and rates of injection are analyzed. Results indicate that significant pressure maintenance effects may be realized in a carefully designed reinjection operation.

INTRODUCTION

Reinjection of separated geothermal brines and condensate was initially considered as a possible means of disposing large quantities of these waste fluids. It was soon realized that the more important advantages of reinjection are its potential capability of maintaining reservoir pressures and enhancing the extraction of heat from the reservoir rocks, thus prolonging the commercial life of geothermal fields. However, one factor of great concern that has prevented large-scale reinjection at many sites is the fear of premature arrival at the production wells of the cold temperature front associated with the injected water. A properly designed reinjection operation is required to avoid this. In particular, well locations, depths, and rates of injection must be planned with specific consideration of the characteristics of the geological formations in the field. This paper presents calculations predicting cold temperature front movements and pressure changes in the Cerro Prieto reservoir system for a number of different injection cases.

PREVIOUS STUDIES

Interest in reinjection at the Cerro Prieto geothermal system was reported in the First Cerro Prieto Symposium. Two papers presented at that meeting addressed the problems of reinjection, the first on chemical studies of reinjection effects (Rivera et al., 1978) and the second a hypothetical study of the influence on the producing field of cold temperature fronts resulting from injection operations (Tsang et al., 1978). This latter study assumed the reservoir to be one-layered, with injection carried out in different areas of the field. Based on the average reservoir parameters known at that time, it was shown that the cold temperature front would not reach the nearest production well for a considerable amount of time (>60 years).

It was soon realized that the Cerro Prieto reservoir was far from being a one-layer reservoir system. At the Second Cerro Prieto Symposium a generic study of two-layered reservoirs was presented (Tsang et al., 1979). Effects of injection in the upper reservoir on the lower one and vice versa were calculated. The influence of an opening in the shale layer separating the two reservoirs was also calculated. All these calculations still assumed a very simplified model of the Cerro Prieto reservoir.

Since August 1979, the Comisión Federal de Electricidad has been reinjecting 165°C untreated brines into well M-9. The maximum injection rate was reported to have been approximately 80 t/hr, or 20 kg/s, and the depth of injection was in an interval between 721 m and 864 m. Neighboring production wells, such as M-29, opened at about 1100 m depth, were monitored in order to detect changes in temperature, pressure, and enthalpy of the produced fluids. There has been no report that injection has caused any changes in the characteristics of these wells. This injection test was discussed in a numerical modeling paper presented at the Third Cerro Prieto Symposium (Tsang et al., 1981). A rather realistic geological model of the area near M-9, based on stratigraphic analysis of Lyons and van de Kamp (1980), was used in the 1981 study. This model showed an upper aquifer of about 400 m thickness at the injection level of M-9 and a lower aquifer of 180 m average thickness, representing what is commonly known as the A or α reservoir, at the production level of M-29. The two aquifers were assumed separated by a 20 m thick less-permeable layer. Based on this geological model, detailed numerical calculations indicate that over the injection-test period (about 1.5 years by 1981), no significant effects due to injection should be expected at the production wells. This conclusion is consistent with the field experience.

PRESENT STUDY AND APPROACH

Based on experiences gained from previous studies, the present paper attempts to predict long-term reinjection effects at Cerro Prieto, using a recently developed geologic model of the field. Such predictions, with proper short-term validations, will give an estimate of both the beneficial and adverse effects of long-term reinjection at this site and will also help in designing reinjection strategies, including well location, depth, and flow rate.

In our calculations the stratigraphy of Cerro Prieto developed by Halfman et al. (1982) is used. Due to the lack of full three-dimensional geological information, we will model only a vertical cross section of the system. Figure 1 presents a two-dimensional multilayered model that fits Halfman's stratigraphy of the western part of the field along a line through wells M-9, M-29, and M-10. This layered model, on which our reservoir calculations are based, includes several major features of the geology of the area such as the variations in thickness and depth of the various layers. The model has a closed boundary 1225 m southwest of well M-9, which is assumed to be associated with the strike-slip Cerro Prieto fault. The intent of our study is to calculate the pressure and temperature distribution in the cross section being modeled when reinjection is carried out at different locations and depths.

Figure 2 shows a discretized version of part of our two-dimensional (2-D) vertical section. This grid will be used for mass and heat flow calculations based on an Integrated Finite Difference Method discussed below under "Methodology". Figure 1 shows a multilayered reservoir model, which consists of an upper aquifer, the α reservoir, and the β reservoir, separated by less-permeable layers. The production region at Cerro Prieto corresponds approximately to a 1.5 km x 1.5 km area. In the vertical 2-D section, the zone being produced is represented by the 1.5 km-long diagonally hatched area in the α reservoir.

We will calculate the temperature and pressure changes in the production region resulting from cooler water (165°C) injected into well M-9 (220 m southwest of well M-29) or into 300 m-wide hypothetical reinjection regions centered 595 m southwest of well M-29. Two different depths of reinjection will be considered: one in the upper aquifer and the other in the α reservoir. The four reinjection regions are indicated as cross-hatched zones in Figure 2.

It is apparent from Figure 2 that the mesh is finer in the region around well M-9 and coarser elsewhere. This will tend to introduce some numerical dispersion which will artificially spread the thermal front as the injected water moves from well M-9 into the coarser parts of the mesh. However, considering the general nature of this study, such a dispersive effect is not expected to alter our overall conclusions.

EQUIVALENT INJECTION RATE IN A VERTICAL SECTION

A major problem in studying a three-dimensional system using a vertical two-dimensional model is how to represent the equivalent injection rate. This is still an open problem and requires further study. For our present paper, the following approach is proposed. Figure 3 shows schematically an areal view of the production field represented by a 1.5 km x 1.5 km area. The vertical 2-D section which we are to study is represented by the zone between the two broken lines, chosen arbitrarily to be 150 m wide, with a fluid extraction rate in the production region of $Q_p(150/1500) = Q_p/10$, if we neglect edge effects. The two-dimensional flow rate for an injection well having a flow rate Q_i, located at distance, S, southwest of the production area, is estimated as follows. First, assume that $Q_i/2$ of the injected flow rate goes towards the production area in response to the lower pressure there, i.e., half the injected fluid flows towards and half away from the production zone. Thus $Q_i/2$ is contained in the angle γ between lines stretching from the injection well to points A and B in Figure 3. Then, the injected fluid entering the vertical section of interest will be proportional to the angle, θ, between lines stretching from the injection well to points V and W. This flow rate is $(Q_i/2)(\theta/\gamma)$. Therefore, for the entire model which extends on both sides of the injection well, the flow rate to be used should be $Q_i\theta/\gamma$. This expression has the proper limits for an injection well very close or very far from the production area. Table 1 shows the weighting factor θ/γ for different distances between production and injection zones. This technique is used in our calculations and will be further investigated in a future study to determine its validity as well as its limitations.

METHODOLOGY

Two computer codes developed at Lawrence Berkeley Laboratory were employed to predict the effects of reinjection at Cerro Prieto. Program PT (for Pressure-Temperature) (Bodvarsson, 1982) is an expanded and revised version of code CCC used in earlier Cerro Prieto reinjection studies. It models single-phase (liquid) heat and mass transport in permeable media, employing the Integrated Finite Difference Method (IFDM) which permits the analysis of three-dimensional systems with complex geometry. The code has been validated against analytic and semi-analytic solutions and has also been carefully verified against a series of field experiments. It has been applied extensively to many thermohydrological problems.

The other code, SHAFT79 (Pruess and Schroeder, 1980), also developed at Lawrence Berkeley Laboratory, is a two-phase (liquid-vapor), IFDM code that models heat and steam-water flow in three-dimensional porous media. Recent developments enable it to model fractured porous media as well. It has been validated against a number of analytic results and experimental data, and has been applied to the study of several geothermal development problems.

These programs have been applied to calculate several hypothetical cases of long-term reinjection at Cerro Prieto. These are summarized in Table 2. All cases are calculated for $Q_i = 0.3\ Q_p$. For the single-phase (liquid) calculations, we shall assume that the principle of superposition holds and the injection effects are calculated over an injection period of 30 years. Any temperatures and pressures obtained will be predicted changes due to long-term injection. On the other hand, for two-phase (steam-water) calculations, we cannot assume that the principle of superposition holds. Thus, both a 9-year production period and a subsequent 5-year injection period with ongoing production are simulated.

TABLE 1. TWO-DIMENSIONAL FLOW-RATE DETERMINATION $Q_{2d} = \theta/\gamma(Q_i)$, Q_i = 200 kg/s = 30% Q_p

S(m)	θ/γ	Q_{2d}(kg/s)
1	.99	198
25	.81	162
50	.65	130
100	.45	90
220 *	.26	52
595 *	.14	28
2000	.10	20

* cases simulated in this paper.

TABLE 2. CASES CALCULATED

	Injection distance from edge of production zone	Injected layer	Other Conditions
Single-phase Calculations			
Case 1	220 m (into M-9)	upper aquifer	
Case 2	220 m (into M-9)	α reservoir	
Case 3	595 m (300 m injection zone)	upper aquifer	
Case 4	595 m (300 m injection zone)	α reservoir	
Case 5	220 m (into M-9)	upper aquifer	A break is assumed in the intervening layer separating upper aquifer and α reservoir.
Case 6	220 m (into M-9)	α reservoir	A break is assumed in the intervening layer separating α and β reservoirs.
Case 7	220 m (into M-9)	α reservoir	A break is assumed in the intervening layer separating upper aquifer and α reservoir.
Two-phase Calculations			
First, production is simulated for 9 years, then injection into M-9 as production continues.			
Case 1	220 m (into M-9)	upper aquifer	
Case 2	220 m (into M-9)	α reservoir	
Case 3	220 m (into M-9)	upper aquifer	A break is assumed in the intervening layer separating upper aquifer and α reservoir.

INITIAL CONDITIONS AND PARAMETERS USED

The material parameters of the different layers used in the calculations are shown in Table 3. These are reasonable values for Cerro Prieto based on information obtained to date. The initial temperature and pressure conditions over the vertical multilayered system are obtained by equilibrating a vertical column in the mesh shown in Figure 2 assuming constant-temperature, closed-flow boundaries on top and at the bottom. By assuming the upper boundary to be at 225°C and the lower boundary at 325°C, pressure and temperature profiles are obtained as shown in Figure 4. These match reasonably well with field measurements from the production region. These column-equilibrated pressure and temperature values were assigned to the entire mesh, and equilibration was carried out for up to 60 years. Changes after 30 years were minimal. Thus the temperature and pressure distributions after 30 years of equilibration were used as the initial conditions for all our calculations. The error introduced due to a further 30-year equilibration period is estimated to be about 1 psi and 0.5°C.

RESULTS - SINGLE-PHASE CALCULATIONS

The calculated temperature and pressure changes for each single-phase reinjection case listed in Table 2 are presented as contour plots in Figures 5-12. The pressure increases in response to reinjection are quickly established and then change little with time, so only one pressure distribution (after 10 years of injection) is shown for each case. On the other hand, the temperature varies with time, so the calculated temperature changes after 10, 20, and 30 years of injection are shown. In the plots the less permeable layers between the aquifers are shaded, and the M-9 injection interval and the location of M-29 (the production well closest to the injection location) are indicated by vertical bars. The 300 m-wide injection region is indicated by a rectangle.

