TEMPERATURE AND PRESSURE IN THE SVARTSENGI GEOTHERMAL RESERVOIR

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ABSTRACT

This report is a study of the distribution of and changes in temperature and pressure in the high temperature geothermal field of Svartsengi. Use is made of the various measurements of the 12 individual wells at different periods and the cross-sections made from these measurements. Consideration is given to the effect of drilling, redrilling and reinjection on the temperature profiles of the wells and the cross-sections and appropriate selections are made of reliable and representative profiles of the many measurements. Boiling conditions of the reservoir and evolution with time is studied. Some possibilities that can cause the reservoir to be cooling down are presented and discussed. They are boiling effects, lateral cold inflow, episoidal cold inflow and decreased lateral inflow of hot fluids.

This study shows that there is a substantial cooling and pressure drawdown due to exploitation deep in the reservoir. It is found that temperature of the fluid is fairly stable during exploitation. However, in the time between 1982 and 1983 significant temperature changes are observed in the reservoir. The reason for the cooling of the reservoir is found to be most likely a recharge of cold inflow.

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1 INTRODUCTION

1.1 Scope of the report

The author fulfilled one of the requirements of the UNU Geothermal Training Programme Fellows by producing this work during the last ten weeks of the six month training during the summer of 1983 at the National Energy Authority of Iceland, which was financed both by the United Nations University and the Government of Iceland.

The Training Programme commenced with a six week introductory lecture course on the relevant aspects of geothermics delivered by specialists from the N.E.A. and the University of Iceland and complemented by appropriate field excursions. The author further had specialized lectures, seminars, tutorials, field practices and supervised readings on borehole geophysics and reservoir engineering for six weeks, and additional lectures and seminars during the two week field excursions to geothermal fields of Iceland.

The author found it viable to take on this project as a practical exercise because of the availability of the tools involved and in view of the immediate applicability of the methods in the geothermal fields of his home country.

1.2 Aims and objectives

The Svartsengi geothermal reservoir has been observed to be cooling down. There are various possibilities for causing this. Identifying the real ones and locating the optimum zone for feasible exploitation is important to ensure that the power plant will keep on producing for a long time. This problem can be tackled by studying the temperature and pressure in one, two, or in three dimensions. The individual well measurements and compilations of these measurements into cross-sections (usually vertical and

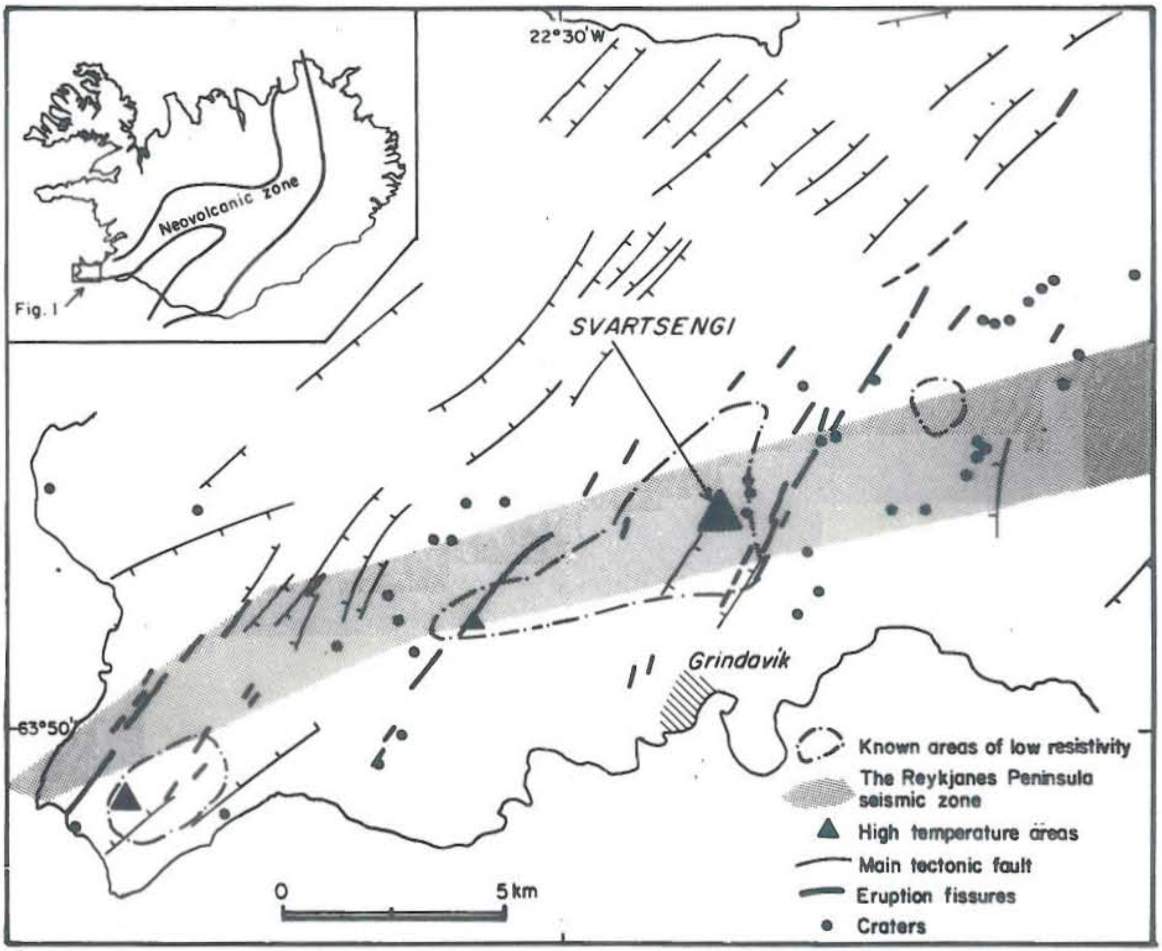

Fig. 1 Western Reykjanes peninsula and location of Svartsengi high temperature field (from Franzson, 1983).

horizontal planes) are used in the study of the behaviour of the reservoir as a function of time. Boiling conditions as a function of time are also included.

1.3 Geographical setting of Svartsengi

The Mid-Atlantic Ridge surfaces on to Iceland at the southwestern end of the Reykjanes peninsula where it crosses the country in a northeasterly direction. The rift process on the Reykjanes peninsula is characterized by an ENE-WSW trending seismic zone below 2-3 km depth, but on the surface by NE-SW fissure swarms arranged en echeleon to the former (Georgsson, 1981; Franzsson, 1983). At an intersection of the two types is the Svartsengi high-temperature field located (Fig. 1).

1.4 Data used in the report

The temperature and pressure measurements used in this study were all taken by the Geothermal Division of the NEA in the period between '76.07.12 and '83.06.16. The differences in the well conditions at the time of measurement range from the wells having been closed for as long as one year, up to measurements made right after production.

1.5 Limits to the study

The work is restricted to the time and spatial distribution of temperature and pressure at depths of 500 m and below in the Svartsengi reservoir.

2 GENERAL DESCRIPTION OF THE FIELD

Location of wells, faults and dikes in the Svartsengi field is shown in Fig. 2. The Svartsengi high-temperature area in Iceland is a part of the Reykjanes geothermal system. The geothermal wells at Svartsengi yield 235°C water in 1983 which is 5°C less than the 240°C before production began. The salinity is roughly two-thirds that of sea water (Thorhallsson, 1979).

2.1 Geological setting

The geological succession of the field consists of lava successions with intervening hyaloclastite formations (Franzsson, 1983). Some 20-40 % of the succession below 800 m depth consists of intrusions. The reservoir acquifers are predominantly controlled by intrusives and some tectonic fractures/faults. The alteration pattern can be subdivided into distinct episodes where low temperature conditions are seen to have prevailed prior to high-temperature conditions. Two distinct episodes of high-temperature activity are observed, where the latter one rises separately to higher elevation. The dominant alteration pattern conforms reasonably well to the present thermal regime in the field (Franzsson, 1983).

2.2 Chemical studies

Chemical analysis of the geothermal water indicates about 67 % sea water, but deuterium measurements give only about 57 % sea water (Arnason, 1976). The difference is explained by flashing of the water in the conceptual model of Kjaran et al.(1979). It is assumed that the recharge area for the geothermal water is located in the vicinity of lake Kleifarvatn.

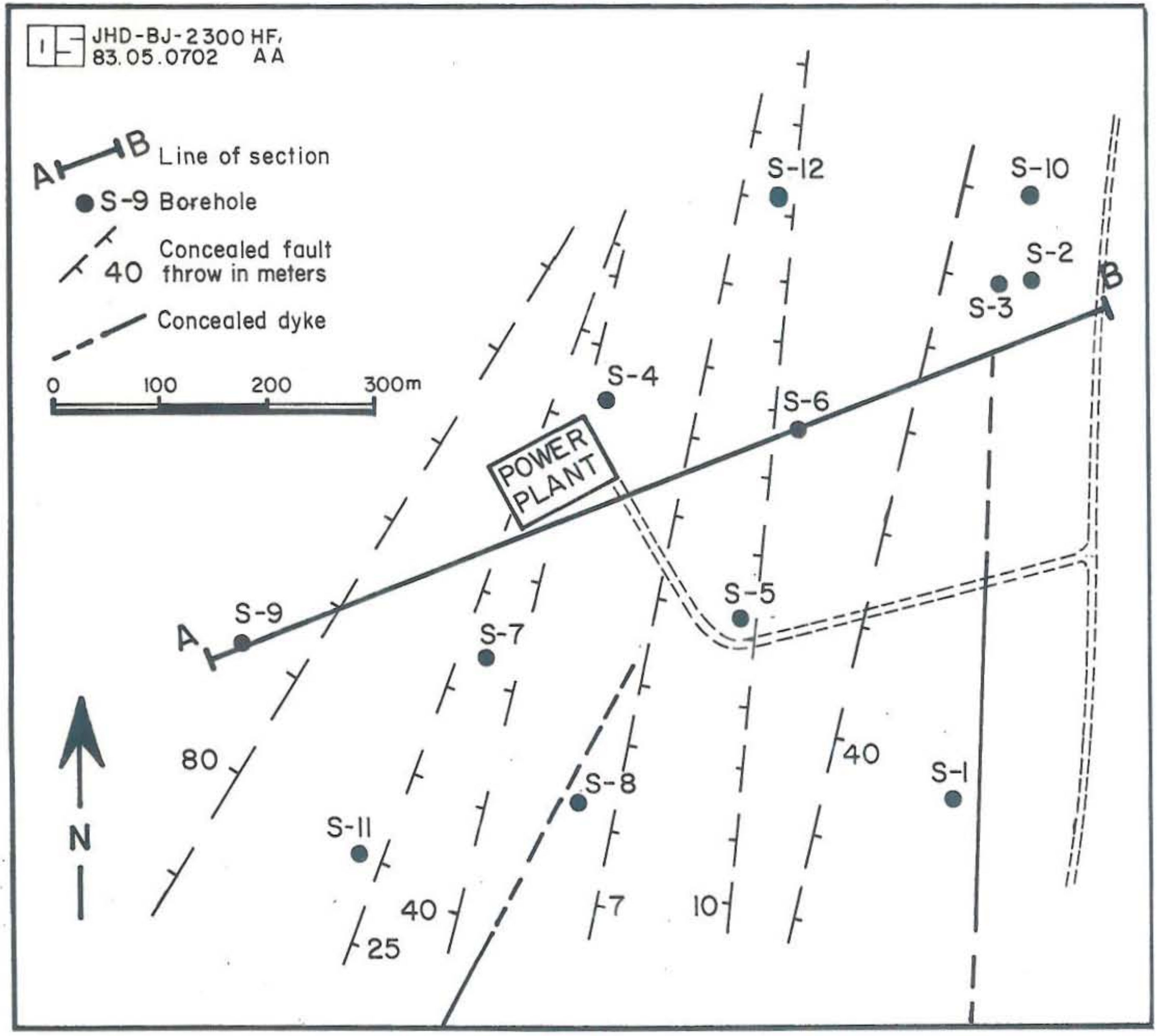

Fig. 2 Location of wells, faults and dykes in the Svartsengi production field (from Franzson, 1983).

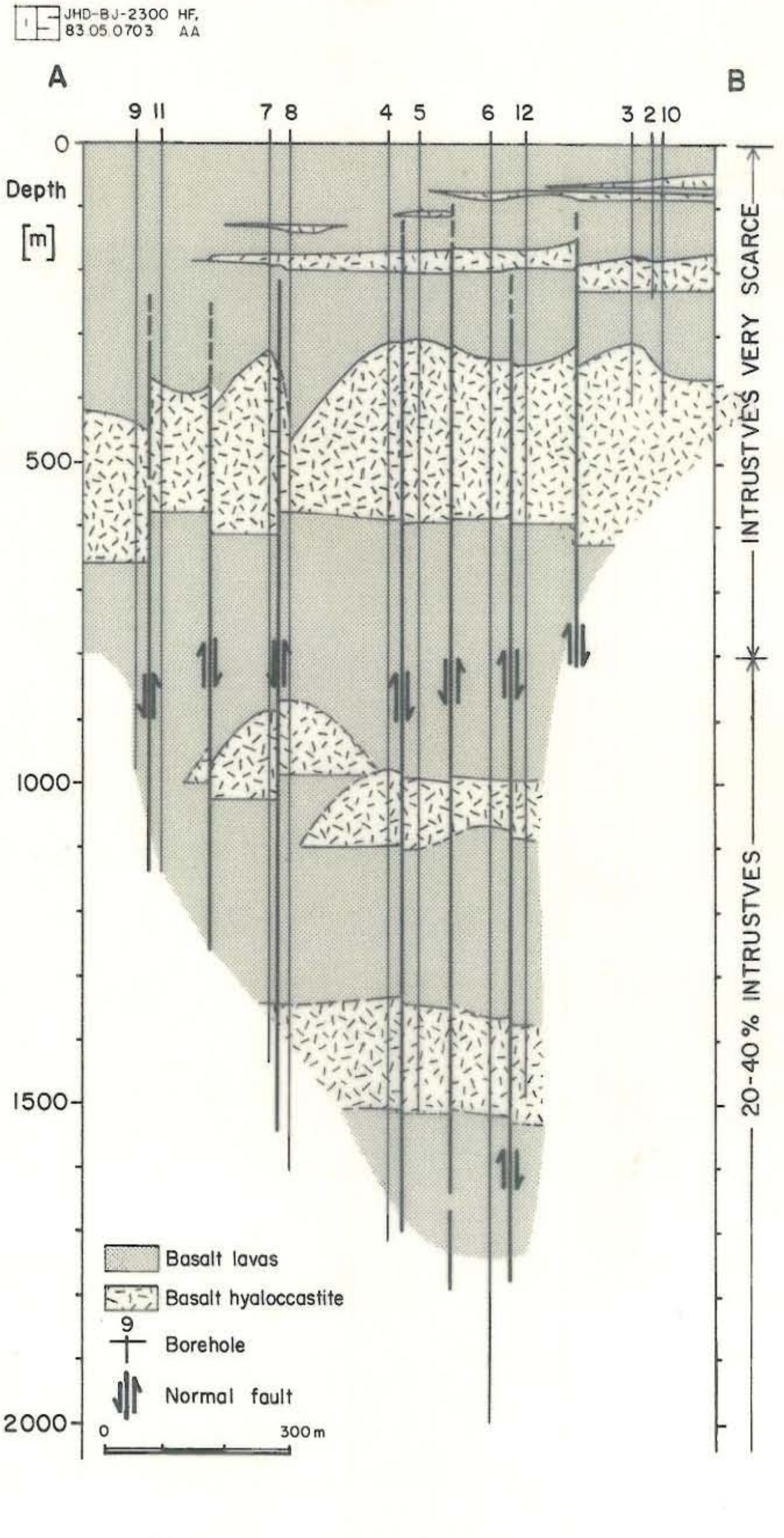

Fig. 3 A simplified geological cross-section of the production field in Svartsengi. Line of cross-section shown in Fig. 2 (from Franzson, 1983).

2.3 Resistivity studies of the field

Surface hydrothermal manifestations are meager within the Svartsengi field and only scattered over about 4 square kilometers. The resistivity surveys (Fig. 4) show the geothermal area to be elongated NE-SW in the northern part but ESE-WSW in the southern part (Georgsson, 1981). A continuous E-W striking low resistivity zone which coincides fairly closely with the Reykjanes seismic zone that has been interpreted as a plate boundary. Study of correlation between resistivity , salinity and temperature seem to confirm that the low resistivity can only be explained by anomalously high heat flow. This indicates that exploitable geothermal energy may be found in the uppermost 1-2 km along the plate boundaries on the Reykjanes Peninsula even far away from surface manifestations.

2.4 Tectonic activity of the Reykjanes peninsula

One can see the main zone of earthquakes and location of quake epicenters on the area from Fig. 1. The tectonic activity increases the permeability and thus creates some sort of a drainage system along the zone of earthquakes. Some geothermal areas like Svartsengi are situated where surface fissure swarms intersect the main zone of earthquakes .

2.5 Hydrological characteristics of the geothermal system

The water percolates down from the infiltration area and flows along the permeable earthquake zone. On its way it warms up and mixes with intrusive seawater. Where the surface fissure swarms intersect the earthquake zone, the permeability becomes great enough to allow free convection, thus forming a geothermal area.

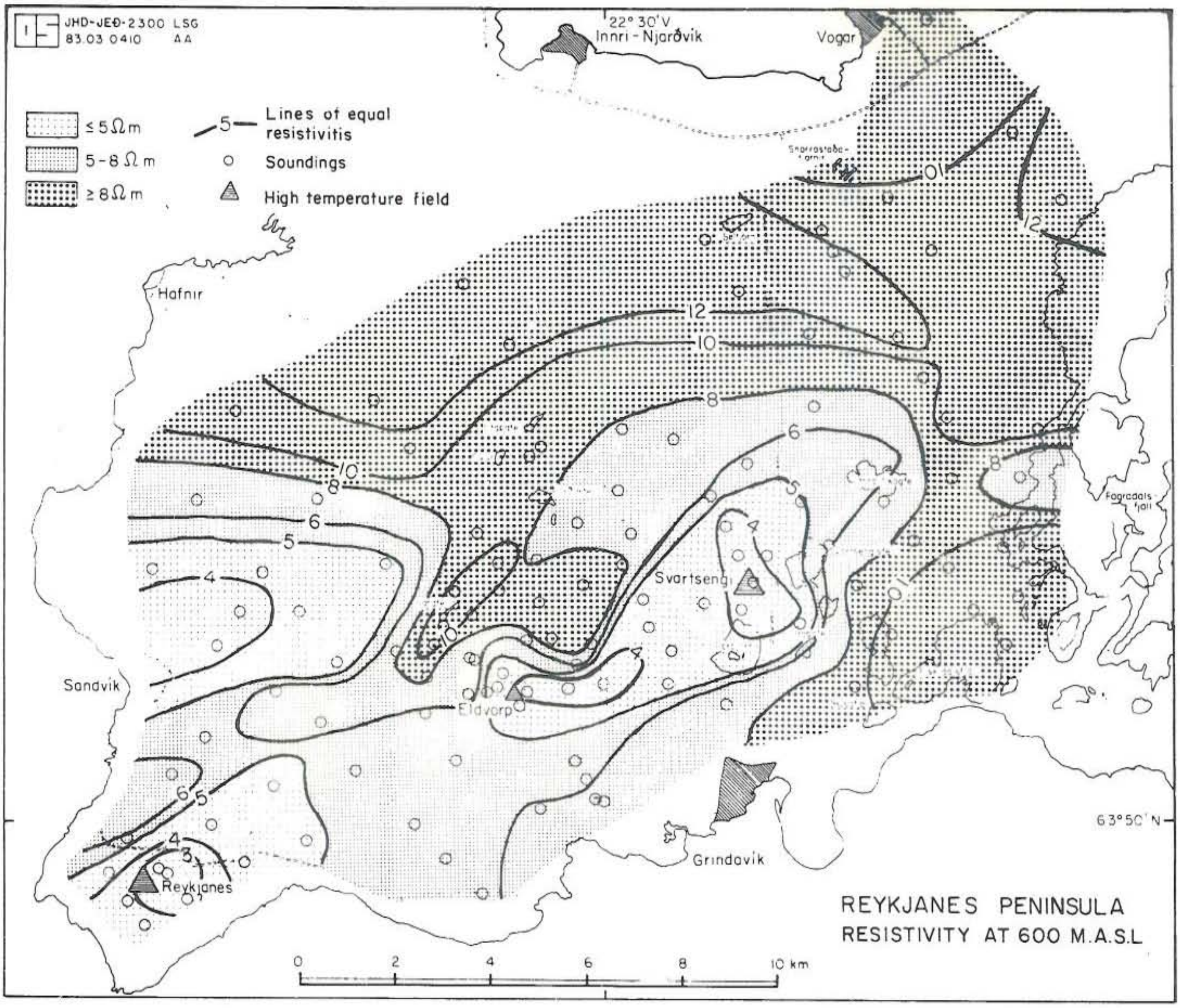

Fig. 4 Resistivity at 600 m depth below sea level at the western part of the Reykjanes peninsula (from Georgsson et al., 1983).

Fresh water is pumped from shallow wells at a distance of 4 to 5 km from the plant. There is a fresh water lens of only 45 m thickness in porous surface lavas. The lens is floating on top of the seawater below. The pumping is done with great care in order to avoid pumping "salt" water which could happen if the drawdown of the fresh water surface in the well is too much.

2.6 Proposed reservoir model by Kjaran et al. (1979)

This conceptual model for the regional geothermal system is a hybrid convection model for the geothermal area itself linking together reservoir performance and well performance to give an estimate of the reservoir capacity.

Free convection exists to some extent in most geothermal reservoirs (Eliasson, 1973), increasing considerably the normal heat flow to the surface. The heat flux has to penetrate the caprock and it can be shown that it is almost impossible that heat transport be only by conduction. There has to be some heat transport by discharge of hot water and steam to keep the convection going. If there is such an outflow from the reservoir it must be expected to be balanced by an equal amount of inflow . This inflow is assumed to be the infiltration at lake Kleifarvatn, flowing along the main earthquake zone, as shown in Fig. 5. The recharge and discharge flow and the convection are the premise for the hybrid convection model shown in Fig. 5. From this figure one can write down six equations: three continuity equations at each point E and D. The equations are: continuity of mass, enthalpy and chloride concentration. There are six equations and twelve unknowns. So six unknowns have to be assumed. At Svartsengi these parameters were either measured or estimated thus enabling the authors to solve for the remaining unknowns. The natural heat loss can then be calculated as the difference of the upward and downward heat flow. The calculated value was about 300 MW, which was three times the necessary power

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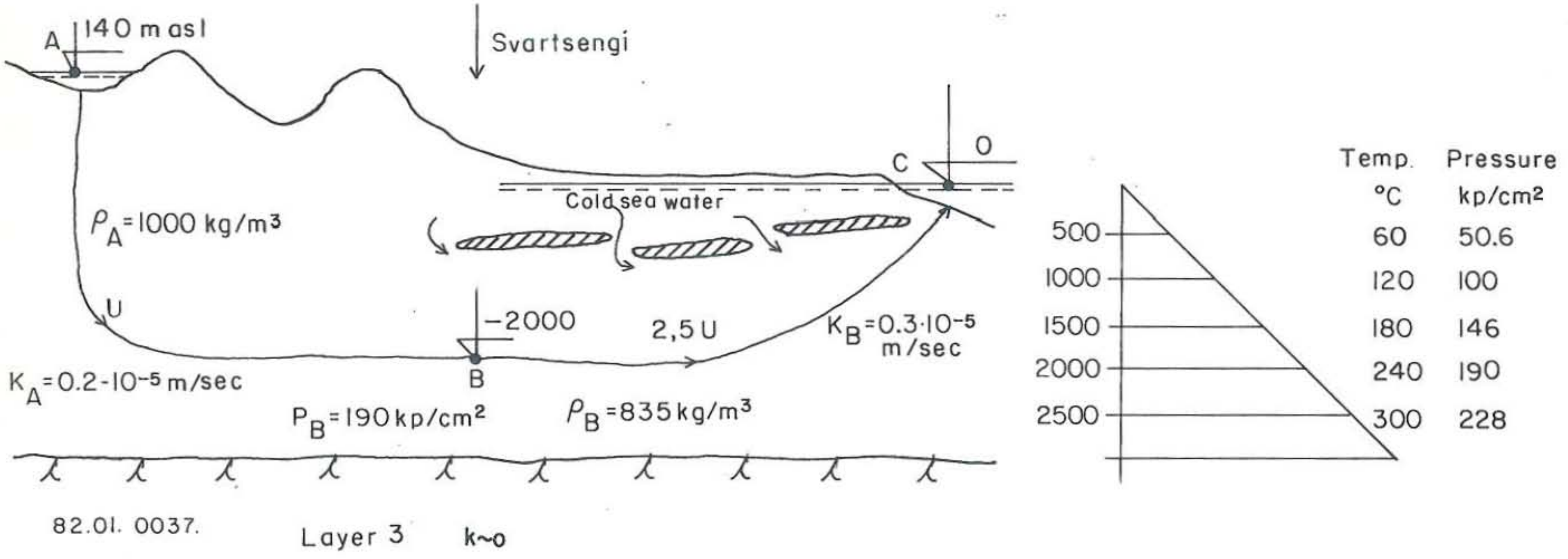

Fig. 5 Conceptual flow model from the Reykjanes peninsula (from Kjaran et al., 1980).

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SVARTSENGI
HISTORY OF EXPLOITATION

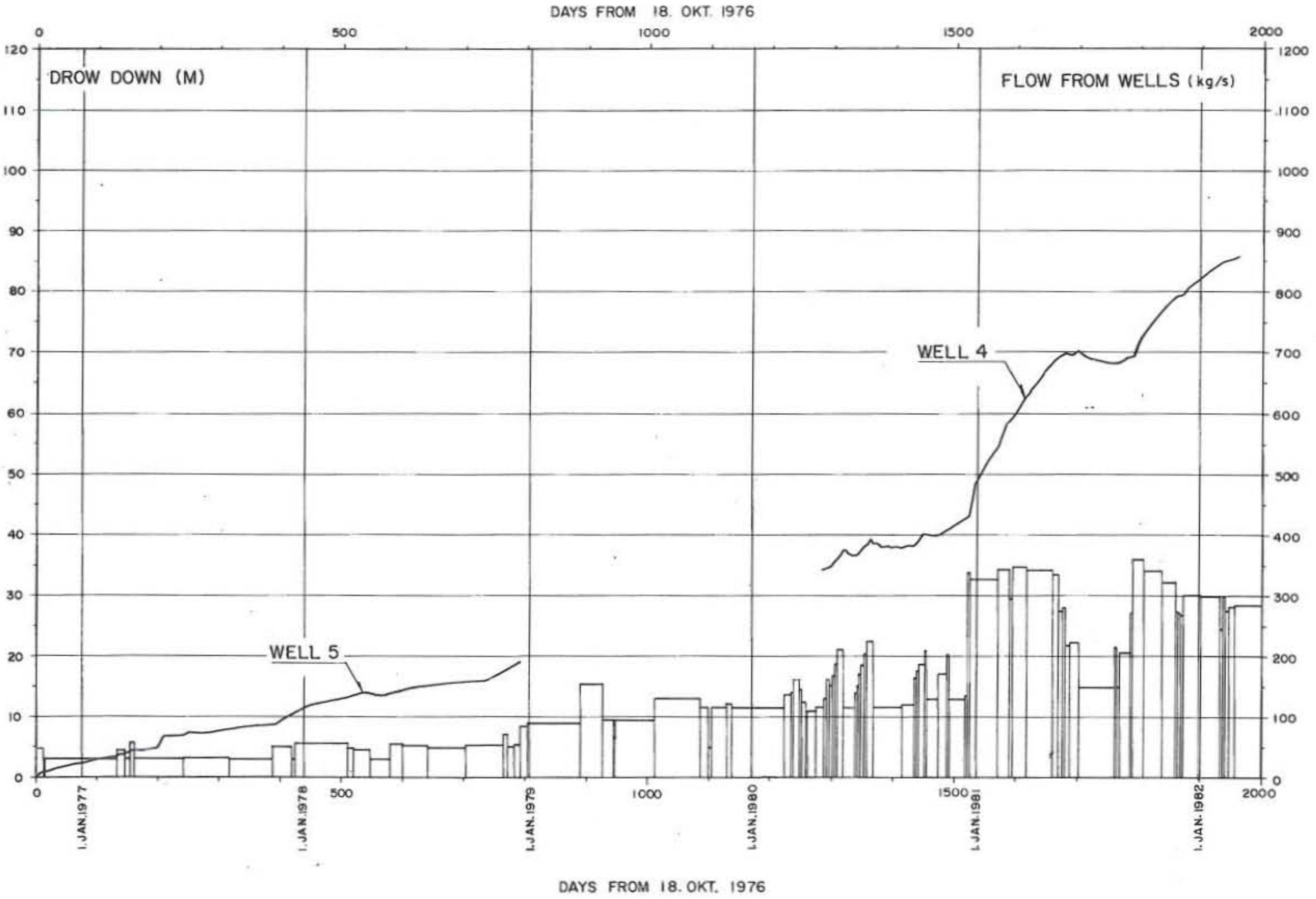

Fig. 6 History of exploitation of the Svartsengi reservoir from 1977 to 1982 (from Vatnaskil Ltd., 1982).

consumption of the geothermal heating plant. Fig. 6 shows the discharge of wells and drawdown in the Svartsengi reservoir from 1976 to 1982.

