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NATURAL STATE MODEL OF THE NESJAVELLIR GEOTHERMAL FIELD, ICELAND

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ABSTRACT

The Nesjavellir geothermal system in southern Iceland is very complex from both a thermal and hydrologic point of view. There are large pressure and temperature gradients in the wellfield and zones with drastically different pressure potentials. Thus, natural fluid flow is substantial in the system and flow patterns are complex. We have developed a two-dimensional natural state model for the Nesjavellir system that matches reasonably well the observed pressure and temperature distributions. The match with field data has allowed determination of the energy recharge to the system and the permeability distribution. Fluids recharge the system at rate of 0.02 kg/s/m with an enthalpy of 1460 kJ/kg. The permeability in the main reservoir is estimated to be in the range of 1.5 to 2.0 md, which agrees well with injection test results from individual wells. Permeabilities in shallower reservoirs are about an order of magnitude higher. Most of the main reservoir is under two-phase conditions, as are shallow aquifers in the southern part of the field. The model results also suggest that the low temperatures in the shallow part of the northern region of the field may be due to the young age of the system; i.e., the system is gradually heating up. If this is the case the estimated age of the system near the wellfield is on the order of a few thousand years.

INTRODUCTION

The Nesjavellir high temperature geothermal field is located in the northern part of the Hengill geothermal area, which is estimated to be one of the largest geothermal areas in Iceland. The Nesjavellir field is now under extensive investigation by the Reykjavik Municipal District Heating Service for possible cogeneration of hot water and electricity.

The geothermal system at Nesjavellir is extremely complex from a hydrological standpoint (Stefansson, 1985). There are very large lateral pressure gradients in the present wellfield as well as large differences in pressure potential between feed zones in many of the wells. There are also large temperature variations in the field, generally with high temperatures to the south and lower temperatures in the north. It has been postulated from the pressure and temperature data that the southern part of the field is boiling, and that the northern part is in sub-cooled liquid conditions (Steingrimsson and Stefansson, 1979; Stefansson, 1985).

The present paper describes a two-dimensional model of the natural state of the Nesjavellir system. When the model was developed, field data were available for wells 2 - 10, and these data were used in the model development. Since then six additional wells have been drilled in the field and data from these recent wells change somewhat the conceptual model of the field. The new data will be incorporated into future models, including a three-dimensional natural state model.

CONCEPTUAL MODEL

To date, sixteen wells have been drilled at Nesjavellir (Fig. 1). The depth of the wells varies from 400 to 2200 m. Stefansson (1985) has described the pressure and temperature conditions as inferred from well data. Figure 2 shows feed zone pressures in wells 3 - 10. These data suggest the presence of several different aquifers with different pressure potentials (Stefansson, 1985; the pressure gradient from southwest to northeast can be seen in Figure 6). The temperature distribution in the system is also very complex, as illustrated in Figure 3. Temperatures are highest in the southwest, especially at shallow depths.

Stefansson (1985) presents a plausible conceptual model of the Nesjavellir system. He suggests that the main upflow zone feeding the system is southwest of the present wellfield. The fluids flow toward the northeast between well 12 and the other wells in the field, recharging the main wellfield. Feed zone pressures (Fig. 3) suggest that there are four zones with different pressure potentials in the wellfield area, but chemical characteristics of the fluids suggest a common origin.

In developing a two-dimensional natural state model, the complex temperature distribution of the system has to be explained. Of particular importance is the large SW-NE temperature gradient in shallow regions of the system (Fig. 3).

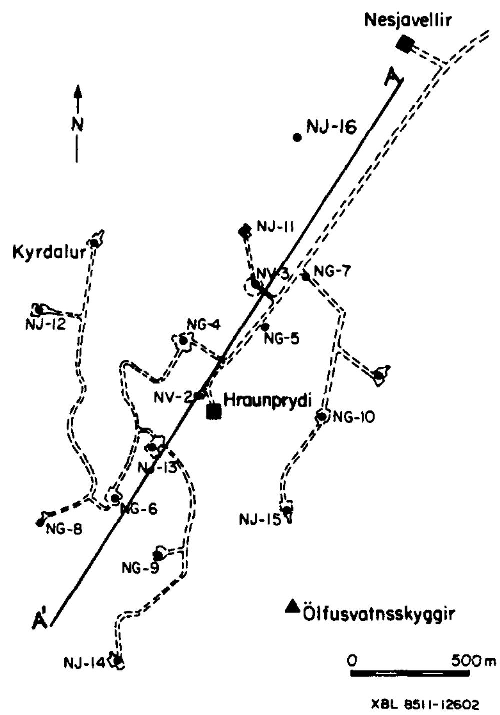

Figure 1. *The wellfield at Nesjavellir. The line A-A' represents the cross-section considered in the two-dimensional natural state model.*

There are several possible explanations for the declining temperature towards the northeast, including:

(1) *Fluid mixing:* Fluids flowing from the south mix with colder groundwater and cool down as they flow towards the north.

