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DETAILED THREE-DIMENSIONAL MODELING OF THE BOTN HYDROTHERMAL SYSTEM IN N-ICELAND

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ABSTRACT

A detailed three-dimensional numerical model has been developed for the low-temperature hydrothermal system at Botn in Central North Iceland. It is based on a conceptual reservoir model which has evolved during two decades of geothermal research in the area and on the 10 year production history of the system. The model consists of: (1) A powerful recharge system at depth, (2) a shallow production reservoir and (3) a cold ground-water system at the surface. About 10 million tons of hot water have been extracted from the production reservoir since late 1981. The presence of the powerful recharge system results in a very slow long-term pressure decline. Flow of water in the production reservoir appears to be controlled by a highly permeable, vertical fracture-zone confined by low-permeability rocks. Cold ground-water flows down into the fracture-zone during production causing some cooling of the extracted water.

INTRODUCTION

The low-temperature geothermal field at Botn is one of four geothermal fields utilized for space-heating by the town of Akureyri (pop. 13000) in Central North Iceland (Figure 1). Two production wells, HN-10 and BN-1, have been drilled in the Botn field in addition to four exploration wells (Table 1). Prior to production a 18-22 bar well-head pressure was observed in the production wells.

The total production from the field, from 1981 through 1992, is about 10 million tons. Well HN-10 has produced an average of 25 l/s of 84° C water and well BN-1 5 l/s of 96° C water, during this period. The mass withdrawal has induced a 40 bar draw-down in well HN-10, but it is somewhat less in well BN-1. Most of this drawdown took place in the first months of production. Since then, draw-down in production wells has remained almost stable due to recharge from the overlaying ground-water and from a powerful recharge system of an unknown location. In addition to the pressure draw-down, a 3 - 4 ° C temperature decline has occurred in well HN-10 (Flóvenz et al., 1992).

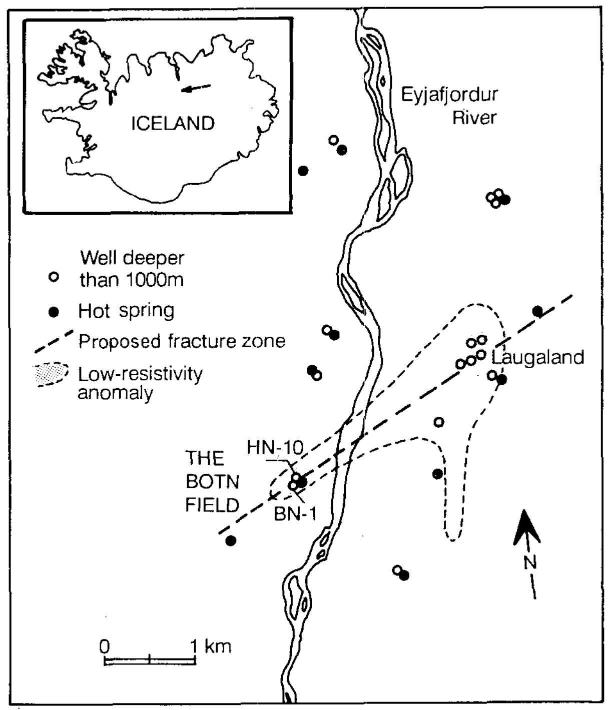

Figure 1. *Location of the Botn geothermal field and the proposed fracture zone.*

Table 1. *Wells in the Botn hydrothermal field.*

Well	Drilled	Depth (m)	Type
BN-1	1981	1830	Prod. well
BY-2	1989	446	Expl. well
BY-3	1989	300	Expl. well
BY-4	1989	403	Expl. well
HN-10	1980	1050	Prod. well
HY-12	1989	318	Expl. well

The Botn geothermal system has been studied extensively during the last two decades (Flóvenz et al., 1989 and 1991; Axelsson et al., 1988). Detailed subsurface resistivity mapping has been carried out, four exploration wells have been drilled, the production response has been monitored carefully and lumped modeling of the Botn system performed. The main objective of this work has been to locate permeable zones in the recharge system mentioned above. However, the results have been too inconclusive for locating sites for new production wells.