2.7 General temperature conditions

The general temperature picture of the field is described by Fig. 7. There is a 300 m layer of warm water system having a temperature of 40-60°C which can be seen from measurements of wells which water level is 15-20 m below ground level. The geothermal system between the depths of 600 m and 2000 m had a temperature of at least 240°C when the undisturbed water level was between 64 and 73 m before 1976. In other words the warm water system overlies the geothermal system at all locations except in the western part of the field (Wells SG-2, 3 and 10) where the latter is vented to the atmosphere through fumaroles. There the subsurface temperature follows the boiling point curve down to 400-500 m where a temperature of about 240°C is reached.

2.8 The power plant

The power plant at Svartsengi is the first geothermal plant of its kind in the world (Thorhallsson, 1979). The thing that makes it unique is that a high temperature brine is used as a heat source for space heating and also for the generation of electricity, called co-generation, thus making better use of the geothermal energy than is ordinary for high-temperature geothermal installations. This plant was constructed in several stages. The geothermal fluid is exploited by using heat exchangers for the space heating of all the communities in the western Reykjanes peninsula and the international airport at Keflavik (Thorhallsson, 1979). It was first built to generate 50 MWt (megawatt thermal) and 2 MWe (megawatt electric) for a district heating system. A 75 MWt and 6 MWe addition was later completed. The heat is extracted by flashing the brine in two stages to 60°C and using the

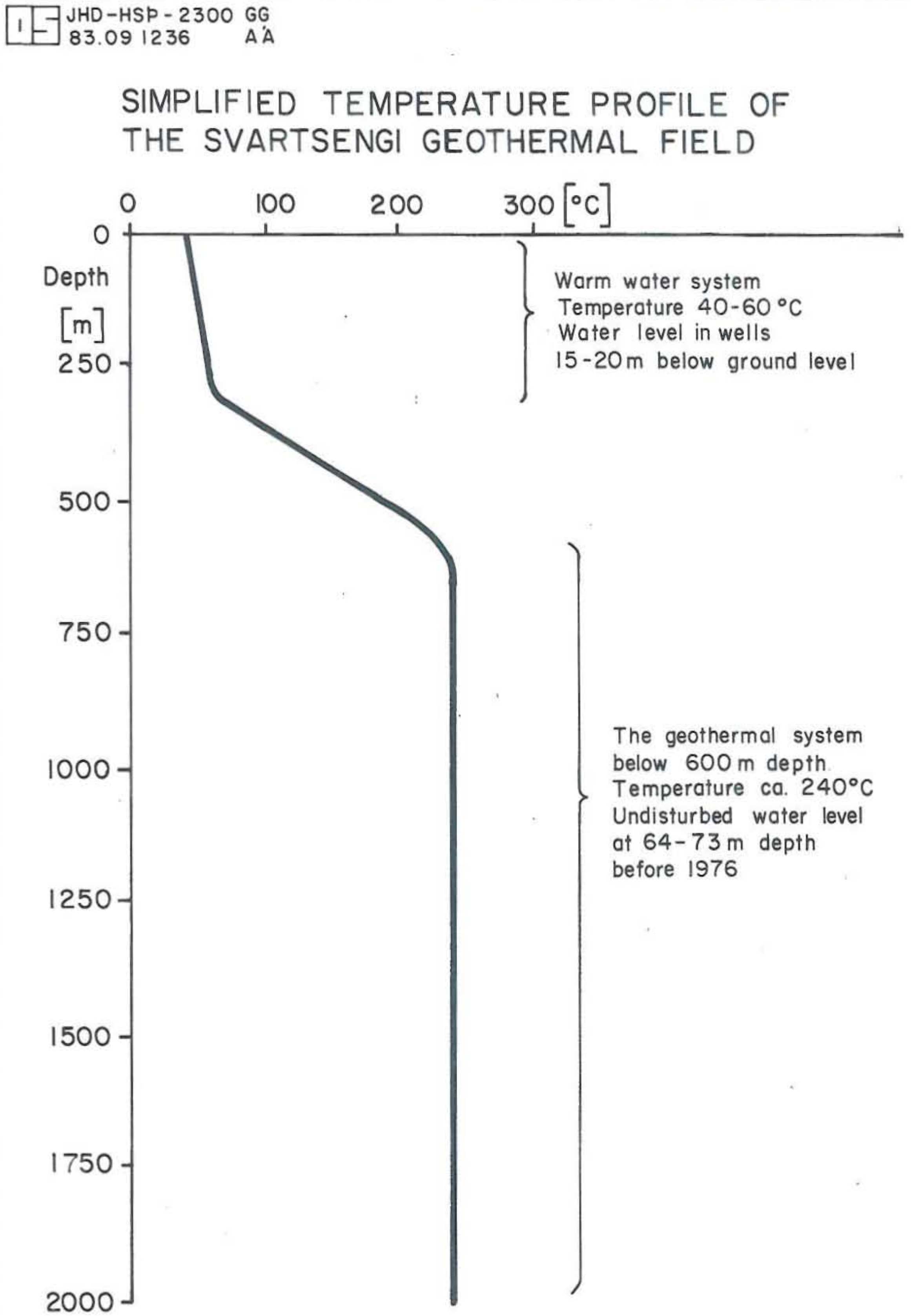

Fig. 7 Simplified temperature profile of the Svartsengi geothermal field.

flash steam for heat and electricity generation. The pilot plant studies were the basis for the design of the first stages in constructing the plant . Nevertheless a lot of details, materials and components had to be tested before the main plant was designed and constructed. All the same the power plant has been able to supply thermal energy to the different communities according to the requirement at any time since the commencement of the programme.

2.9 History of development

The highlights of the historical development of the project are as follows (Bjornsson, 1983):

1971-1972 Wells SG-2 and SG-3 were drilled to depths of 240 and 400 m respectively. The results turned out to be very encouraging proving there was a high temperature field with a brine temperature of 235°C.

1974 The Orkustofnun (NEA) built a pilot plant at Svartsengi. Two wells were drilled, SG-4 (1700 m) and SG-5 (1525 m).

1974-1975 Tests were carried out by the Orkustofnun (NEA) in the pilot plant which later became the basis for the design of power plant 1.

1976 Preliminary power plant of 3 MWt was commissioned on November 6.

1977 First unit of power plant 1 of 8 MWt was commissioned in November.

1978 First 1 MWe turbogenerator was commissioned in April. Second unit of power plant 1 of 12.5 MWt was commissioned in November. Well SG-6 was drilled to a depth of 1734 m.

1979 Third and fourth units of power plant 1 of 2 X 12.5 MWt were commissioned. The second 1 MWe turbogenerator was commissioned. Well SG-7 was drilled to a depth of 1438 m.

1980 Third 6 MWe turbogenerator was commissioned. Wells SG-8, SG-9, SG-10, and SG-11 were drilled to depths of 1603, 994, 425 and 1141 m respectively.

1981 First unit of power plant 2 of 25 MWt was commisioned in May. Second and third units of power plant 2 of 2 X 25 MWt were commissioned in September.

1982 The total installed capacity in power plants 1, 2 and 3 became about 46 MWt + 2 MWe, 75 MWt and 6 MWe respectively. The last well to date, namely SG-12 was drilled to a depth of 1488 m. Reinjection was done for 25 days in the months of September and October.

3 INSTRUMENTATION

The Amerada mechanical gauges were used for both temperature and pressure measurements used in this research project.

There are two main types of mechanical gauges, namely the Amerada temperature gauge, which has a bourdon tube where the boiling pressure of a special fluid is recorded, and the Kuster gauge which has a bimetal sensor where the temperature torsion of the bimetal indicates the temperature. When using the mechanical gauges data is not transmitted to the surface, but is recorded inside the probe on a clock driven recorder. As many as 20-30 measuring points can be recorded during one run in the well.

The Amerada gauges consist of three basic parts, the recording section, a clock and either a pressure sensor or a temperature sensor (Figures 8 and 9).

3.1 Pressure element

The active element in the pressure element is a helical bourdon tube, fixed at one end and free to rotate at the other. The interior of the tube is subjected or exposed to the pressure in the well. The resulting rotation of the free end of the bourdon tube is transmitted directly to a recording stylus without the use of gears or levers. The stylus records on a metal chart made of thin metal coated on one side with a special paint. The paint renders friction extremely low and the scribed lines are so easily visible that the chart scanner user can measure chart deflections to obtain the accuracy the gauge is capable of producing. The chart is carried on a removable cylindrical chart holder, the position of which is controlled by a clock.

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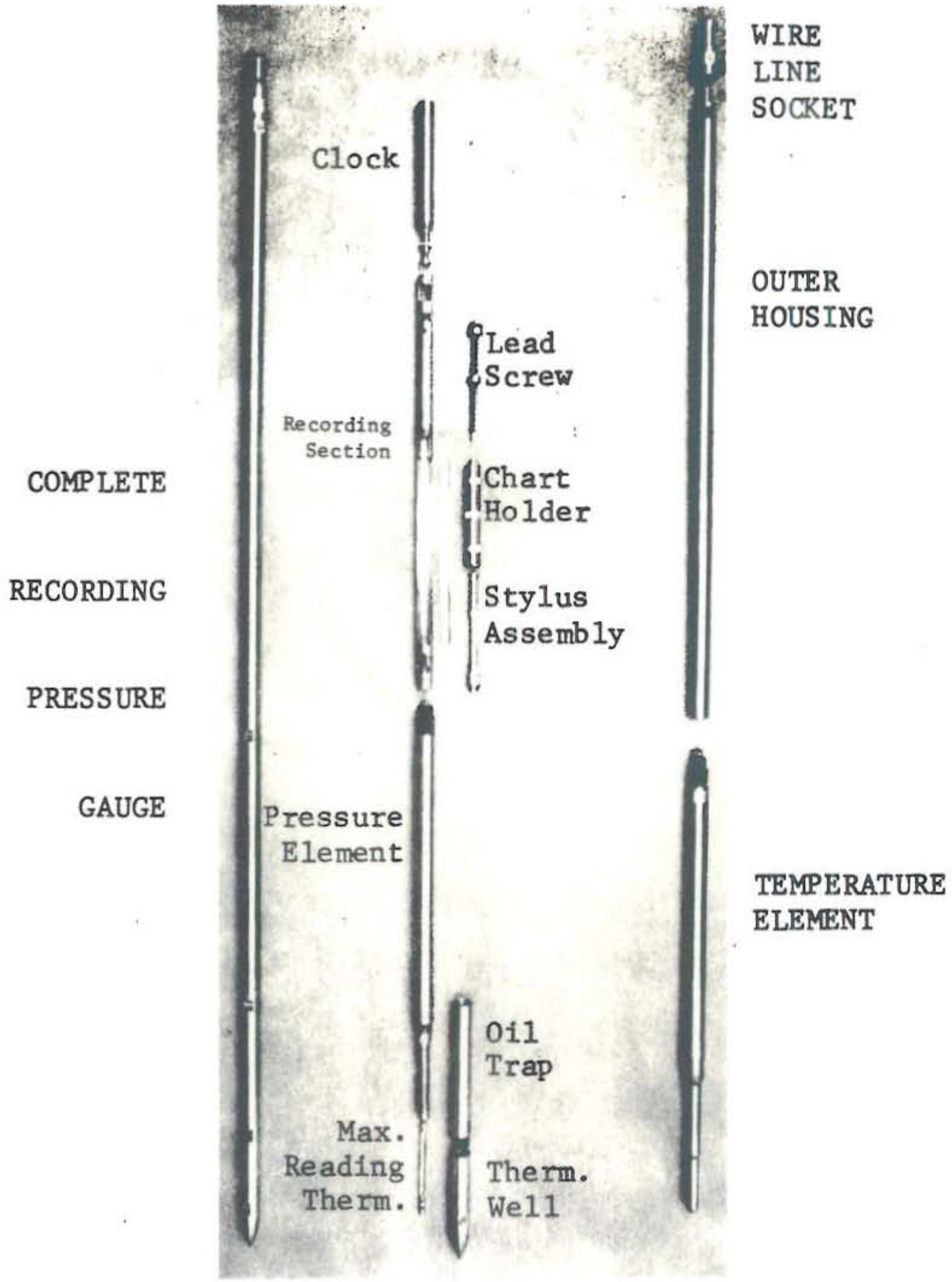

BOTTOM HOLE RECORDING

PRESSURE OR TEMPERATURE GAUGE

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RPG-3 1 ¼" Dia. RPG-4 1" Dia.

Fig. 8 Amerada recording gauges for pressure and temperature.

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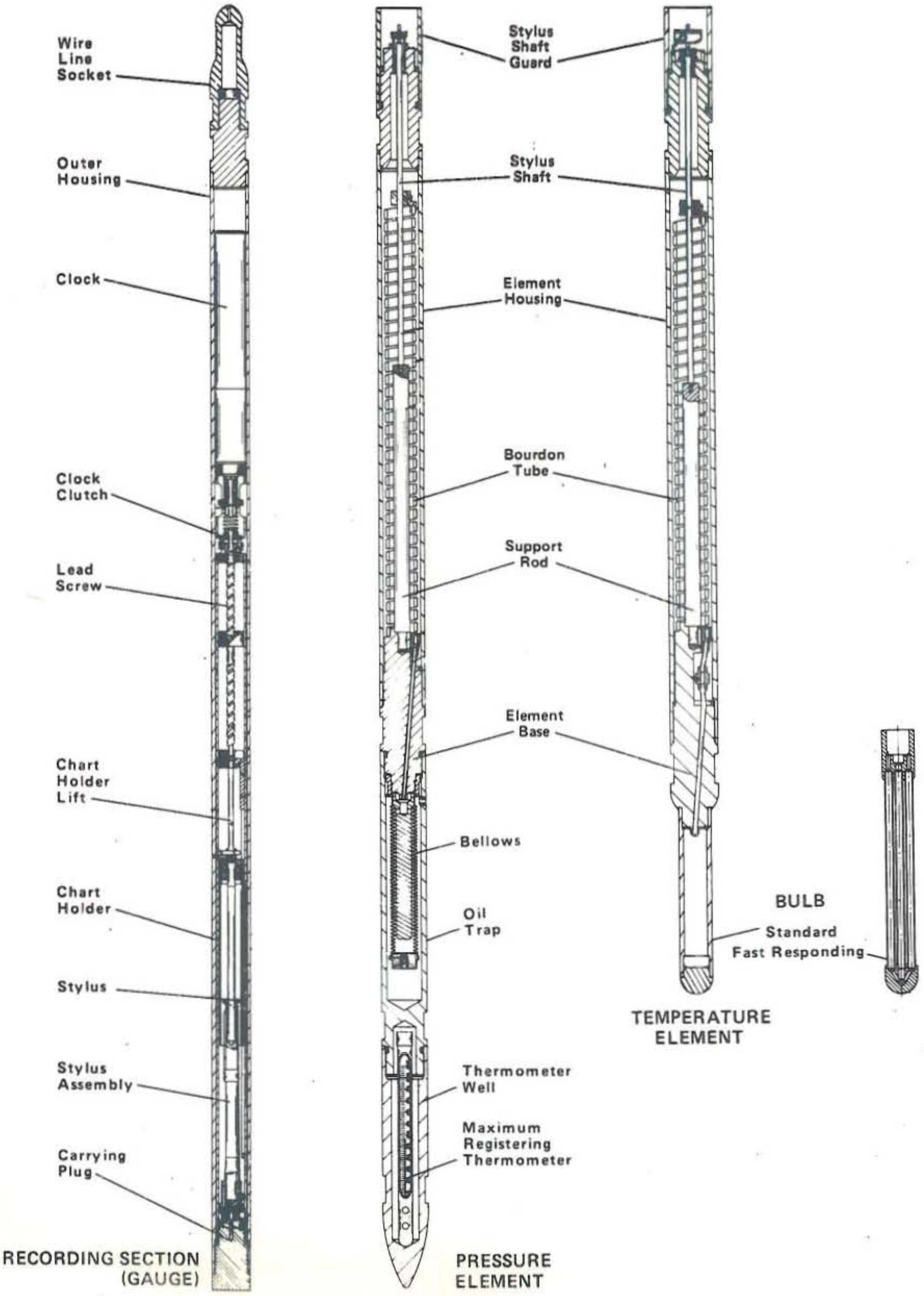

Fig. 9 Cross-sections of Amerada pressure and temperature probes.

3.2 Temperature element

The bourdon tube in the temperature element is sealed. Variations in temperature create different boiling pressure inside the bourdon tube. The vapour pressure of the enclosed liquid is directly related to its temperature, making the rotated position of the free end of the bourdon tube an usable measure of the temperature of the element. This rotation is recorded on the gauge chart as described above.

3.3 Limits of accuracy

The repeatability of a properly maintained gauge is better than ~0.1% of full range of the pressure element in use, while the absolute accuracy is 0.2%. Temperatures above 70°C affect the strength of most Bourdon tubes , so calibrations are necessary to maintain the accuracy of the instrument. The sensitivity of the gauge is 0.2% of full scale deflection.

The absolute accuracy of the temperature gauge is usually assumed to be 2°C but this is related to the calibration and operation of the instruments.

4 INDIVIDUAL WELLS

There have been drilled 12 wells in the high temperature field of Svartsengi (Fig. 2). The temperature changes with respect to time and the boiling conditions are discussed in this chapter.

Well SG-1 is a shallow well with relatively low temperature. It was drilled for the purpose of using its water in drilling the other wells. The depth of the well is 250 m and the temperature is less than 50°C. A peak in temperature is measured at the ground water level of 25 m depth (Fig. 10). This indicates a considerable horizontal flow in this shallow acquifer, most probably a run off from the main geothermal field (Stefansson and Steingrimsson, 1981). The maximum temperature measured in this well is 47°C at the bottom at 250 m depth. The temperature at this depth in the nearest well (SG-5) is about 200°C, showing the abrupt demarcation of the geothermal system at this location and depth. The cold ground water reaches down to little more than 200 m depth, but beneath that the temperature increases more steeply, which might be a sign that a hotter fluid can be found at greater depth at this location.

The pressure gradient in the well is hydrostatic (Fig. 11) corresponding to a mean density of 1022 kg/m^3. The density of seawater at 35°C is 1021 kg/m^3.

Well SG-2 is a shallow well (about 250 m deep) located in the area where the geothermal system is vented to the atmosphere. It was initially boiling up to at least 175 m. Now it is boiling from top to bottom. Unlike many other wells of the Svartsengi geothermal field, this well has increased in temperature with time (Fig. 12). This is the result of increased boiling in the top of the reservoir due to the pressure drawdown in the reservoir. The boiling level is continuously migrating to larger depths, which results in higher pressure and temperature of the steam cap in the top of the system. Between 1976 and 1981 the

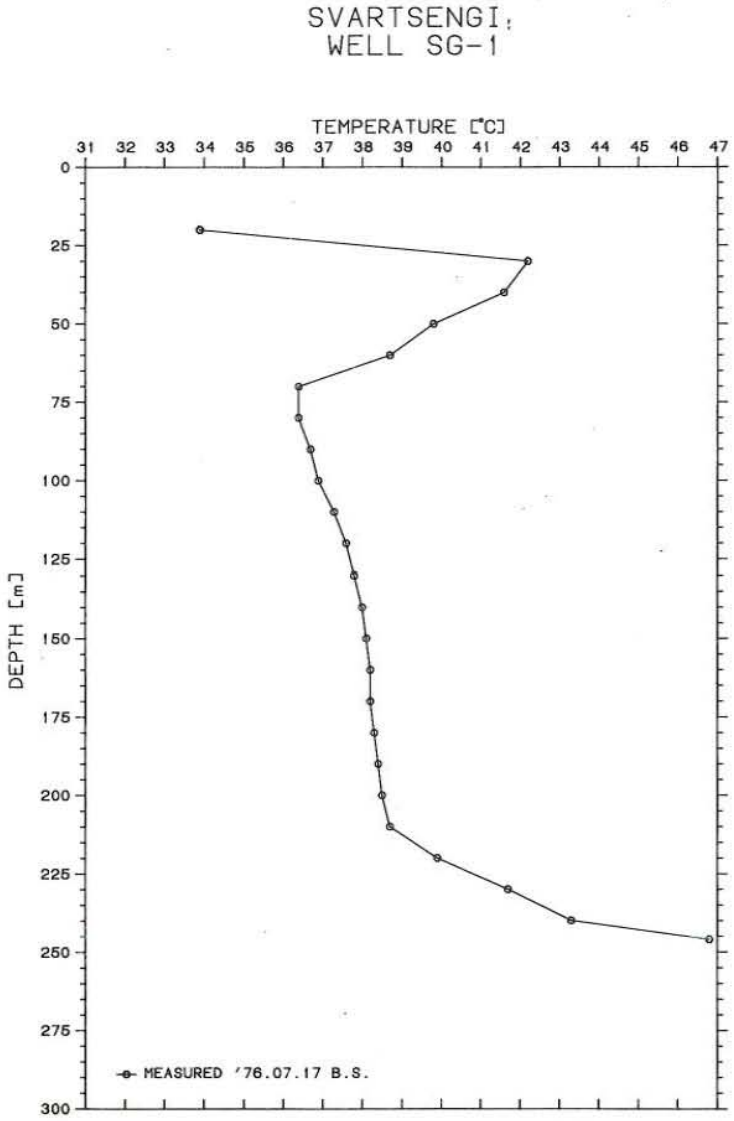

Fig.10 Svartsengi well SG-1. Temperature profile in 1976.

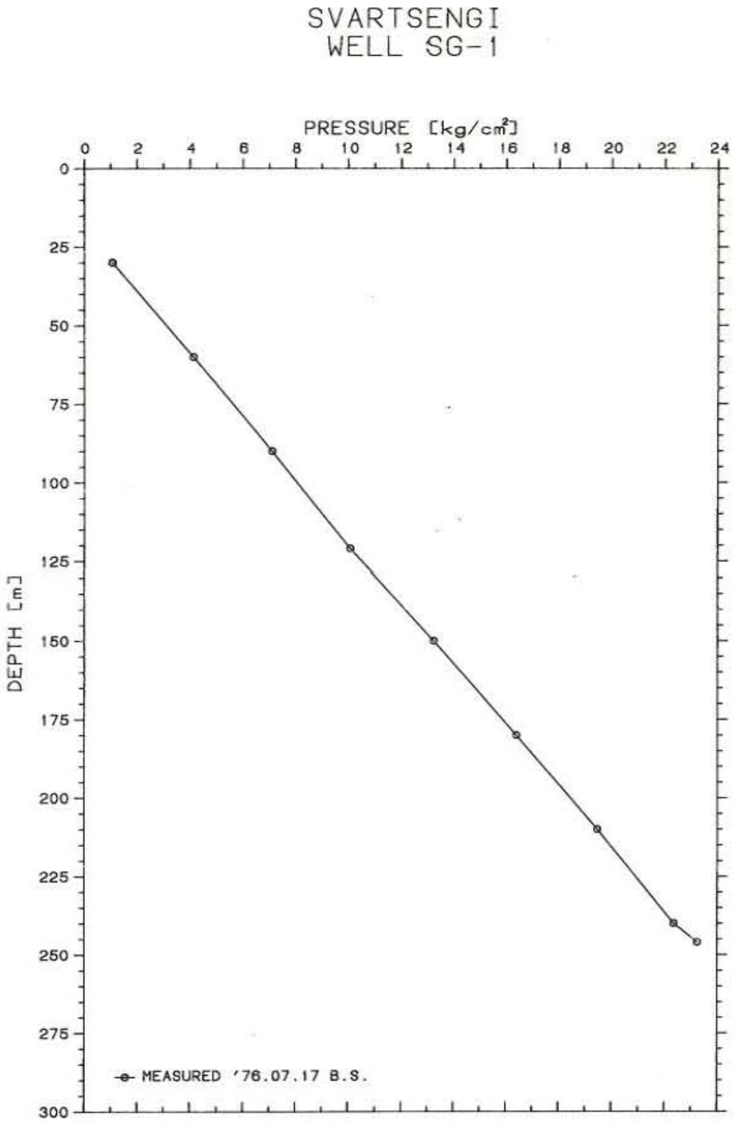

Fig.11 Svartsengi well SG-1. Pressure profile in 1976.

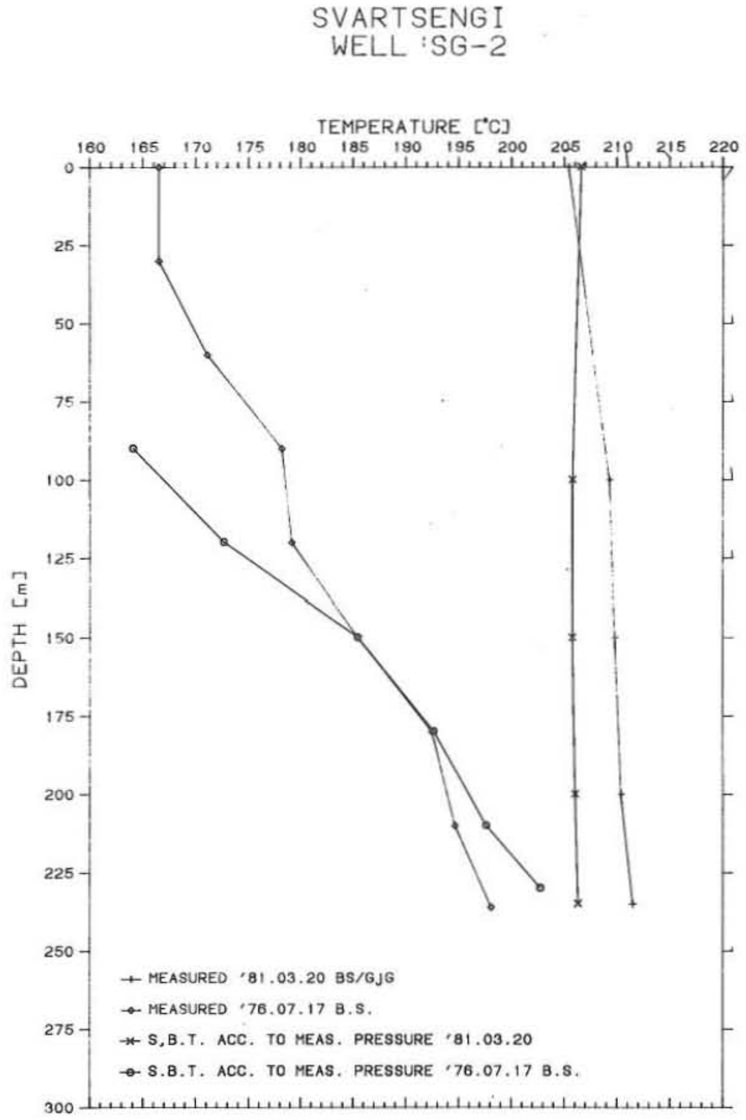

Fig.12 Svartsengi well SG-2. Temperature in 1976 and 1981 with corresponding saturation curves.