Pressure Changes (after 10 years of injection)

Case 1. The pressure increase due to injection into the upper aquifer through well M-9 (Fig. 5A) is not confined to the upper aquifer, but penetrates through the less permeable layers into the α and β reservoirs. The less permeable layers retard the pressure response somewhat, so at a given lateral distance from M-9 the pressure change decreases as one goes from the upper (injected) aquifer to the lower β reservoir. The effect of the closed southwest boundary of the field (Fig. 1), is shown by the shape of the contour lines to the left of M-9. The asymmetry of the pressure change contours with respect to the injection well (M-9) is due to the reflection of the pressure pulse off that closed boundary.

TABLE 3. MATERIAL PROPERTIES AND TOTAL PRODUCTION/INJECTION RATES

	Permeability (md)	Compressibility (Pa^{-1})	Porosity
Upper Aquifer	50	2×10^{-10}	0.18
Intervening Layer	0.5	5×10^{-10}	0.40
α Reservoir	50	2×10^{-10}	0.22
Intervening Layer	5	5×10^{-10}	0.40
β Reservoir	50	2×10^{-10}	0.22

Production Rate Q_p = 670 kg/s
Injection Rate $Q_i = .30\ Q_p \approx 200$ kg/s.

Case 2. The pressure changes resulting from the injection into the α reservoir through M-9 (Fig. 5B) show the same general characteristics as those of Case 1. The less permeable layers retard the pressure response but do not completely confine it to the layer into which injection is carried out. The pressure reflection off the closed boundary is also evident. These features are common to all the single-phase calculations we have done.

Cases 3 and 4. Figures 5C and D show the pressure changes due to injection into the upper aquifer and the α reservoir, respectively, through a 300 m-wide injection zone whose center is 595 m southwest of well M-29. Note from Table 2 that the injection rate into this zone is smaller than it was for Cases 1 and 2 (injection into M-9). This reflects the fact that, when the injection region is farther away from the production zone, less of the injected fluid flows into the two-dimensional section of the production zone considered by our model. However, even in these cases a significant pressure increase is seen in the production zone.

Cases 5, 6, 7. The effect of a break in either intervening layer is shown in Figures 5E-G. Different pressure changes are observed in each of the cases, but in all of them the pressure is readily transmitted through the breaks.

A comparison of Cases 1 through 7 shows that, in all cases, reinjection causes a pressure increase throughout the multilayered reservoir systems considered in our model. The closed boundary to the southwest further enhances these pressure increases. It is to be noted that these calculations are based on liquid-phase systems. In the case of steam-water systems, the high compressibility of the two-phase fluid will result in much lower values for the calculated pressure increases (see next section). However, the qualitative conclusions above still hold.

Temperature Changes

Case 1. The thermal response to reinjection into the upper aquifer through well M-9 (Figs. 6A-C) is the formation of a cool region that steadily grows with time and sinks due to the higher density of the cooler injected water. The less permeable layers slow the downward movement of the cool water but do not stop it entirely. After 10 years of reinjection the cool water has just reached the top of the α reservoir; after 30 years it has spread through it and just penetrated the top of the β reservoir.

Case 2. The temperature response to injection into the α reservoir through M-9 (Figs. 7A-C) shows that after only 10 years of reinjection, temperature changes have reached the upper aquifer and the β reservoir, and have extended into the production zone of the α reservoir. After 30 years, much larger temperature changes have reached the α and β reservoirs than in Case 1 (with injection into the upper aquifer).

Case 3. After 10 years of injection into a 300 m-wide injection zone in the upper aquifer centered 595 m from well M-29, the temperature changes (Fig. 8A) are confined to the upper aquifer. After 20 years (Fig. 8B) a small temperature change has reached the α reservoir, but it is far from the production zone. After 30 years (Fig. 8C), the cool water still has not reached the α reservoir production zone or the β reservoir.

Case 4. Even after 30 years of injection into the α reservoir through the 300 m-wide injection zone, the temperature changes have just barely extended into the production zone of the α reservoir (see Figs. 9A-C). There is a temperature decrease in the β reservoir after 30 years, but it is largely limited to the region under the injection zone.

Case 5. This case considers the effect of a gap in the intervening layer separating the upper aquifer and the α reservoir as injection is carried out into the upper aquifer through well M-9 (Figs. 10A-C). After only 10 years of injection the discontinuity in the lower permeability layer has a strong effect (compare Figs. 6A and 10A). With a continuous intervening layer (Case 1) the temperature change has barely penetrated the top of the α reservoir; with a break in the layer the cool water extends well into the α reservoir. After 30 years, the largest temperature decrease is found in the α reservoir, rather than in the upper aquifer, and in general the cool region has moved farther down towards the β reservoir.

Case 6. In this case, the effect of a break in the intervening layer between the α and β reservoirs is studied, as colder water is injected into the α reservoir through well M-9 (Figs. 11A-C). After 10 years of injection, the gap in the layer has very little influence on the temperature changes (compare Figs. 7A and 11A). After 20 and 30 years, more cool water has flowed into the β reservoir than in Case 2 with its continuous intervening layer. However, even after 30 years, the break has only a minor effect on the overall shape and extent of the cooler region.

Case 7. The gap between the upper aquifer and the α reservoir considered in Case 5 is again assumed, with injection into the α reservoir through M-9 (Figures 12A-C). Although the temperature changes do propagate into the upper aquifer through the break in the layer, the overall effect of the gap on the shape of the cool region is much less dramatic when injection is carried out below the gap (this case) than when injection is done above it (Case 5). This is because the cooler injected water, denser than the native hot water, tends to sink due to gravity.

The extent of the cold temperature front after 30 years of reinjection varies from case to case. Moving the reinjection zone farther away from the production zone both laterally (Cases 3 and 4) and vertically (Cases 1 and 3) results in smaller temperature changes in the production zone of the α reservoir and in the β reservoir.

The break in the intervening layer between the upper aquifer and the α reservoir (Cases 5 and 7) strongly affects the downward propagation of the cold temperature front from the upper aquifer into the α and β reservoirs, but has less influence when fluid is injected into the α reservoir, below the break. The gap in the intervening layer between the α and β reservoirs (Case 6) located farther away from the reinjection area has only a small influence on the overall advance of the cold temperature front.

RESULTS -- TWO-PHASE CALCULATIONS

In the two-phase calculations, we cannot assume the principle of superposition because of the nonlinear characteristics of the phenomena involved. Thus instead of calculating pressure and temperature changes as in the single-phase cases described above, we have to calculate actual temperature, pressure, and steam saturation values.

Production is first simulated for nine years, then the three cases of reinjection listed in Table 2 are performed as production continues. The results are presented as contour plots of pressure and temperature changes from the initial conditions shown in Figure 4. Vapor saturation distribution in the system is also plotted; initially, the vapor saturation was assumed to be zero throughout the model. Below, the results of the initial nine years of production and the subsequent five years of reinjection are presented for each of the two-phase cases studied.

Production Simulation

The calculated temperature, pressure, and saturation changes are given in Figures 13 and 14 after 3 and 9 years of production, respectively. The pressure change after 3 years (Fig. 13A) is concentrated in the production region as expected, but also penetrates to the other layers. The effect of the southwestern boundary of the field is also reflected by the shape of the contours left of well M-29. The initial pressure and the temperature distribution with depth (Fig. 4) represents water near its saturation point in the β reservoir; the drop in pressure from production causes flashing to occur there as the pressure falls below the steam saturation pressure (Fig. 13C). This leads to wide-spread boiling and eventually to the lowering of the temperature seen in the lower β reservoir (Figure 13B) as pressure continues to drop.

The higher temperature regions directly below the production zone are due to the upward flow of hotter fluids toward the production zone. In particular, the steam from the two-phase β reservoir is migrating upward and condensing in the cooler liquid of the lower region of the α reservoir. This condensation releases latent heat raising the temperature of this region. Temperature increases as a consequence of production, caused by upward migration and condensation of steam, have been observed in several geothermal fields as well as in numerical studies of field behavior (Bodvarsson et al., 1982).

The results after 9 years of production show a further development of these phenomena. The pressure changes (Fig. 14A) have extended farther into the β reservoir and show a more pronounced effect of the closed boundary to the west. To the northeast, a constant pressure boundary (Fig. 1) allows fluid and heat recharge, but to the southwest the closed boundary does not allow it, thus enhancing the growth of the two-phase zone there (Fig. 14C). The region of increased temperature above the β reservoir (Fig. 14B) moves to the west along with the two-phase zone, because of steam condensation effects.

Reinjection Simulation

Case 1. The results of five years of injecting 30% of the mass produced into the upper reservoir through well M-9 are shown in Figure 15. The pressure contours (Figure 15A) show significant effects in both the upper aquifer and the α reservoir despite the low permeability layer separating them. For example, the pressure drop at well M-29 has decreased approximately 50 psi since injection began. However, in the β reservoir, more than 500 m below the injection zone, the pressure decline due to production continues. The high compressibility of the two-phase zone makes the pressure increases due to injection very slow.

The temperature contours (Fig. 15B) show the region of injected cooler water very clearly. It is apparent that the denser colder water is drawn to the producing zone located in the α reservoir. The vapor saturation (Fig. 15C) decreases in the production zone, but is relatively unchanged in the layers below it.

Case 2. The pressure response to injection in the α reservoir through well M-9 (Fig. 16A) shows the strong influence of the injected water in the liquid regions of the α reservoir and of the upper aquifer, but the high compressibility of the two-phase zone around the production region and in the β reservoir tends to diminish the pressure increase there.

Significant temperature changes (Fig. 16B) have occurred in the production zone. The vapor saturation (Fig. 16C) decreases in the α reservoir and in the intervening layer just below M-9 and M-29. The lower part of the β reservoir returns to a one-phase liquid condition.

Case 3. The effect of a gap in the intervening layer separating the upper aquifer and the α reservoir (after the production period was simulated assuming a continuous layer) is shown for injection into the upper aquifer through well M-9 (Figs. 17A-C). The pressure effects are clearly seen to be greater in the α reservoir than for the case of a continuous intervening layer (compare Figs. 15A and 17A). For example, the pressure at M-29 has dropped approximately 20 psi less than it did in Case 1. In the upper reservoir, however, the pressure decline is greater than it was in Case 1.

The temperature contours show cooler waters entering the production zone through the gap in the intervening layer (Fig. 17B). This development occurs earlier here than for the case of a continuous intervening layer (compare to Fig. 15B), due to the higher permeability channel now available. There is also a slightly greater contraction of the 0.1 saturation curve in the production region. The influence of the gap on the saturation in the intervening layer between the α and β reservoirs and in the β reservoir just begins to be apparent after five years (Fig. 17C). Thus even a relatively small break in the intervening layer can have a measurable effect on the pressure and temperature distributions after only five years of injection.

A comparison of these three two-phase cases shows that reinjection causes pressure increases in the production region when fluids are injected either in the upper aquifer or in the α reservoir. However these increases are much smaller than in the single-phase liquid cases discussed in earlier sections. This is due to the high compressibility of the two-phase zones which diminishes the pressure changes. Nevertheless a definite pressure-increase effect is seen even in these cases. There are also declines in the saturation levels in the production region near the injection intervals. Temperature reductions in the producing (α) reservoir are important only if the reinjection is carried out in the same reservoir or when significant breaks exist in the lower permeability layers between the produced and injected reservoirs.