As the final stage of geothermal research in the area, a detailed three-dimensional numerical model was developed for the Botn geothermal system (Axelsson and Björnsson, 1992). A brief overview of this modeling study is given here. The numerical model simulates available information on the nature and structure of the system, downhole temperature- and pressure data as well as the production response of the system during the last decade. The computer code PT was utilized for calculations in the modeling study (Bodvarsson, 1982).

Simple modeling, such as lumped modeling, has been used extensively to model pressure responses due to production from low-temperature geothermal systems in Iceland (Axelsson, 1989 and 1991). The numerical model of the Botn system is, however, the first model of it's kind for a low temperature system in Iceland. Previously detailed three-dimensional numerical models have been developed for two high-temperature geothermal systems and much simpler two-dimensional modeling has been performed for a few other geothermal systems in Iceland (e.g. Tulinius and Sigurðsson, 1991; Bodvarsson et al., 1990; Vatnaskil Consulting Engineers, 1989; Tulinius et al. 1987; Bodvarsson et al., 1984).

THE CONCEPTUAL MODEL

The numerical model of the Botn system is based on a conceptual model which has evolved during two decades of geothermal research in the area (Axelsson and Björnsson, 1992). An important element in the conceptual model is a NE-striking feature, probably a fracture-zone, which passes through the Botn area as well as the Laugaland geothermal area NE of Botn (Figure 1). This feature is evident as a common trait in resistivity, subsurface temperature and water-level data. Productive/successful wells in both areas as well as locations of hot springs support the existence of this feature. Well HN-10 is believed to produce from this zone.

A simple sketch of the conceptual model of the Botn geothermal system is presented in Figure 2. The main features of the model are the following:

- Flow of water in the upper part of the geothermal system (above 1000-1500 m depth), or the **production reservoir**, is controlled by a fracture-zone with a northeasterly direction (the NE-striking feature). This fracture-zone intersects older N-S striking structures such as dikes and faults.

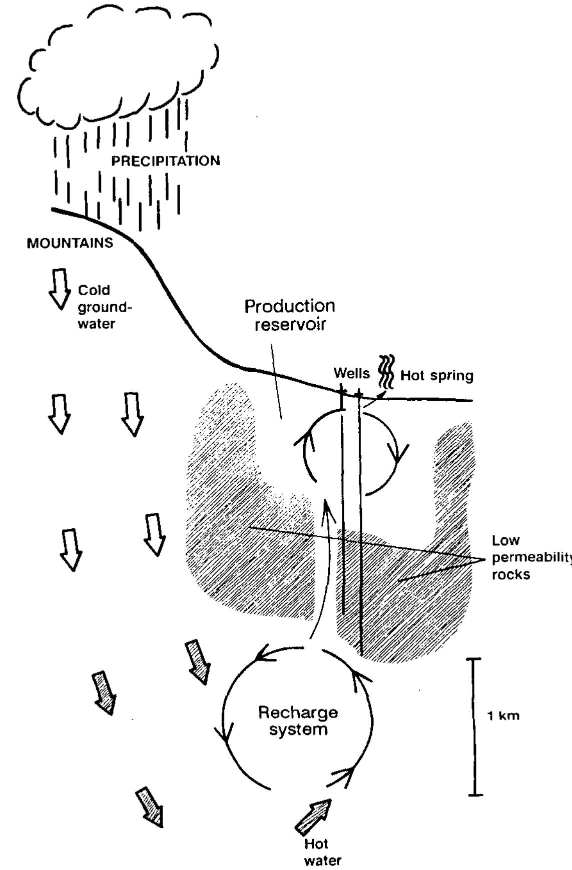

Figure 2. *Simplified sketch of the conceptual model of the Botn geothermal system.*

- The production reservoir is small in volume and the fracture-zone is confined by low-permeability rocks. In fact the production reservoir appears to be horizontally isolated. Interference from the Botn area is not seen in wells located 1-2 km to the north and east and warm springs to the SW and SE are still unaffected despite the great drawdown at Botn. In addition, a fault to the west of the Botn area probably acts as an impermeable barrier.
- A thin (100 m) caprock confines the Botn system from above. Yet some isolated channels through the caprock link the geothermal system with the ground-water system. Prior to production these channels allowed hot water to escape to the surface and form hot springs.
- At depth, perhaps below 1500 m, a powerful geothermal system, or the **recharge system**, exists. It's exact location is not known. This system has a large reservoir storage coefficient, probably because of it's connection to ground-water systems in the mountains west of the Botn area (Figure 2). Pressure changes are slow in the recharge system due to it's

great storage coefficient. A low-permeability layer, perhaps intersected by one or more fractures, separates the production reservoir from this deeper part.