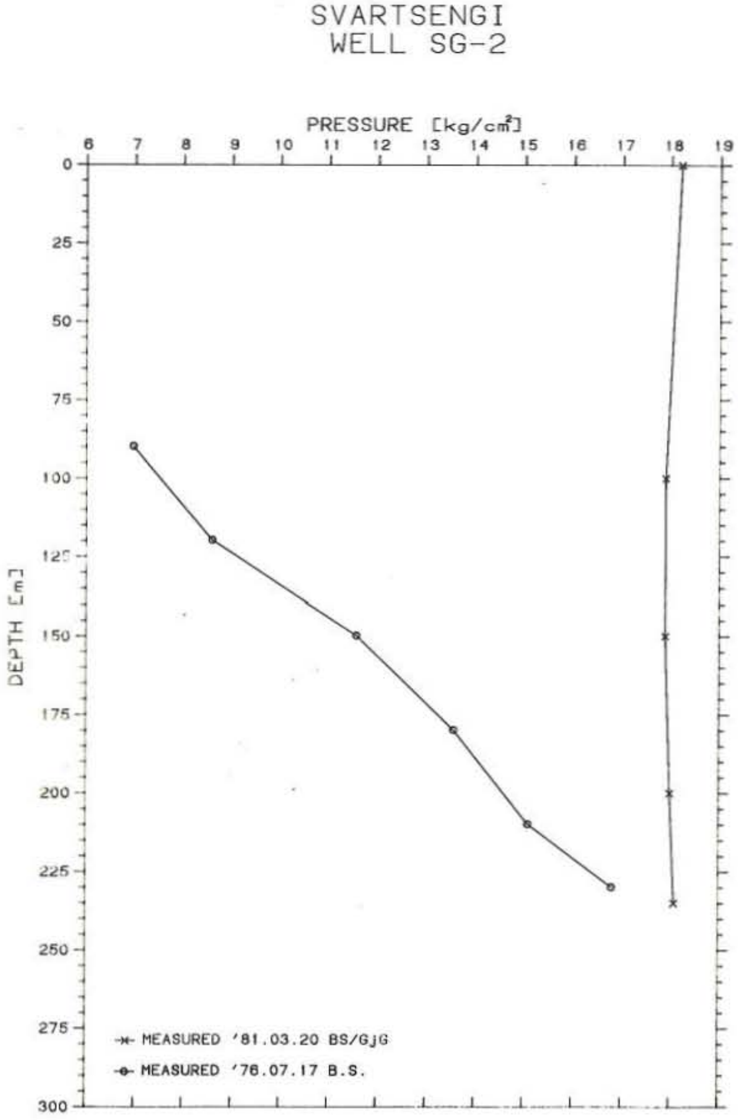

Fig.13 Svartsengi well SG-2. Pressure profiles in 1976 and 1981.

temperature at the bottom of the well has increased by 15°C (Fig. 12), and the corresponding pressure increase is 1.3 bar (Fig. 13).

Well SG-3 is located close to well SG-2. It is 402 m deep and has a bottom temperature of about 225°C as measured in '77.06.14. At that time, a two-phase zone reached up to approximately a depth of 250 m (see Fig. 15). In 1981 the boiling level has migrated down to 375 m (Fig. 15) and the temperature has decreased by about 15°C. Further drawdown in the reservoir has resulted in a pure steam cap down to the bottom of the well. Both temperature and pressure have increased in the period from 1981 to 1983 as can be seen in Fig. 14 and 15.

Well SG-4 was initially drilled to 1713 m depth, and for a long time it was a production well with 1680 m clear depth. Casing damage occured in the well in 1980 and the attempt of repairing it by redrilling was unsuccessful. The drill bit went out of the casing. Presently the well is open to 540 m depth and cannot be utilized for power production. The top of the geothermal system is fairly well defined by the temperature profiles in the well (Fig. 16). The steep temperature increase between 400 m and 600 m reflects the impermeable layer at the top of the reservoir at this depth. The initial temperature in this well was close to 240°C and the temperature was rather uniform at least down to 1700 m depth. The pressure gradient is hydrostatic and boiling conditions have not been observed in the well during static conditions (Fig.17).

Well SG-5 is 1519 m deep. There has been a temperature change of 3°C deep in the well. The pressure drawdown between the years 1976 and 1983 has been about 13 kg/cm3 (Fig. 21). Boiling levels were at 300 and at 400 m in the years 1982 and 1983 respectively (Fig. 19 and 20). whereas no boiling is recorded in 1976 (Fig. 18).

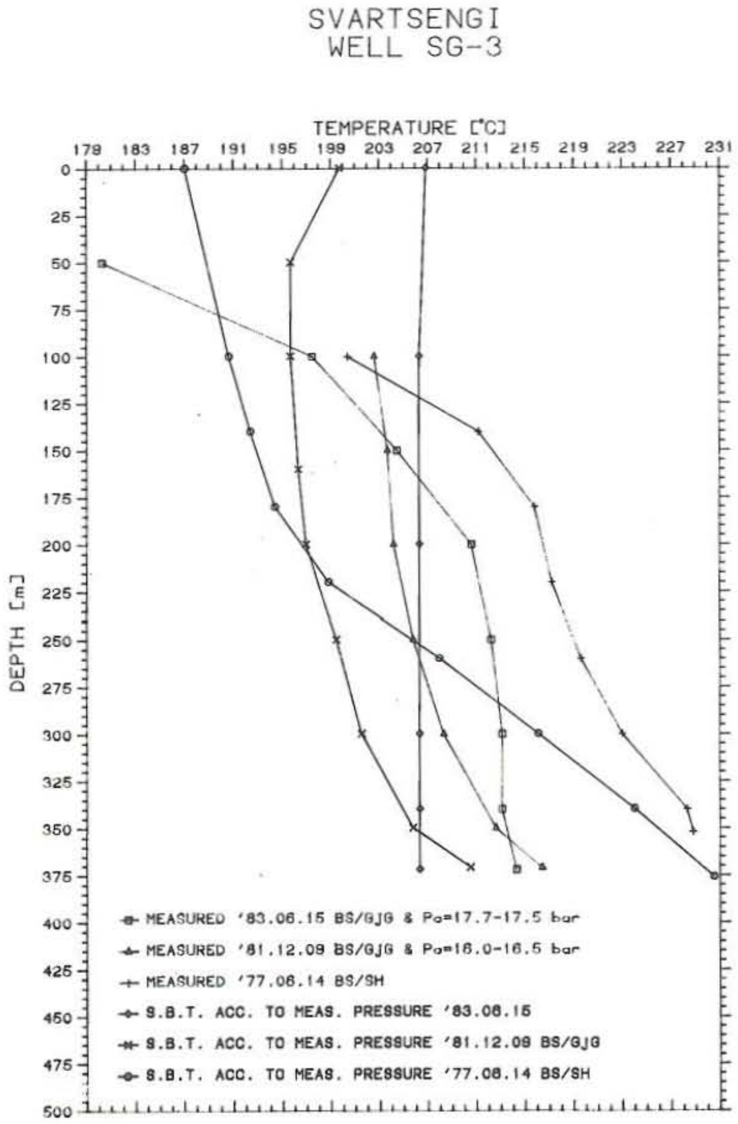

Fig.14 Svartsengi well SG-3. Temperature profiles in 1976, 1981, 1983 and corresponding saturation temperature profiles.

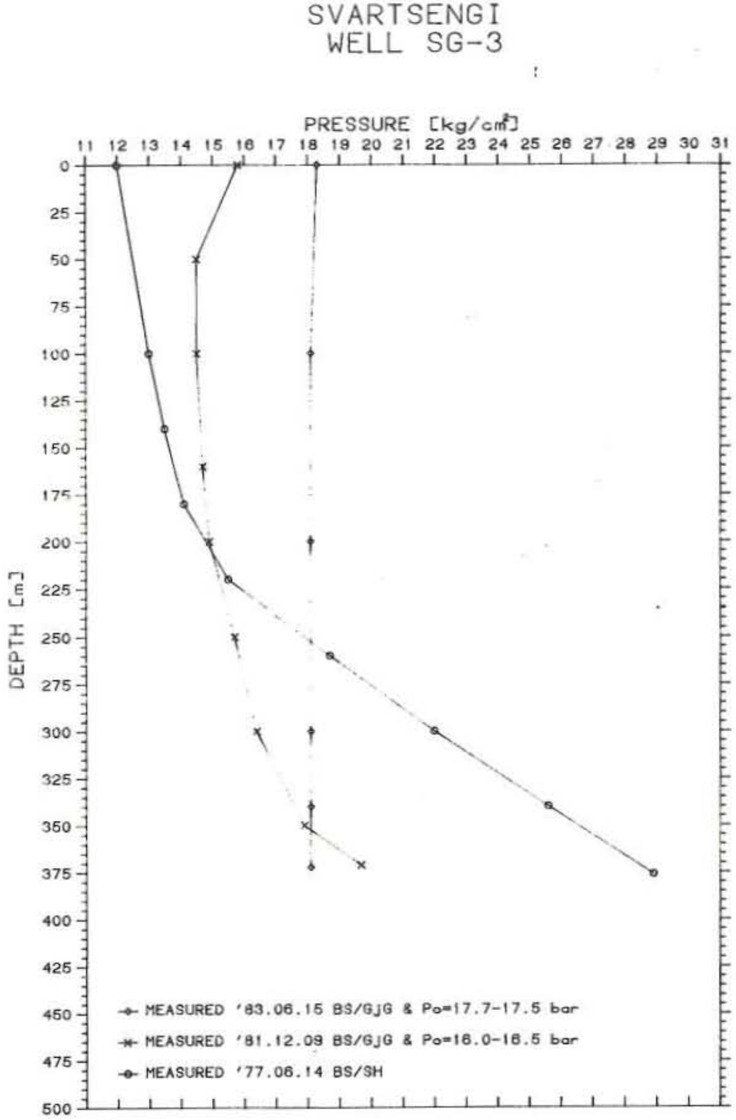

Fig.15 Svartsengi well SG-3. Pressure profiles in 1977, 1981 and 1983.

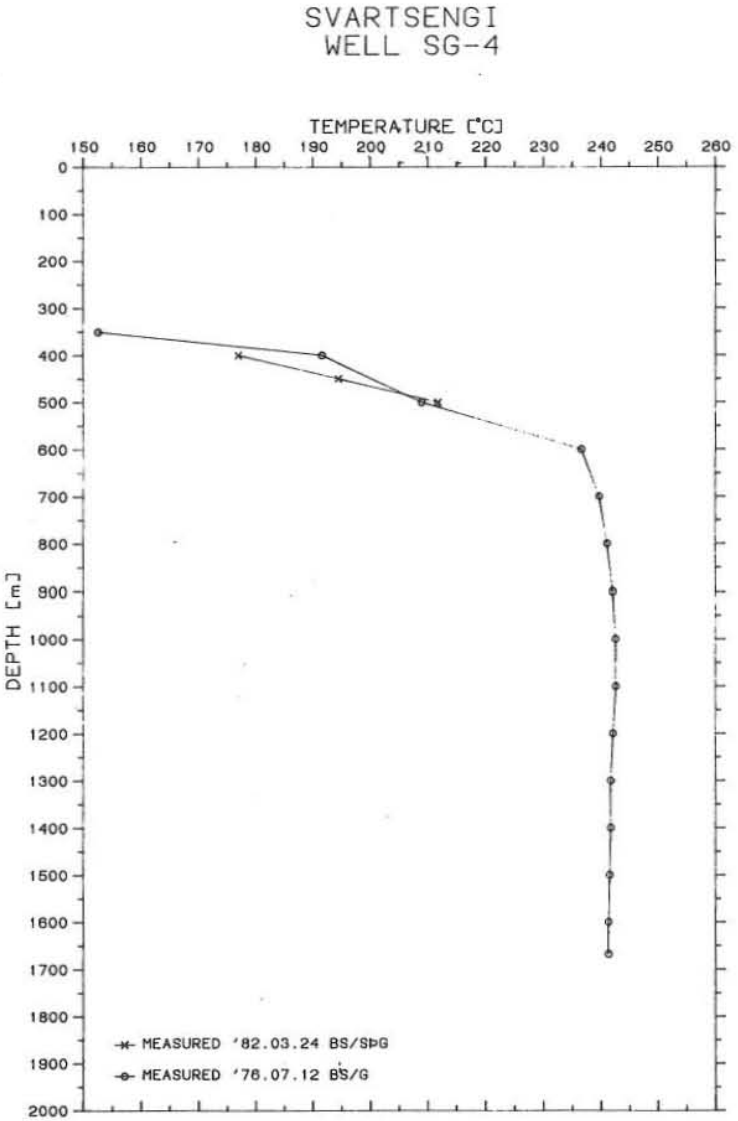

Fig.16 Svartsengi well SG-4. Temperature profiles in 1976 and 1982.

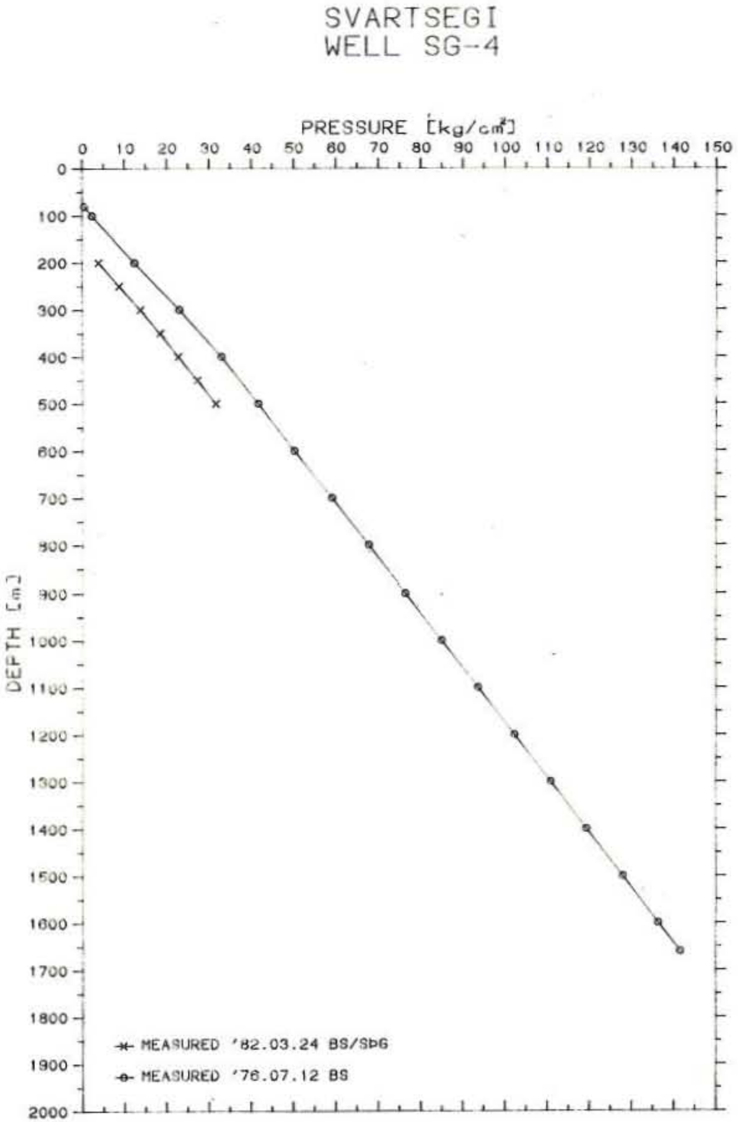

Fig.17 Svartsengi well SG-4. Pressure profiles in 1982.

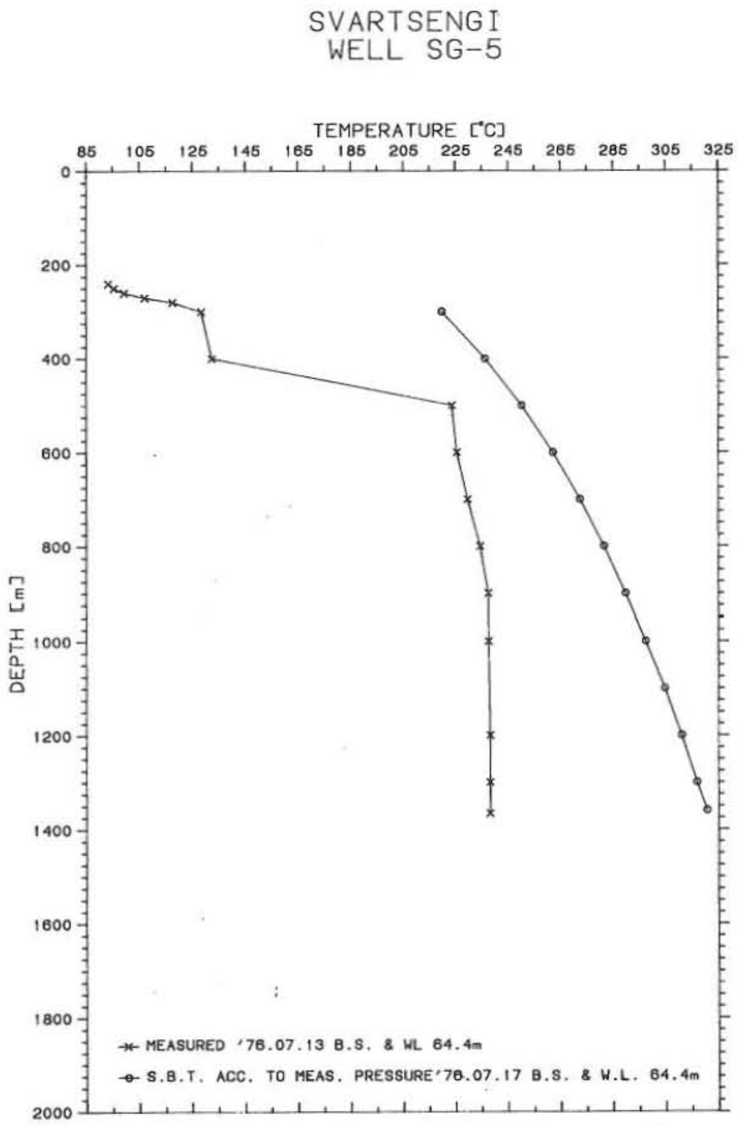

Fig.18 Svartsengi well SG-5. Temperature profile in 1976 and corresponding saturation profile.

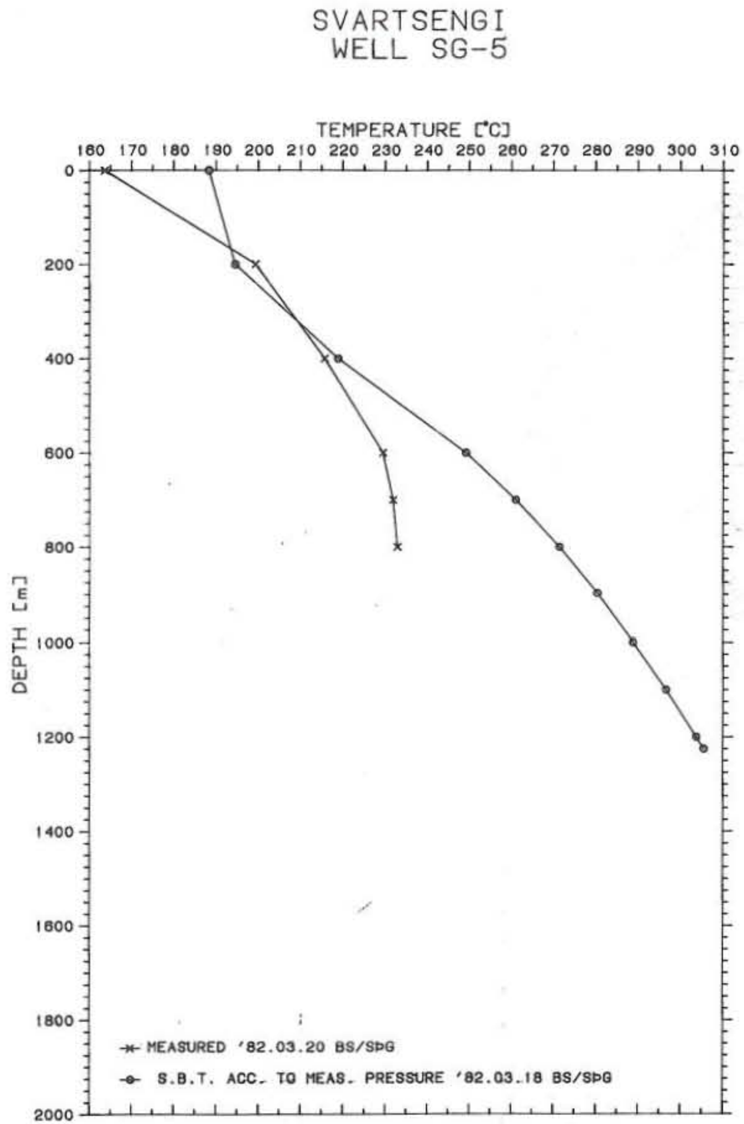

Fig.19 Svartsengi well SG-5. Temperature profile in 1982 and corresponding saturation profile.

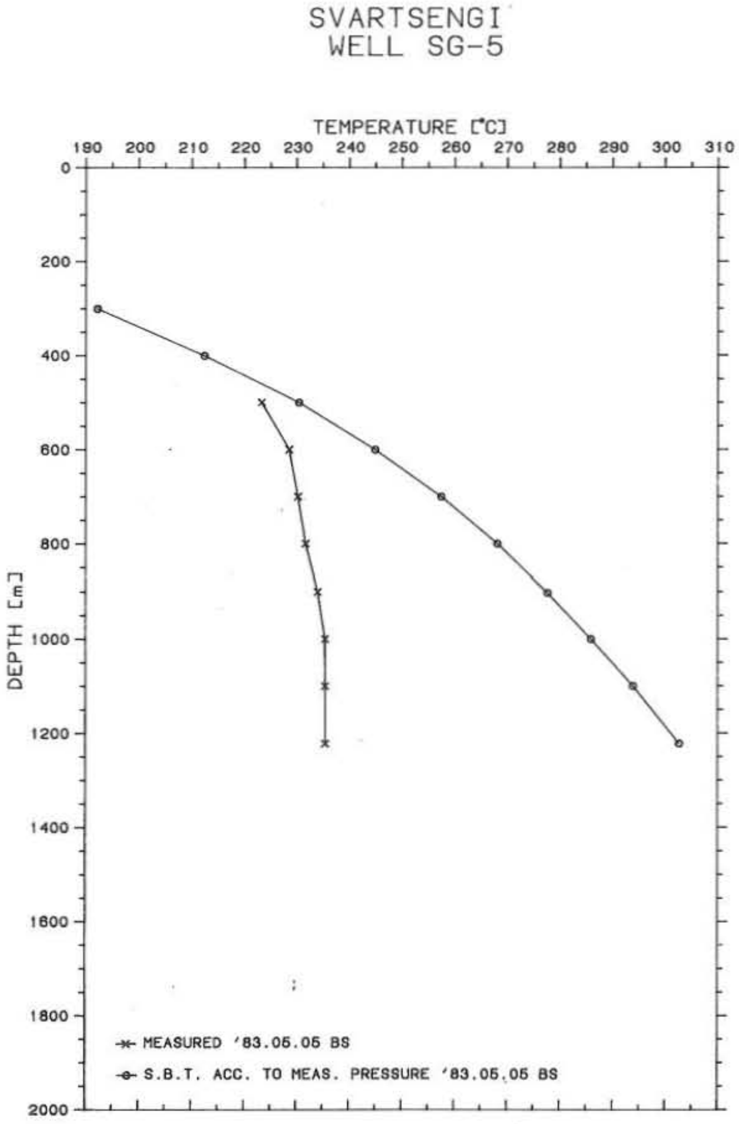

Fig.20 Svartsengi well SG-5. Temperature profile in 1983 and corresponding saturation profile.

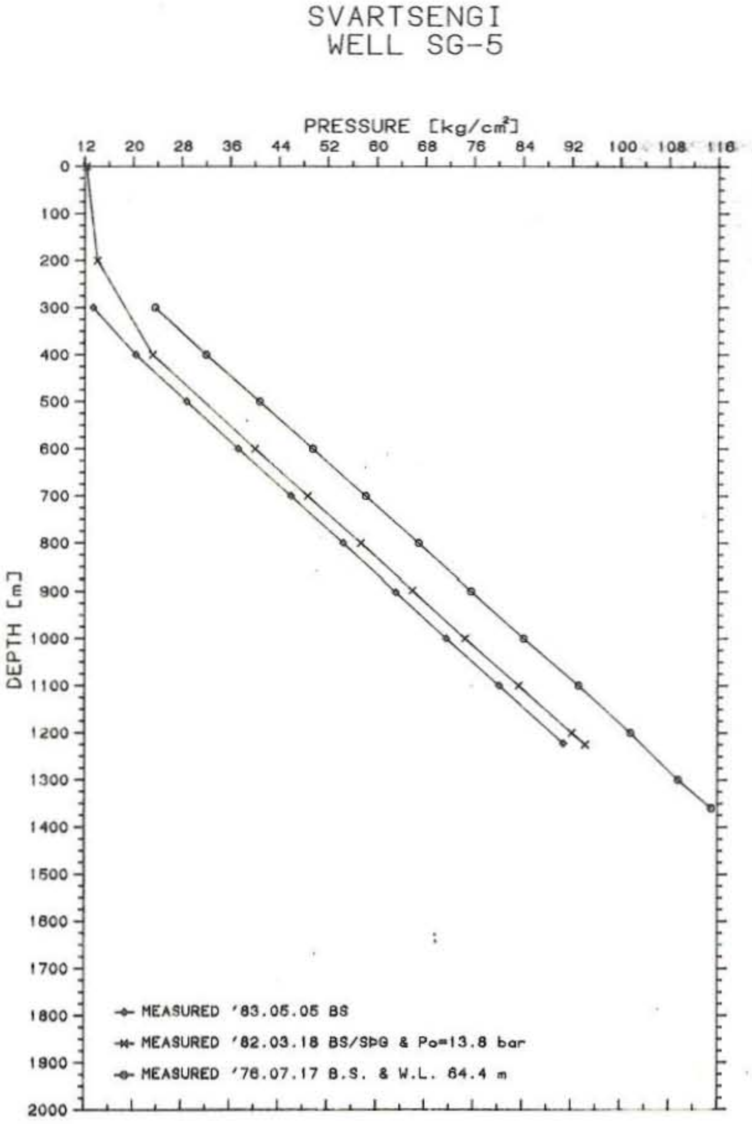

Fig.21 Svartsengi well SG-5. Pressure profiles in 1976, 1982 and 1983.

Well SG-6 was 1734 m deep before it was redrilled in 1982 to a depth of 1954 m. Apparent changes in temperature profiles in 1982 are due to the cooling effect of this redrilling. The cooling effects are therefore badly documented in this well. Deep in the well it has cooled down by 4°C between the measurements of '81.12.09 and '83.06.15 (Fig. 22). In the same period there has been a pressure drawdown of about 4 kg/cm^2 (Fig. 23). In 1983 the boiling level has gone deeper than 500 m.

Well SG-7 is 1438 m deep. There has occured a cooling of about 8°C (Fig. 25) and a pressure drawdown of 3 kg/cm^2 between the '82.03.15 and '83.05.04 measurements (Fig. 26). But between the '80.10.08 and '83.05.04 dated measurements there has been a cooling of 4 to 7°C (Fig. 24) and a pressure drawdown of 7 kg/cm^2 (Fig. 26). In 1980, 1982 and 1983 the boiling levels were at 400, 450 and 500 m respectively (Fig. 25).

Well SG-8 has a depth of 1603 m and has undergone a change of 7°C cooling (Fig. 27) and a pressure drawdown of 2 kg/cm^2 between the measurements dated '82.03.16 and '83.03.16 (Fig. 28). According to the measured pressure on these dates the boiling level was 425 and 450 m respectively (Fig. 27).

Well SG-9, which is 994 m deep, experienced a cooling of 9°C at depth (Fig. 29) with a pressure drawdown of 2 kg/cm^2 between '82.03.17 and '83.05.04 (Fig. 30). At the latter date it was boiling at a level of about 450 m whereas there is no indication of any boiling atthe former date.

Well SG-10 is 425 m deep and close to wells SG-2 and SG-3. At this location, the reservpoir is boiling down to the bottom of the well. The steam cap is down to 400 m. The temperature has changed moderately in the period 1980-1982 (Fig. 31). The form of the temperature profiles indicate, however, that the boiling level is migrating downwards at this location. This is further strengthened by the

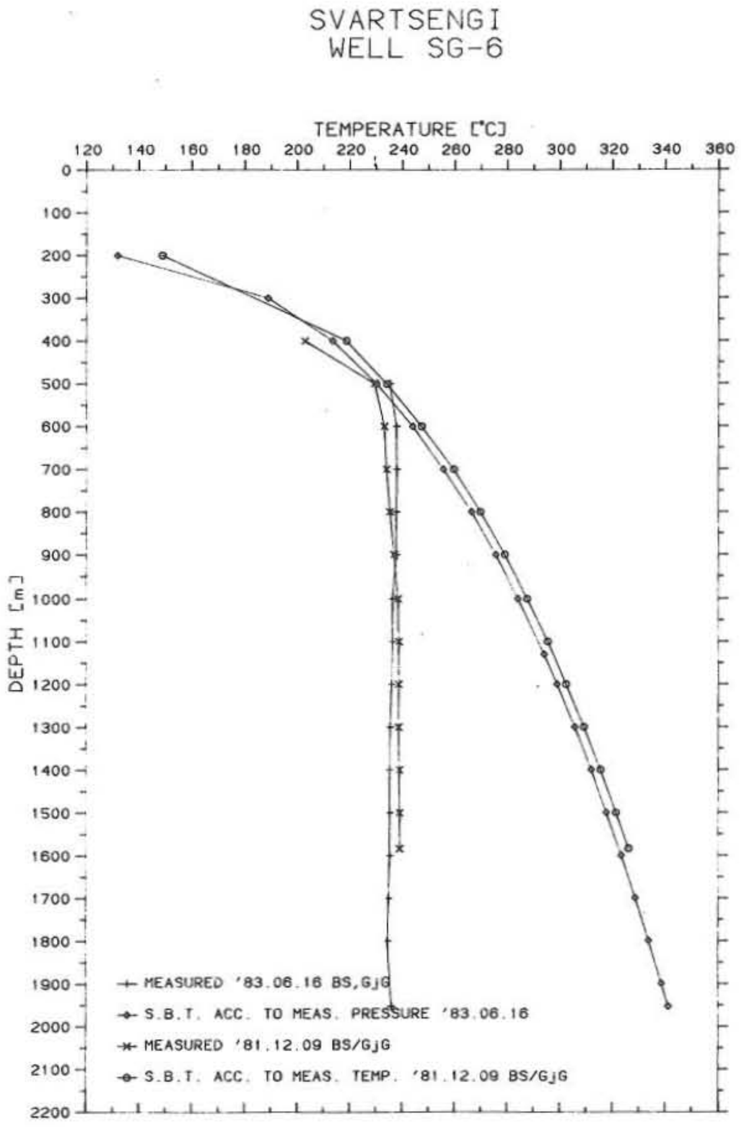

Fig.22 Svartsengi well SG-6. Temperature profiles in 1981, 1982, 1983.