(2) *Rainfall cooling:* The hot fluids flowing to the north are cooled down due to mixing with cold infiltrating rainwater.

(3) *Steam losses:* Vaporization (boiling) occurs as fluids flow from the south, and steam escapes to surface manifestations, leaving behind colder fluids (e.g., Krafla field, Bodvarsson et al., 1984).

(4) *Permeability barriers:* Low permeability zones prevent the hot fluids from the south from flowing into the shallow aquifers in the northern part.

(5) *Young system:* The system is very young and still heating, with the thermal anomaly gradually extending to the north.

At present it is difficult to determine which one(s) of these alternatives is most likely to explain the observed trends. However, it appears that the first alternative, fluid mixing, is rather unlikely because the shallow pressure gradient is rather consistently from southwest to northeast at all depths; hence, fluid mixing is probably limited. One also expects that cooling due to rainfall infiltration cannot explain the temperature decrease to the north, because the very shallow groundwater aquifers in the northern part of the field have very different pressure potentials from those deeper. In the top 100 m, the water level is around 10 m below

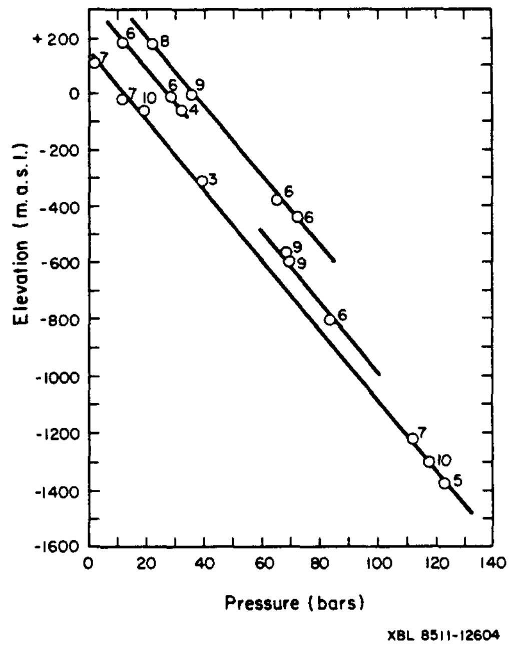

Figure 2. *Pressures at feed zones in the wells.*

ground surface, whereas below a depth of approximately 100 m the water level is approximately 70 m below ground surface. This suggests very low vertical permeability in the shallow part of the northern region; hence, it is unlikely that significant percolation to deeper aquifers occurs.

Vaporization of steam and flow to surface manifestations can also explain the sharp decrease in temperature to the north. At present, we do not have sufficient data regarding flow rates and enthalpies of fluids feeding the surface springs to judge if this is a realistic alternative explanation.

In the present work we investigate alternatives 4 and 5. In the basic model we assume that there is limited hydraulic communication between the shallow aquifers in the south and north. We use this model to calculate steady-state temperatures and pressures and compare them to the observed data. Then we investigate briefly the transient thermal development of such a system and the possibility that the Nesjavellir system is young and still developing based upon the thermal and hydraulic data that have been collected.

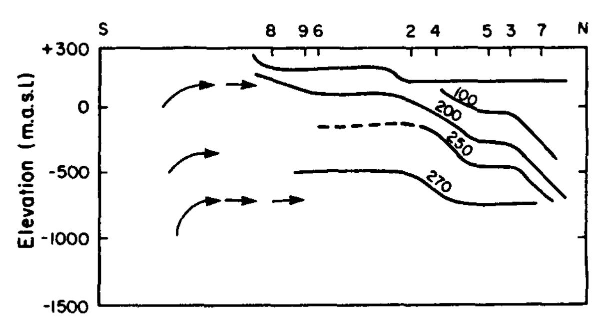

Figure 3. *A north-south cross-section of the temperature distribution in the system.* XBL 8511-12607

APPROACH

The fluid and heat flow patterns within the Nesjavellir systems are very complex, and cannot be explained entirely in terms of the simple two-dimensional model. However, in all modeling work it is best to start with as simple a model as possible in order to reproduce the main features of the geothermal systems. From such a simple model, more complex models can be developed in order to reproduce more details of the geothermal system. With this in mind, we have developed a simplified two-dimensional model of the Nesjavellir system. This model can readily be extended to three dimensions.