- The initial pressure and temperature distribution in the Botn system indicates temperatures greater than 100° C in the recharge system whereas temperatures in the production reservoir are quite variable, or between 60 and 90° C (Axelsson and Björnsson, 1992). The entire geothermal system was overpressurized prior to production, probably because of the caprock and the hydrological connection to the mountains in the west. It is estimated that in the natural state pressure at 750 m depth was about 95 bars and greater than 191 bars at 1750 m depth.

THE NUMERICAL MODEL

The structure of the numerical model for Botn is shown in figures 3-5. It is composed of 8 horizontal layers with a total of 429 blocks, that vary in size from 0.00025 to 1 km^3. The blocks are connected by 1361 connections. Figure 3 shows a surface view of the model, which has an area of 5 km^2. The model is closed on all sides to simulate the systems apparent horizontal isolation.

Figure 4 shows a simplified three-dimensional view of the numerical model. It consists of three main units: (1) The recharge system below 1500 m depth, simulated by layers F and G. (2) The production reservoir, between 100 and 1000 m depth, composed of layers B, C and D. (3) The ground-water system above the geothermal system (layer O, not shown in Figure 4). Layer E,

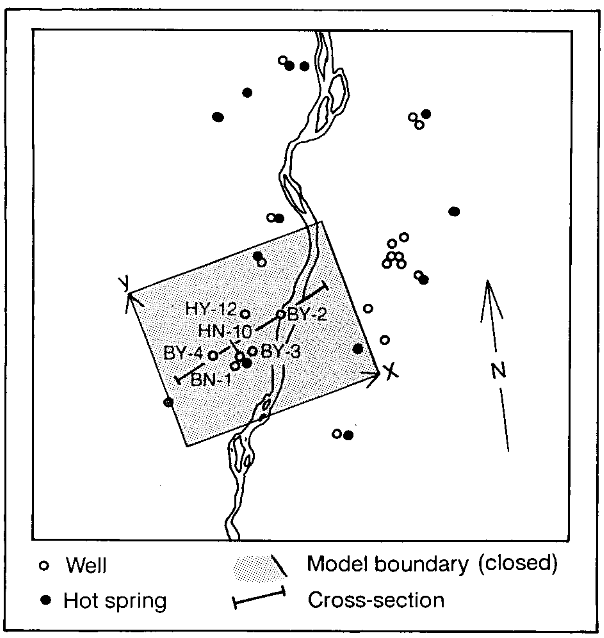

Figure 3. *Surface view of the numerical model.*

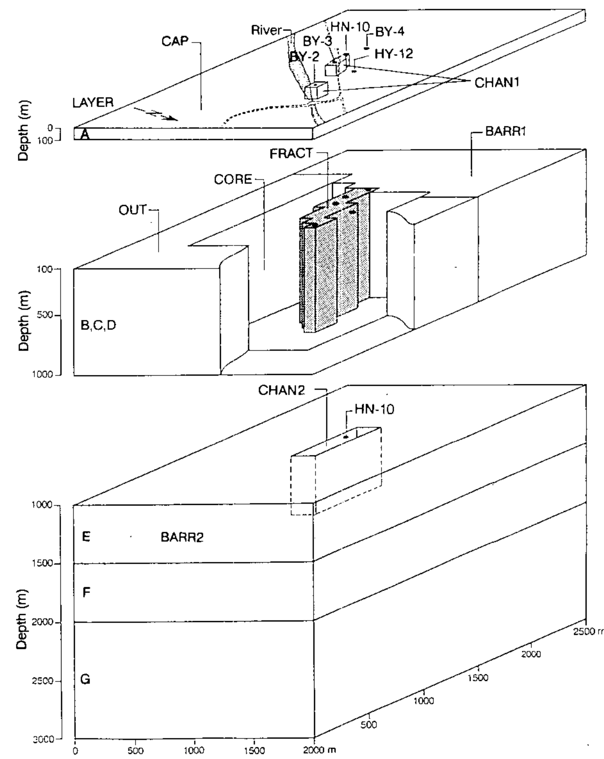

Figure 4. *Simplified three-dimensional view of the numerical model.*

which separates parts 1 and 2 of the model has a very low permeability except for a narrow channel, which connects the recharge system and the production reservoir. Layer A simulates the caprock above the geothermal system (0-100 m depth). Two channels are introduced through the caprock to simulate the connection between the ground-water system and the production reservoir (i.e. hot spring channels).