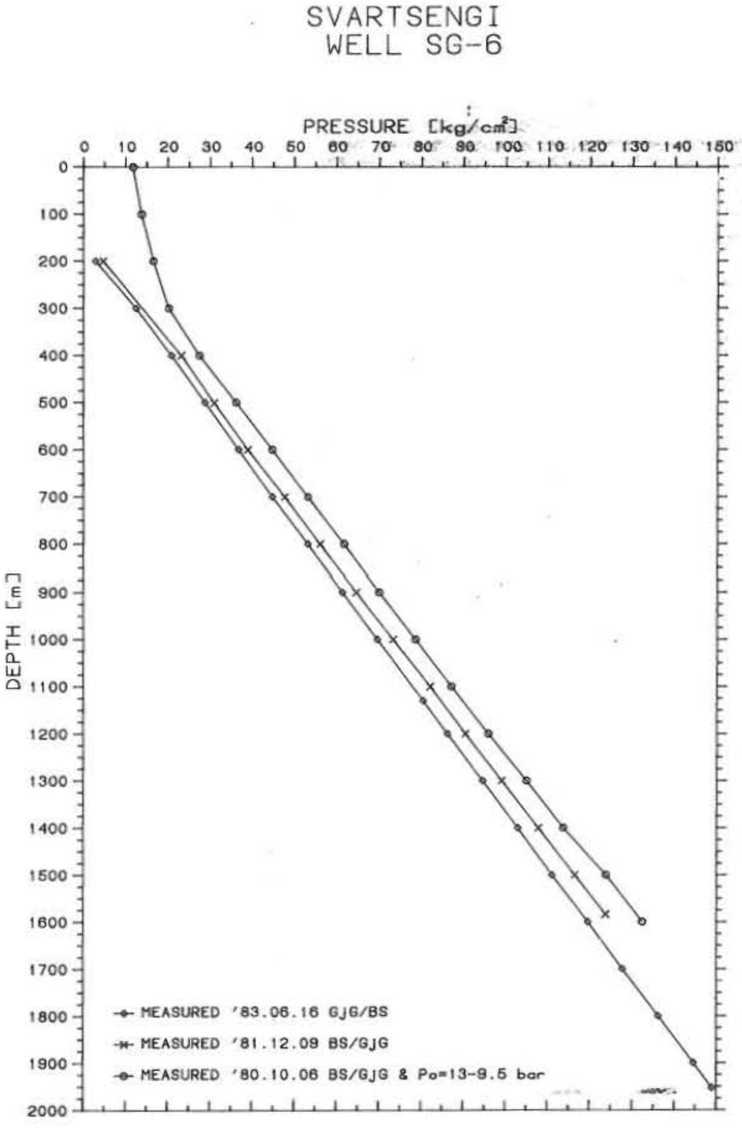

Fig.23 Svartsengi well SG-6. Pressure profiles in 1980, 1981, 1982 and 1983.

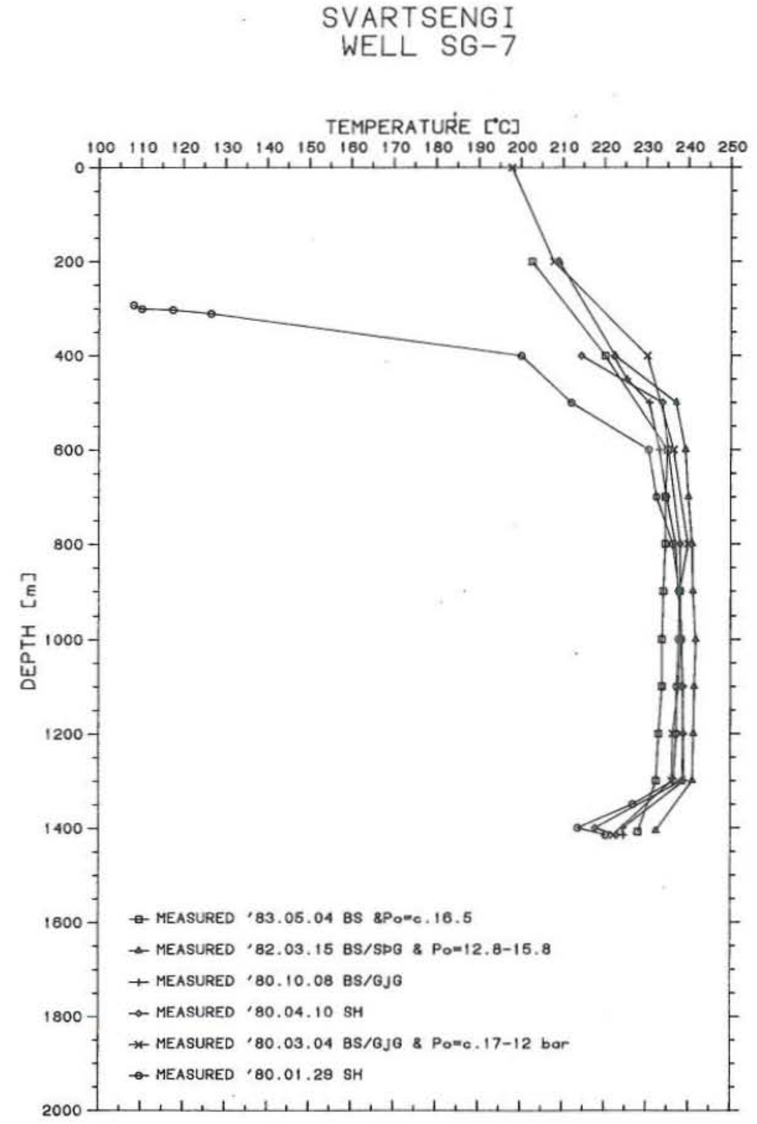

Fig.24 Svartsengi well SG-7. Temperature profiles in 1980, 1982 and 1983.

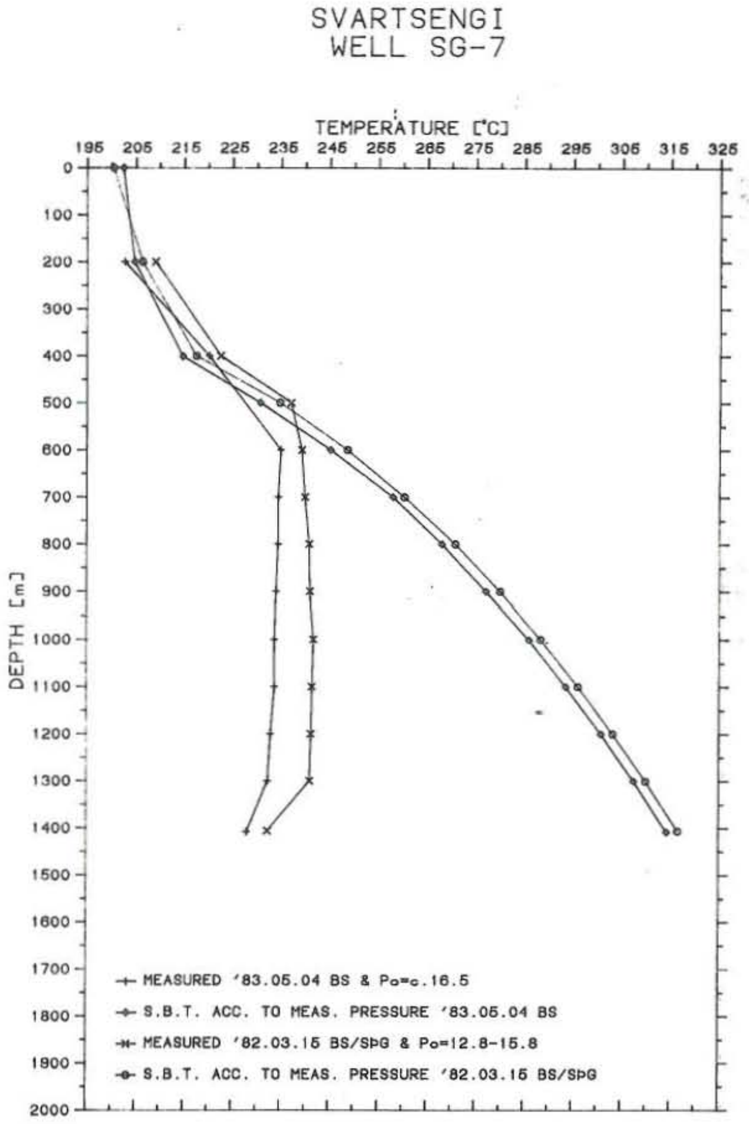

Fig.25 Svartsengi well SG-7. Temperature profiles in 1982, 1983 and corresponding saturation profiles.

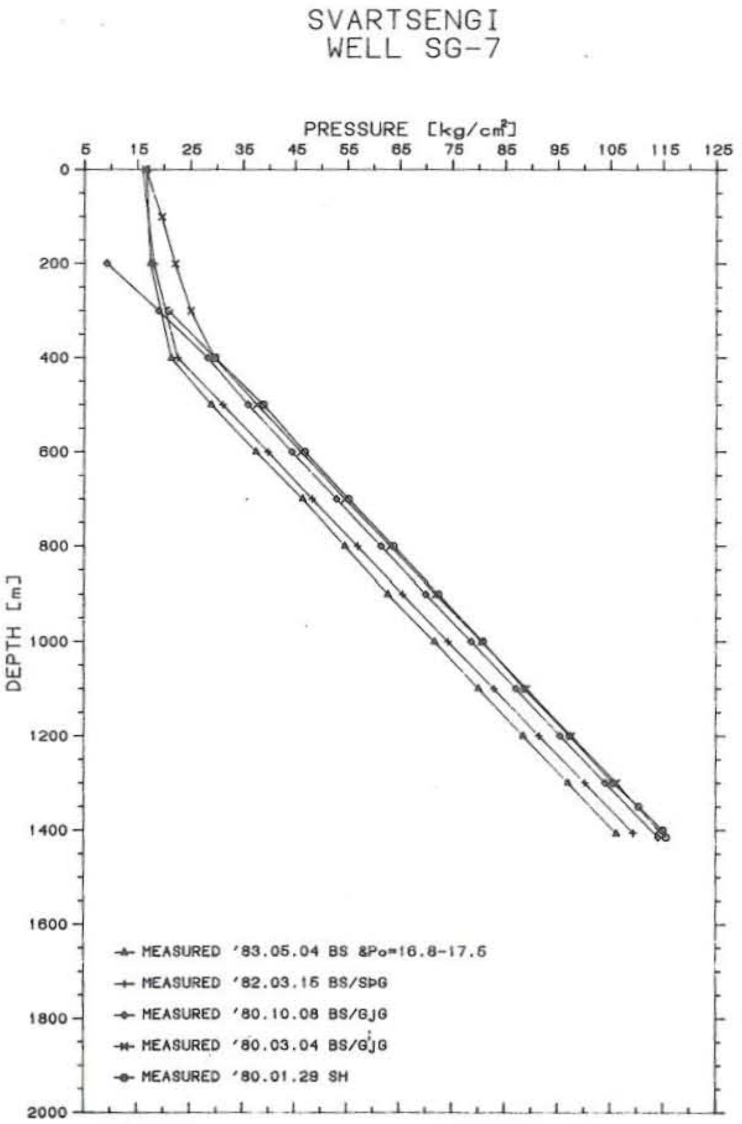

Fig.26 Svartsengi well SG-7. Pressure profiles in 1980, 1982 and 1983.

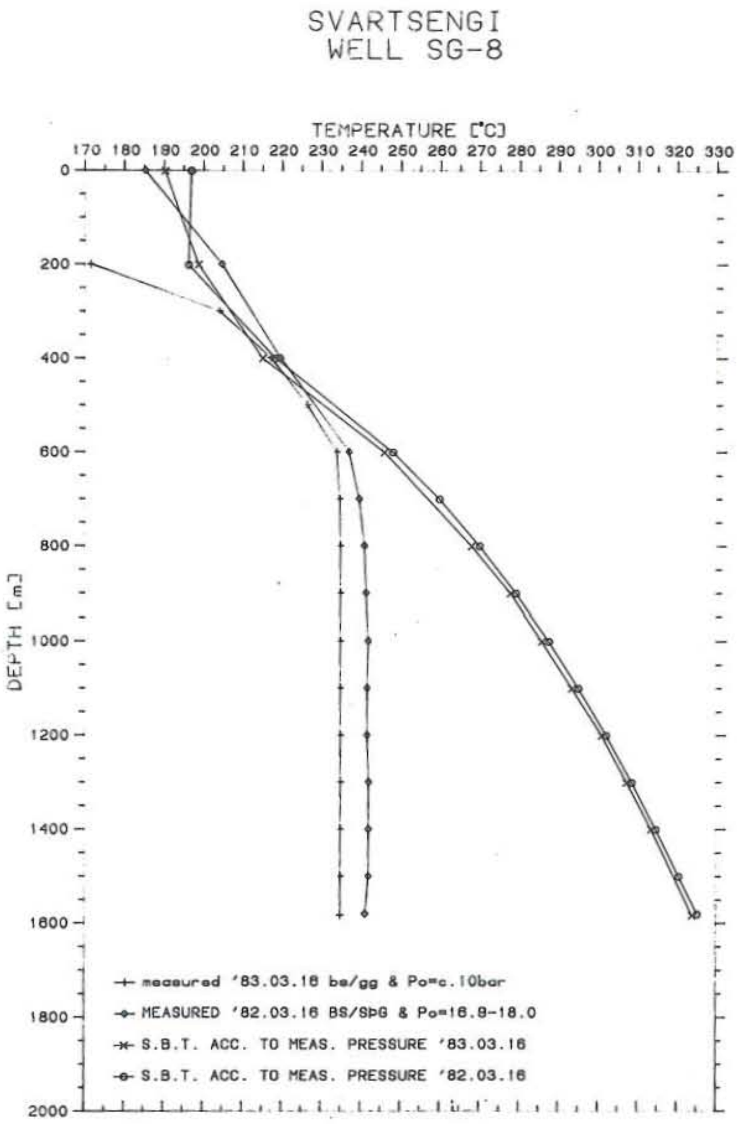

Fig.27 Svartsengi well SG-8. Temperature profiles in 1982 and 1983 with corresponding saturation profiles.

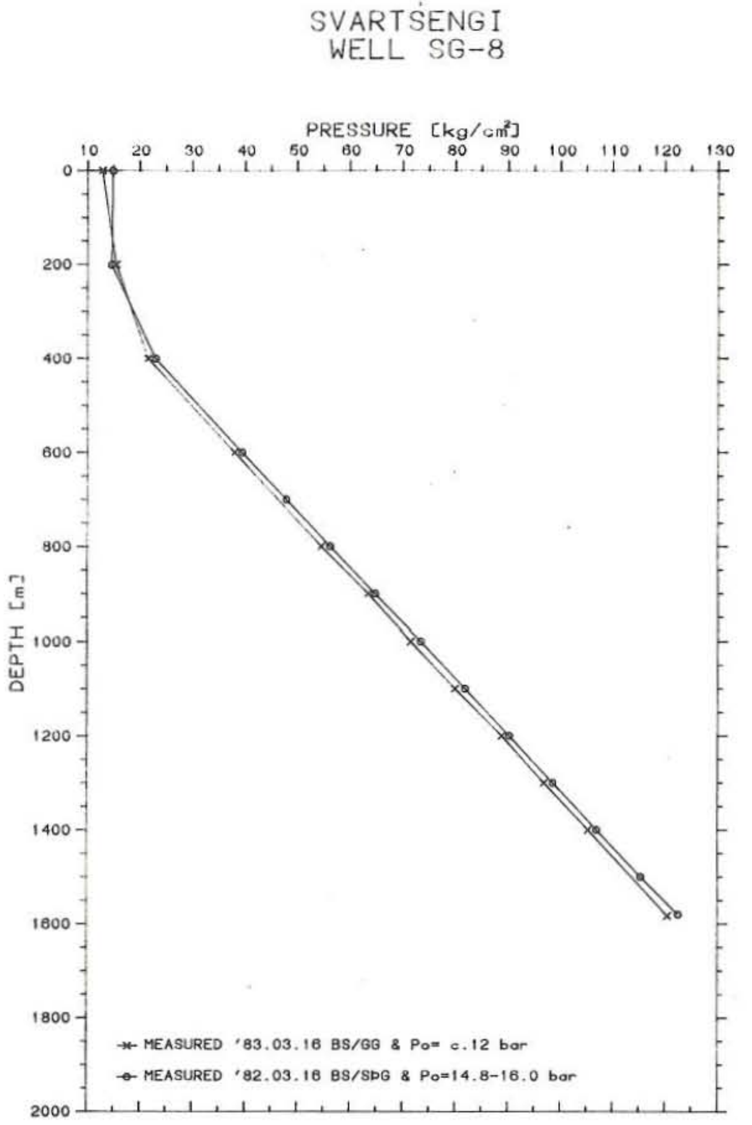

Fig.28 Svartsengi well SG-8. Pressure profiles in 1982 and 1983.

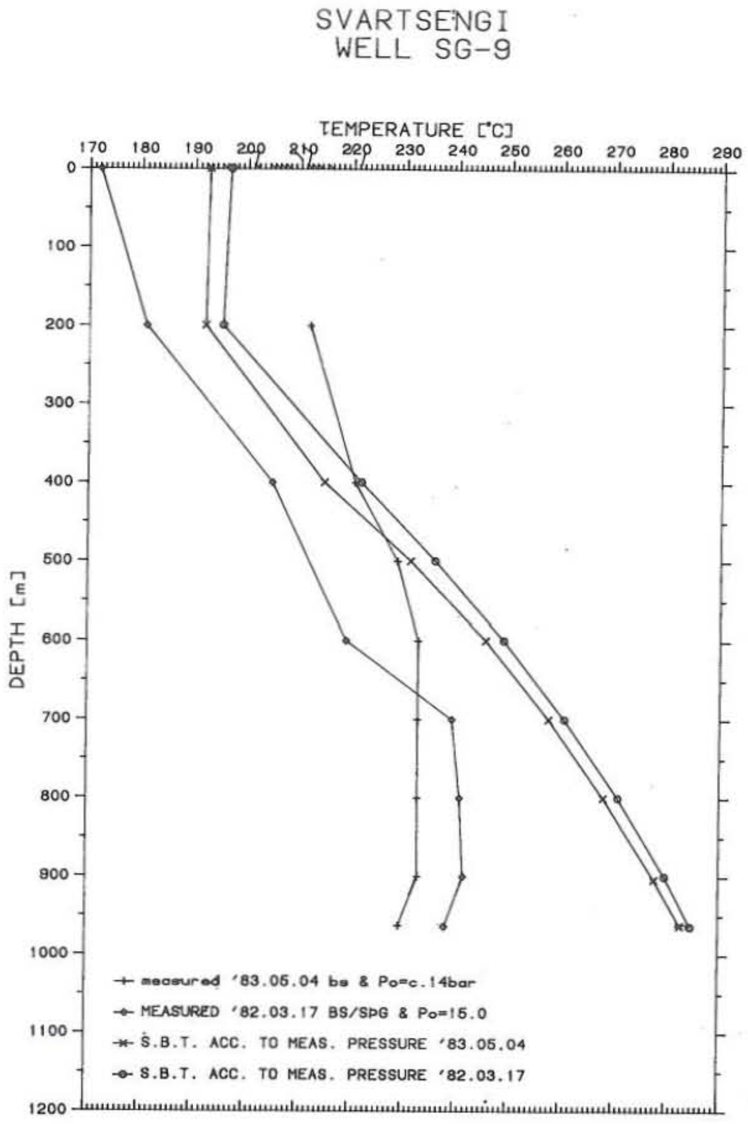

Fig.29 Svartsengi well SG-9. Temperature profiles in 1982, and 1983 with corresponding saturation curves.

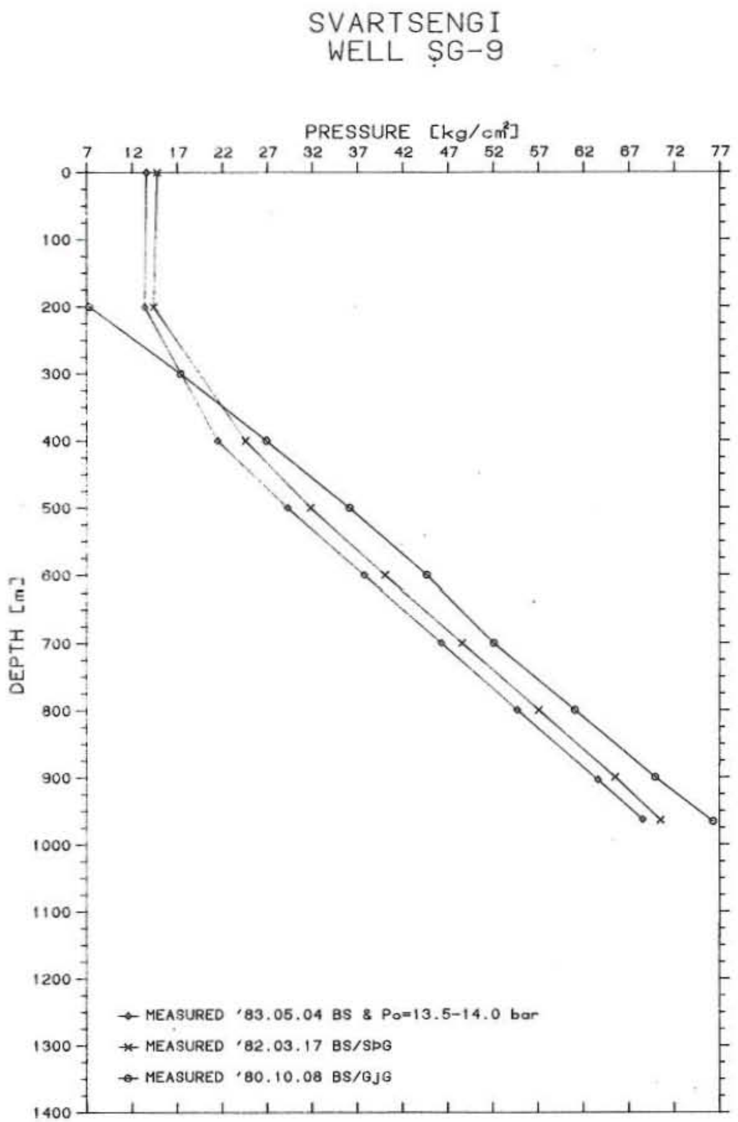

Fig.30 Svartsengi well SG-9. Pressure profiles in 1980, 1982 and 1983.

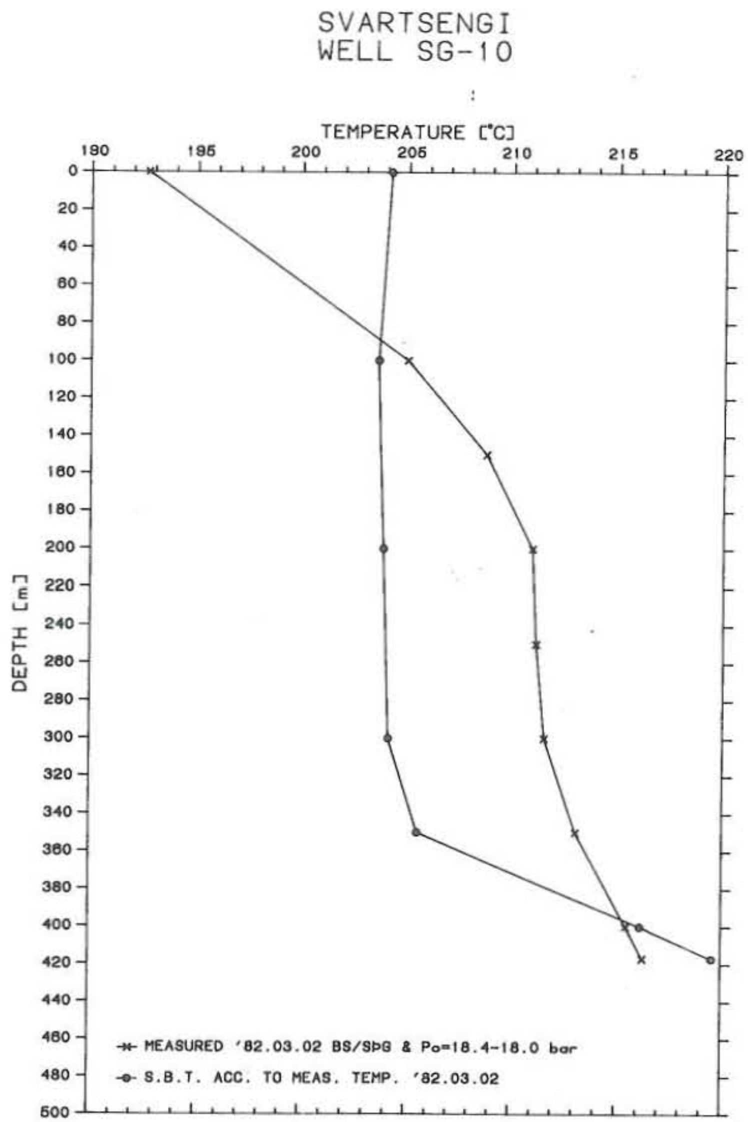

Fig.31 Svartsengi well SG-10. Temperature profile in 1982 and corresponding saturation profile.

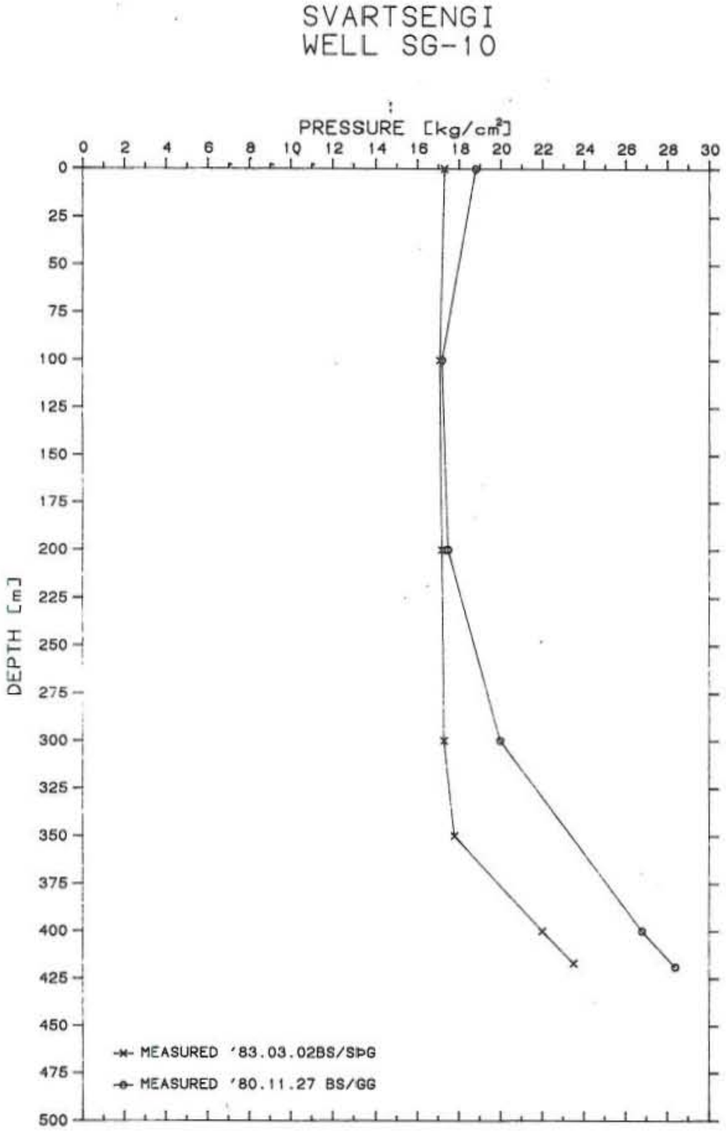

Fig.32 Svartsengi well SG-10. Pressure profiles in 1980 and 1983.

pressure profiles in Fig. 32. In 1980 a pure steam cap reaches down to approximately 300 m, but in 1983 the lower level of the steam cap is at least at 350 m depth (Fig. 32).