The results discussed in this section depend strongly on initial reservoir conditions which are only very roughly known. Thus further calculations much beyond the five-year injection into the two-phase reservoir may not be so meaningful. Our proposal is to check calculated results against actual field reinjection data for a period of one to five years in order to validate the numerical models and initial conditions employed. The validated model and conditions may then be used to make longer-term predictions.

SUMMARY AND CONCLUSION

The most recent geologic model of the Cerro Prieto geothermal system, developed from well-log analysis, was used to calculate the expected effects of reinjection at different locations relative to the field's production zone. This is part of a series of reinjection studies made on this geothermal field.

The Cerro Prieto reservoir system is considered to be multilayered, with an upper colder aquifer, an intermediate (α) geothermal reservoir, and a lower (β) reservoir. Reinjection into the upper aquifer and α reservoir are the two alternatives studied in this paper. Injection locations are assumed to be 220 m or 595 m southwest of the edge of the production area, the former corresponding to the position of well M-9. Both single-phase (liquid) and two-phase (steam-water) calculations are carried out using numerical models PT and SHAFT79, developed at the Lawrence Berkeley Laboratory.

The results of our study show that significant pressure-sustaining effects can be obtained in the production zone by reinjecting 30% of the fluid mass extracted.

The breakthrough of the injected cold water into the production zone is strongly dependent on the location of the injection wells. Breakthrough is very significant if large-scale injection is carried out near well M-9. On the other hand, it seems to be safe to inject 30% of the fluid produced if reinjection is carried out 595 m (or farther) from the production area. Gaps in the low-permeability layers between the injected and produced reservoirs have a significant effect on the advance of thermal fronts into the exploited zones.

In conclusion, we would recommend that, because of the significant benefit in pressure maintenance in the reservoir, reinjection be carried out in a carefully planned and carefully monitored fashion. Early results over one to five years may be used to validate our assumptions and models. Once validated, the method can be used to predict reservoir behavior with considerably more confidence.

ACKNOWLEDGEMENTS

We would like to acknowledge discussion with and assistance from S. Halfman and K. Pruess of Lawrence Berkeley Laboratory. We also thank our colleagues of the Comisión Federal de Electricidad for providing some of the data used in this study. This work was supported by the Assistant Secretary of Conservation and Renewable Energy, Office of Renewable Technology, Division of Geothermal and Hydropower Technologies of the U. S. Department of Energy under Contract No. DE-AC03-76SF00098.

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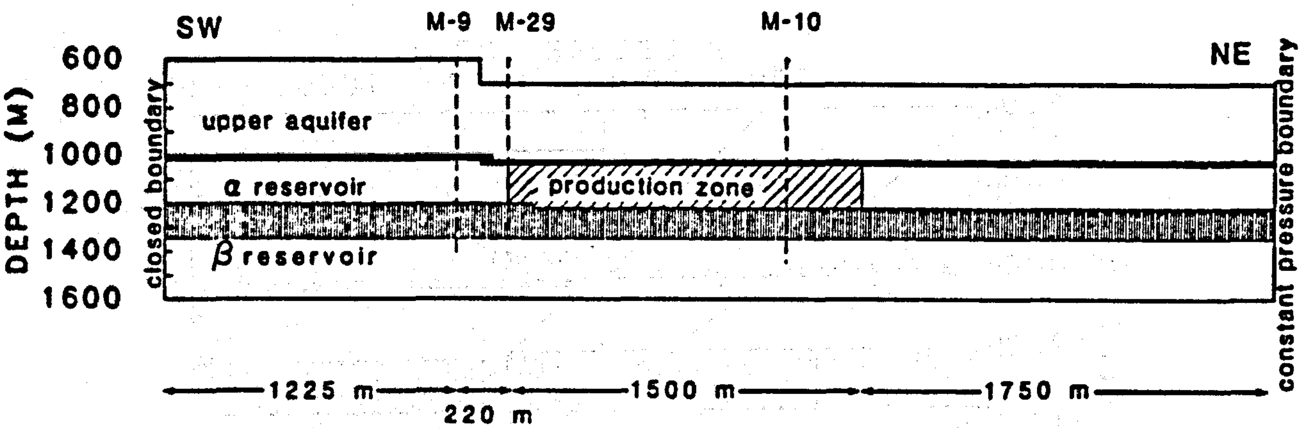

Figure 1. Vertical two-dimensional model used for the calculations. The shaded areas represent less permeable layers. The diagonally hatched area is the production zone.

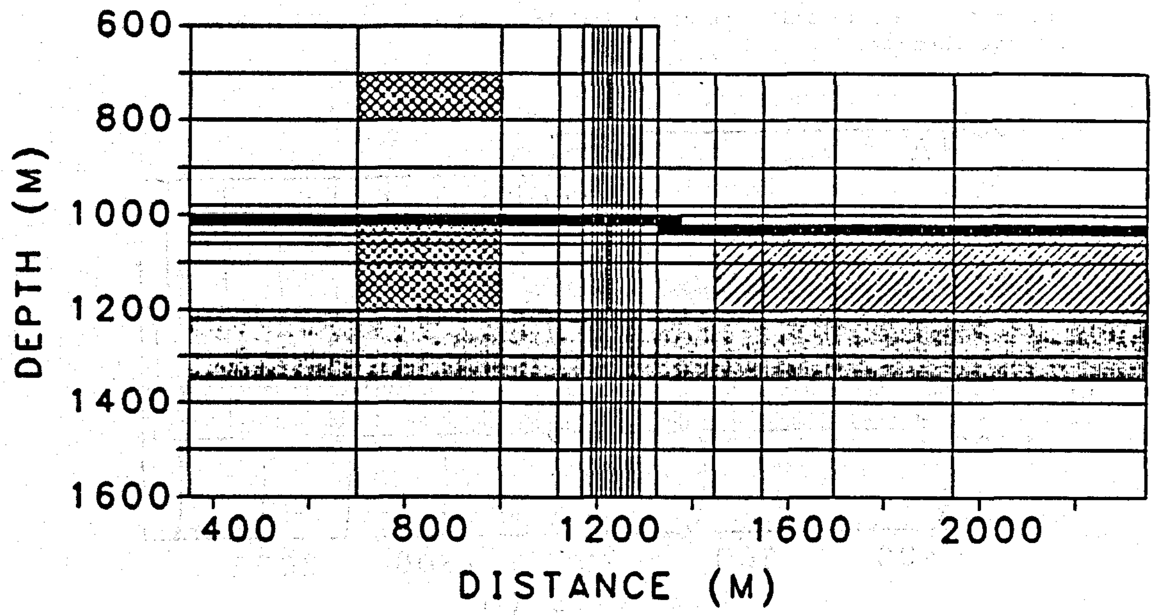

Figure 2. The central portion of the vertical two-dimensional model (given in Fig. 1) showing the spatial discretization used to calculate the heat and mass flows. The four alternate injection regions are shown cross-hatched. The diagonally hatched area is the production zone.

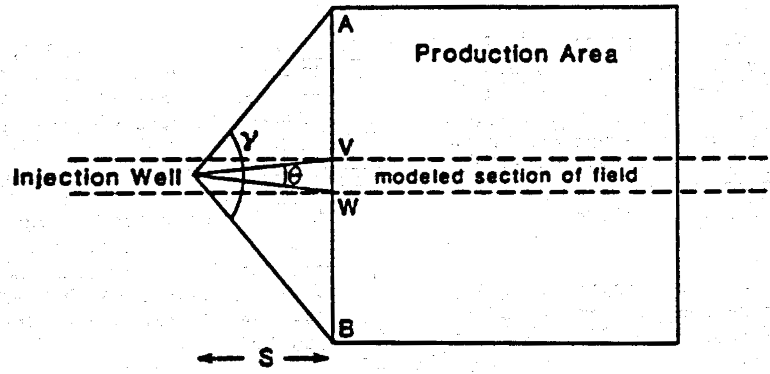

Figure 3. A schematic areal view of the Cerro Prieto field and the vertical section modeled. Used to determine the two-dimensional injection flow rate.

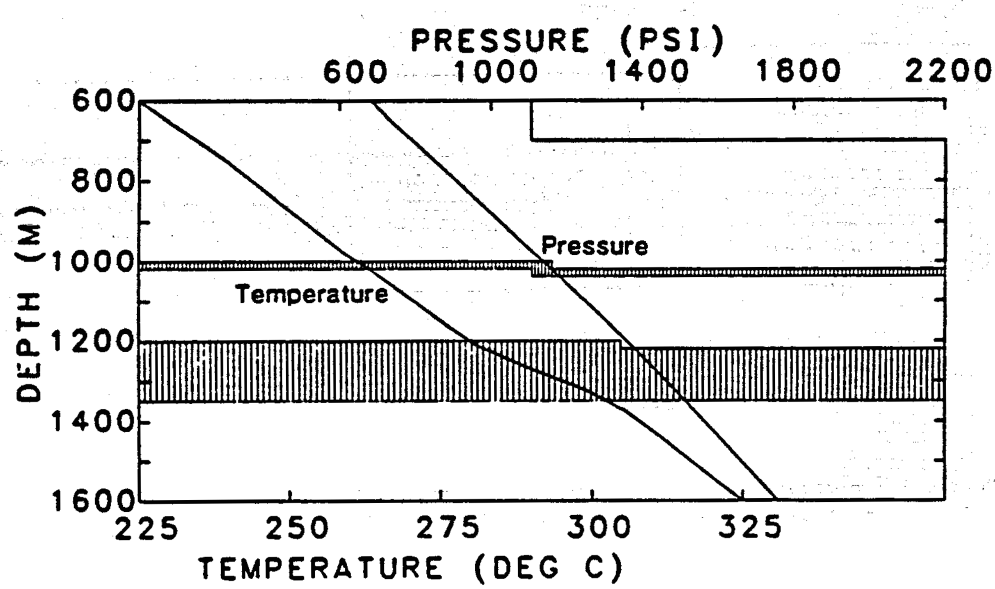

Figure 4. Pressure and temperature profiles used as initial conditions for the calculations.

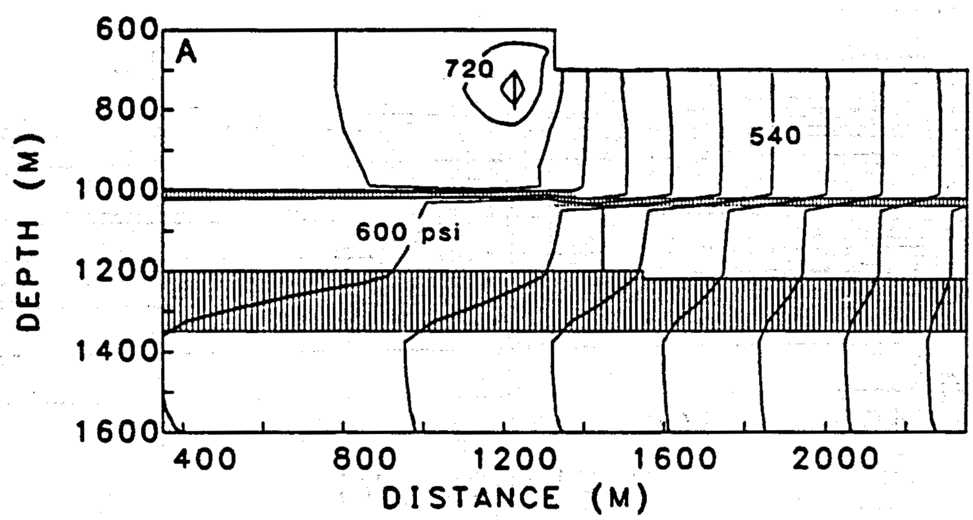

Figure 5. Pressure changes after 10 years of injection in single-phase calculations (Cases 1-7). The vertical lines indicate the location of the injected interval and the open interval in well M-29. Contour interval: 30 psi.