Figure 5 shows the division of layers B, C and D into blocks and rock types. The grid for these layers is presented as an example, whereas the grids for the additional layers are presented by Axelsson and Björnsson (1992). Note that layers A, B, C and D include 348 of the 429 blocks in the model. This is due to the detailed data available for the uppermost 500 m of the geothermal system. The hydrological and physical properties of the 10 different rock types used in the model are presented in table 2 below.

The numerical model simulates the following: (i) The natural state of the system. (ii) Observed long-term water-level changes and temperature decline of water produced from well HN-10. (iii) Water-level changes observed in exploration wells during a pressure recovery test in the summer of 1990. When a satisfactory natural state simulation had been obtained some changes were made in the model such that it also simulated items (ii) and (iii) above. This in turn required a recalibration of

Table 2. *Properties of different rock types in the model.*

Rock type	Permeability ($10^{-15}m^2$)	Anisotropy k_y/k_x	Porosity (%)
CAP	0.01	1.0	5
CHAN1	14	1.0	10
BARR1	0.01	1.0	5
FRACT	180	0.0002	10
WELL	800	0.0002	10
CHAN2	40	0.1	1
OUT	0.5	1.0	10
CORE	2	0.2	8
BARR2	0.1	1.0	5
LAYERS F,G	5	1.0	20

Rock matrix heat capacity = 850 J/kg°C
Heat conductivity = 2.1 - 2.5 W/m°C
Rock matrix density = 2900 kg/m^3
Rock matrix compressibility = $2\times10^{-11}Pa^{-1}$
Compressibility of water = $5\times10^{-10}Pa^{-1}$

the model for the natural state simulations. Thus several iterative cycles had to be completed until a "best model", which simulated all three items, resulted. The authors believe that this procedure is the most accurate way of reservoir modeling, even though it turned out to be very time consuming.

Natural state simulations

During the natural state simulations a **fixed inflow**, or recharge, into layer G was assumed to have started about 10,000 years ago, or at the end of the last glacial period in Iceland (Bodvarsson, 1982). At this time, a uniform 60°C/km thermal gradient was assumed in the model and the pressure followed a hydrostatic gradient. The simulations then involved adjusting the permeability distribution of the model and the inflow until a satisfactory match between measured and calculated data was obtained. In the "best model" a recharge of 6.5 l/s of 105°C hot water was required. Figure 6 presents a comparison between initial and calculated temperatures

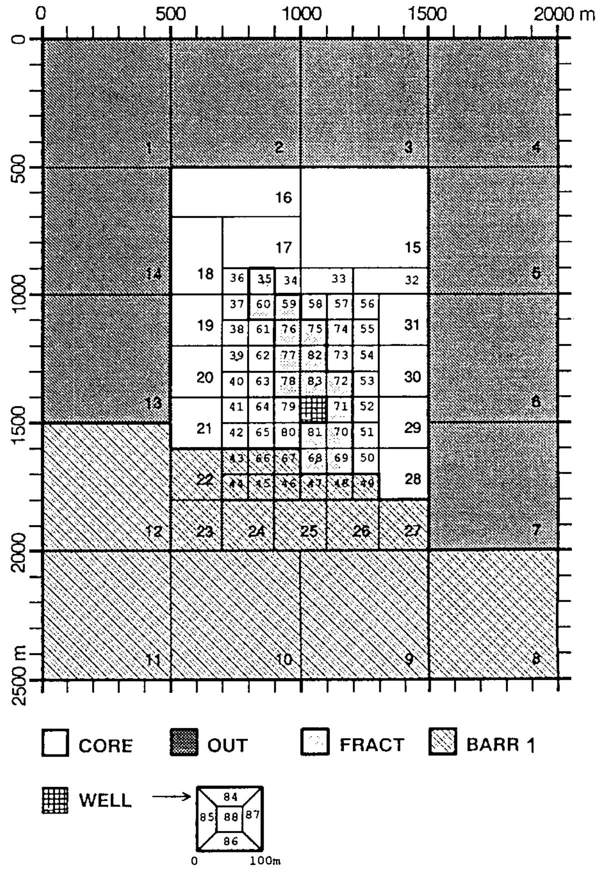

Figure 5. *Division of layers B, C and D of the numerical model into blocks and rock types.*

