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# THE NESJAVELLIR HIGH TEMPERATURE GEOTHERMAL FIELD IN ICELAND

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## ABSTRACT

The Nesjavellir High Temperature Geothermal Field is located in the Northern part of the Hengill Geothermal Area, which has been estimated to be one of the largest geothermal areas in Iceland. Drilling started at Nesjavellir some 20 years ago with five wells. In 1982 a renewed exploration phase began and five additional wells have been drilled during the last three years. The pressure distribution within the geothermal system is very inhomogenous in both horizontal and vertical directions. Variations in temperature are also considerable. The highest pressure and temperature is found in the southwestern part of the investigated area and both pressure and temperature descreases towards northeast. There seem to be four different zones of pressure potential in the system, which require the existence of both horizontal and vertical barriers in the system. Some parts of the geothermal system are in two-phase condition whereas other parts are in single phase liquid condition. The chemical composition of the fluid seem to be relatively uniform and a common origin of the fluid is assumed. The transmissivity of wells is in the range $(1,3-3,5)10^{-8}$ $m^3/Pa \cdot s$ whereas the flowing enthalpy ranges from 1200 - 2100 kJ/kg. The thermal output of wells are 40-60 MW. The geothermal system at Nesjavellir shows a high degree of three-dimensional variation, but a simple conceptual model described in the paper, seem to be in agreement with all observation made so far in the field.

## INTRODUCTION

One of the largest high temperature areas in Iceland is the Hengill geothermal area. The Nesjavellir high temperature geothermal field is the northernmost part of the Hengill area (Fig. 1). The geothermal area has been described by Arnason et al. (1969) and the geology of the Hengill central volcano is described by Saemundsson (1967). Extensive geophysical investigations have been carried out in the area and are described by Bjornsson and Hersir (1981).

Studies of the Nesjavellir Field started many decades ago, and the first well was drilled in 1965. Up to 1973 there were drilled five wells in Nesjavellir. In 1982 the exploration of the field was continued by drilling and during the last three years five additional wells have been drilled in the field.

The information gained from the recent wells in Nesjavellir, together with the experience of the operation of wells tapping two phase reservoirs (Stefansson 1981, Stefansson and Steingrimsson 1980b, Palmason et al. 1983) has etablished a new picture of the geothermal system at Nesjavellir. The aim of the present paper is to describe the present picture of the Nesjavellir geothermal system.

## PRESSURE AND TEMPERATURE

Up to 1976 all known high temperature geothermal fields in Iceland were single phase liquid dominated systems. The exploration of the Krafla geothermal field showed in 1977 that part of that geothermal system is in two-phase condition (Stefansson 1981). Already in 1979 it was proposed that similar conditios might exist in the Nesjavellir field (Steingrimsson and Stefansson 1979).

Drilling of well NG-6 in 1982 revailed an unique pressure distribution in the reservoir (Fig. 2). The pressure gradient above 800 m depth seemed to be higher than corresponding to the hydrostatic pressure of cold water. Below the depth of 800 m the reservoir pressure was much lower, and the existence of dry steam zone between 800 and 1100 m depth was proposed (Stefansson et al. 1983, Palmason et al. 1983). The physical condition of such steam zone had to be at 84 bar pressure and 297 C temperature. It was decided to test this hypothesis by casing the next well in this area down to 800 m depth in order to get the fluid from these depths uncontaminated to surface.

Well NG-9 was cased to 824 m depth and this well has discharged dry steam when it was first put on discharge. This behaviour is in agreement with the hypothesis of a steam zone existing below 800 m depth. Later the flowing enthalpy decreased to some 2000 kJ/kg. A detailed study of the reservoir pressure in the five wells NG-6-NG-10 has resulted in far more complex picture of the geothermal system.

Figure 3 shows the reservoir pressure distribution in different wells in the Nesjavellir geothermal field, and fig. 4 shows the location of the wells. Fig. 3 shows that the pressure seems to divide the geothermal system into four different parts of pressure potential.

The reservoir pressure is partly determined as the pivoit point in pressure profiles measured durinq the heatinq of wells after completion,- and partly as pressure measurement of the first aquifer intersected by drilling beneath the cemented casing. The data points given in Fig. 3 are therefore considered to be fairly good determination of reservoir pressure (Stefansson and Steingrirnsson 1980a, Grant 1979).