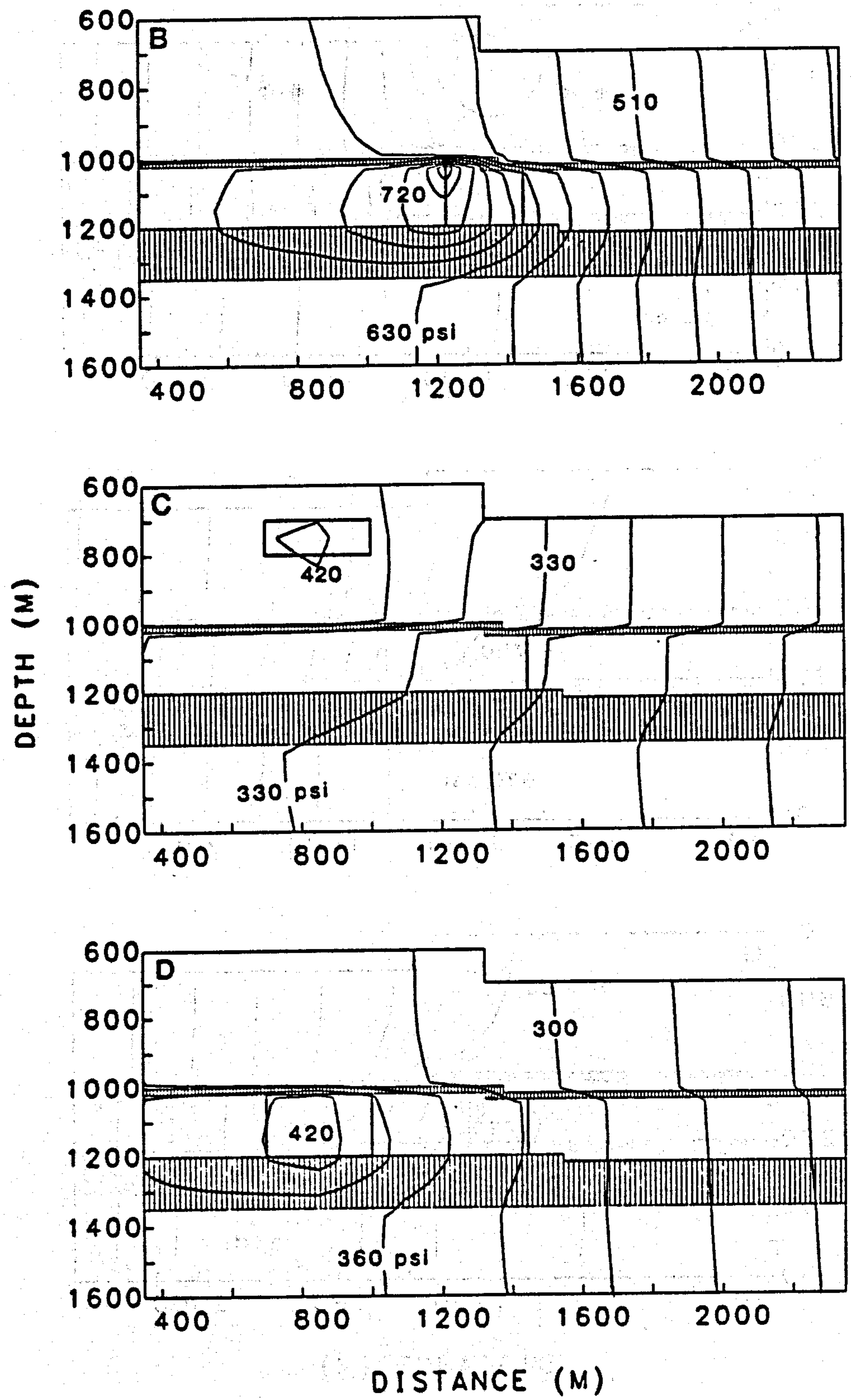

Figure 5 (continued). Pressure changes after 10 years of injection in single-phase calculations (Cases 1-7). The vertical lines (horizontal rectangle) indicate the location of the injected interval (zone) and the open interval in well M-29. Contour interval: 30 psi.

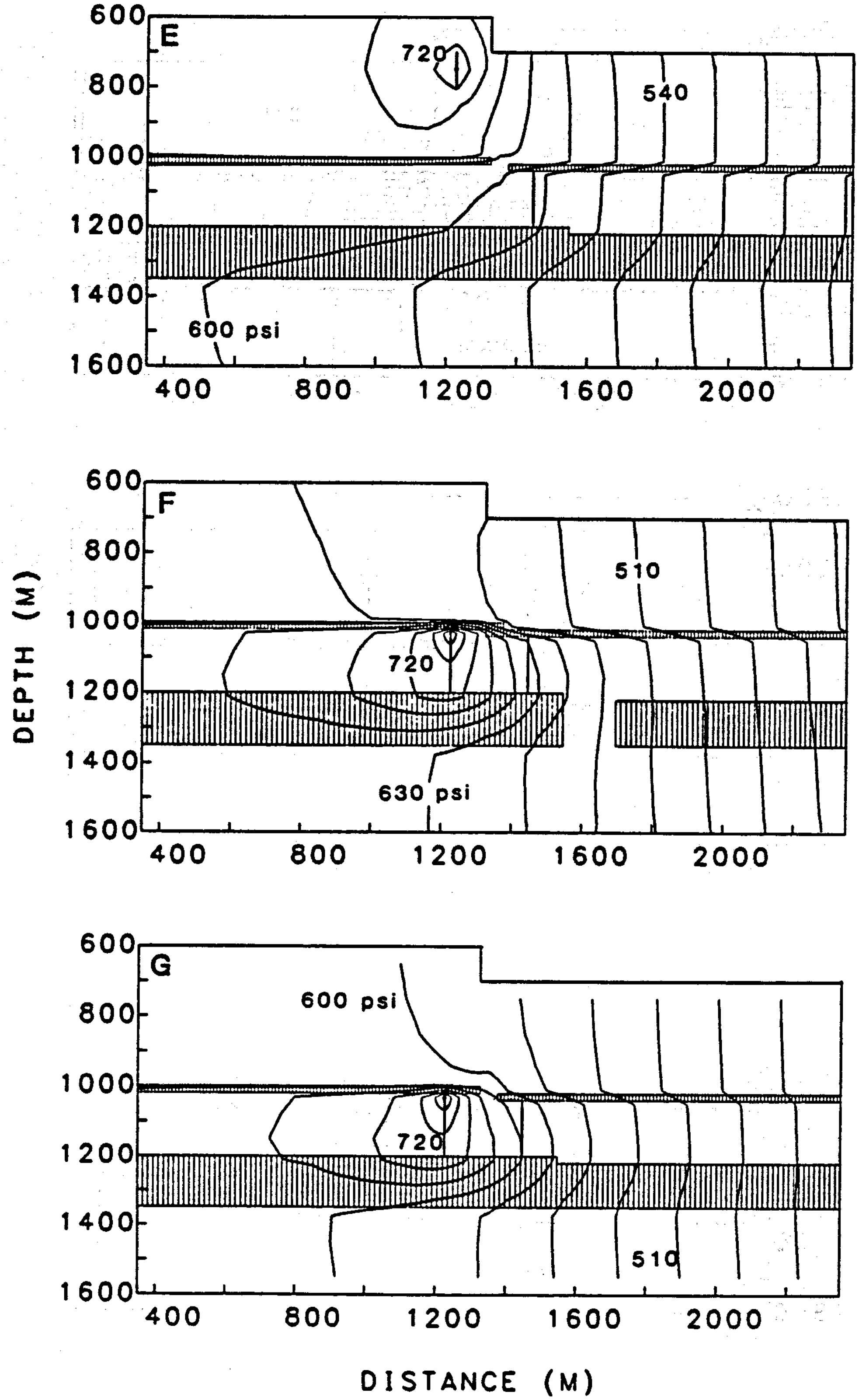

Figure 5 (continued). Pressure changes after 10 years of injection in single-phase calculations (Cases 1-7). The vertical lines indicate the location of the injected interval and the open interval in well M-29.
Contour interval: 30 psi.

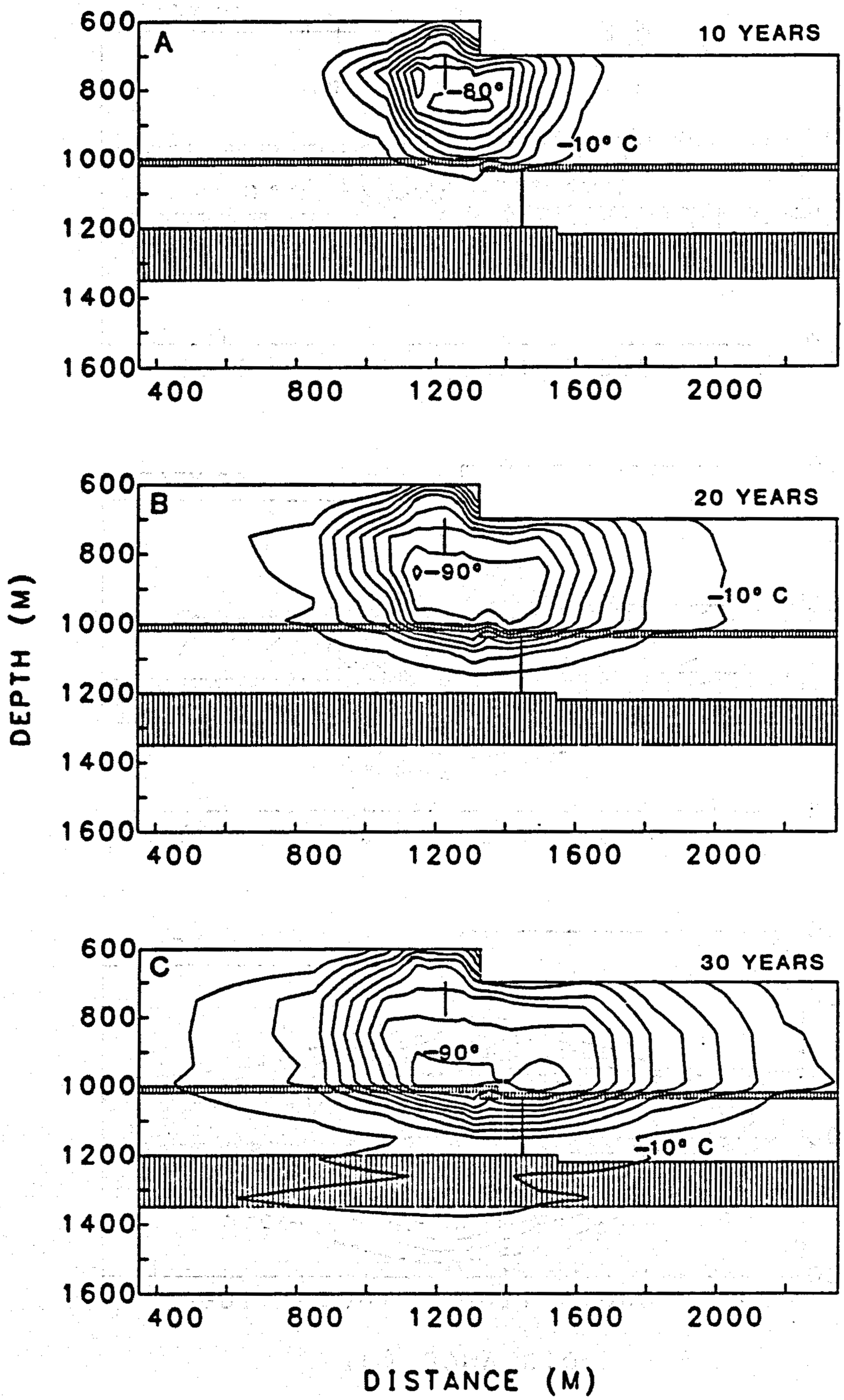

Figure 6. Temperature changes due to injection into the upper aquifer through well M-9 in single-phase calculations (Case 1). Contour interval: 10°C.