in wells in the area. It should be mentioned that the numerical model was close to steady state conditions at the end of the natural state simulations.

Figure 7 shows the calculated temperature distribution along a SW-NE cross-section through the center of the numerical model. The temperature distribution reflects clearly that hot water flows from the recharge system below 1500 m up through the fracture-zone and into the ground-water system at the surface.

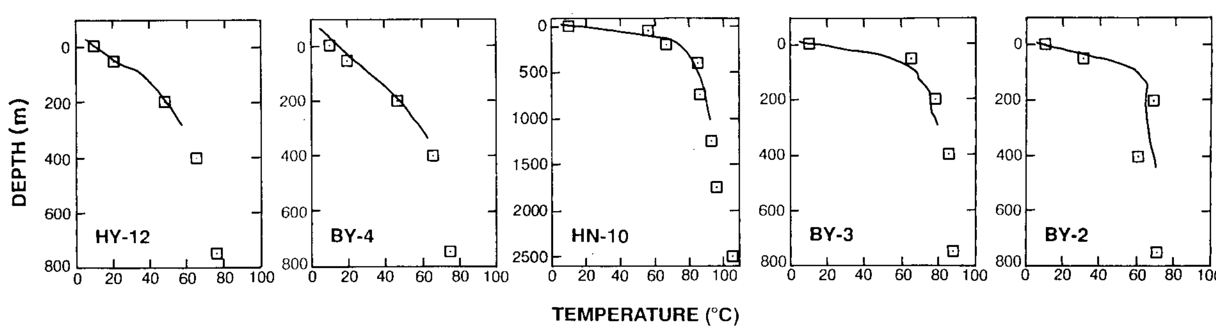

Figure 6. *A comparison between observed temperature profiles (solid lines) and model temperatures (small squares).*

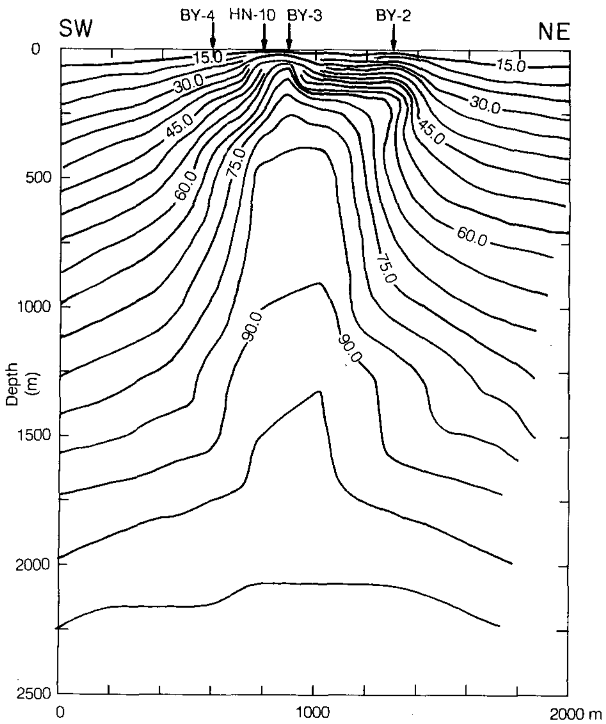

Figure 7. *Calculated temperature distribution along a cross-section shown in Figure 3.*