Comparing the reservoir pressure below 800 m depth (- 500 masl) in wells 6 and 9 shows, that the reservoir is in boiling condition at

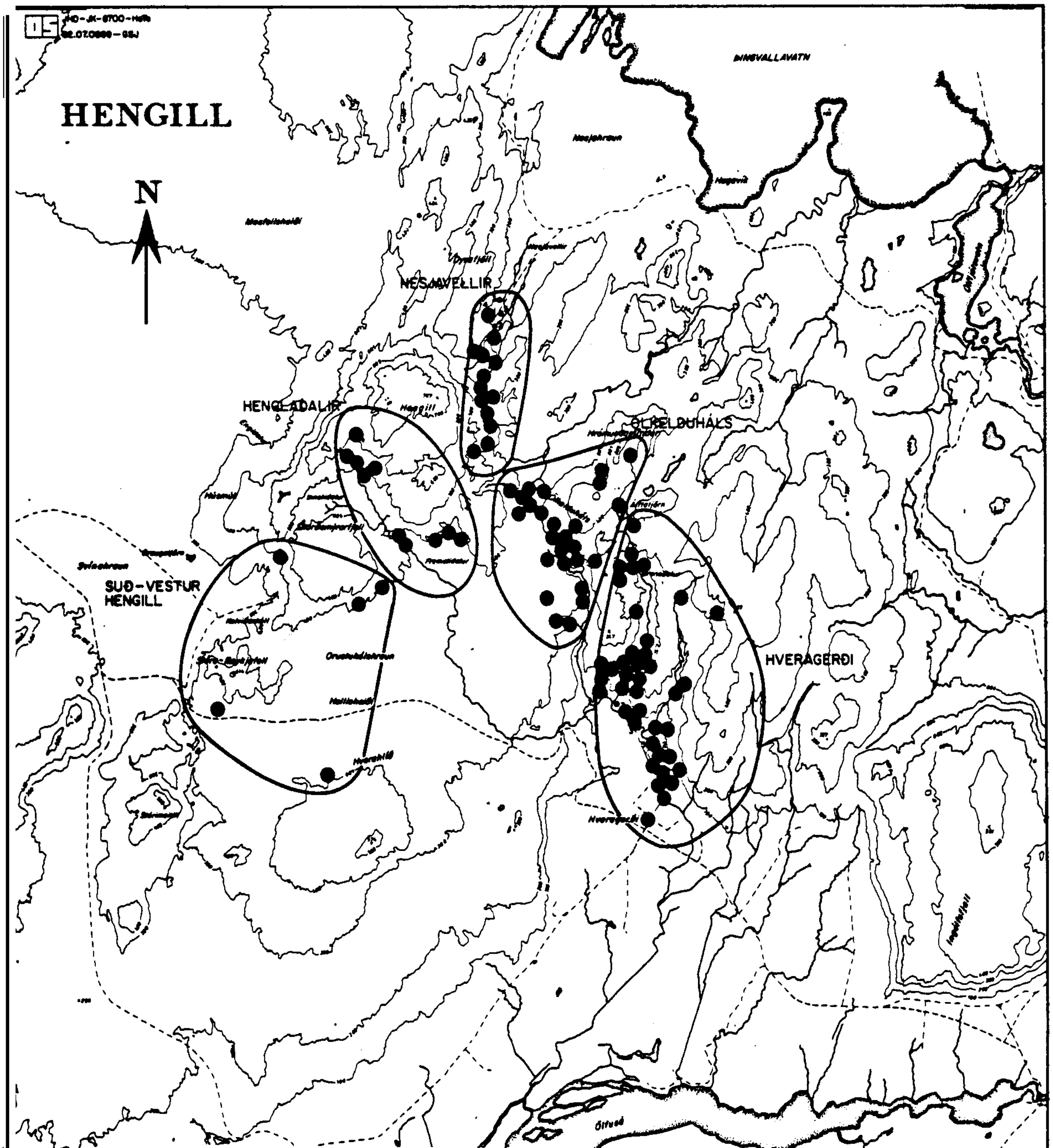


Fig. 1 Hengill High Temperature Geothermal Area. Block dots are steam vents.