Well SG-11 is 1141 m deep. It has cooled down by about 13°C at depth between the dates '82.03.18 and '83.05.05 (Fig. 33). The boiling level in 1982 right after completion of the well was at a depth of 400 m, but due to the cooling of the reservoir fluid the boiling levelin 1983 is almost at the same level as in 1982 inspite of a drawdown in the reservoir during that time.

Well SG-12 was initially drilled as an reinjection well to a depth of 1467 m. Its flow has been tested and an experiment on injection has been carried out with this well. Between 1982 and 1983 (Fig 35) a cooling seems to be taking place in the well, but the experiment on injection might have disturbed these measurements. The drawdown in the reservoir at this place seems to be of the order of 7 bars between 1982 and 1983 (Fig. 36). No boiling effects have been detected in this well.

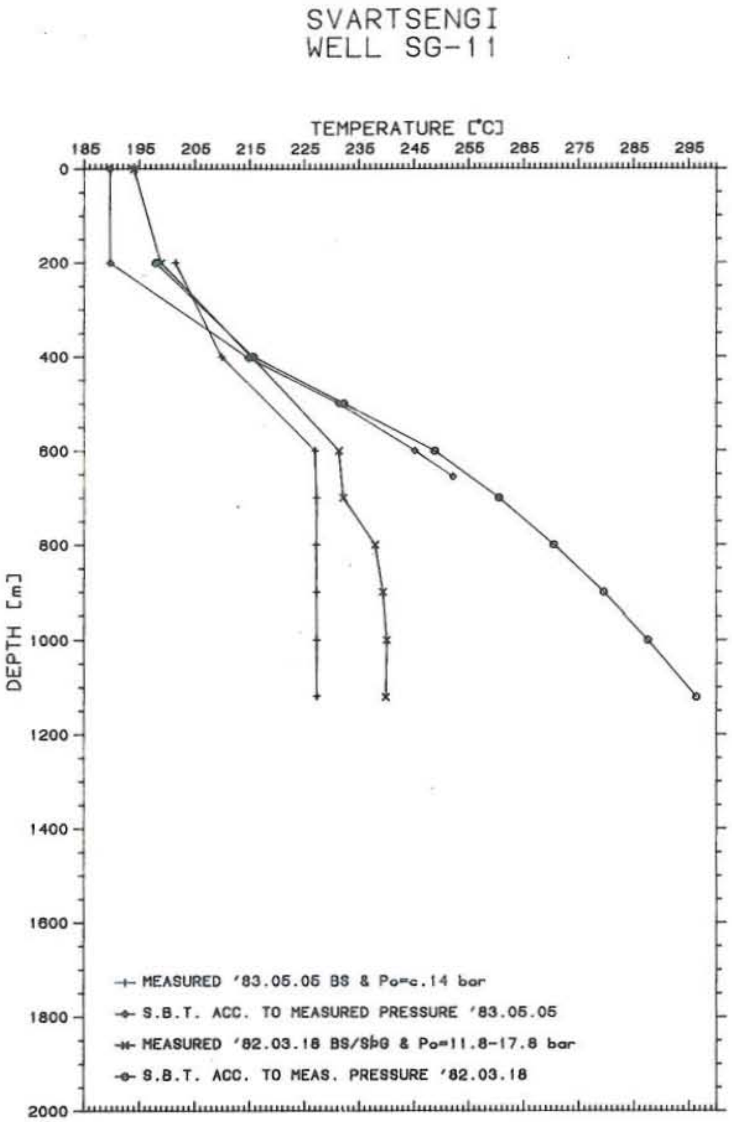

Fig.33 Svartsengi well SG-11. Temperature profiles in 1982 and 1983 with corresponding saturation profiles.

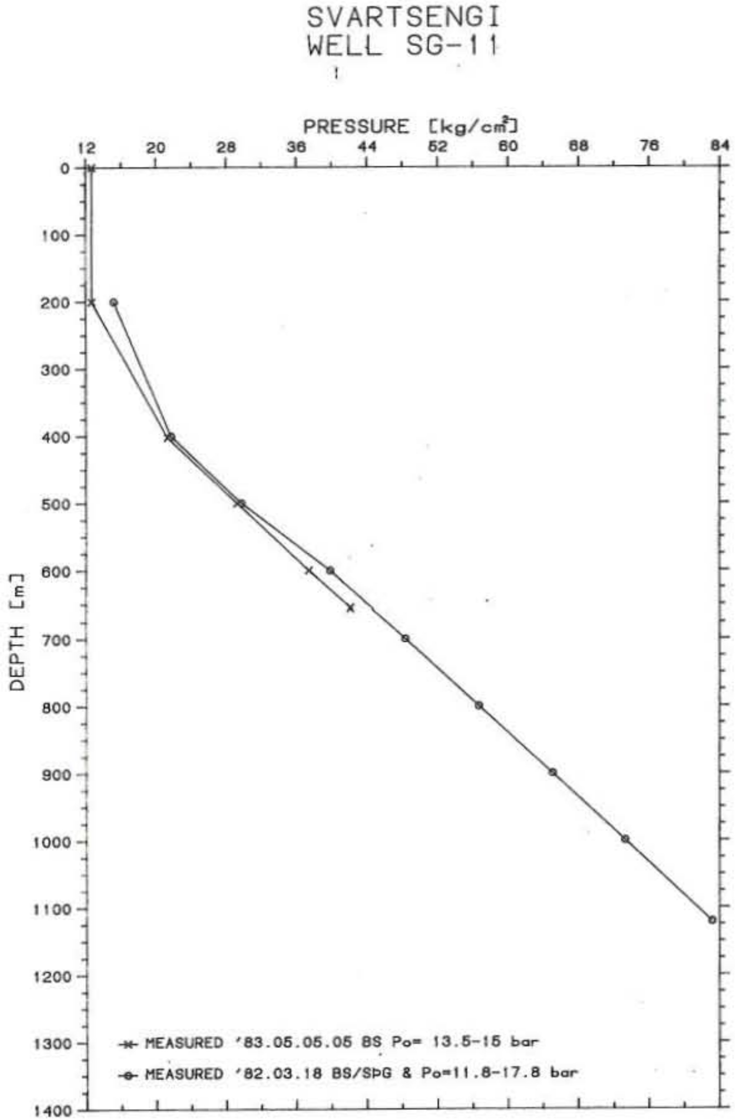

Fig.34 Svartsengi well SG-11. Pressure profiles in 1982 and 1983.

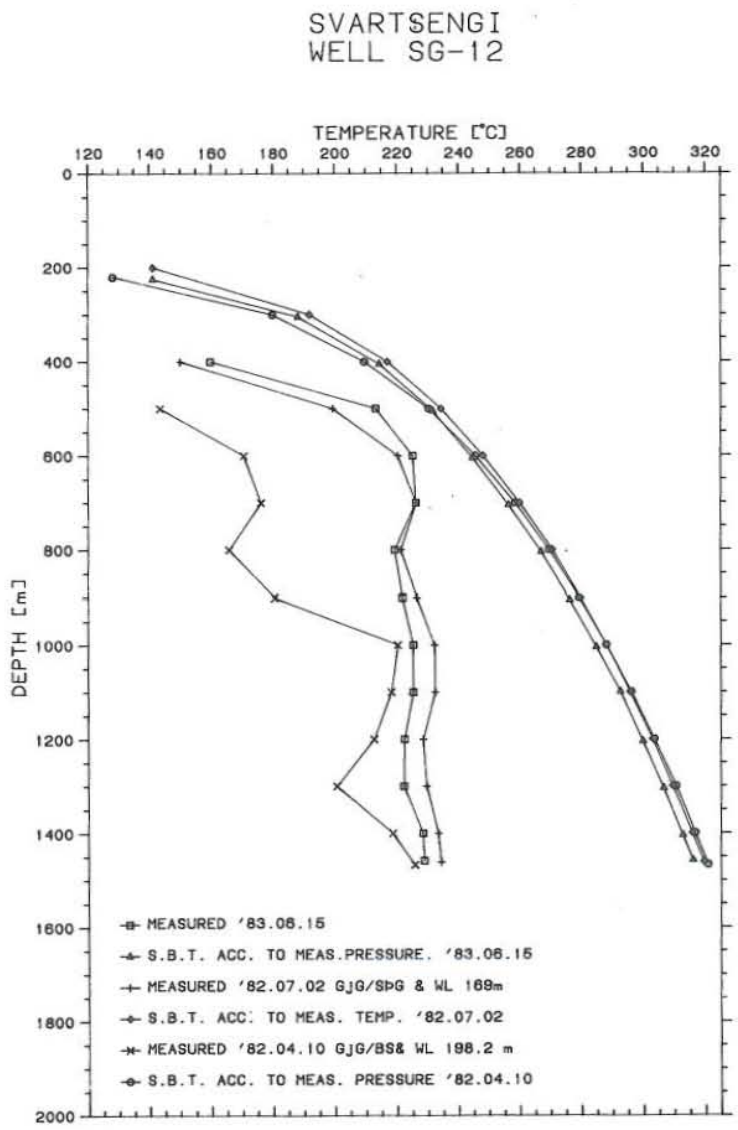

Fig.35 Svartsengi well SG-12. Temperature profiles in 1982 and 1983 with corresponding saturation profiles.

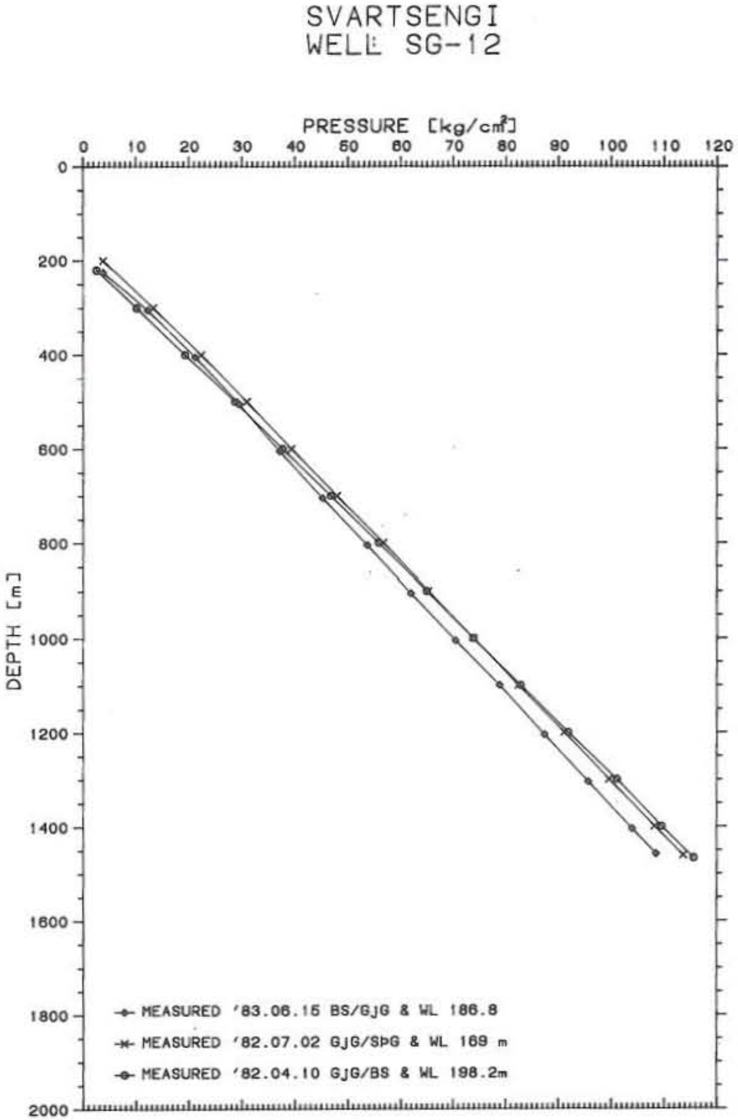

Fig.36 Svartsengi well SG-12. Pressure profiles in 1982 and 1983.

5 SPATIAL DISTRIBUTION OF TEMPERATURE AND PRESSURE IN THE RESERVOIR

Location of wells and cross-sections is shown in relation with the location of the power plant in Svartsengi (Fig. 37). In order to show both the vertical and the horizontal distribution of the temperature, several cross-sections have been selected together with planar maps at various depths.

5.1 Vertical distribution

The wells in Svartsengi are more or less alligned in the SW-NE direction. Cross-section A will therefore be the principal one (Fig. 37). In addition five other cross-sections have been selected in order to see better the three dimensional variation of temperature in the geothermal system. We will now discuss each cross-section individually.

5.1.1 Cross-section A

The location is shown in Fig. 37, and the temperature distribution is shown for 1976 (which is close to the initial state of the reservoir), 1982 and 1983. Before exploitation, temperatures in excess of 240°C were found in wells SG-4 and SG-5 (Fig. 38), but in 1982 such temperatures were only observed in the SW part of the field in wells SG-11, 9, 8 and 7 (Fig. 39). In 1983 temperatures of 240°C cannot be found in the reservoir (Fig. 40). The hottest part of the reservoir at this time is 230-235°C. There seems to be a temperature inversion in the SW part of the field, and the hottest part at large depth seems to be around wells SG-5 and SG-6. The disappearance of the 240°C fluid can be associated with the utilization of the field. Production started from the northern part of the field, and up to 1981, the production was only from wells SG-3, 4, 5 and 6. This means that the mass taken out of the

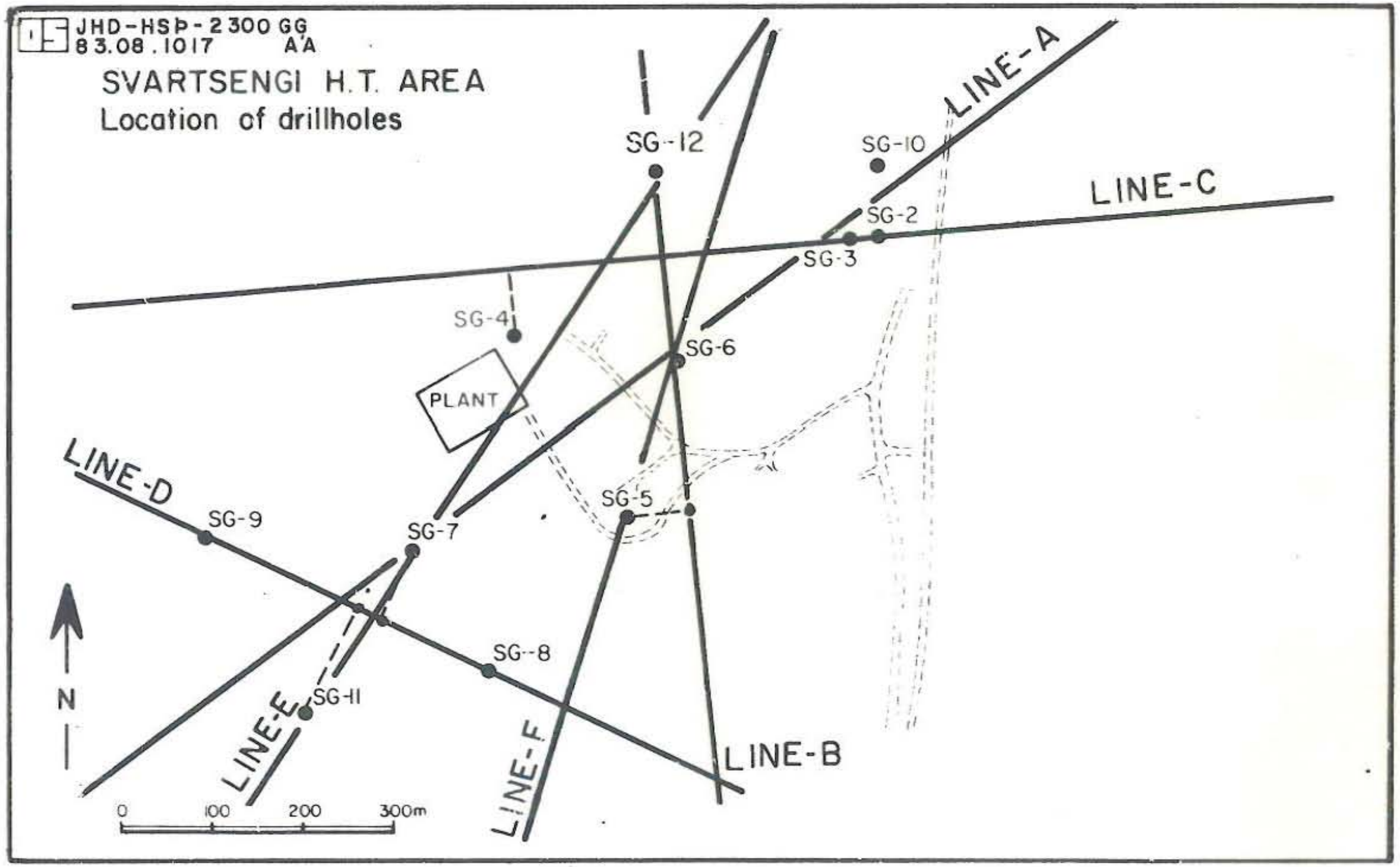

Fig.37 Location of cross-sections A, B, C, D, E, and F.

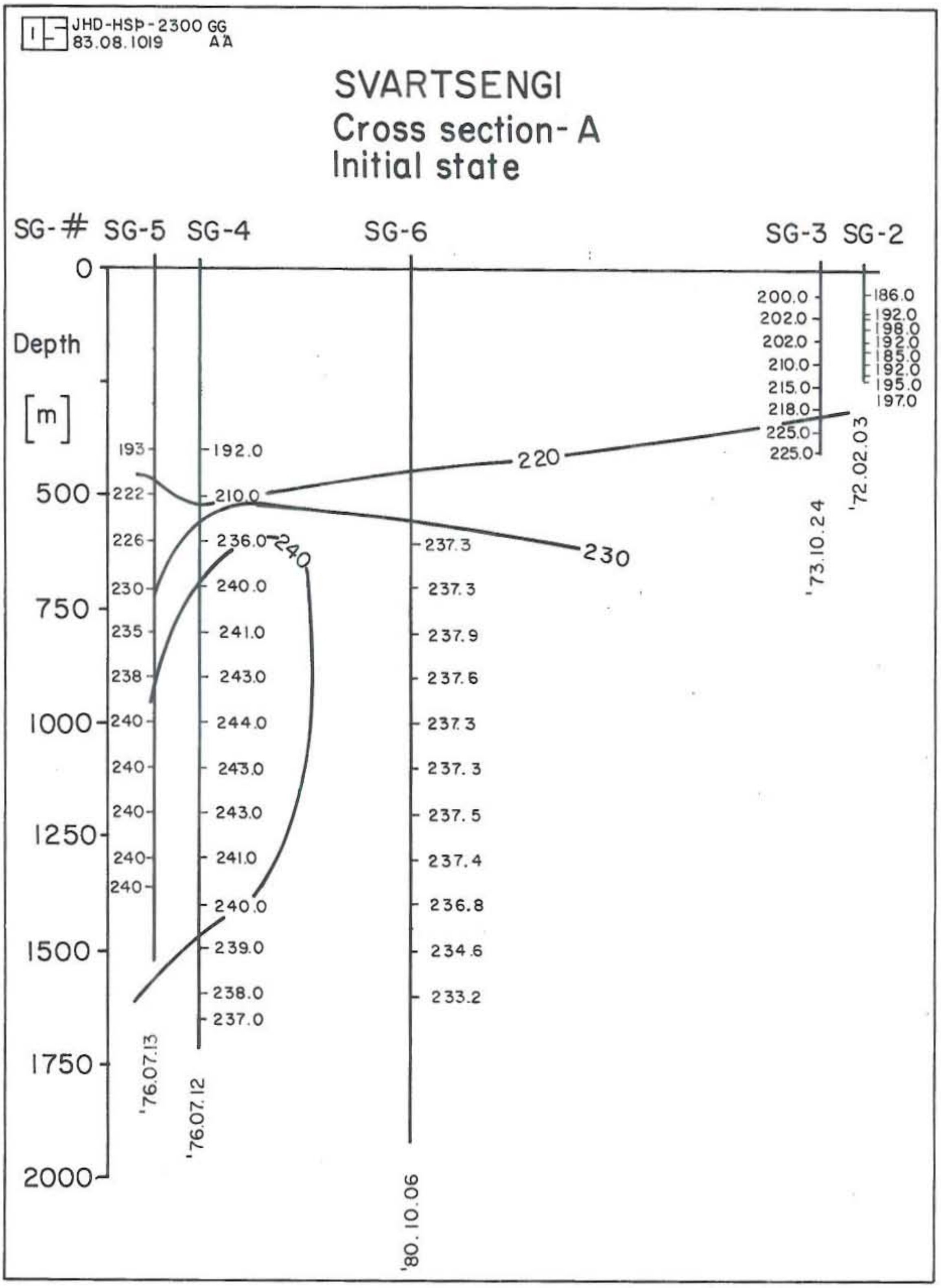

Fig.38 Cross-section A. Initial temperature distribution.

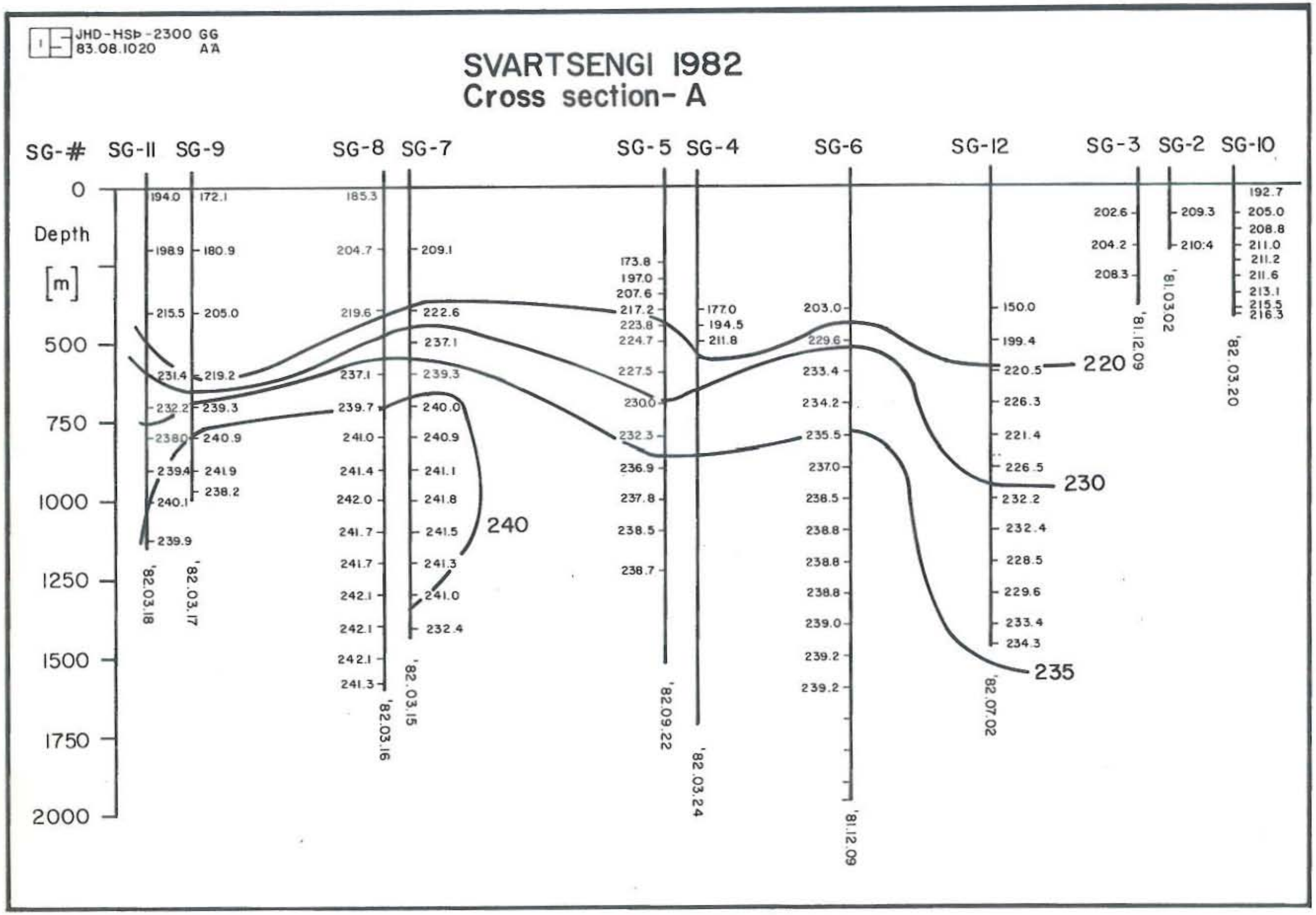

Fig.39 Cross-section A. Temperature distribution in 1982.

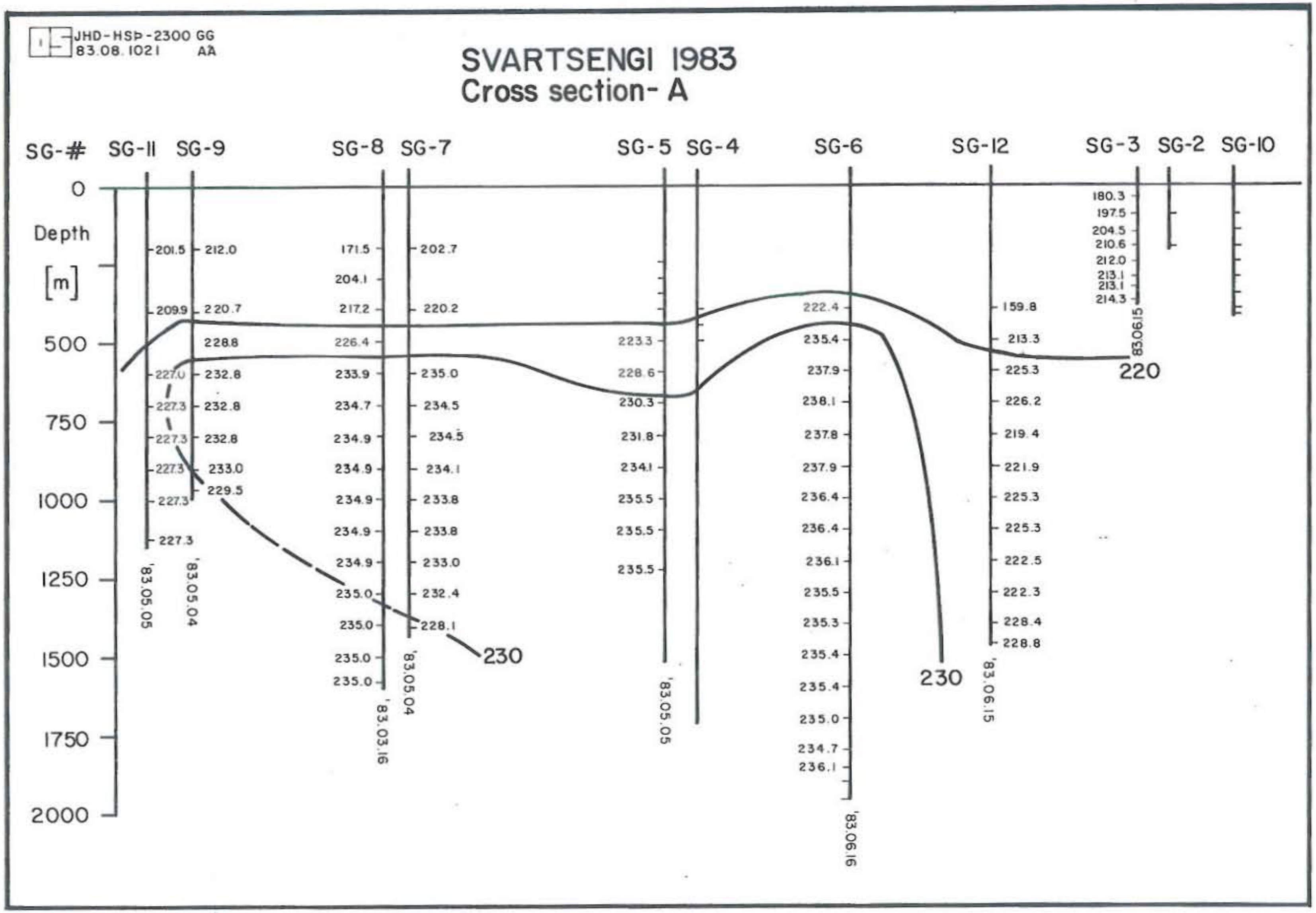

Fig.40 Cross-section A. Temperature distribution in 1983.

reservoir during 1976-1981 is from wells which are to the northeast of the power plant. On the other hand the production from wells to the southwest started in 1981 and has been of the order of 300 kg/s since then (Fig. 6). In 1982 the 240°C hot fluid is not found in wells SG-4 and SG-5 (Fig. 38), but is measured in wells in the SW part of the field (Fig. 39). This part of the reservoir had at that time been in production for about a year. We are therefore tempted to assume that temperatures up to 240°C were found in this part of the reservoir prior to production. In 1983, however, the whole reservoir has a temperature lower than 240°C (Fig. 40). The temperature distribution in 1983 (Fig. 40) suggests the upflow zone in the system to be near to wells SG-5 and SG-6 and further suggests there is a lateral flow at 600-800 m depth from wells SG-5 and SG-6 towards wells SG-9 and SG-11.