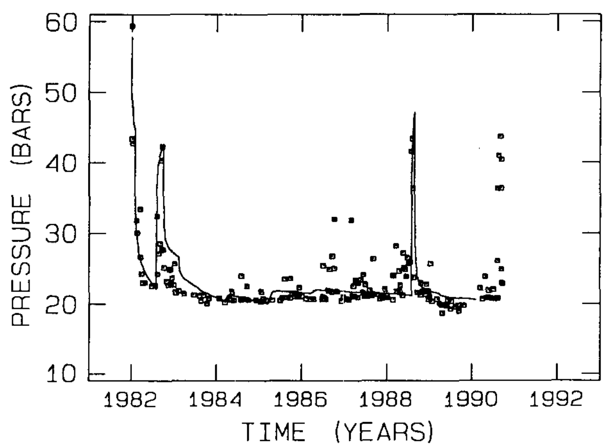

Figure 8. *Comparison between observed (squares) and calculated (solid line) pressure response of production well HN-10.*

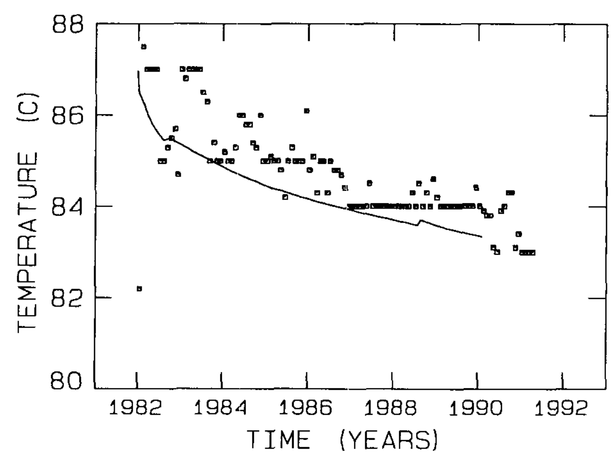

Figure 9. *Comparison between observed (squares) and calculated (solid line) temperatures for production well HN-10.*

Production simulations

The production simulations basically involved adjusting the permeability distribution of the model, the properties of the fracture-zone (FRACT) and the size and porosity of the recharge system (layers F and G). The production simulations were for the most part constrained by a 10 year history of water level measurements in well HN-10 and measurements of the production temperature of the same well. The comparison between the observed data and the response of the "best model" are presented in figures 8 and 9.

As already mentioned flow of water in the production reservoir appears to be controlled by a permeable fracture-zone with a northeasterly direction. In the numerical model this fracture-zone was simulated by a thin volume of blocks, 900 m high and about 900 m long, labeled FRACT (see figures 4 and 5). The decline rate of production temperatures, as well as water-level changes in well HN-10, are very sensitive to the fracture-zone properties, in particular it's thickness. The properties of the fracture-zone were consequently scaled to simulate a variable thickness until a satisfactory match between the observed and calculated response was obtained. As it turned out a thickness of 10 m resulted in the best match.

The simulated long-term pressure decline in well HN-10 is controlled by the storage properties of layers F and G (the recharge system), which in turn is simulated by their volume and porosity. A volume of 300 km^3 and porosity of 20% was used. These are a very great volume and high porosity, which probably indicates storage not only due to rock/water compressibility but also due to lowering of a free liquid surface. This is most likely caused by a hydrological connection with ground-water systems in the mountains west of the Botn area. Therefore, neither the size, porosity nor position of the recharge system in the numerical model should be considered to be real.

Figure 10 shows calculated cooling of the production reservoir in a cross-section along the fracture-zone, after ten years of production. One of the channels linking the production reservoir and the ground-water system is located below a now extinct warm spring, Botnslaug (by well BY-3). A second channel, situated

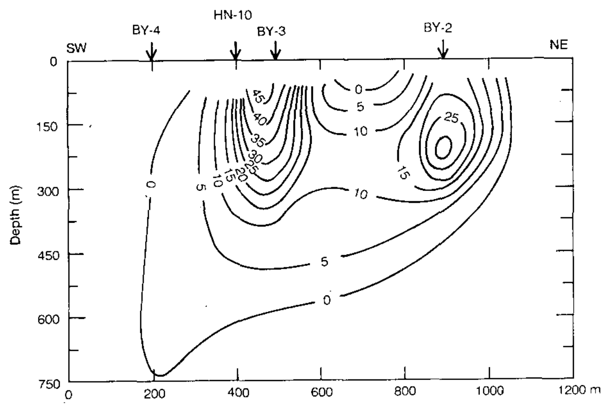

Figure 10. *Calculated cooling of the cross-section shown in Figure 3 after 10 years of production.*

½ km northeast of the production wells (by well BY-2), was required in the numerical model for a satisfactory match. A hot spring is not known there, but since the bedrock in this location is covered by about 100 m of alluvial sediments and a major river flows through the area, a subsurface hot spring is not unlikely. Figure 10 shows that the pressure draw-down allows cold groundwater to flow down through these channels causing a considerable cooling of the uppermost part of the fracture zone. A cooling of water produced from wells HN-10 and BN-1 follows in accordance with the measured data.