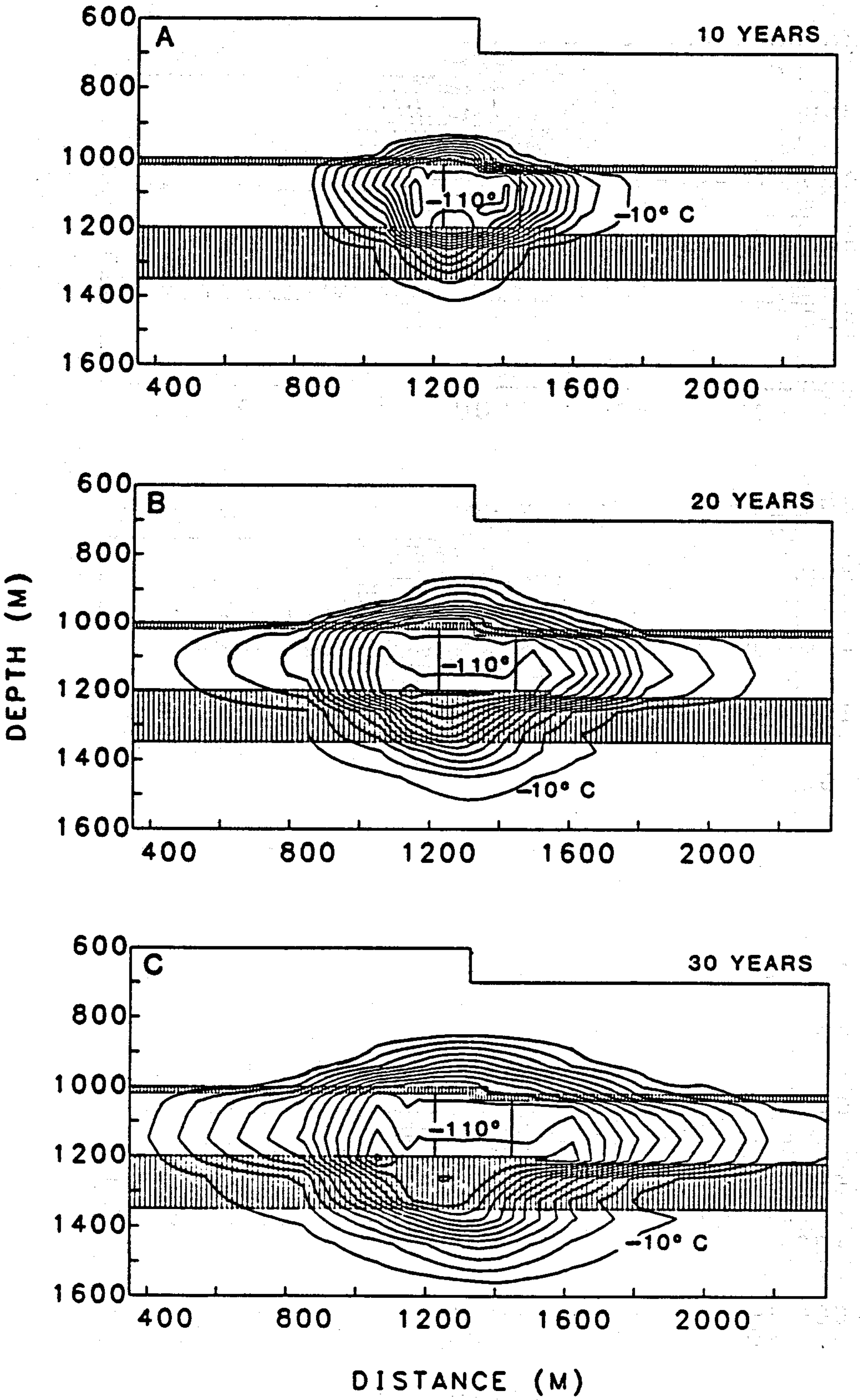

Figure 7. Temperature changes due to injection into the α reservoir through M-9 in single-phase calculations (Case 2). Contour interval: 10°C.

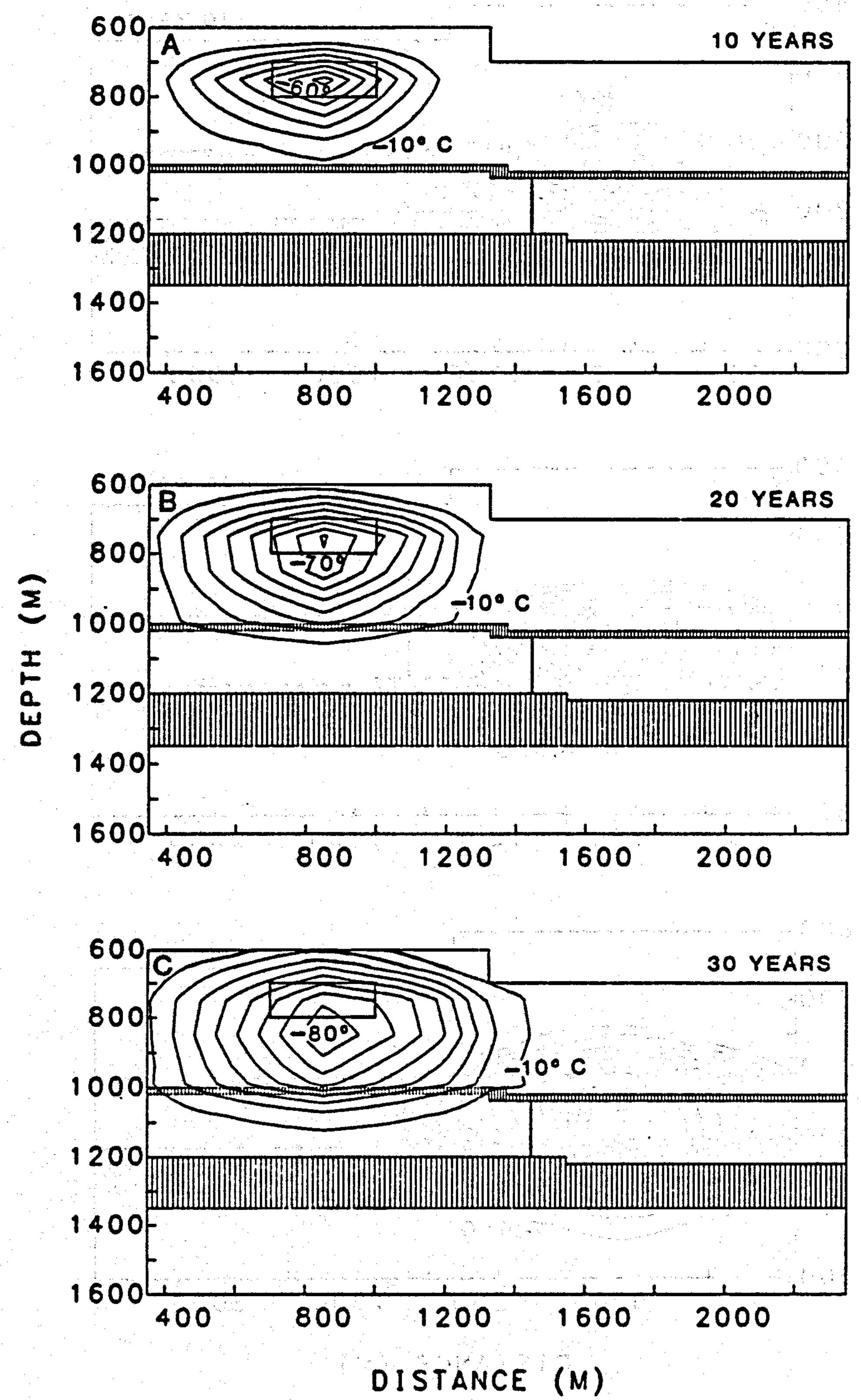

Figure 8. Temperature changes due to injection into the upper aquifer through a 300 m-wide injection zone centered 595 m southwest of well M-29 in single-phase calculations (Case 3). Contour interval: 10°C.