5.1.2 Cross-section B

It is almost in the N-S direction (Fig. 37). It shows only three wells, namely SG-5, SG-6 and SG-12. The temperature distribution for 1982 is shown in Fig. 41 and for 1983 in Fig. 42. These figures are in agreement with the hypothesis that the upflow zone can be near wells SG-5 and SG-6. The cooling observed in well SG-12 can be due to the reinjection experiment performed in September and October 1982, or alternatively increased cold recharge from the north.

5.1.3 Cross-section C

It is almost in E-W direction in the northern part of the production field (Fig. 37). Only the initial temperature distribution is shown in Figure 43. This figure reflects the fact that the natural discharge to the surface is the boiling area around wells SG-2, SG-3 and SG-10. At shallow depth the temperature is higher there than elsewhere in the production field.

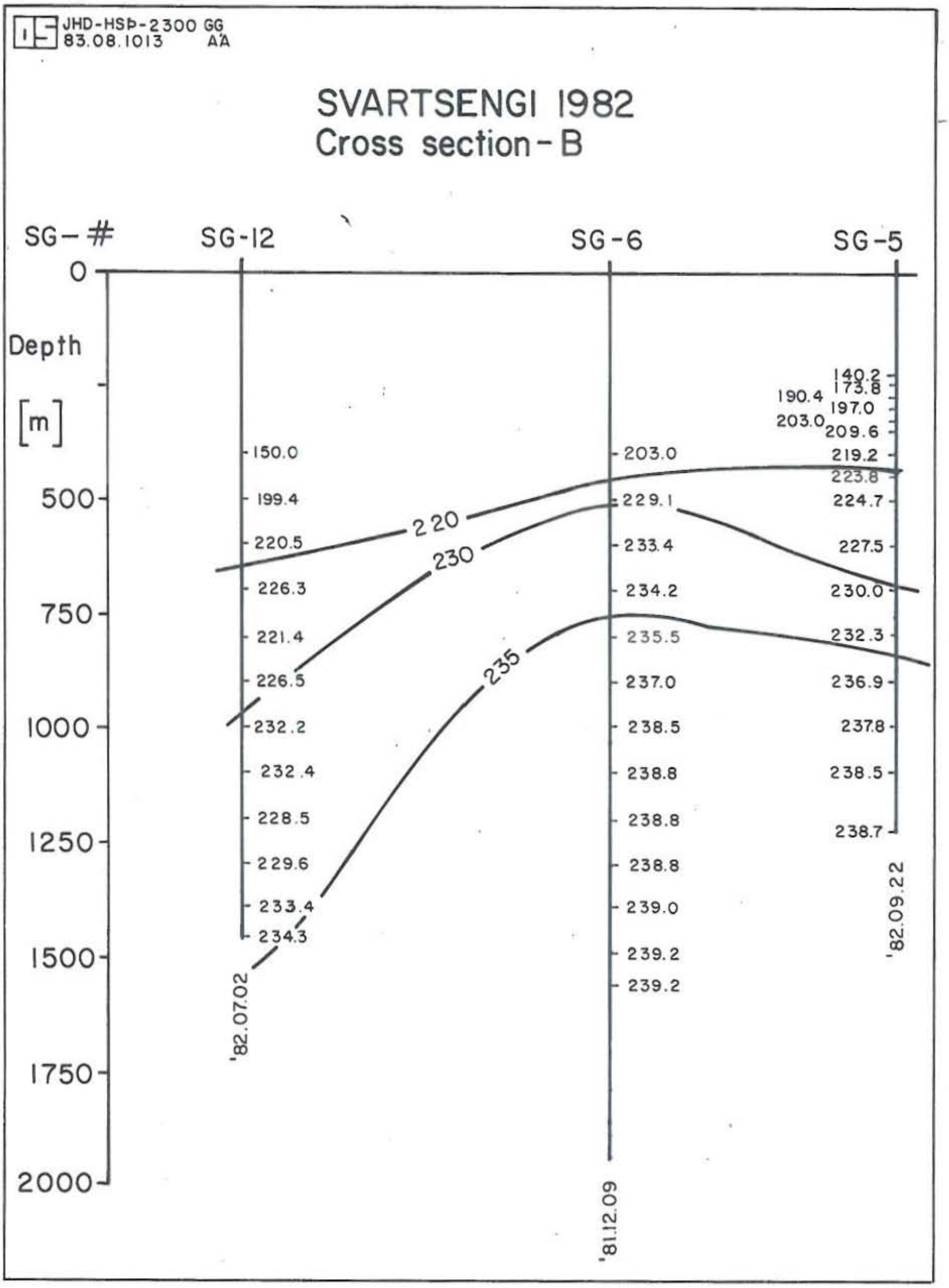

Fig.41 Cross-section B. Temperature distribution in 1982.

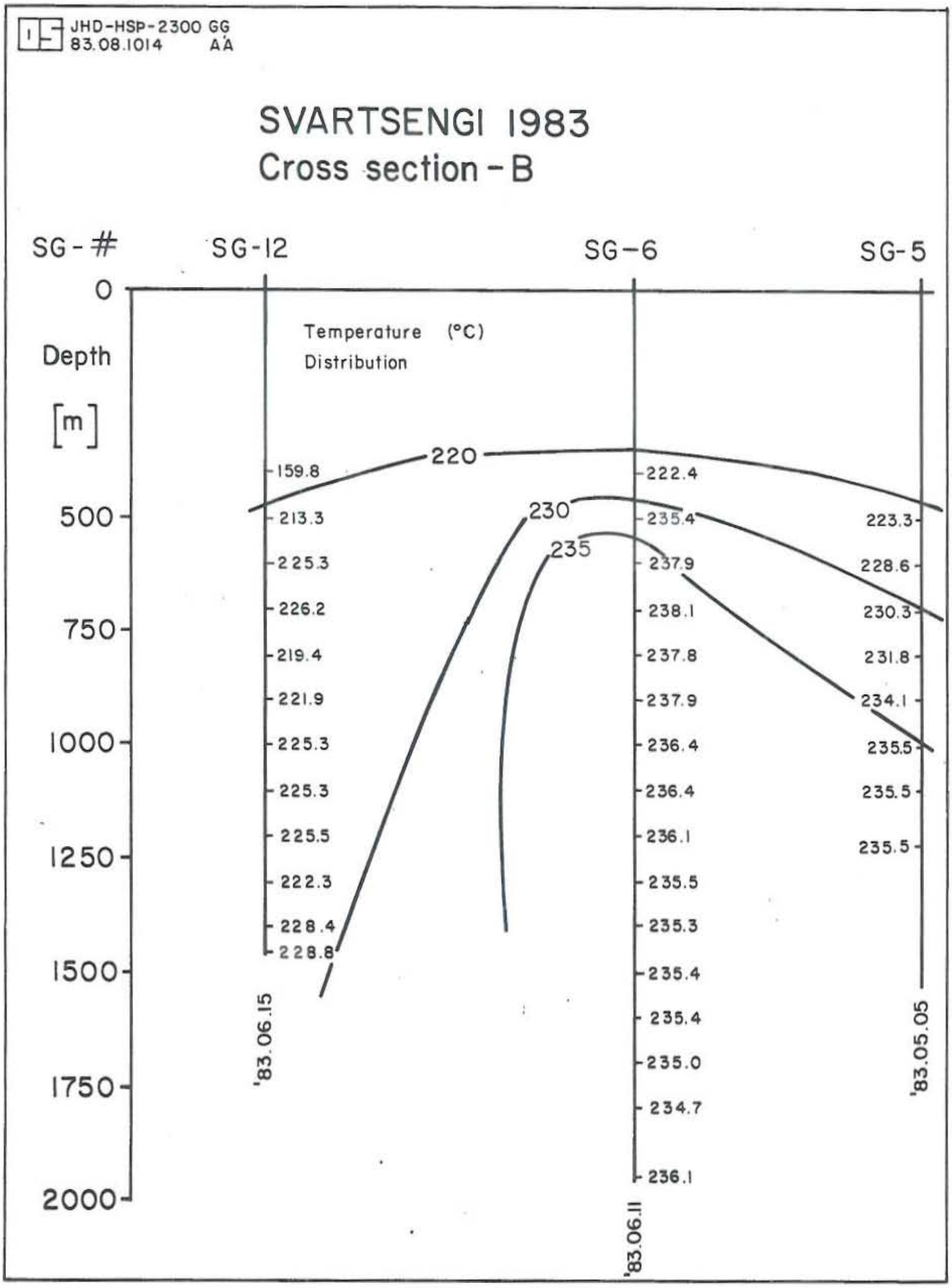

Fig.42 Cross-section B. Temperature distribution in 1983.

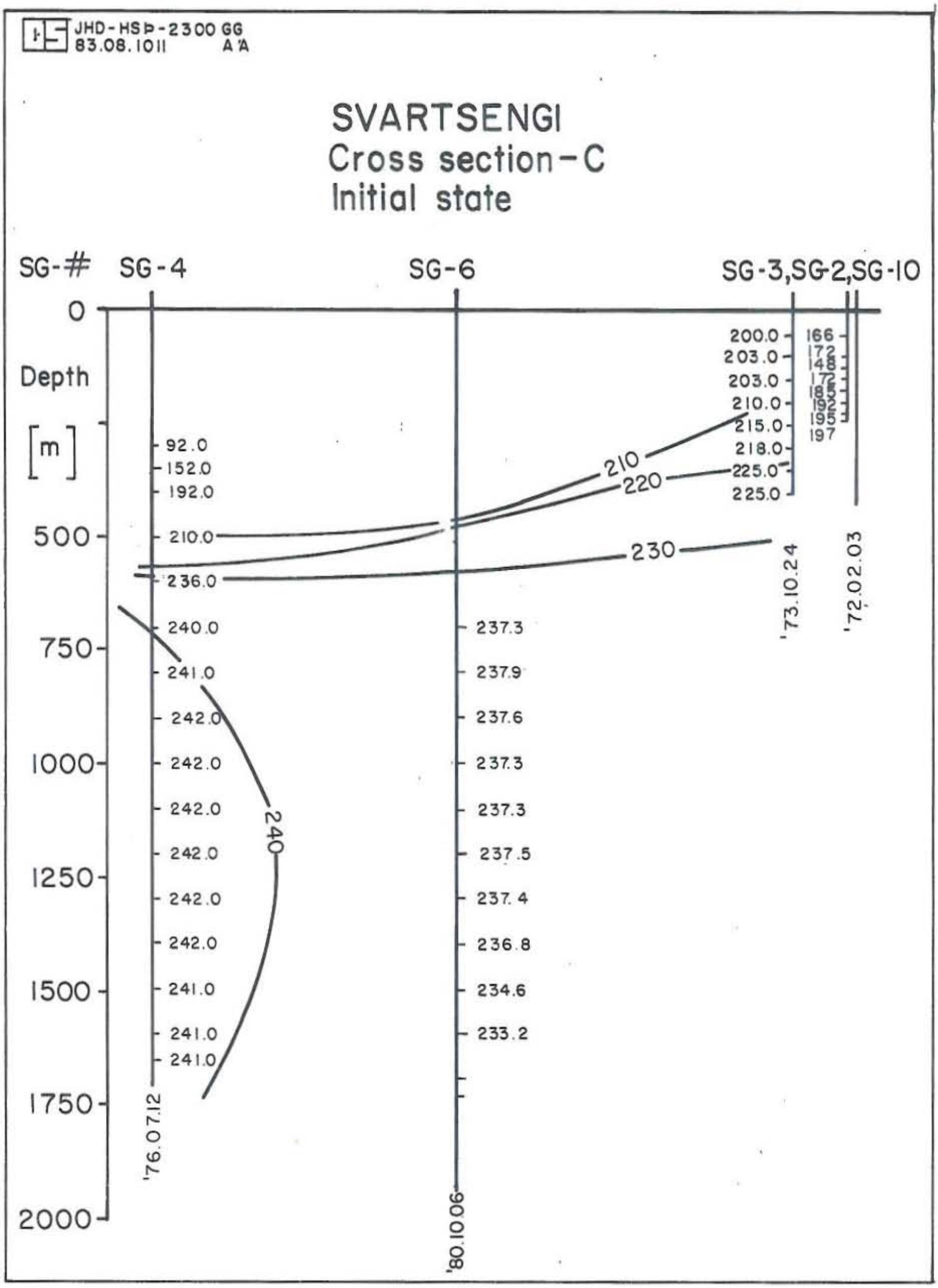

Fig.43 Cross-section C. Initial temperature distribution.

5.1.4 Cross-section D

It is an E-W section in the southern part of the production field (Fig. 37). The temperature distribution in 1982 is shown in Fig. 44 and the distribution in 1983 is shown in Fig. 45. Quite large temperature changes are taking place in this part of the reservoir during one year. In 1982 the temperatures are fairly uniformly distributed in this E-W cross-section. A possible temperature inversion is noted in wells SG-7 and SG-11. The temperature distribution of 1983 suggests that substantial cooling has taken place, particularly in well SG-11, and this raises the question whether this cooling is through well SG-11. As seen in Fig. 33 the possibility of downflow in 1983 in well SG-11 cannot be ruled out from the present available data. On the other hand, the temperature profile from 1982 does not indicate a downward flow at that time. Temperature inversions seem to be present in wells SG-7 and SG-9 in 1983 and the temperatures in these wells are in general 7-10°C colder than in 1982. The cooling in well SG-11 is 13°C between 1982 and 1983.

The lower end of the cemented casing in SG-11 is at 582 m depth, and a large acquifer was noticed during drilling at 604 m depth. It is possible that a downflow from the acquifer at 604 m caused the cooling of the reservoir at larger depth. This situation might be at hand in some other wells in this part of the field. The temperature profile in well SG-8 from '83.03.16 (Fig. 27) is in an agreement with an internal downflow in that well.

5.1.5 Cross-section E

Its location is shown in Fig. 37, and the temperature distribution in 1982 and 1983 is shown in Fig. 46 and 47 respectively. The temperature variation within the reservoir in this SW-NE section is rather smooth at each

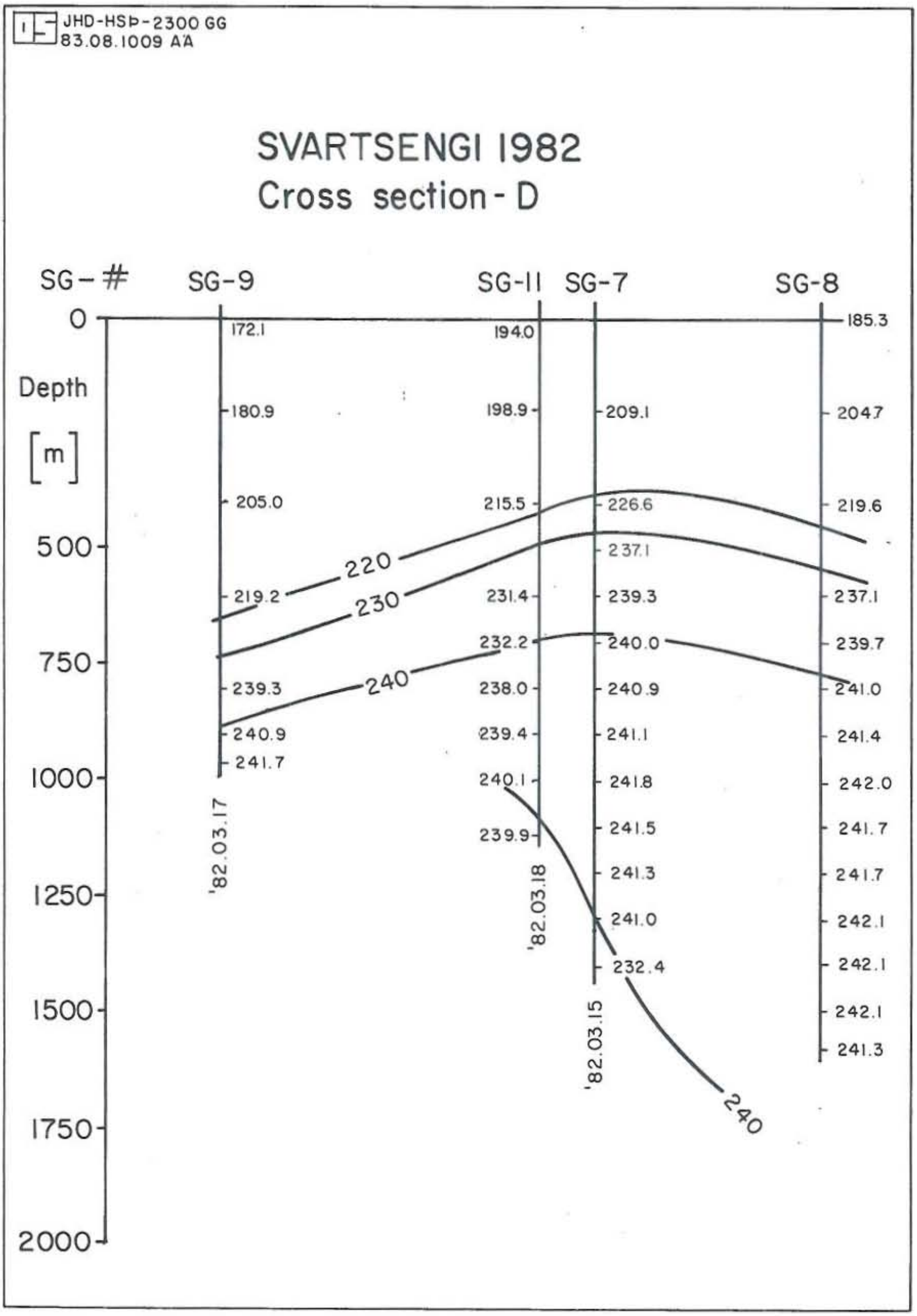

Fig.44 Cross-section D. Temperature distribution in 1982.

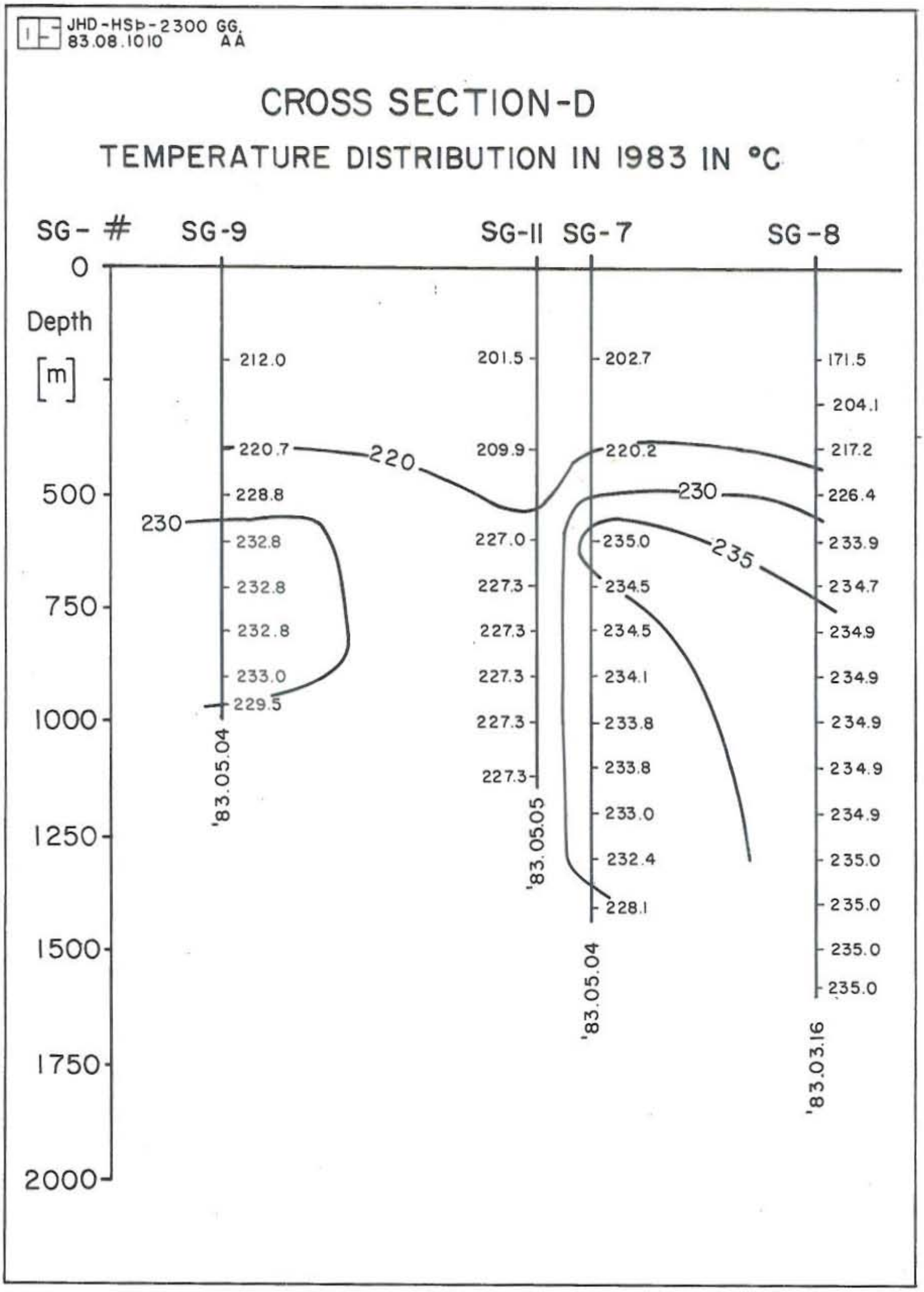

Fig.45 Cross-section D. Temperature distribution in 1983.

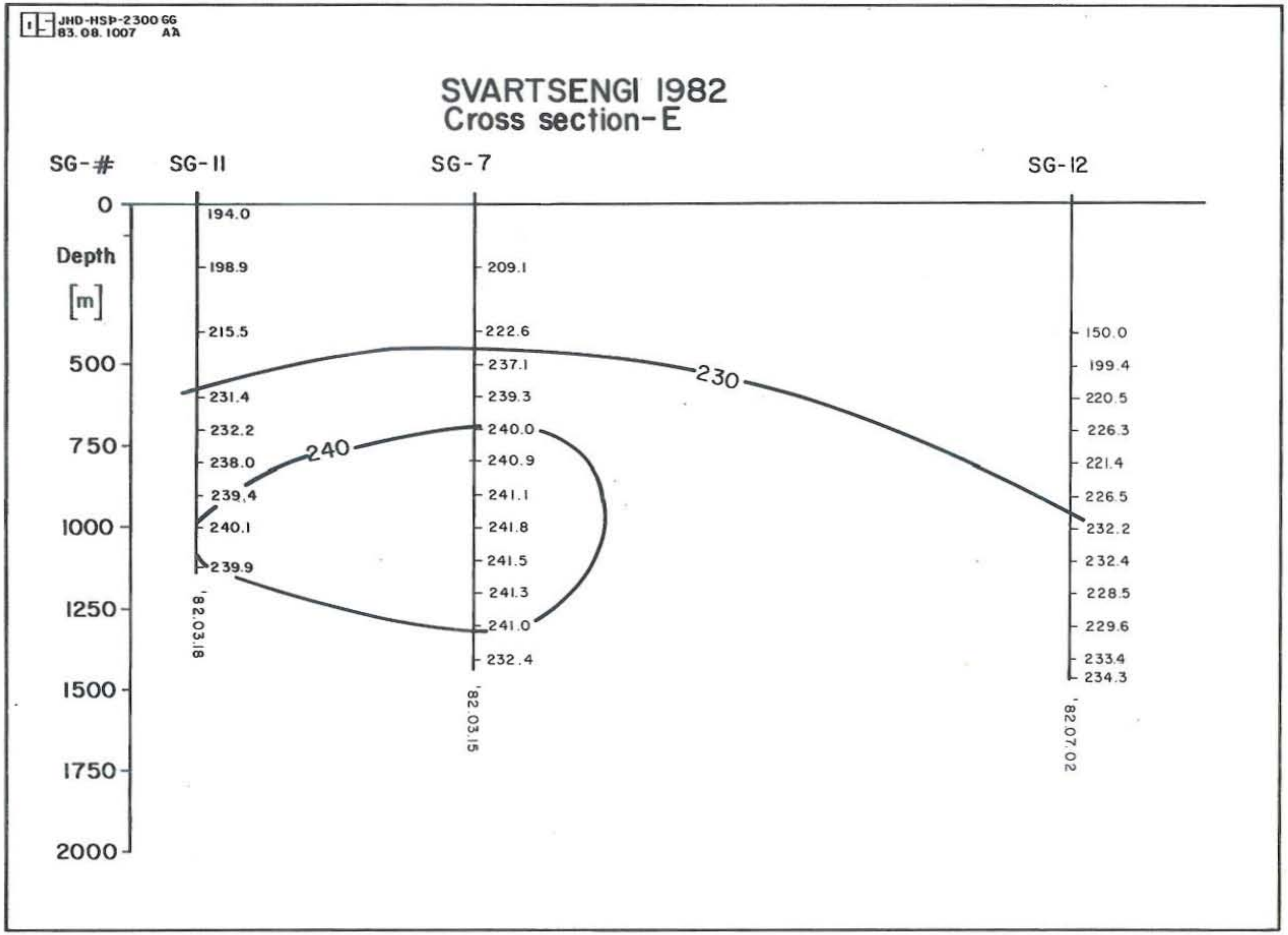

Fig.46 Cross-section E. Temperature distribution in 1982.

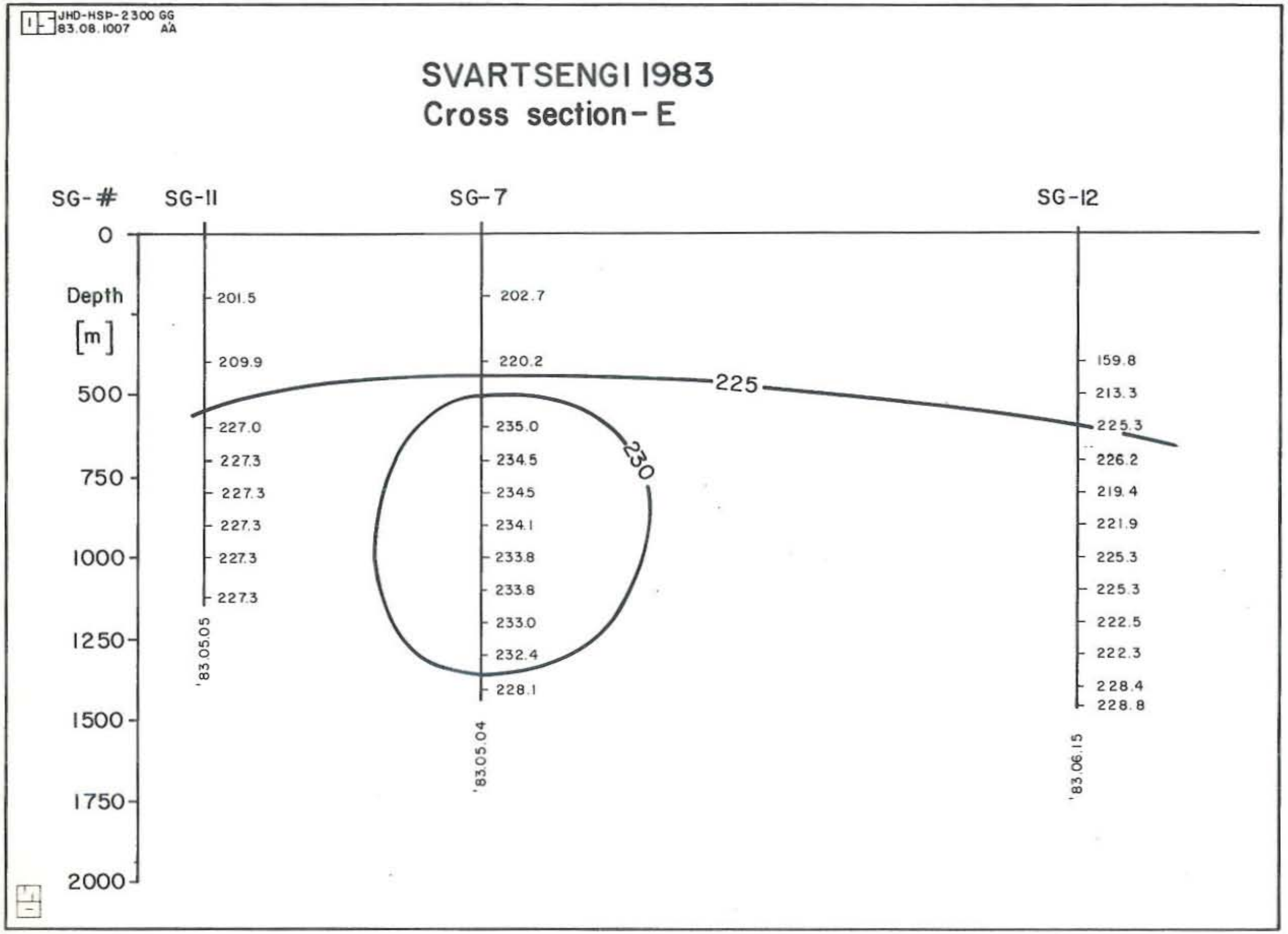

Fig.47 Cross-section E. Temperature distribution in 1983.