According to the numerical model, about 10 % of the water currently produced originates as cold groundwater. Changes in the chemical content of the water produced support this result (Axelsson and Björnsson, 1992). The recharge system provides 85 % of the mass produced and the remaining 5 % are taken from storage above 1500 m depth.

Pressure recovery simulations

In the summer of 1990 production from well HN-10 was discontinued for about a month. During this period water level changes were monitored very carefully in all available wells in the Botn area, and in several wells in surrounding areas. The data from this extensive build-up and interference test were used for a more detailed calibration of the permeability distribution of the numerical model. A comparison between the observed and calculated pressures in wells BY-2, BY-3, BY-4 and HY-12 is presented in Figure 11.

This final stage of the simulations resulted in the following: The fracture-zone (rock-type FRACT) was defined in more detail, in particular extended slightly further to the NE and it's anisotropy increased considerably. The channel, up through the caprock, close to well BY-2 was required. In addition the barrier on the western edge of the Botn system (BARR1 in figures 4 and 5) had to be moved closer to well BY-4.

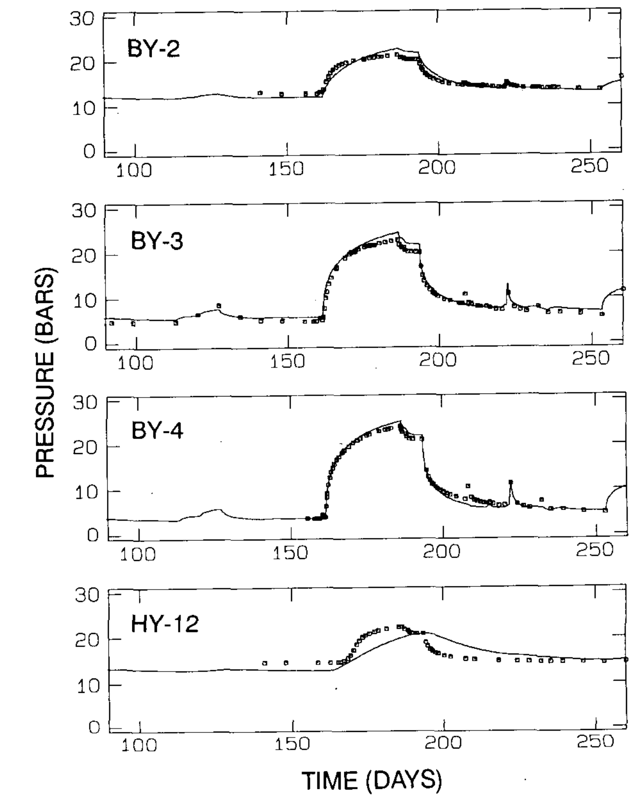

Figure 11. *Comparison between observed (squares) and calculated (solid lines) pressure changes during a recovery test in 1990.*

Predictions

Finally the "best model" was used to predict draw-down and cooling of wells for twelve different future scenarios. Axelsson and Björnsson (1992) present results for several production cases as well as predictions for cases of cold water injection into the exploration wells BY-2 and BY-4, which are about 540 and 220 m from well HN-10, respectively. Figures 12 and 13 provide examples of the predicted water level and production temperatures for the main producer HN-10. Four cases of constant future production from wells HN-10 and BN-1 are considered.