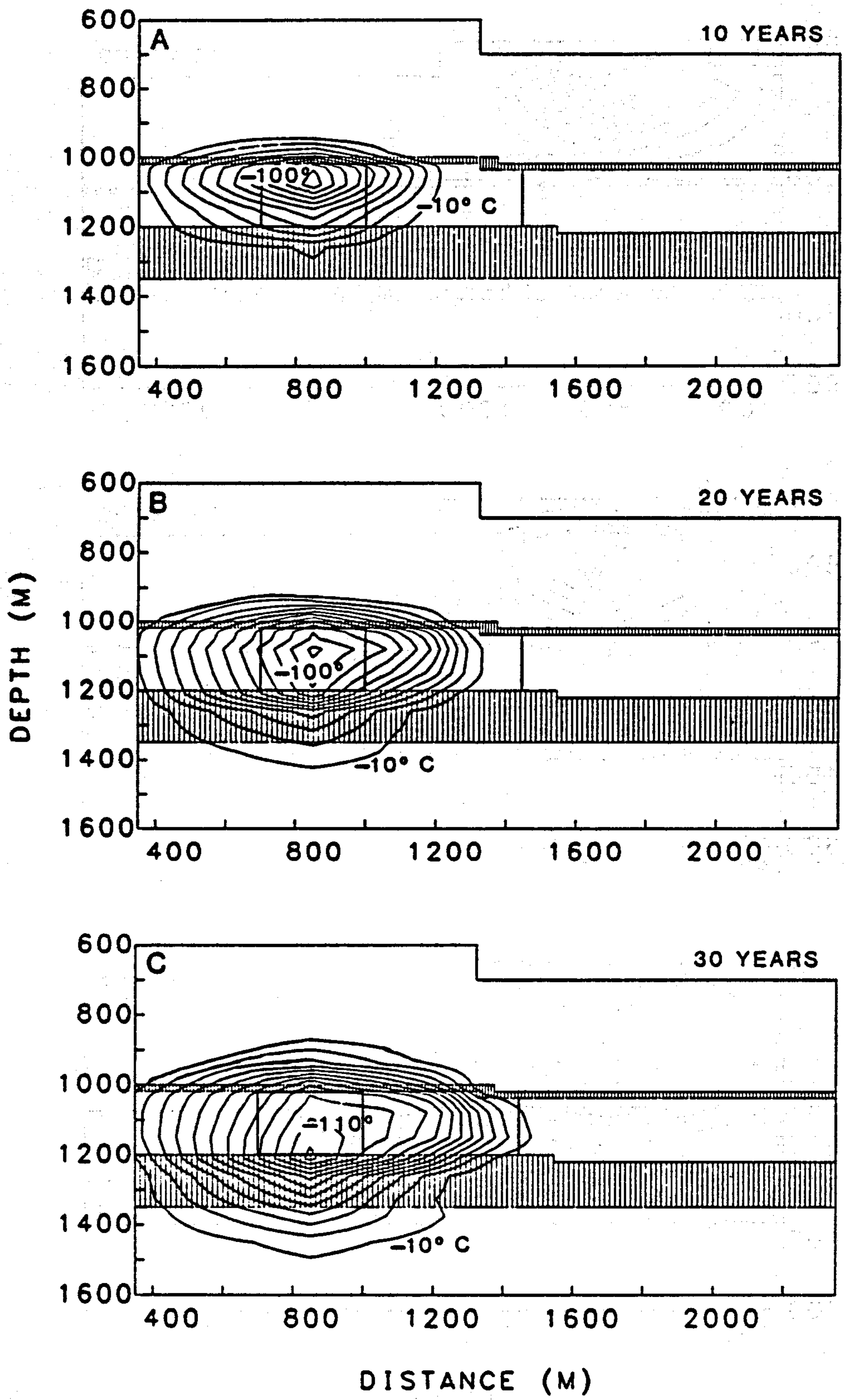

Figure 9. Temperature changes due to injection into the α reservoir through a 300 m-wide injection zone centered 595 m southwest of well M-29 in single-phase calculations (Case 4). Contour interval: 10°C.

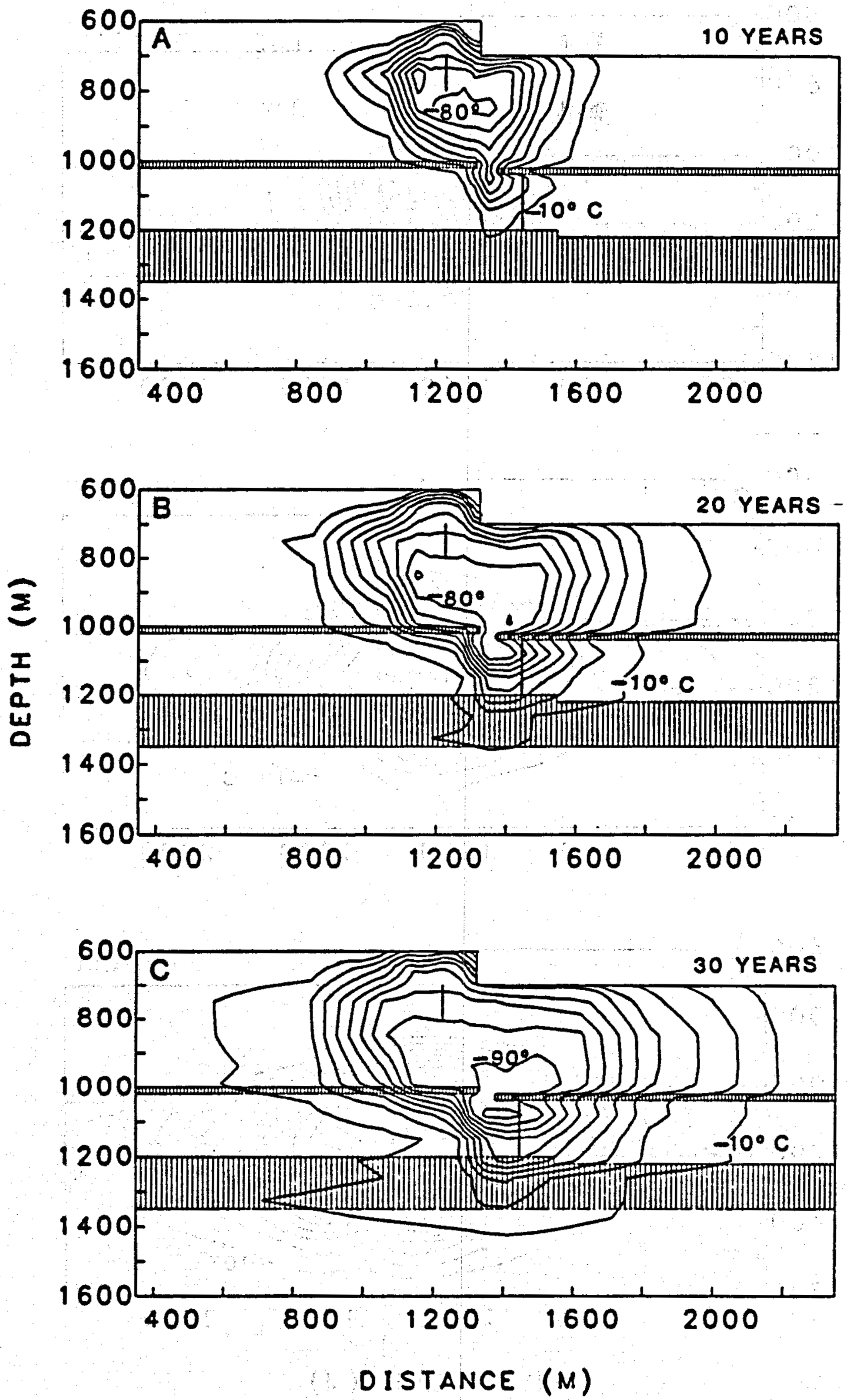

Figure 10. Temperature changes due to injection into the upper aquifer through well M-9 when there is a break in the intervening layer between the upper aquifer and the α reservoir, in single-phase calculations (Case 5). Contour interval: 10°C.

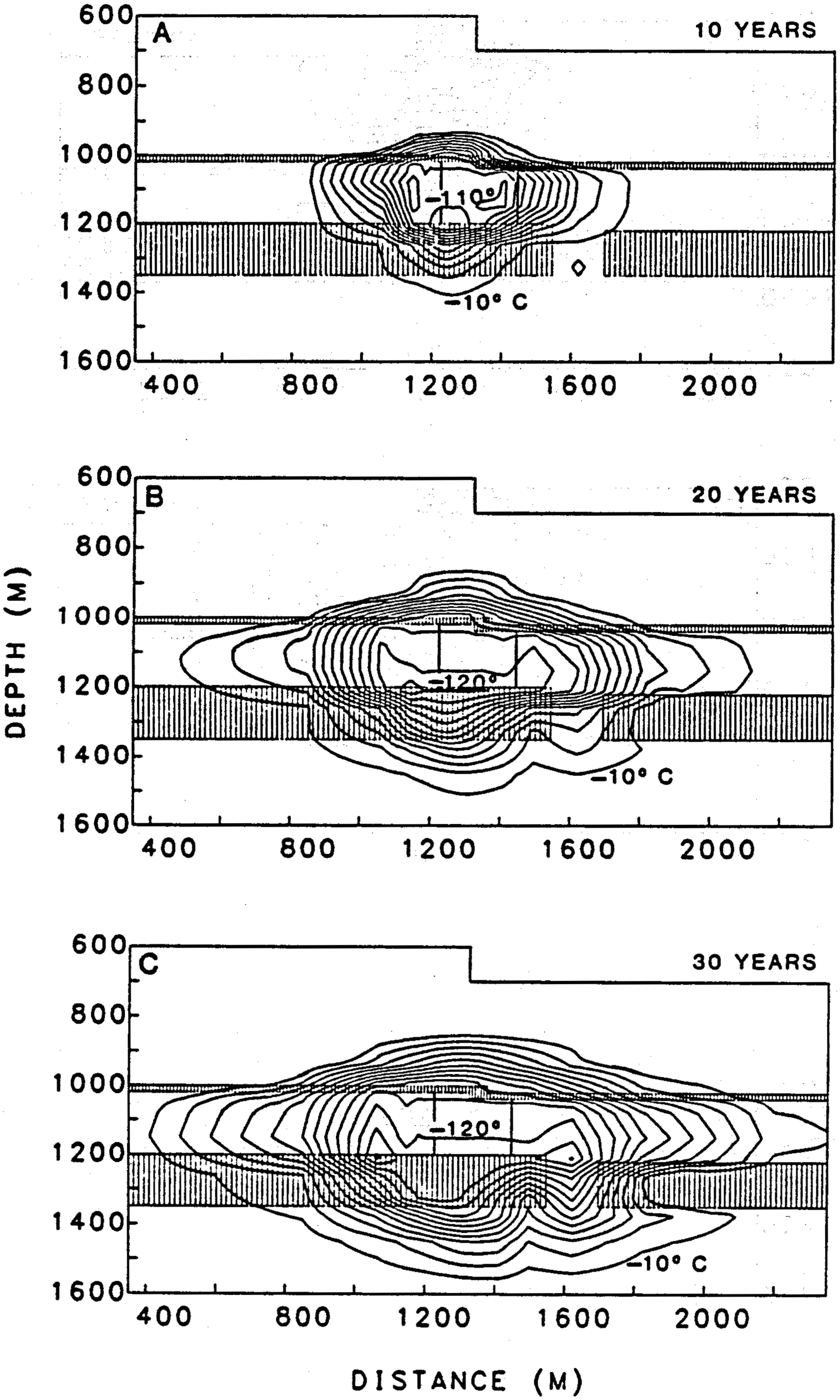

Figure 11. Temperature changes due to injection into the α reservoir through M-9 when there is a gap in the intervening layer between the α and β reservoirs, in single-phase calculations (Case 6). Contour interval: 10°C.