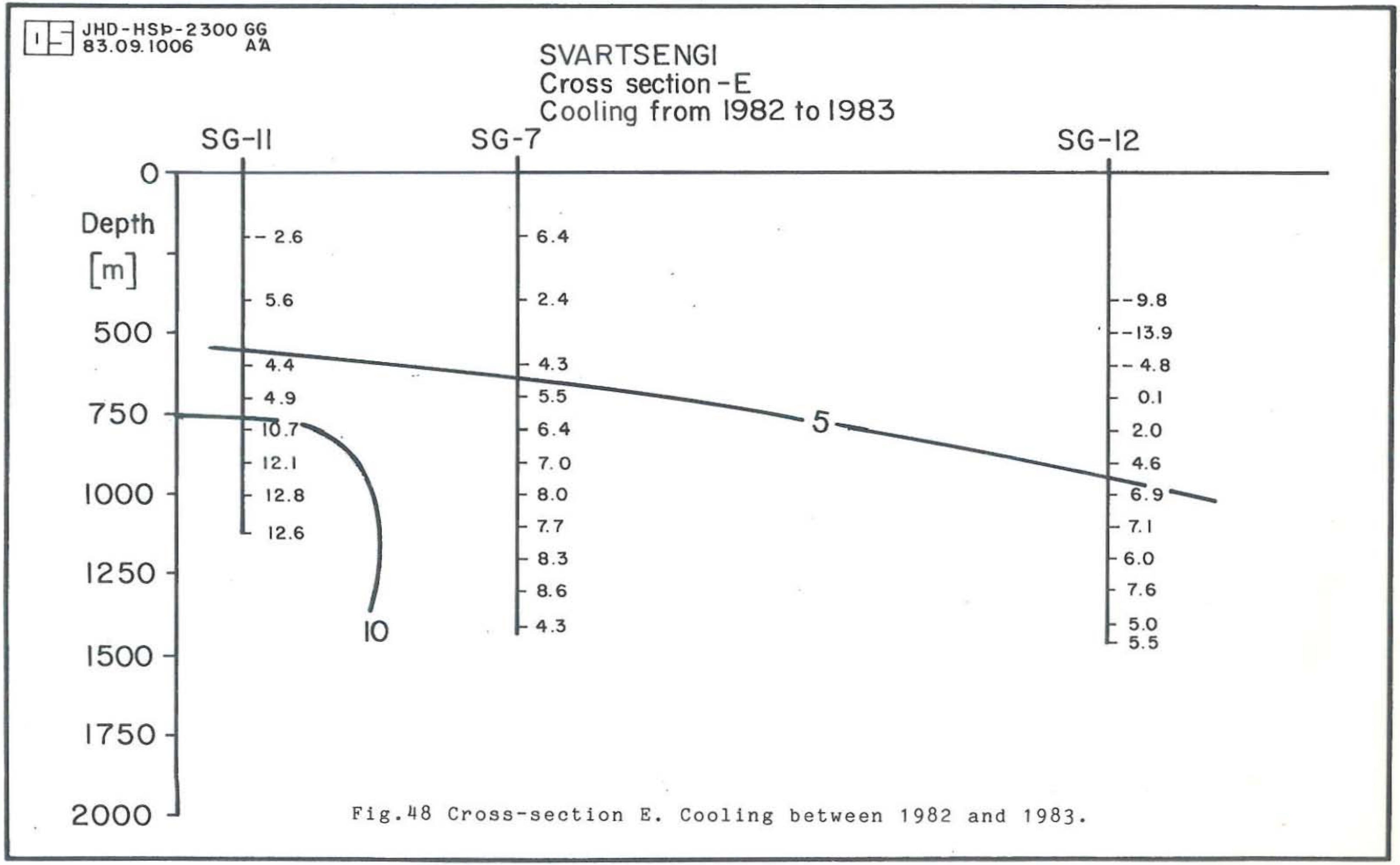

Fig.48 Cross-section E. Cooling between 1982 and 1983.

time, but the change in temperature from 1982 to 1983 is quite noticeable (Fig. 48). The cooling in all three wells is in excess of 5°C and at the bottom of well SG-11 the cooling is 13°C. Fig. 48 indicates that the cooling of the Svartsengi reservoir is quite general, though the largest cooling is observed in well SG-11. Furthermore, the largest cooling is observed at depth in the reservoir.

5.1.6 Cross-section F

It is almost parallel to cross-section E, but located farther east in the production field (Fig. 37). The temperature distributions for 1982 and 1983 are shown in Fig. 49 and 50 respectively. Temperature variations within the reservoir are quite moderate at each time, but a cooling of approximately 5°C is observed both in the southern and in the northern end of this cross-section, i.e. at wells SG-8 and SG-12. Temperatures in wells SG-5 and SG-6 have not changed significantly in the same time. Fig. 49 and 50 might indicate that a cold recharge is entering the geothermal reservoir both from the south and from the north. The effect of reinjection into SG-12 in 1982 might of course mask this picture. Significant cooling at large depth has not been confirmed in well SG-5 and SG-6. This can indicate that the upflow zone in the Svartsengi reservoir is located near these wells.

5.2 Horizontal distribution

The horizontal distribution of temperature has been studied at three levels, namely at 700, 1000 and 1100 m depth. This was done for 1978, 1982 and 1983. Data available from 1978 or before can be regarded as close to the initial state of the reservoir, but the situations in 1982 and 1983 reflect the effect of full production in the field.

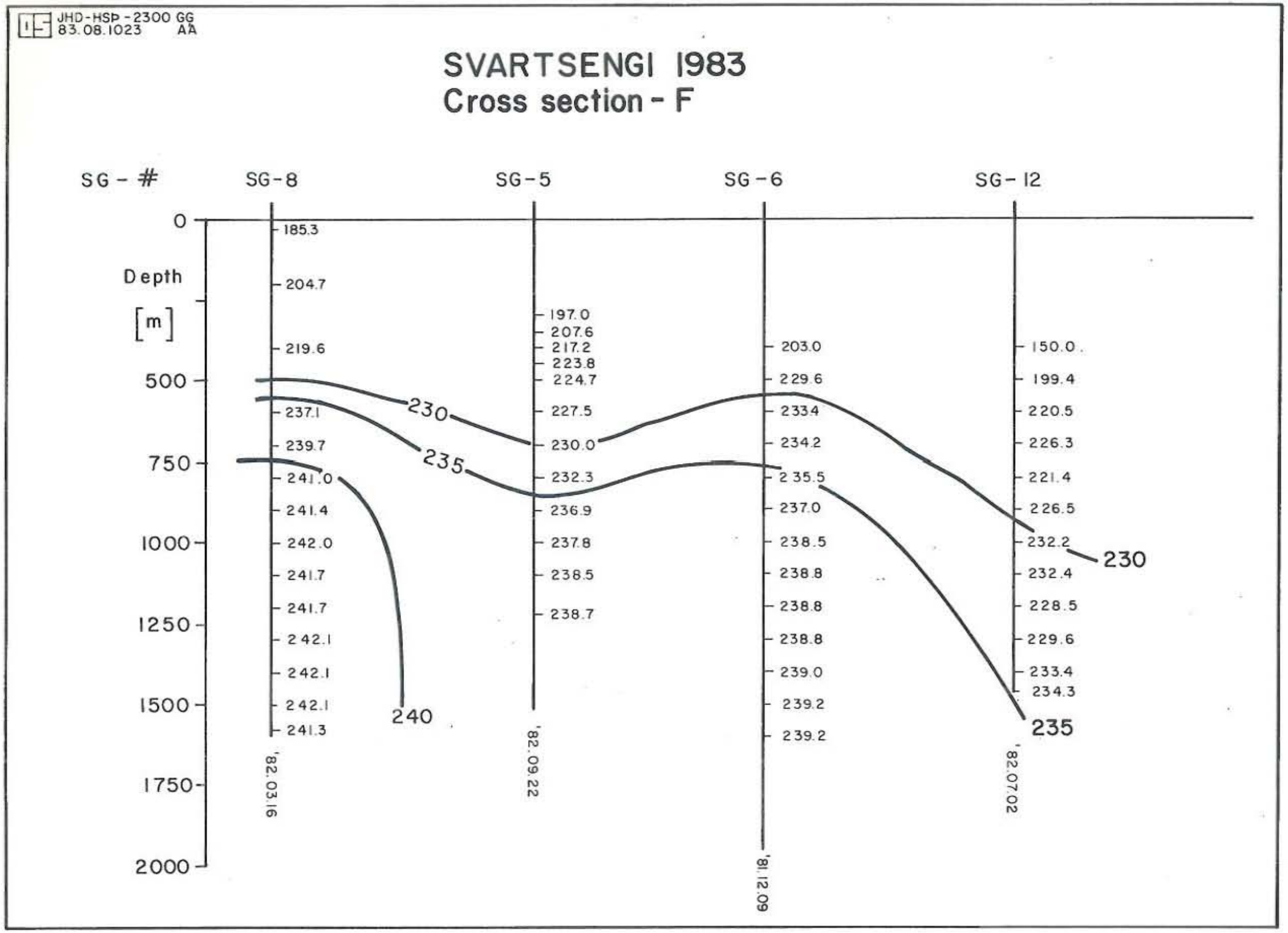

Fig.49 Cross-section F. Temperature distribution in 1982.

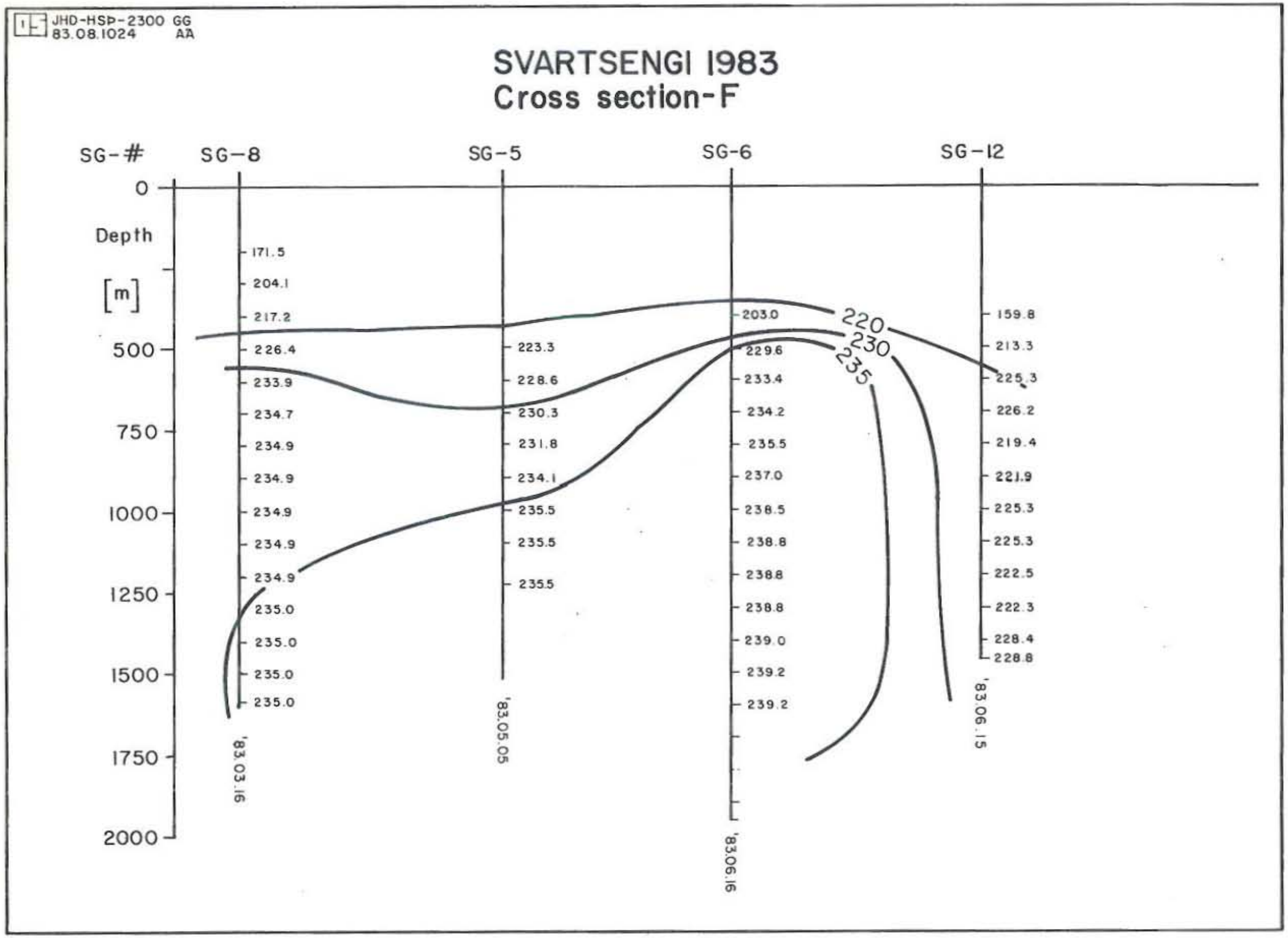

Fig.50 Cross-section F. Temperature distribution in 1983.

5.2.1 Distribution at 700 m

The temperature distribution in 1978, 1982 and 1983 are shown in Figures 51, 52 and 53. In the beginning of production in 1978 for well SG-4 and in 1982 for wells SG-7, SG-8 and SG-9, temperatures close to 240°C are observed at this depth. In 1983 the highest temperatures at this level are approximately 235°C. The level at 700 m depth is selected here to represent the top of the geothermal reservoir in Svartsengi.

5.2.2 Distribution at 1000 m

This level is considered to represent the mean level in the Svartsengi reservoir. Temperature distributions in 1978, 1982 and 1983 are shown in Fig. 54, 55 and 56. In the initial state (Fig. 54) temperatures of 240°C can be expected in wells SG-4 and SG-5, and most probably also to the SW of these wells. In 1982 the hottest part of the reservoir is in the south where 240°C is still recorded in wells SG-7, SG-8 and SG-11 (Fig. 55). One year later the hottest place in the reservoir is in the SE and the temperature there is approximately 235°C.

5.2.3 Distribution at 1100 m

This level was chosen in order to represent the deepest common level in the production interval of the reservoir. Due to the different depths of the production wells, it was necessary to select a level where all wells can be represented. The temperature distributions at this level for the years 1978, 1982 and 1983 are shown in Fig. 57, 58 and 59. The picture obtained is almost identical to the changes observed at 1000 m depth. The hottest part of the reservoir in 1983 is the eastern part including wells SG-8, SG-5 and SG-6. From these considerations and others

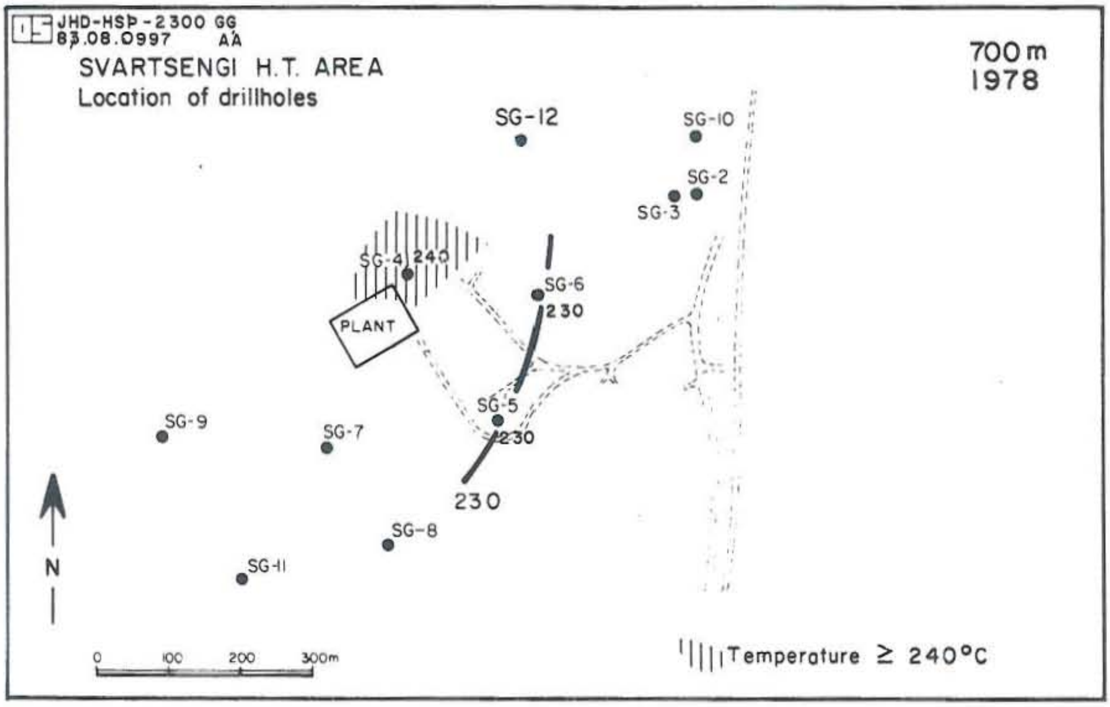

Fig.51 Temperature distribution at 700 m depth in 1978.

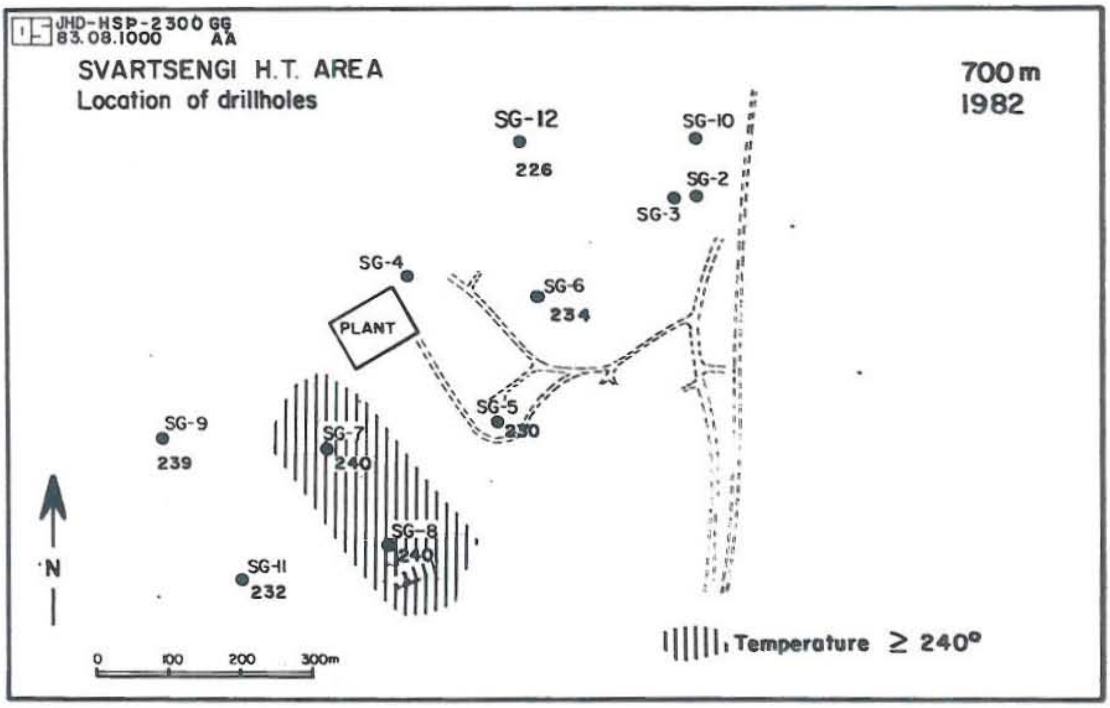

Fig.52 Temperature distribution at 700 m depth in 1982.

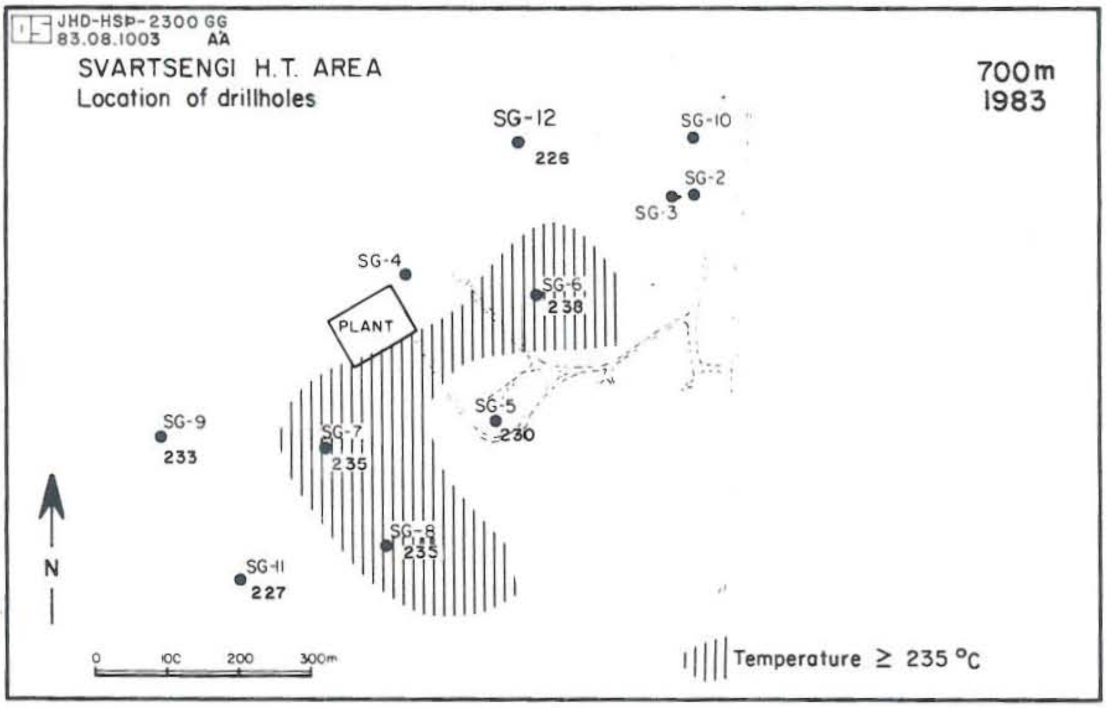

Fig.53 Temperature distribution at 700 m depth in 1983.

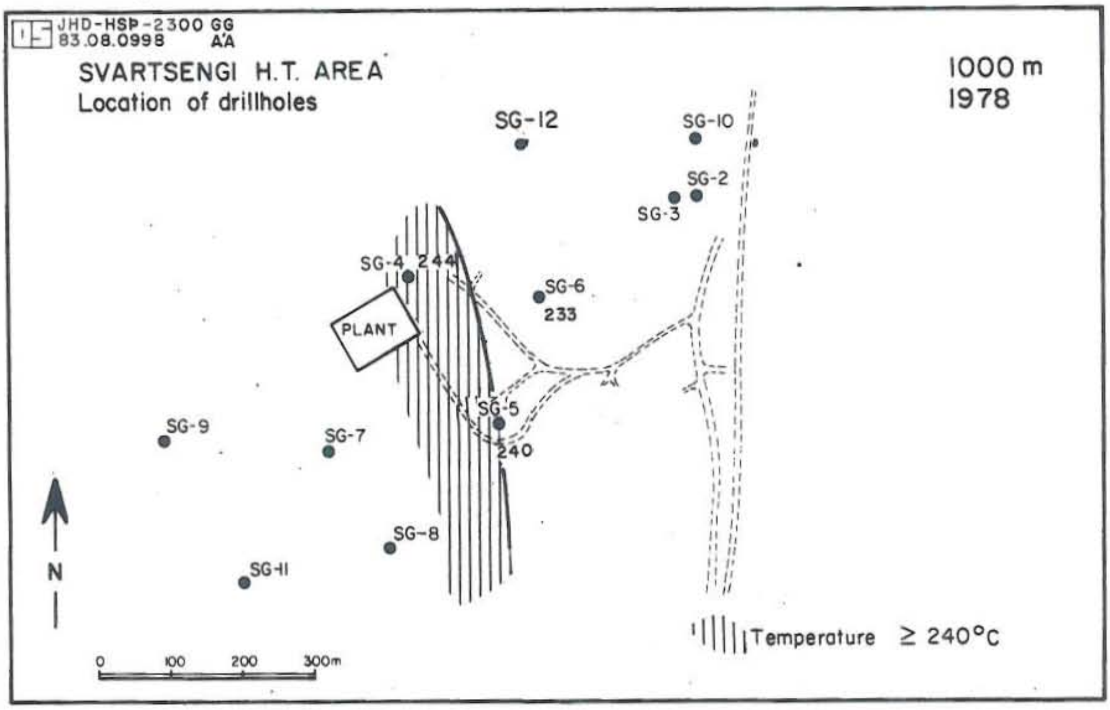

Fig.54 Temperature distribution at 1000 m depth in 1978.

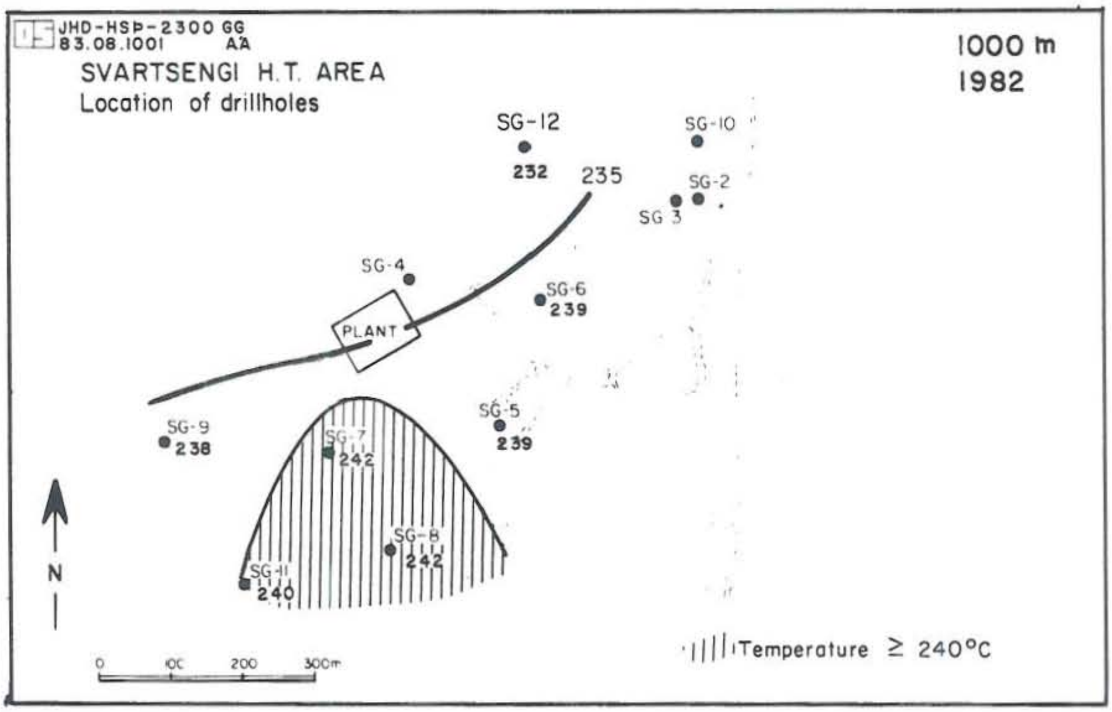

Fig.55 Temperature distribution at 1000 m depth in 1982.