The model developed is a two-dimensional cross-section extending from southwest to northeast through the wellfield, as shown by line A-A' in Fig. 1. The model is intended to reproduce the main features of the temperature- and pressure-distributions in the system. Figure 4 shows the computational grid used. An upflow zone is assumed to be southwest of the the present wellfield. Fluids from the upflow zone flow upwards and then laterally from southwest to northeast (Fig. 3). Boundary nodes to the north are used to absorb the flowing fluids. The shaded areas in Fig. 4 are assumed to be low permeability zones.

Permeabilities and the flow rate and enthalpy of fluids recharging the system in the upflow zone were adjusted in order to obtain a match with the pressure and temperature distributions. Values for parameters assumed constant are given in Table 1. The numerical code MULKOM (Pruess 1982) was used in this work.

Table 1.
Constant parameters used in the simulations.

Parameter	Value
Porosity:	5%
Rock density:	2650 kg/m^3
Heat capacity:	1000 J/kg/°C
Thermal conductivity:	2.0 W/m/s/°C
Relative permeability:	X-curves $S_{rl} = 0.4$, $S_{rv} = 0.05$

BEST MODEL

After a number of iterations a steady state model was developed which gave a reasonable agreement between the calculated and observed pressure and temperature distributions in the system. Table 2 shows the thermodynamic values assumed for the boundary nodes. Figure 5 shows the calculated pressure distribution, and Figure 6 shows comparisons between observed and calculated pressure contours at 500 m below sea level. Figures 7 and 8 show the calculated temperature distribution and comparison with measured temperatures, respectively.

In general the figures show a rather good agreement with the measured data. There are certainly three-dimensional effects in the data that the two-dimensional model cannot resolve, and the model is not capable of matching large differences in pressure potential between different feed zones. Otherwise the agreement between calculated and observed values is reasonably good.

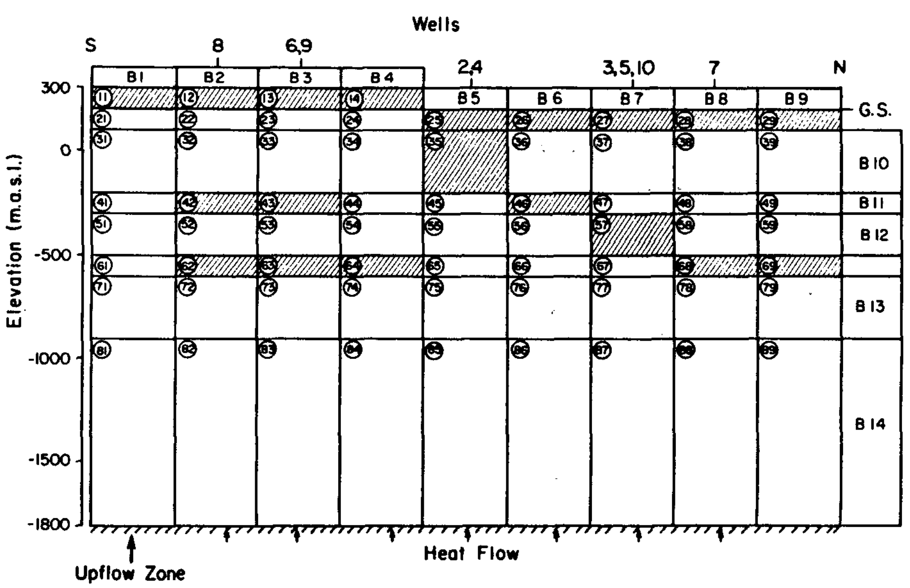

Fig. 4. Internal and boundary elements used for the two-dimensional natural state model. (Low permeability zones are shaded.) XBL 8511-12628

Table 2.
Thermodynamic condition of boundary nodes and mass flow rates into boundary nodes.