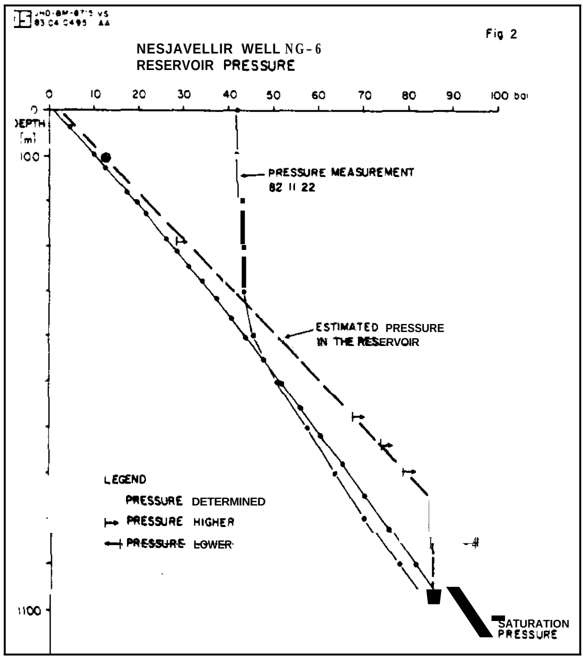


Fig. 2 Reservoir pressure in well NG-6.

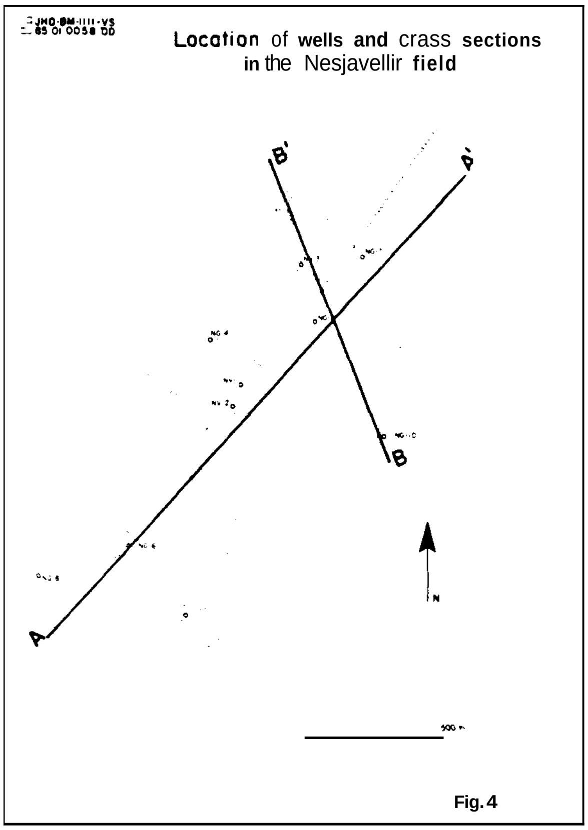


Fig. 4 Location of wells and cross sections in Nesjavellir.

this location and a steam zone cannot be confirmed from the data. The four different parts of the reservoir as defined by the pressure distribution (Fig. 3) are represented on a cross section shown in Fig. 5. It seems necessary to have impermeable barriers both horizontal and vertical in the system. The most remarkable condition is that well 6 seems to intersect three different zones. The geothermal system is highly three dimensional and a two dimensional projection cannot give a true picture of the system.

Figures 6 and 7 show the pressure distribution at sea level and at 500 m below sea level in the Nesjavellir reservoir. In both cases is the pressure highest to the southwest and decreasing towards northeast. There is a large variation in the temperature in the reservoir as well as in the pressure. Figure 8 shows the temperature distribution in the SW-NE cross section and Figures 9 and 10 show the temperature distribution at sea level and at 500 m below sea level.

Both pressure and temperature distributions show highest values in the SW part of the investigated area and decreasing values towards northeast. These circumstances might indicate a lateral flow in the system from SW to NE. The temperature distribution in Figures 9 and 10 indicates, furthermore, that this flow is preferably taking place in the northern part of the area rather than in the southernmost part.