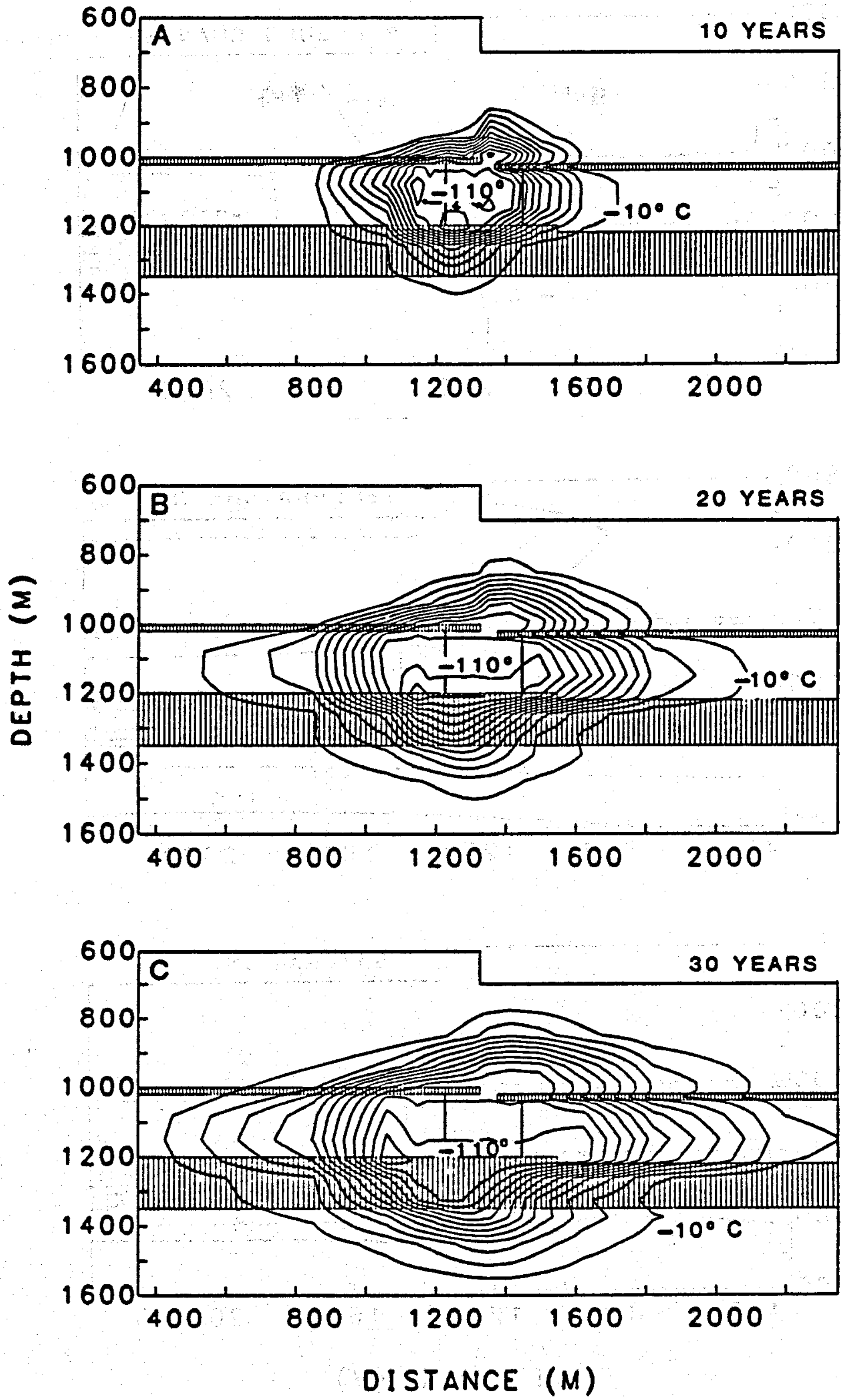

Figure 12. Temperature changes due injection into the α reservoir through M-9 when there is a gap in the intervening layer between the upper aquifer and the α reservoir, in single-phase calculations (Case 7).
Contour interval: 10°C.

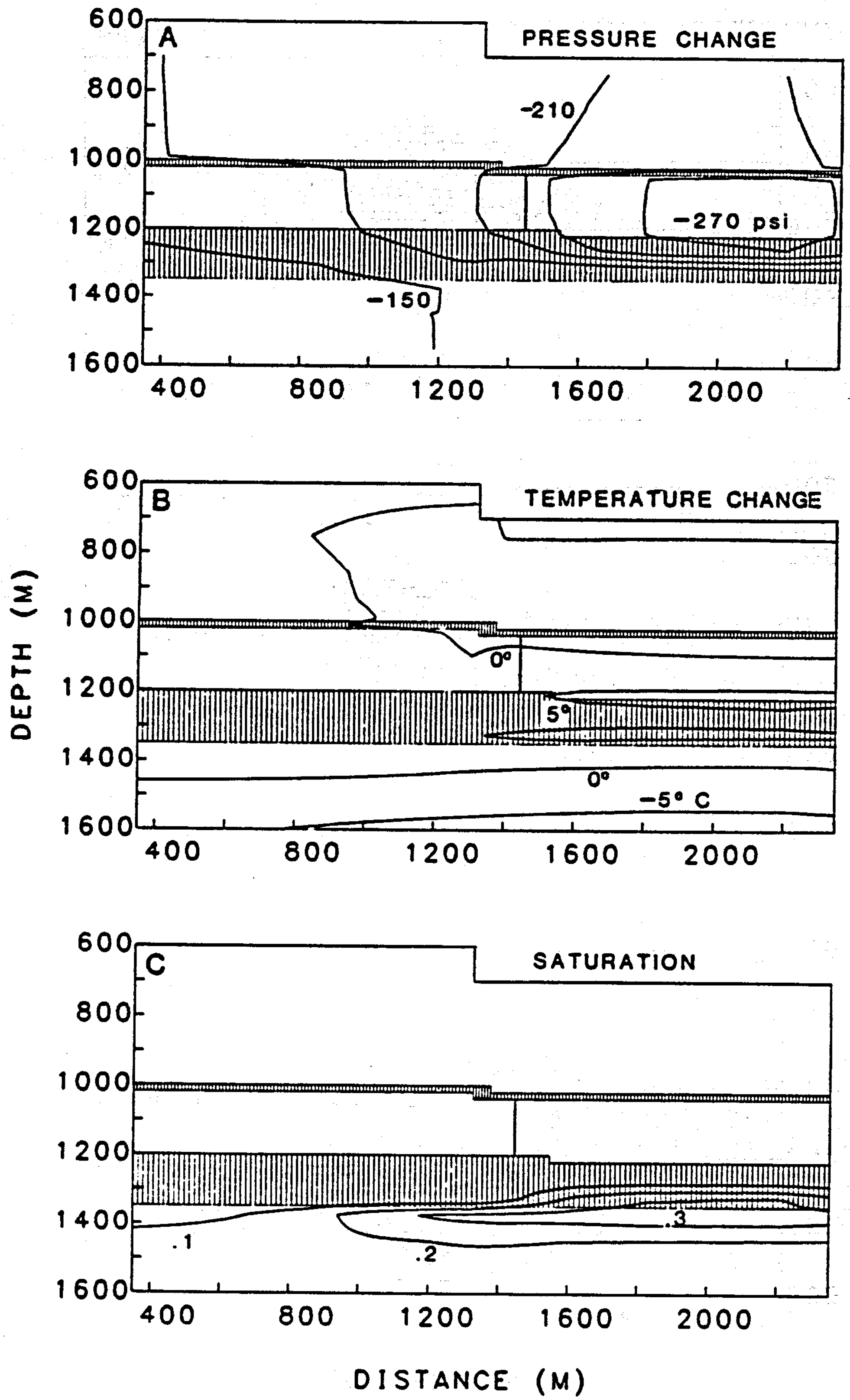

Figure 13. Pressure, temperature, and steam saturation responses after 3 years of production from the α reservoir in two-phase calculations.

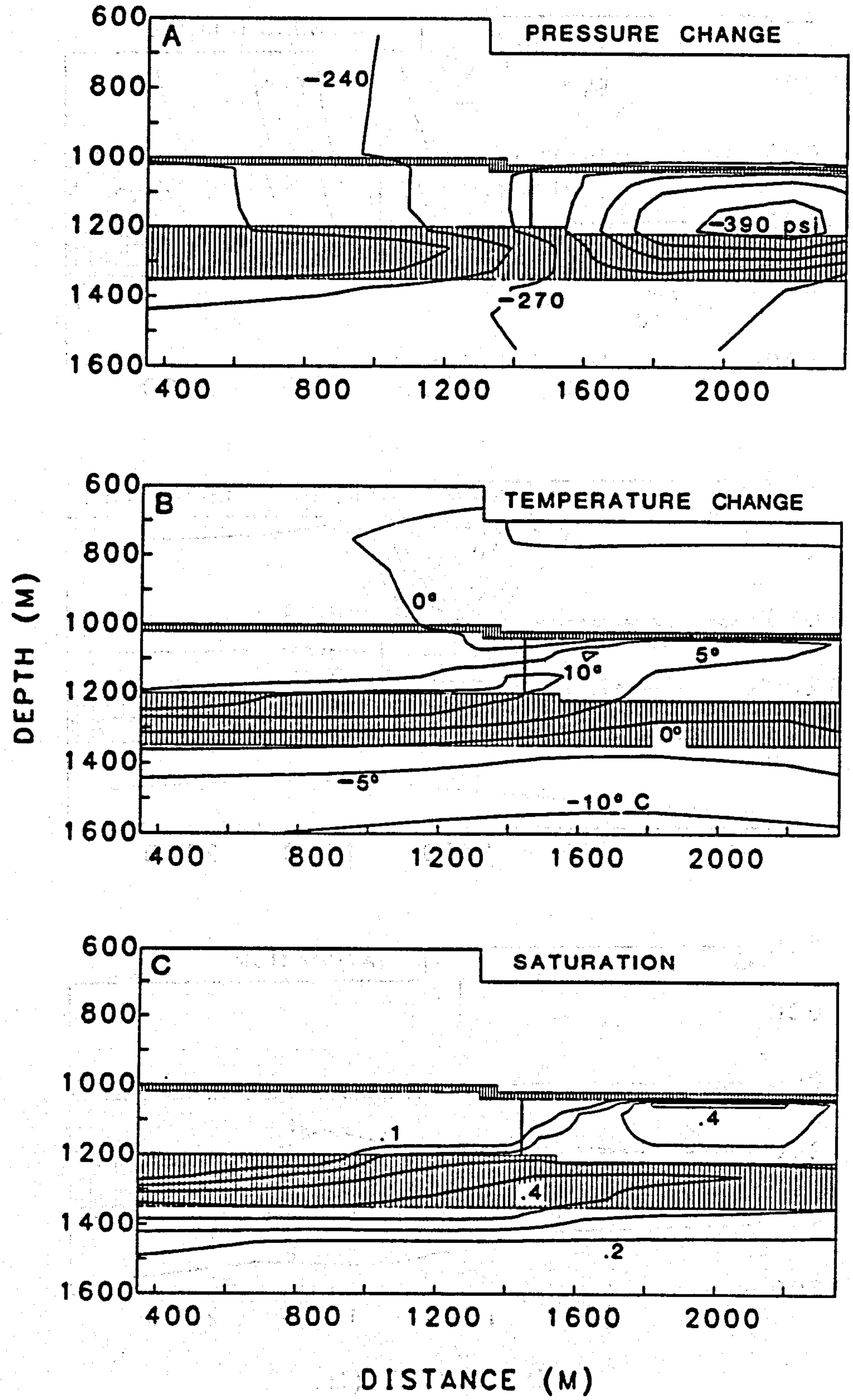

Figure 14. Pressure, temperature, and steam saturation responses after 9 years of production from the α reservoir in two-phase calculations.