Boundary node	Temperature (°C)	Pressure (MPa)	Mass flow rate (kg/s/m)
B-1 to B-9	5	0.1	~ 0.
B-10	50	1.5	~ 0.
B-10	125	3.0	~ 0.
B-12	175	4.0	0.0020
B-13	270	7.0	0.0031
B-14	300	11.0	0.0149

In order to match the measured data, various zones with different horizontal and vertical permeabilities were included in the model. Figure 9 shows the various zones with different permeabilities; the permeability values are given in Table 3. The results indicate that the main reservoir below a depth of 800 - 900 m has a horizontal permeability of 1.5 - 2.0 md, and that the permeability is somewhat higher in the southern part of the reservoir than in the northern part. In the shallow regions in the southern part of the reservoir the calculated permeability is considerably higher than in the main reservoir, or 8 md both horizontally and vertically. The confining layers and the caprock are estimated to have permeabilities in the range 0.1 - 0.001 md.

In the best model 0.02 kg/m/s of fluids with an enthalpy of 1460 kJ/kg recharge the system through the upflow zone. This enthalpy corresponds to a temperature of approximately 320 °C, which is approximately the calculated temperature at the bottom of the model. Heat inflow of some 1.0 W/m^2 was specified at the bottom of the model in order to represent conductive heat flow or steam rising from depth. Figure 10 shows the mass fluxes in the system at steady state conditions. Most of the fluids flow laterally in the

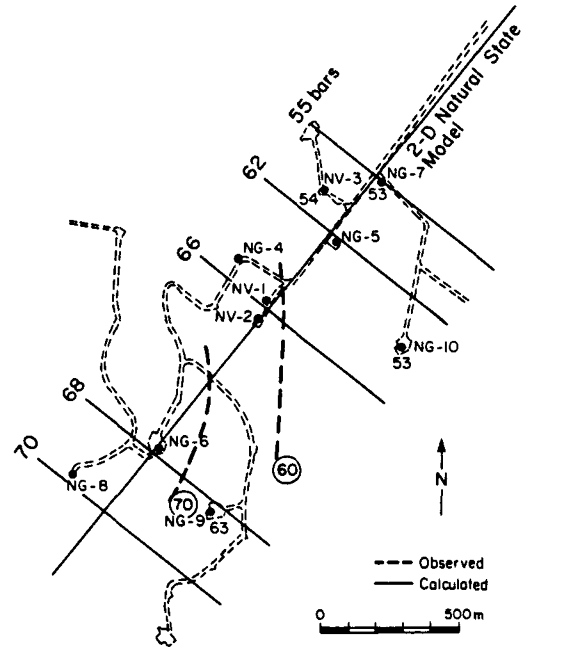

Figure 6. *Comparison between calculated and observed pressures at 500 m.b.s.l.* XBL 8511-12627

main reservoir from south to north. The mass flow rates into the boundary nodes are given in Table 2.

The calculated vapor saturation distribution is shown in Figure 11. Most of the main reservoir is in two-phase conditions, except for the region nearest the upflow zone. The calculated vapor saturation in the main reservoir is low and close to the residual steam saturation for the relative permeability curves used. In the shallow two-phase zone in the southern part of the field, the calculated vapor saturation is much higher, or close to 0.6. This high vapor saturation is in agreement with field data.

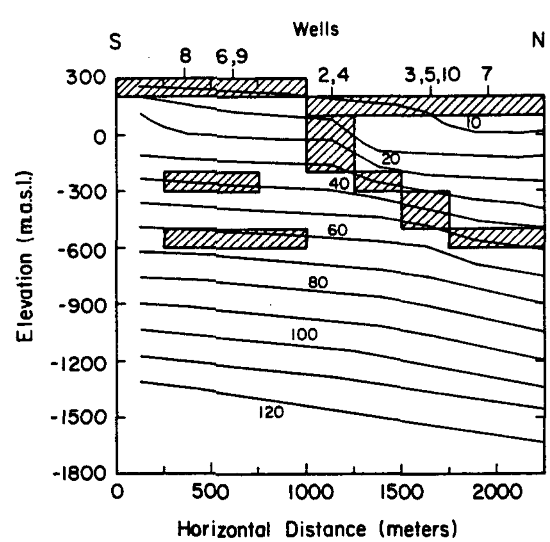

Figure 5. *The calculated pressure distribution using the best model (steady state).* XBL 8511-12605