A cross section of temperature distribution from SE to NW in the northern part of the investigated area shows these conditions clearly, Fig. 11. Comparison of pressure and temperature in the reservoir shows that at depth the reservoir is boiling (two phase) in the southwestern part of the investigated area, but is in liquid phase in the NW part. This is also reflected in the flowing enthalpy of wells. Wells 6 and 9 have flowing enthalpy of about 2000 J/g but wells 5 and 7 have flowing enthalpy 1200 J/g.

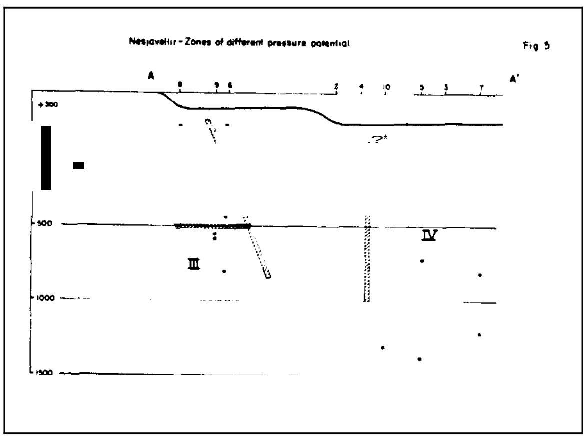


Fig. 5 Cross section of the Nesjavellir field showing the four parts of the reservoir.