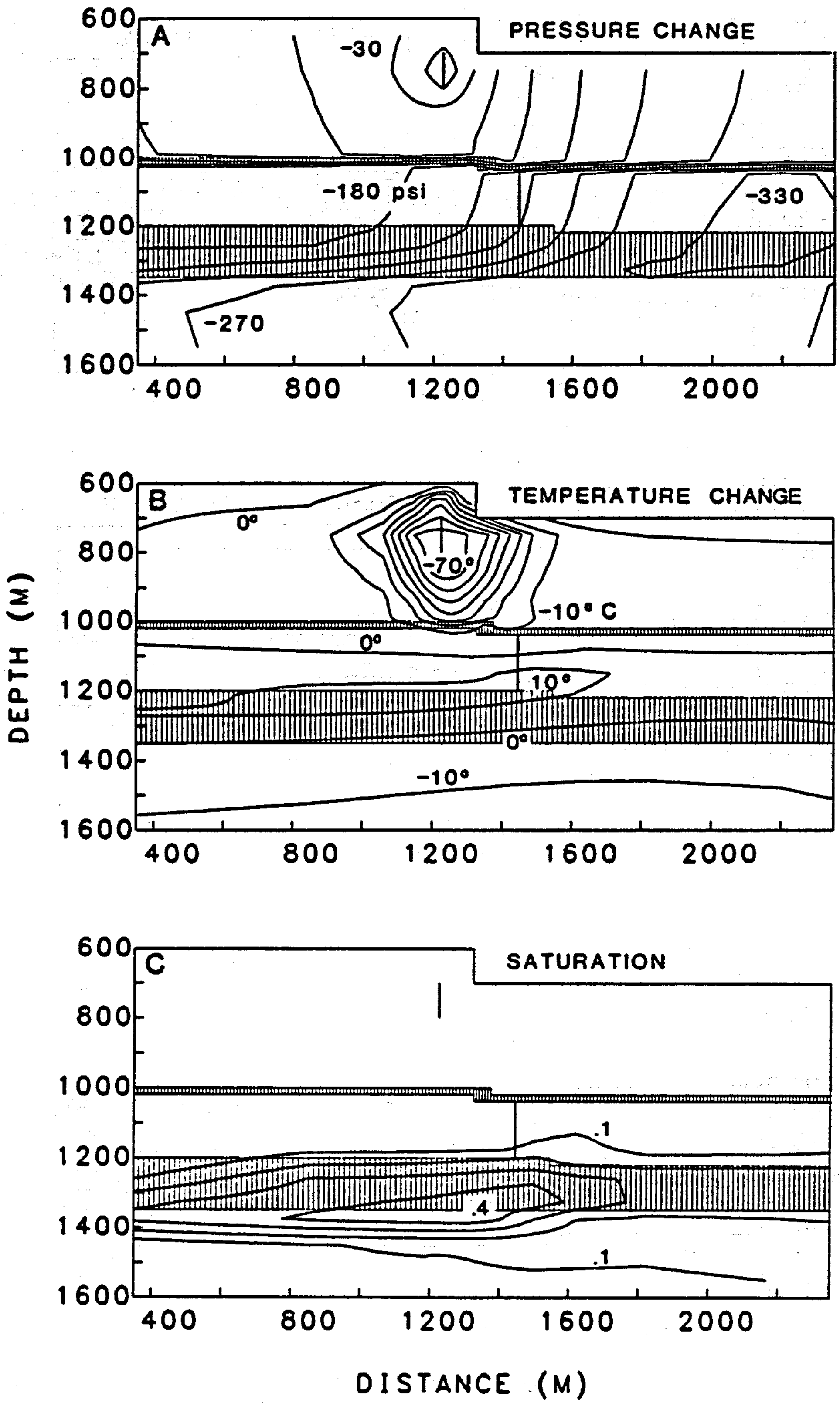

Figure 15. Pressure, temperature, and steam saturation responses after 5 years of injection into the upper aquifer through M-9, with continuing production from the α reservoir in two-phase calculations (Case 1).

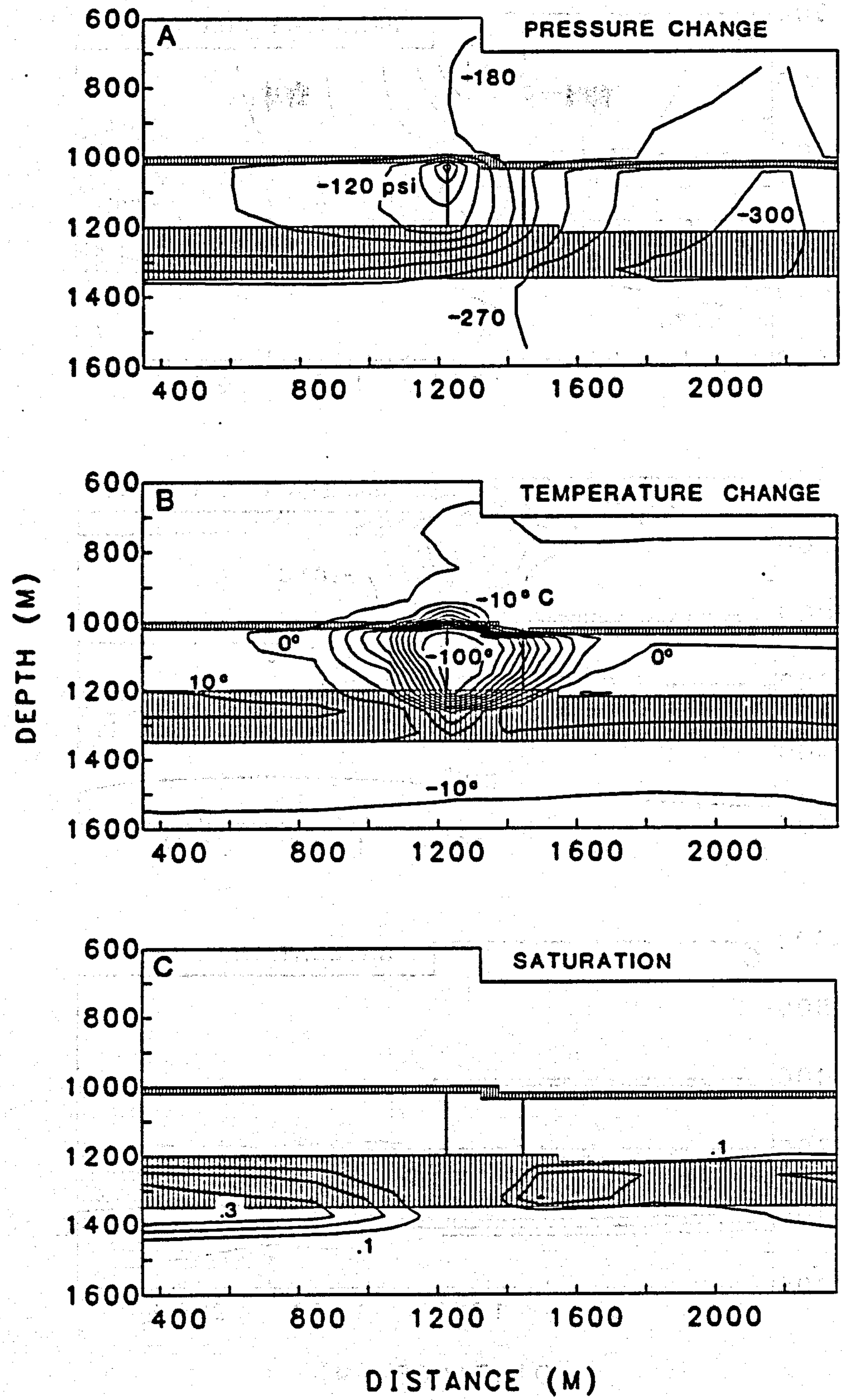

Figure 16. Pressure, temperature, and steam saturation responses after 5 years of injection into the α reservoir through M-9, with continuing production from the α reservoir in two-phase calculations (Case 2).

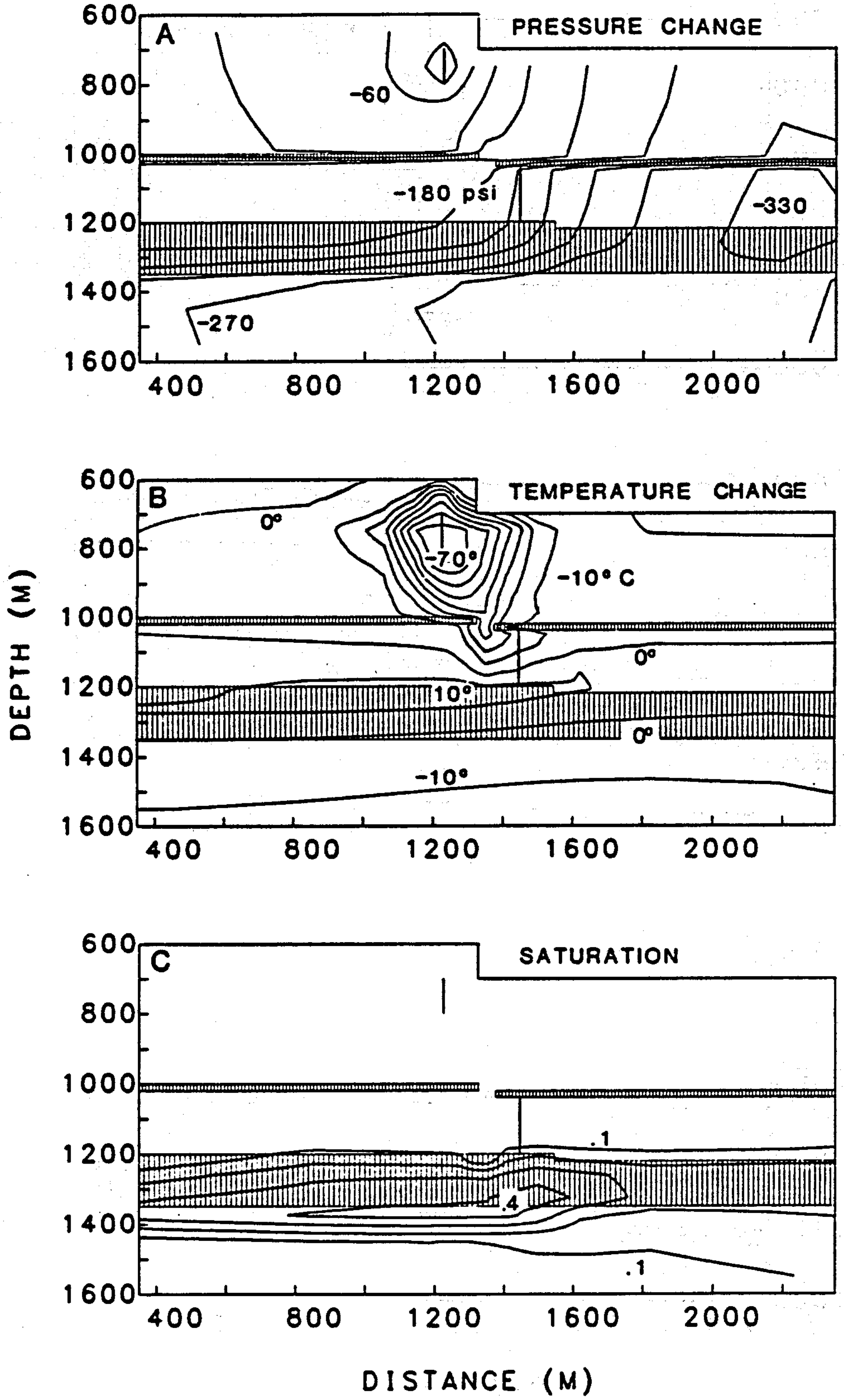

Figure 17. Pressure, temperature, and steam saturation responses after 5 years of injection into the upper aquifer through M-9 with continuing production when the intervening layer between the upper aquifer and the α reservoir is discontinuous, in two-phase calculations (Case 3).