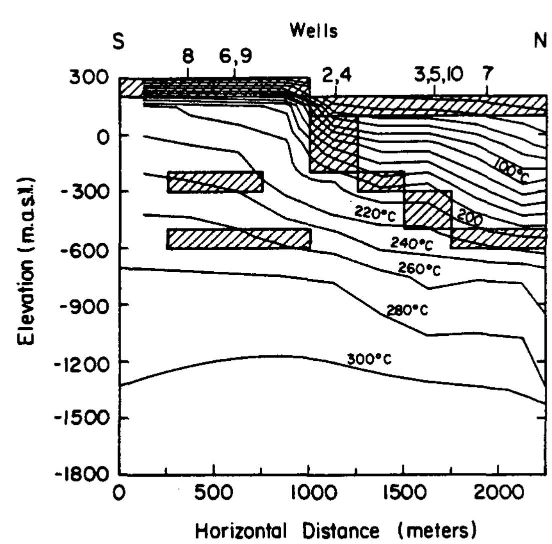

Figure 7. *The calculated temperature distribution.* XBL 8511-12606

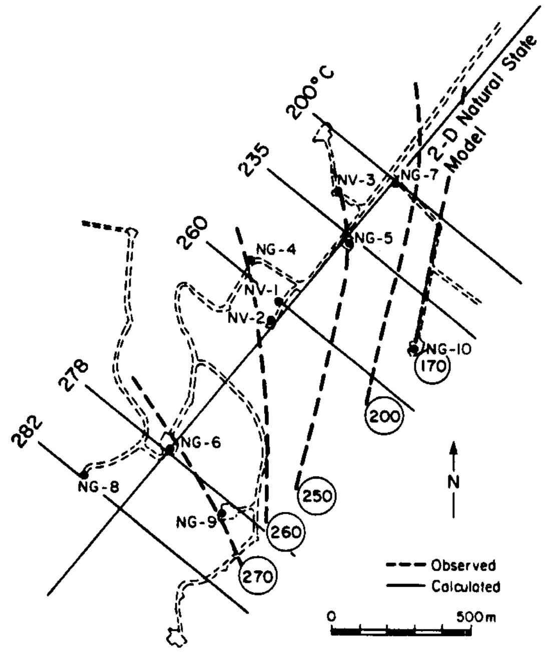

Figure 8. *Comparison between calculated and observed temperatures at 500 m.b.s.l.* XBL 8511-12626

Table 3. Permeabilities of the various reservoir zones.

Pattern	Permeability (md) Horizontal	Permeability (md) Vertical
	0.001	0.001
	0.1	0.1
	8.0	8.0
	2.0	8.0
	1.0	1.0
	2.0	1.0
	1.5	1.0

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TEMPERATURE EVOLUTION

The results from the best model were used to simulate the natural evolution of the system. The simulation is initiated with the entire system at a temperature of 20°C and corresponding hydrostatic pressure distribution. Fluids are removed from the northern-most internal elements (elements to 39, 49, 59, 79 and 89) at the rate determined by the best model. The boundary nodes (B10 - B14) are not used, because they would disturb the initial hydrostatic pressure distribution. At time zero fluid flow into the upflow zone begins at the rate and enthalpy determined from the best model.

Figure 12 shows the temperature distribution after 3,000 years of the evolution. The figure shows that the thermal anomaly in the shallow regions of the system has extended approximately to the assumed low permeability layers. Thus, it appears quite possible that the rather low temperatures observed in shallow regions of the northern part of the system may reflect its young age rather than the presence of low permeability confining layers. If this hypothesis is true, the age of the hydrothermal system is in the range 2000 - 3000 years. There are several observations suggesting that the geothermal system at Nesjavellir is geologically young, such as little mineral alteration at shallow depth, and the lack of equilibrium between the mineral assemblages and observed temperatures (Tomasson et al., 1974; Kristmannsdottir and Tomasson, 1974; Stefansson et al., 1983).