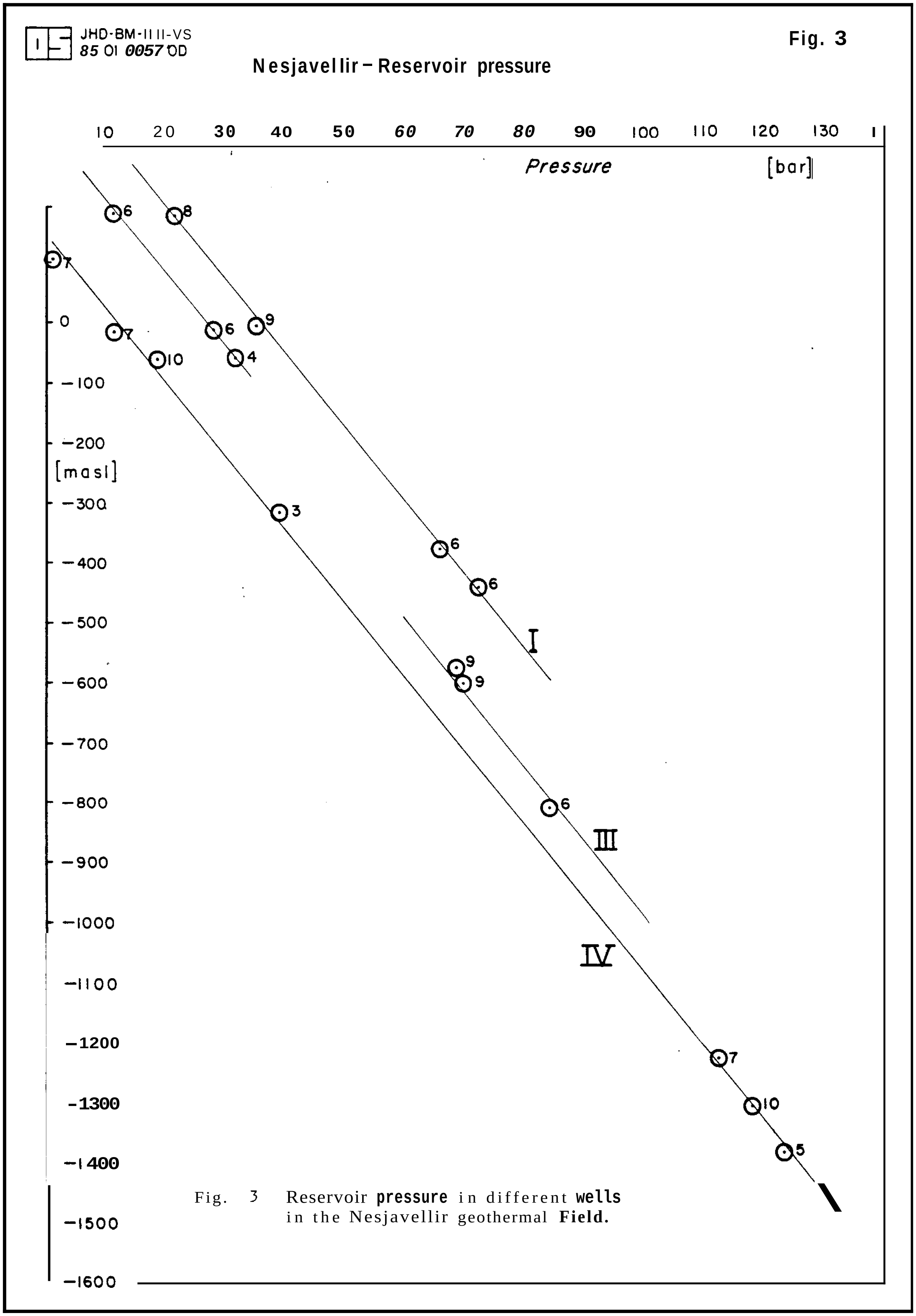


Fig. 3 Reservoir pressure in different wells in the Nesjavellir geothermal Field.

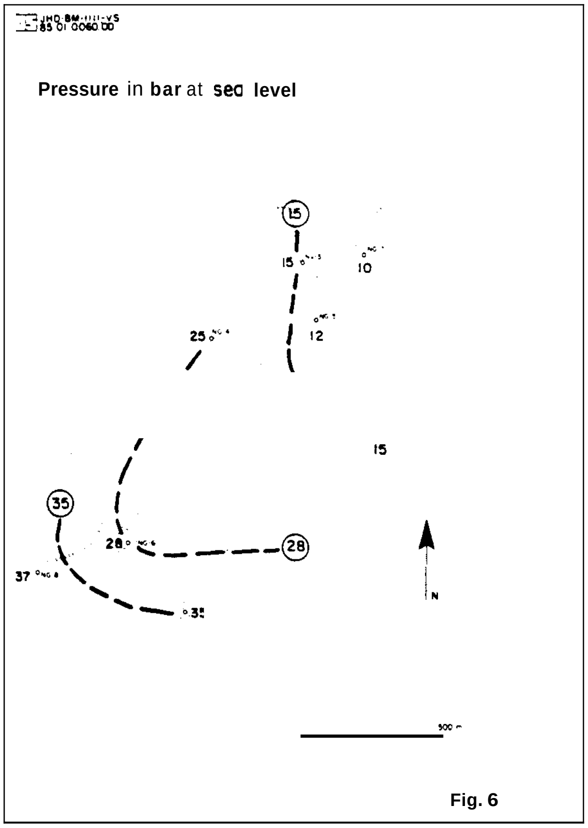


**Fig. 6** Pressure distribution at sea level in the Nesjavellir reservoir.

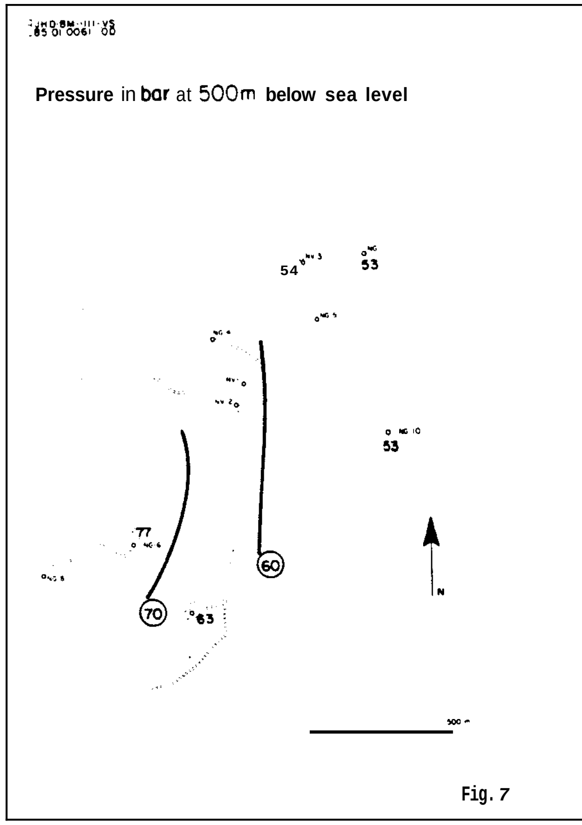


Fig. 7 Pressure distribution at 500 m below sea level in the Nesjavellir reservoir.