In general the numerical model predicts that decline of production temperatures at Botn will slow down in the future and remain within economical limits for some decades. As an example the production temperature of well HN-10 will most likely stay above 80 °C for the next 20 years. If the average 29,5 l/s production during 1986 - 1992 is maintained, lowering or replacement of the present rotary shaft pumps in the production wells will not become necessary. A 25 % increase in production, on the other hand, requires pumps to be lowered down to 400 m from the present depths of 246 m and 175 m in wells HN-10 and BN-1,

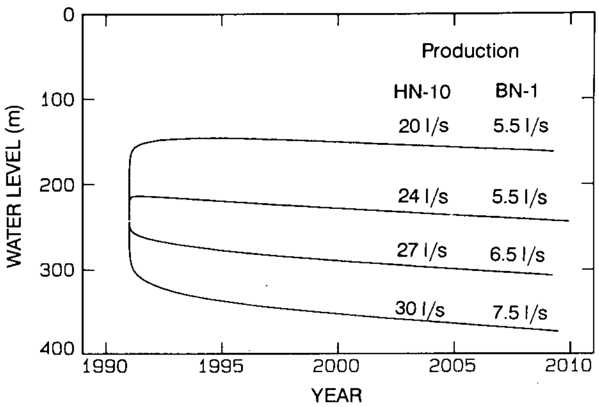

Figure 12. *Predicted water level changes in well HN-10 for different cases of future production.*

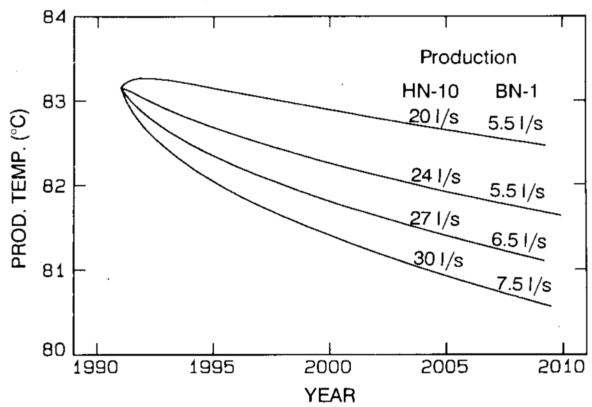

Figure 13. *Predicted changes in production temperature of well HN-10 for different cases of future production.*

respectively. Such an increase in production will only cause an additional 1 °C temperature drop for well HN-10 during the next 20 years..

According to the numerical model injection of cold water into some of the exploration wells reduces the pressure draw-down in the area. However, cold water injection of only 5 l/s into well BY-4 will double the cooling rate of water produced from well HN-10. A moderate injection into two of the exploration wells, 4 l/s into BY-2 and 2 l/s into BY-4, allows a 10 % increase in mass and energy production from well HN-10, without requiring a pump replacement.

CONCLUDING REMARKS

The most important aspects of the detailed three-dimensional modeling of the Botn geothermal system may be summarized as follows:

- The numerical model consists of 429 blocks in 8 horizontal layers. It is one of the most complex models of geothermal systems in Iceland developed to date.
- The numerical model is based on a conceptual model which has evolved during two decades of geothermal research in the Botn area. The model simulates available information on the nature of the system, the natural-state temperature- and pressure distribution, data on the production response during the last decade as well as data from an extensive pressure recovery test.
- The numerical model consists of three main units : (1) A powerful recharge system below 1500 m depth, (2) a production reservoir above 1000 m depth and (3) a ground-water system at the surface. To date production has mostly been from unit 2.
- The recharge system is over-pressurized and has a very large reservoir storage coefficient, probably because of its connection to ground-water systems in the mountains west of the Botn area. It is simulated by 300 km^3 of permeable rocks with 20% porosity.
- The production reservoir is small in volume and appears to be horizontally isolated. Flow of water in this part is controlled by a highly permeable fracture-zone. Decline rates of production temperatures, as well as water-level changes in several wells, are very sensitive to the properties of this zone, in particular it's thickness.
- The Botn system is linked with the ground-water system above through the channels of now extinct warm springs. Cold ground-water flows down through these channels during production causing some cooling of the production wells. According to the numerical model, about 10% of the water currently produced originates as cold ground-water. About 85% originate in the recharge system and the final 5% are taken from storage.
- The numerical model predicts that if the average past production from the Botn field (29.5 l/s) is maintained, replacement of pumps in production wells will not become necessary and temperature of water produced will only drop by an additional 1-2° C during the next 20-30 years. Therefore, this field will continue to provide an important energy base for the district heating system of the town of Akureyri.

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