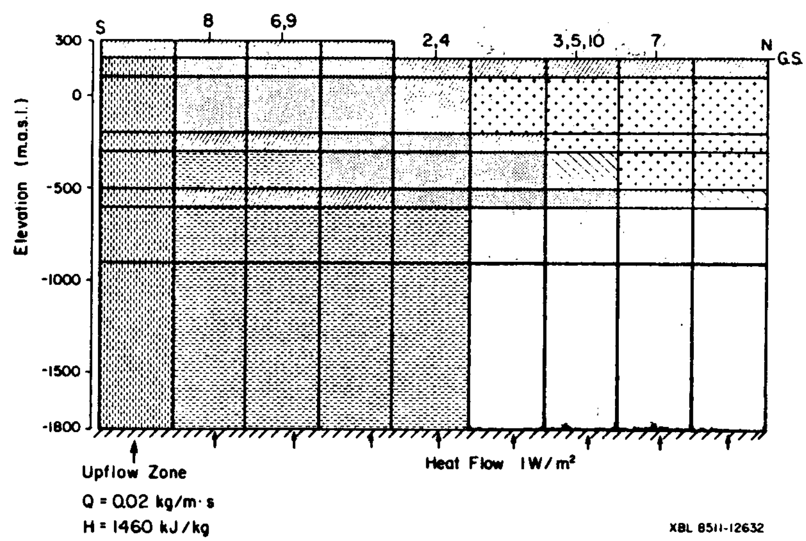

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Fig. 9. *The various reservoir zones with different permeabilities.*

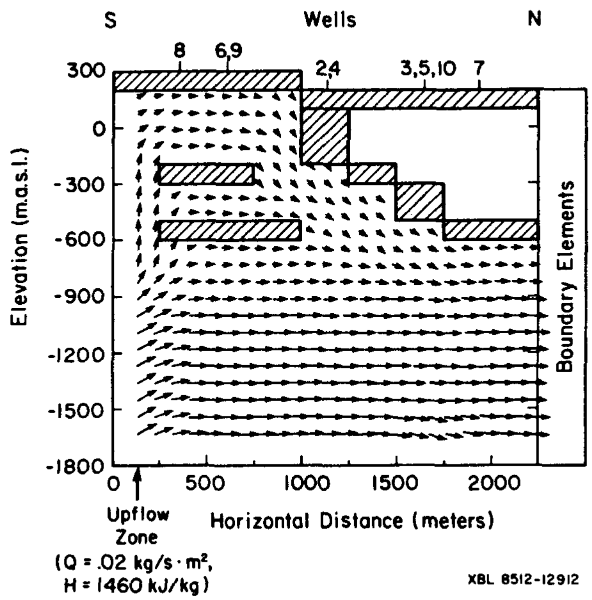

Figure 10. The steady-state flow field.

DISCUSSION

The non-uniqueness of the parameter values determined in this study is probably not a major problem for the system modeled. The main parameters determined from the natural state modeling are the recharge rate, enthalpy of the recharge fluids, and the permeability distribution in the system. It is well known that for isothermal problems the observed pressure distribution can be used to estimate either the mass flow rates or the permeabilities, but not both. In the present model, the temperature distribution is also matched and this allows for the determination of both mass flow rate and permeabilities within some limits. In fact, it is possible to determine approximately the permeability distribution and the total energy recharge rate, which is the product of the mass recharge rate and the enthalpy. Thus, for a given enthalpy, the mass recharge rate and the permeability distribution may be determined.

In the best model a recharge enthalpy of 1460 kJ/kg is used together with a mass recharge rate of 0.02 kg/s/m. Theoretically, the enthalpy of the recharge fluids could be as high as 2800 kJ/kg, but in that case the flow rate would be about 0.01 kg/s/m, and permeabilities would also be about half the values estimated. However, this would require the calculated pressure gradient to be close to vaporstatic in the upflow zone. Such conditions have not been observed so far in the Nesjavellir system. Therefore, the estimated values of the recharge rate and permeability distribution should be within a factor of two of the real values (given the two-dimensional model).

CONCLUSIONS

A two-dimensional natural state model of the Nesjavellir geothermal system has been developed. The model extends north-south through the present wellfield. It matches reasonably well the observed pressure and temperature distributions in the system. The major conclusions of this work are:

(1) In order to match the observed pressure and temperature distributions in the region modeled, an energy recharge rate of 30 kJ/s/m is required. A mass recharge rate of 0.02 kg/s/m and an enthalpy of 1460 kJ/kg were used in the simulations. However, it is possible that the recharge enthalpy is somewhat higher; this would reduce the mass recharge rate accordingly.