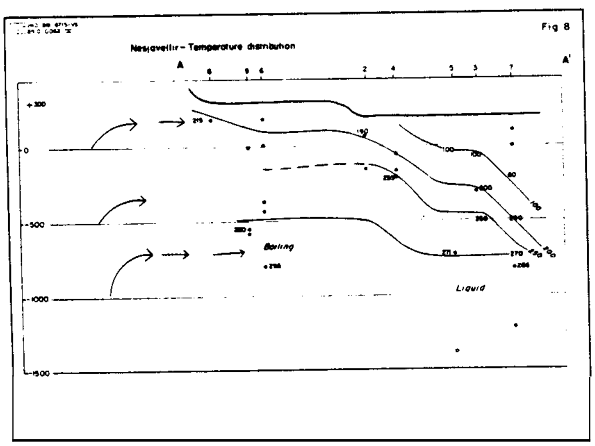


Fig. 8 The temperature distribution in cross section A A in the Nesjavellir reservoir.

## PERMEABILITY

Information on permeability is at present only available from transmissivity determinations made by injection tests at the completion of each well. It has, however, been demonstrated (Sigurdsson et al. *1985)* that carefully analyzed injection tests of 10-20 hours duration in both single phase and two phase geothermal reservoirs give consistent values with recovery tests lasting for several months. It is therefore considered that the injection tests made in Nesjavellir gives fairly reliable values on the transmissivity of different wells in the Nesjavellir reservoir.

TABLE 1

HYDRAULIC PROPERTIES OF WELLS IN THE NESJAVELLIR FIELD

| Wells | $\frac{kh}{\mu}$ $m^3/Pa \cdot s$ | Total flow kg/s | Enthalpy kJ/kg | Heat MW |
|---|---|---|---|---|
| NG- 5 | 1,3 | 23 | 1400 | 32 |
| NG- 6 | 3,5 | 29 | 1920 | 56 |
| NG- 7 | 2,1 | 35 | 1220 | 43 |
| NG- 9 | 3,0 | 29 | 2080 | 60 |
| NG-10 | 1,7 | - | - | - |

Table 1 shows the transmissivity, flow rate, flowing enthalpy and thermal output of wells in Nesjavellir. It is seen in Table 1 that the transmissivity and the thermal output of wells is fairly constant despite the flowing enthalpy varies considerably.

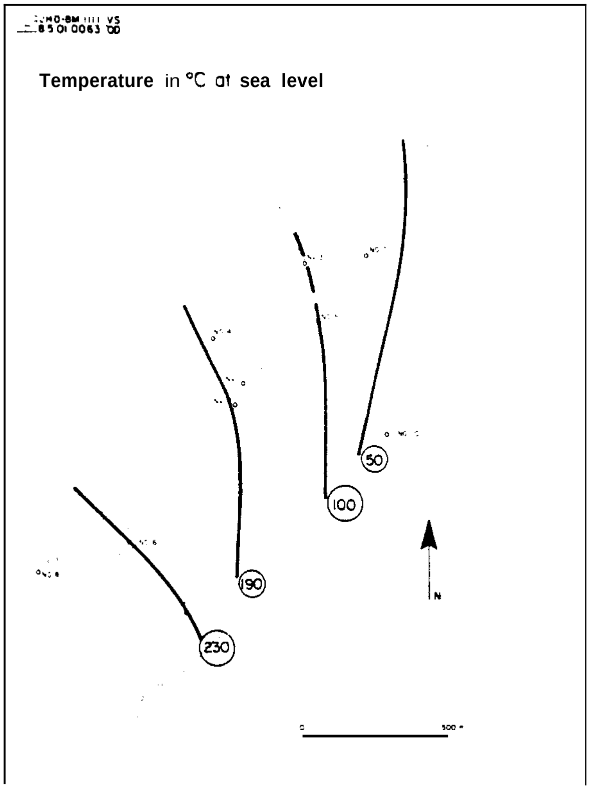


Fig. 9 Temperature distribution at sea level in the Nesjavellir reservoir.

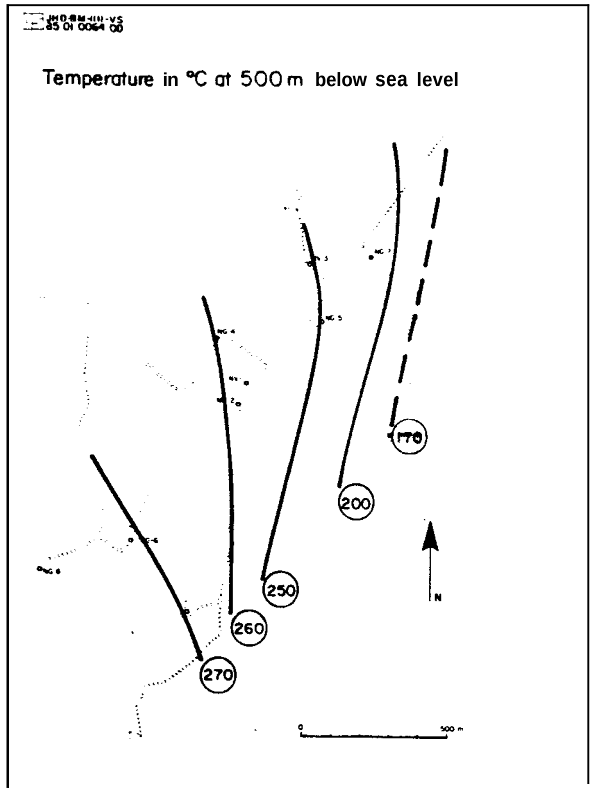


Fig. 10 Temperature distribution at 500 m below sea level in the Nesjavellir reservoir.

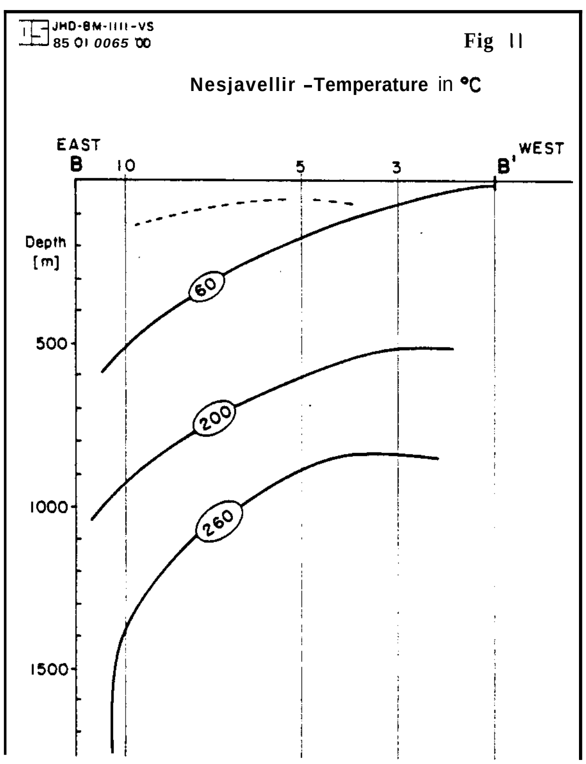


Fig. 11 Temperature distribution in the cross section E E' of the Nesjavellir reservoir.

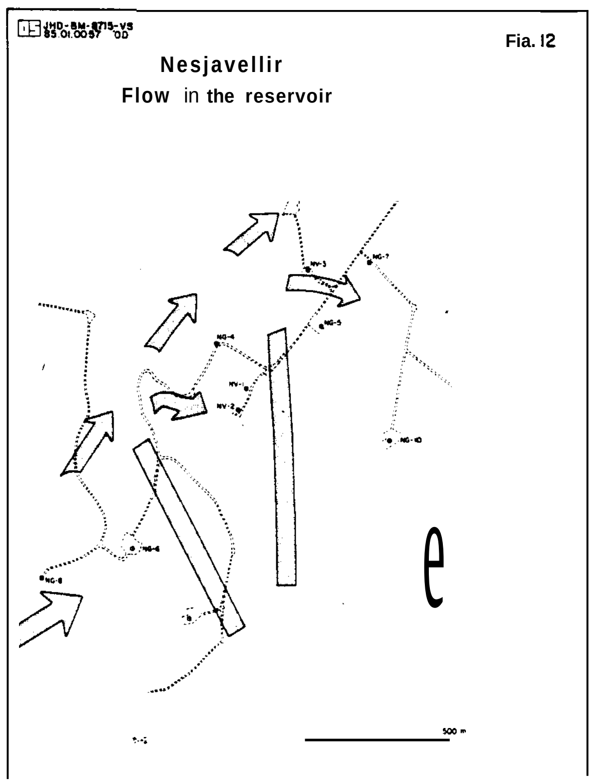


Fig. 12 Flow in the Nesjavellir reservoir.