(2) Permeabilities in the main reservoir deduced from the natural state modeling are in the range of 1.5 - 2.0 md, which compares reasonably well with the results of injection tests performed on individual

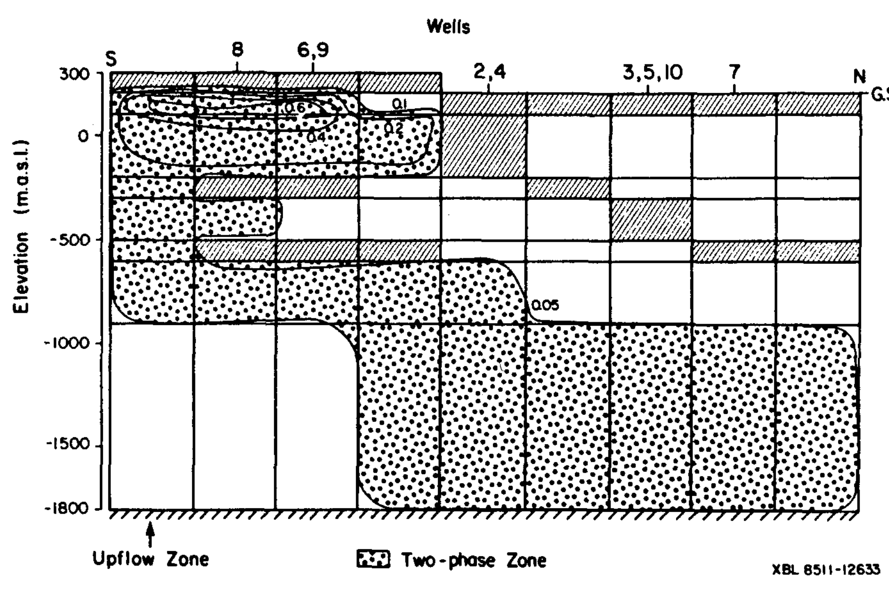

Fig. 11. The location of the two-phase zone in the system.

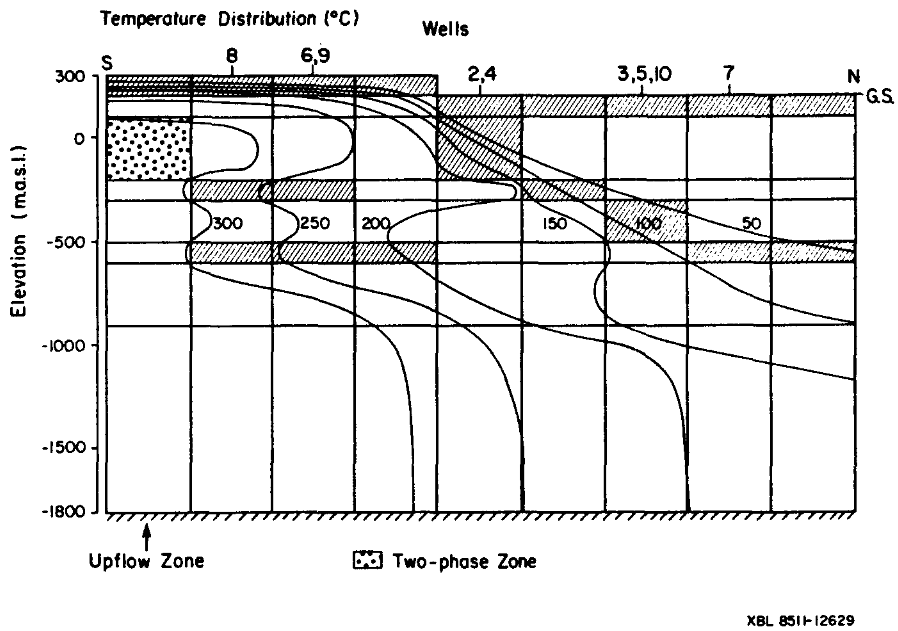

Fig. 12. The temperature evolution after 3,000 years for the evolution model.

wells. Permeabilities in the shallow aquifers in the southern part of the field are estimated to be considerably higher, or about 8 md.

(3) It appears possible from the modeling that the relatively low shallow temperatures in the northern part of the field are simply due to the young age of the system; i.e., the system is still heating up. If this is true, the modeling of the evolution of the system suggests that the age of the system is in the range of 2000 to 3000 years. There is an obvious need to determine if there are actually low permeability layers separating the hot reservoir from the shallower cooler zones.

ACKNOWLEDGEMENT

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