## CHEMISTRY OF THE THERMAL FLUID

Despite the inhomogenity of the physical conditions (pressure and temperature) of the geothermal system at Nesjavellir, the chemical condition seems to be rather uniform. Table 2 shows typical chemical compositions of the fluid discharged from four of the wells in Nesjavellir.

There is a difference in the chemical composition between the high enthalpy and the low enthalpy wells. Especially is the low concentration of in the low enthalpy wells noticeable. In general the chemistry indicates that the fluids in different wells are of common origin.

## CONCEPTUAL MODEL

The characteristics of the Nesjavellir geothermal system are:

- The pressure distribution within the system is very inhomogenous in both horizontal and vertical directions. In general, the highest pressure is found in the southwestern part of the investigated area.
- There are considerable variations in the temperature in the system and the highest temperatures are in the SW part of the area.
- The geothermal system is partly in two-phase condition and partly in single phase conditions.
- The chemical composition of the thermal fluid is relatively homogenous and common origin of the fluid is assumed.
- There is little variation found in permeability between different wells, and thermal output of wells are in the range 40-60 MW.

Combining together these items we arrive at a conceptual model where we have to place the main upflow zone outside the area which have so far been investigated by drilling. The pressure and temperature distributions indicate that the upflow zone should be in the SW direction from the investigated area. Furthermore, both pressure and temperature distributions indicate that there is a substantial lateral flow in NE direction just north of the present drilling area.

There seems to be at least four distinct zones in the system with different pressure potential. These zones are separated by barriers both vertically and horizontally. This means that the three dimensional feature of the system is rather pronounced, and a representation of the system in a two dimensional picture is not an easy task.

In Figure 12 an horizontal projection has been selected to describe the conceptual model. In general this picture could show the natural flow in the geothermal system at -500 masl in the geothermal system. The picture shown in Fig. 12 is a large simplification of the observed data from the Nesjavellir geothermal system. However, this model seems to be in agreement with all observations made so far for the Nesjavellir system. Therefore, this simplified picture is chosen at present as a conceptual model even though it will not describe in details the three dimensional features of this geothermal system.

TABLE 2

CHEMICAL COMPOSITION OF TOTAL DISCHARGE FROM WELLS IN NESJAVELLIR FIELD. CONCENTRATION IN mg/kg.

| WELL | NG-5 | NG-6 | NG-7 | NG-9 |
|---|---|---|---|---|
| DATE | 83-06-24 | 84-09-30 | 84-09-29 | 84-11-21 |
| WPH bar | 7.2 | 20 | 8.8 | 10.2 |
| H kJ/kg | 1240 | 1828 | 1220 | 2185 |
| SiO | 531.7 | 446.5 | 593.5 | 285.6 |
| Na | 101.3 | 59.1 | 132.8 | 53.1 |
| K | 18.3 | 10.8 | 20.8 | 7.1 |
| Ca | 0.20 | 0.03 | 0.36 | 0.01 |
| Mg | 0.02 | 0.00 | 0.00 | 0.00 |
| SO | 27.4 | 3.65 | 22.90 | 1.89 |
| Cl | 1.6 | 43.7 | 4.58 | 30.6 |
| F | 0.78 | 0.40 | 1.11 | 0.23 |
| CO | 1421.0 | 2668.4 | 1'303.6 | 2560.0 |
| H S | 412.0 | 801.5 | 313.9 | 817.4 |
| H | 14.1 | 40.2 | 29.0 | 38.4 |
| CH | 4.6 | 1.75 | 7.4 | 3.4 |
| N | 53.6 | 35.8 | 61.9 | 33.3 |
| O + A | 2.5 | 2.1 | 2.1 | 1.61 |

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