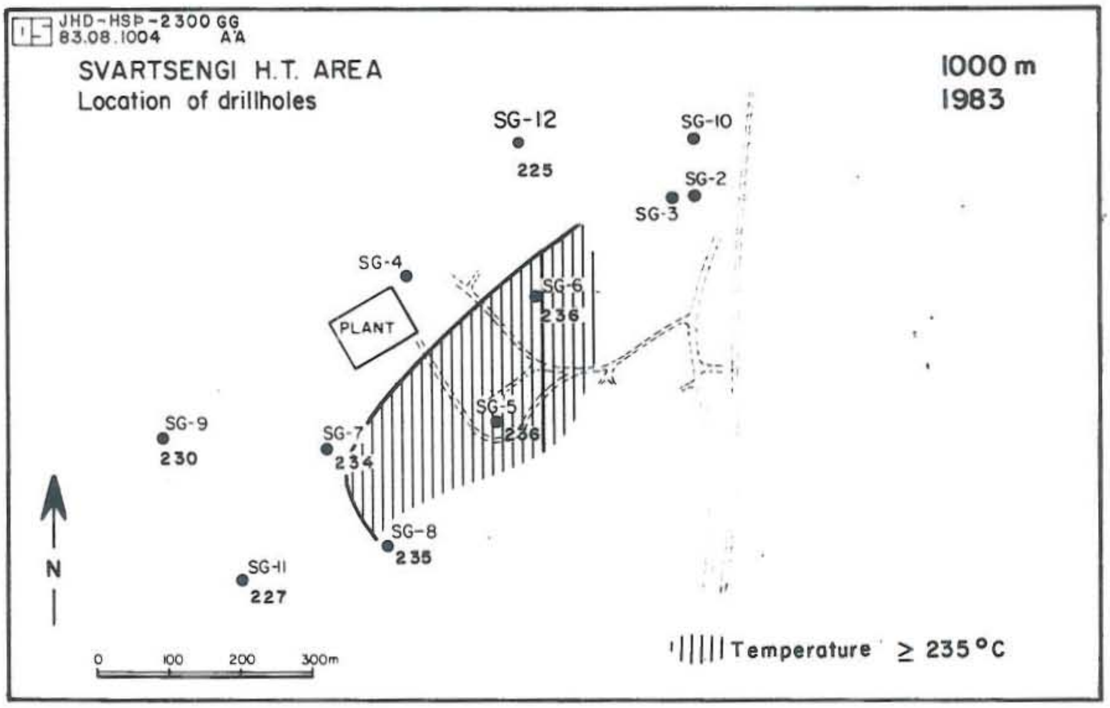

Fig.56 Temperature distribution at 1000 m depth in 1983.

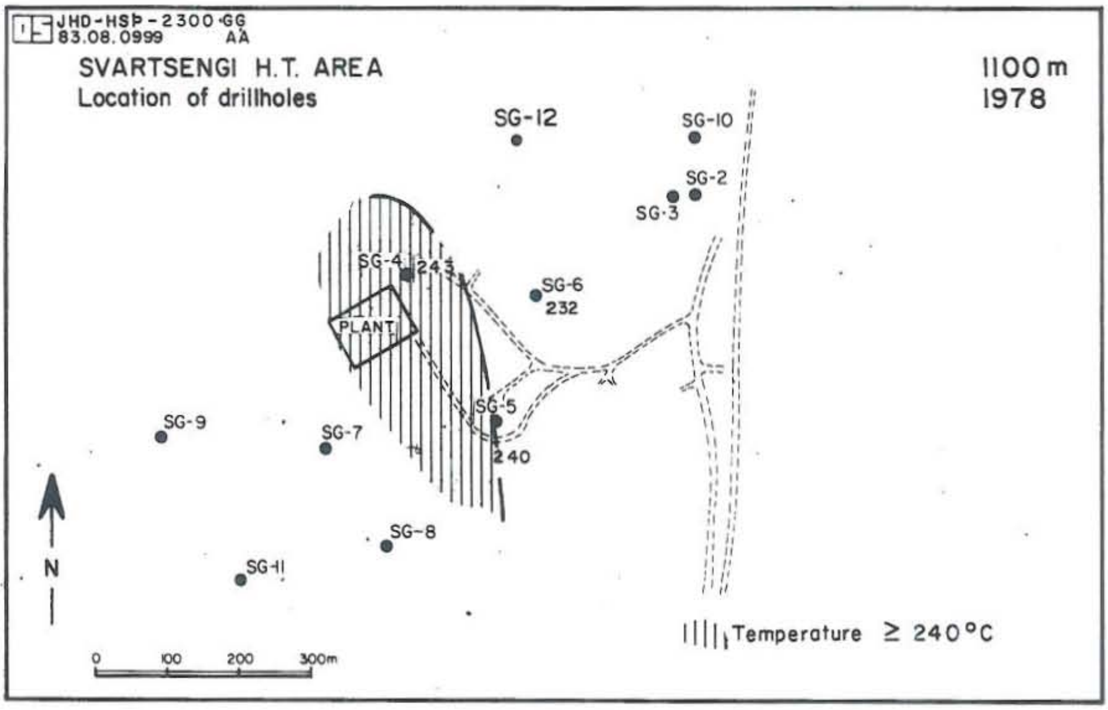

Fig.57 Temperature distribution at 1100 m depth in 1978.

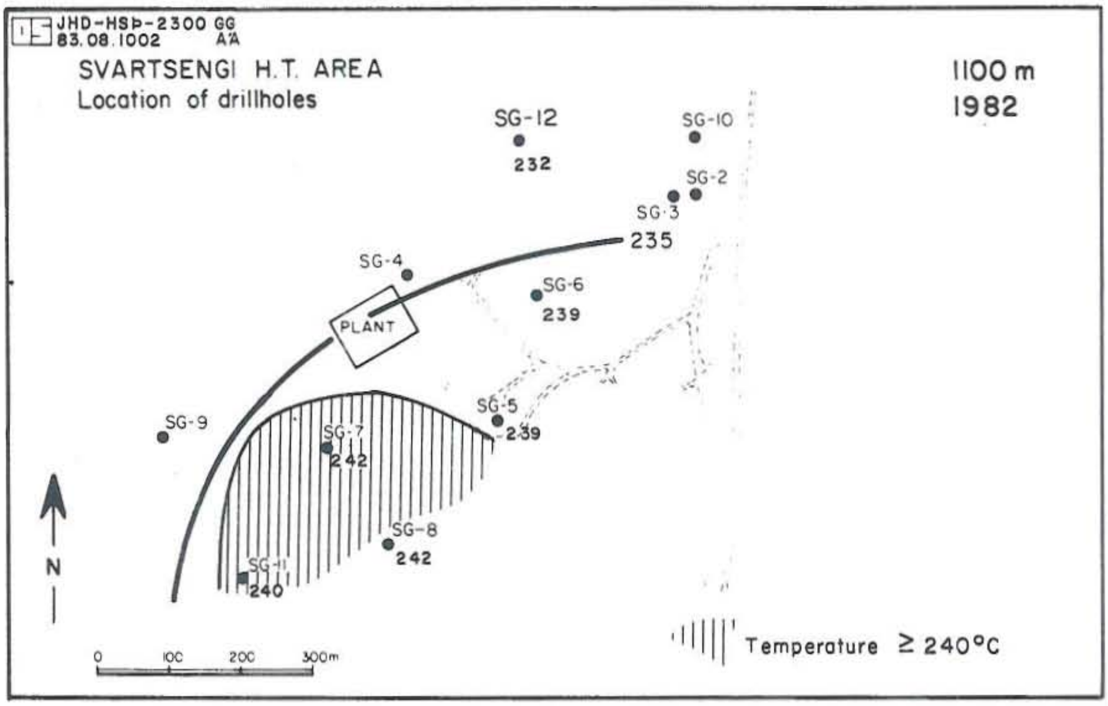

Fig.58 Temperature distribution at 1100 m depth in 1982.

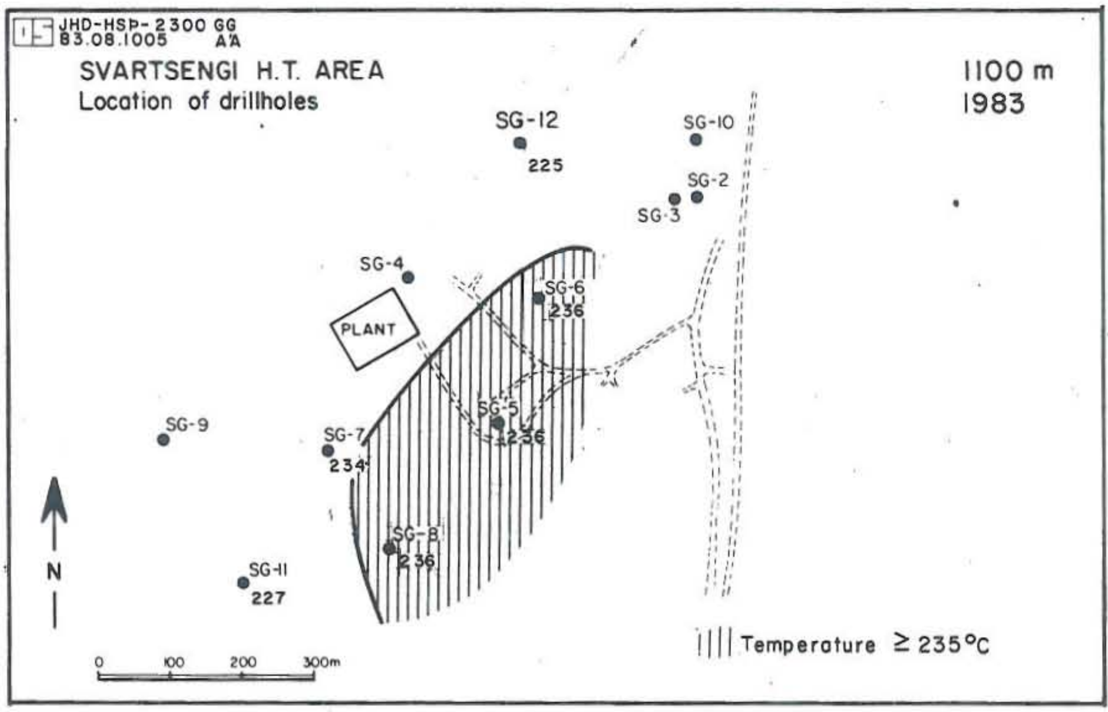

Fig.59 Temperature distribution at 1100 m depth in 1983.

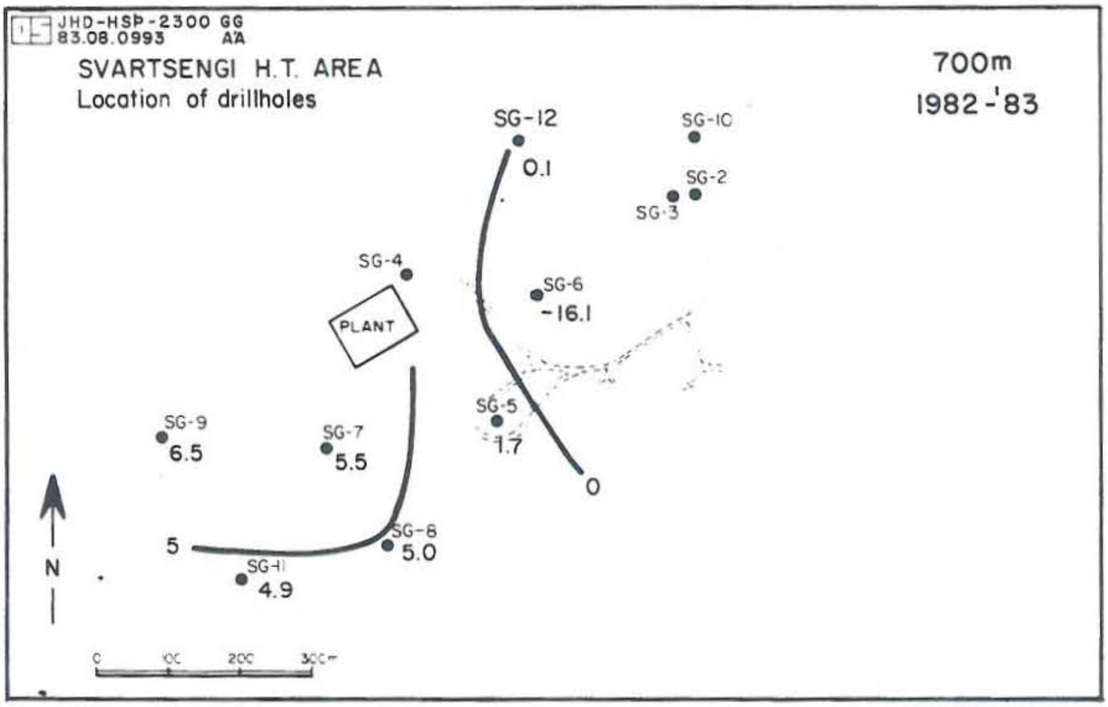

Fig.60 Cooling between 1982 and 1983 at 700 m depth.

already mentioned it is found natural to assume that the upflow zone in Svartsengi is closer to these wells than other wells in that field.

5.3 Cooling between 1982 and 1983 in the reservoir

The cooling of the field is studied by considering the horizontal cooling distribution at four different levels, namely at 700, 800, 1000 and 1100 m depths. This one year cooling is shown in Figures 60, 61, 62 and 63. A common feature of this representation is that the maximum cooling effects are observed in the SW part of the field with the maximum cooling at well SG-11. At depth there is a small or no cooling registered in wells SG-5 and SG-6. The three wells in the NW corner of the production field are unfortunately too shallow to contribute to this representation.

If the cooling of the Svartsengi reservoir is due to cold recharge to the geothermal system, it seems that this cold recharge can come from all directions except from the east. The most prominent cooling seems to come from the SW.

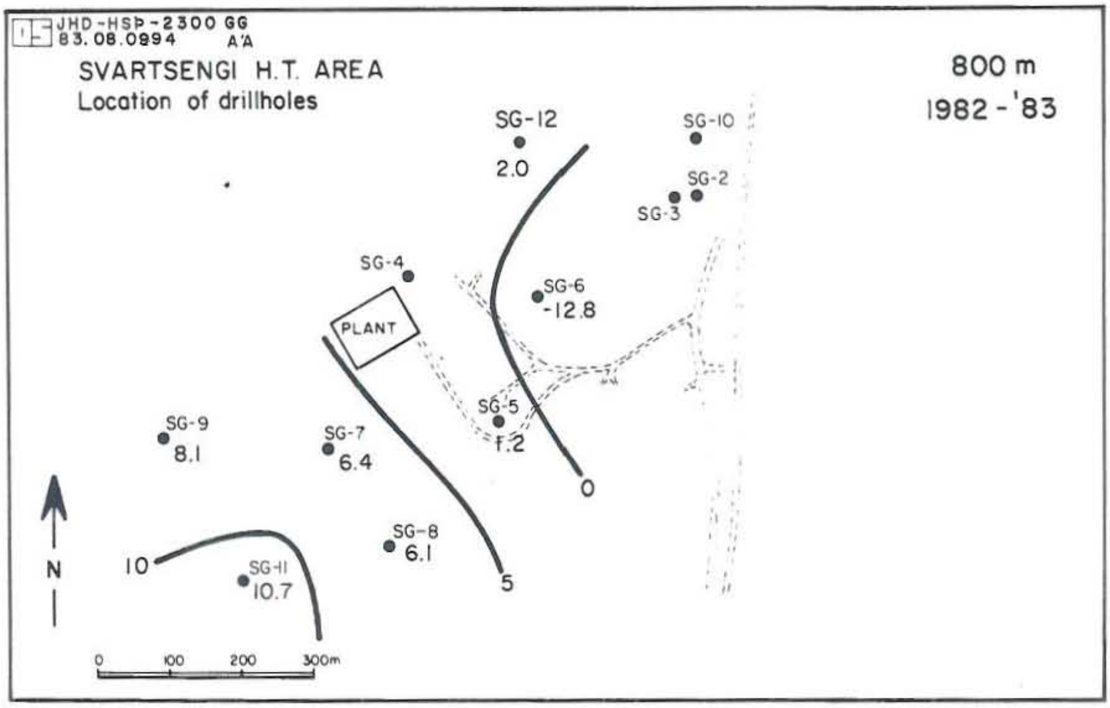

Fig.61 Cooling between 1982 and 1983 at 800 m depth.

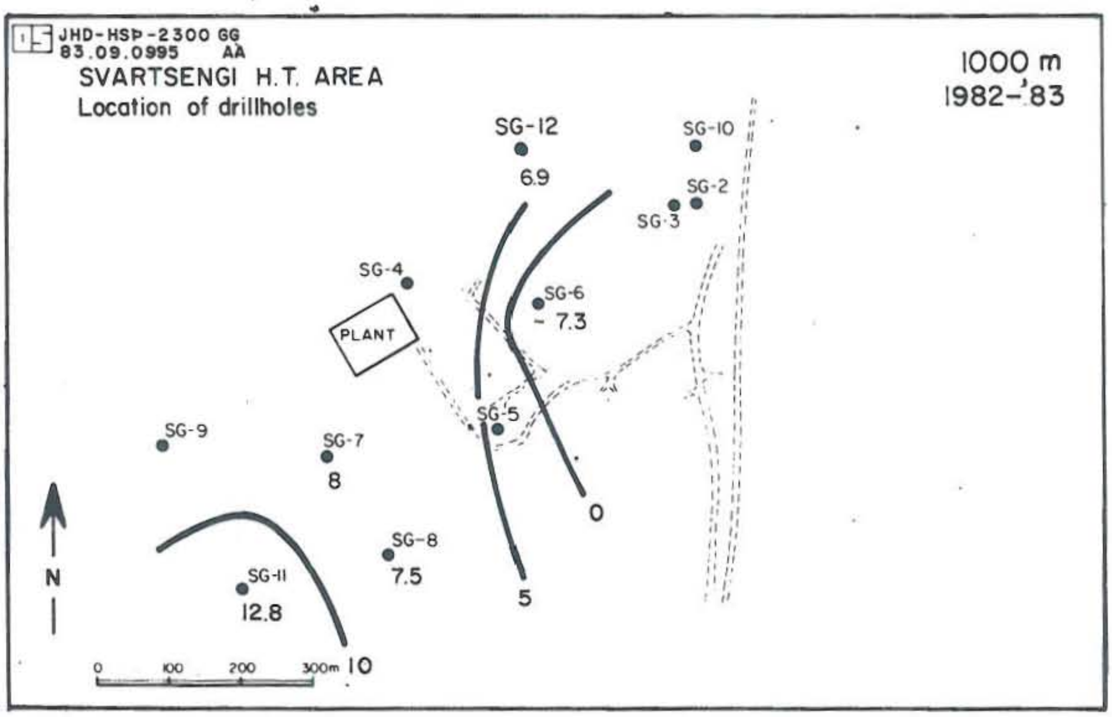

Fig.62 Cooling between 1982 and 1983 at 1000 m depth.

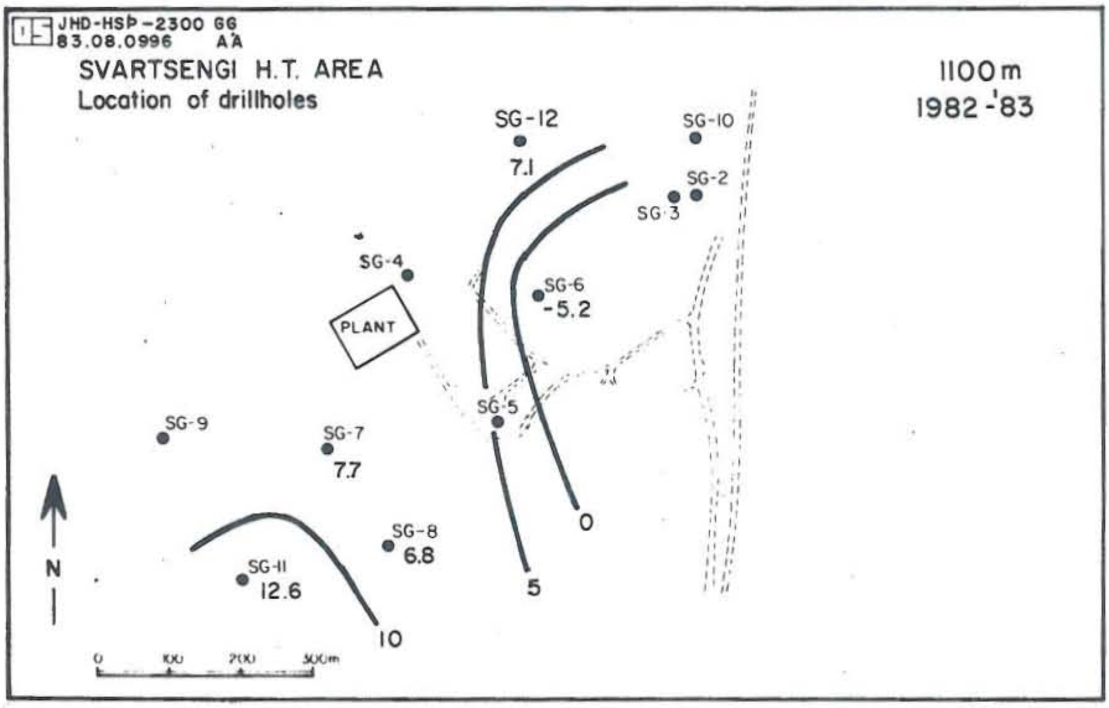

Fig.63 Cooling between 1982 and 1983 at 1100 m depth.

6 EVOLUTION WITH TIME

The production from the Svartsengi reservoir started in October 1976. The history of the production now covers about 2600 days. Fig. 6 shows the first 2000 days of this production. During the first two years the mass flow rate from the reservoir is 50 kg/s, but in 1979 the flow rate increases to approximately 100 kg/s. The next increase in mass flow rate is in 1981, when the winter flow is increased to about 300 kg/s. The production rate has been at this level during the last three years. In the summer time the mass withdrawn from the reservoir is about half of the winter flow rate. The total mass taken out of the reservoir in Svartsengi is now about $4x10^{10}$ kg.

The pressure drawdown in the reservoir has been substantial. Fig. 6 shows that in 1982 the water level in the reservoir is 90 m lower than at the start of production. There is a simple relation between the pressure drawdown in the reservoir and the total mass withdrawn from the reservoir as shown in Fig. 64.

The Svartsengi geothermal reservoir is a typical liquid dominated reservoir where the thermal fluid in the formation is in liquid phase. The temperature of the fluid in the undisturbed state was close to 240°C. However, during the natural surface discharge in the area where wells SG-2, SG-3 and SG-10 are located, the system was boiling and two-phase conditions are still present at shallow depths. During the exploitation of the field, where the pressure in the system has decreased with time, the boiling at shallow level around wells SG-2, SG-3 and SG-10 has increased with time. These conditions were described in Chapter 4 (see Fig. 12, 13, 14, 15, 31 and 32). The lower level of the boiling zone is now at approximately 500-550 m depth.

The top of the main reservoir in Svartsengi is, however, at approximately 600 m depth. The caprock in the geothermal system is most likely the hyaloclastite formation as shown

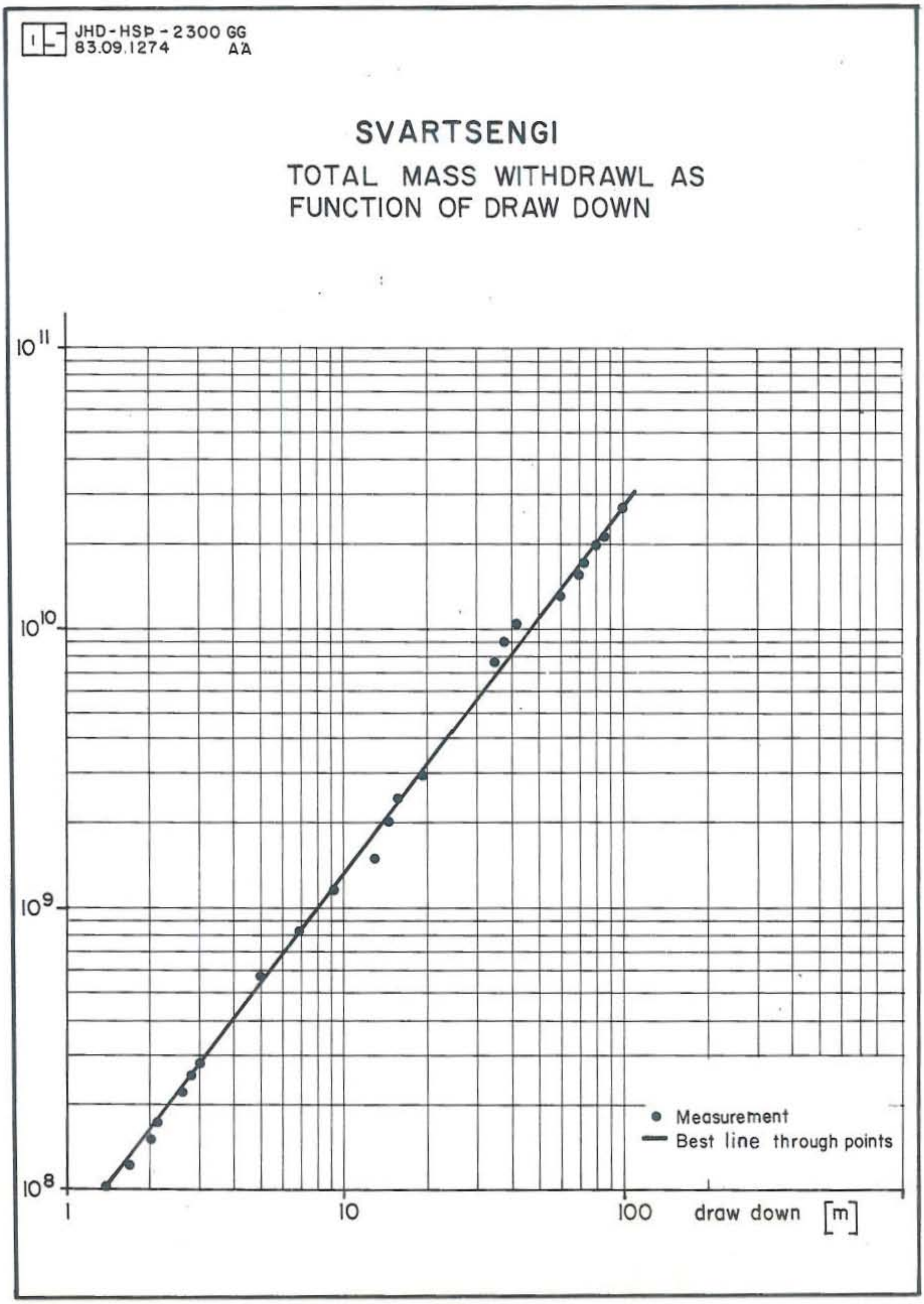

Fig.64 Relationship between pressure drawdown and total mass withdrawn from the Svartsengi reservoir.

in Fig. 3. Significant temperature changes were not recognized until 1983 in the main liquid part of the reservoir , i.e. beneath 600 m depth. However as has been shown in the previous chapters, there were signs of small changes prior to 1983. These changes in temperature were not significantly larger than the absolute accuracy of the instruments used for temperature measurements. Therefore, significant temperature changes in the reservoir could not be detected until 1983.

At present, the response of the Svartsengi reservoir to utilization has been both a decrease in pressure and temperature. The pressure decline is considered to be predictable from natural hydrological considerations. The temerature decline, however, is still a matter of discussion, as the mechanism of cooling has not been defined. The purpose of the present study is to put some constraints on the cooling process presently observed in the reservoir.

7 CAUSES OF TEMPERATURE CHANGES

Exploitation of the Svartsengi reservoir has caused the withdrawal of about 40 million tonnes of geothermal fluid (Thorhallsson, personal communication, 1983). This has caused about 13 bar pressure drawdown in the reservoir. A decrease in pressure causes increased boiling in the top of the reservoir. The recharge of cold water can increase as pressure decreases in the reservoir. Episodic cold inflow from the overlying ground water can take place in association with earthquakes. The decrease in the temperature could also be caused by a decrease in the lateral flow of hot fluid. This chapter will deal with some of the possible cooling processes in the Svartsengi reservoir.

7.1 Boiling

The salinity of the geothermal fluid of the Svartsengi reservoir is roughly 2/3 that of sea water. The saturation temperature of this salt solution is higher than the saturation temperature of pure water by a maximum of 2°C at a depth of about 2000 m (Michaelides, 1981; Grant, 1982) Little or no correction is thus needed when using the steam tables.

Exploitation has caused a pressure drawdown which makes it possible for the reservoir fluid to boil at greater depth than it could initially. In other words, the drop in pressure caused by the exploitation has increased the boiling in the upper part of the reservoir. During boiling, thermal energy is used in changing the state of the fluid from liquid to vapour and this causes cooling in the reservoir. However, as the level of boiling is migrating downwards, hotter and hotter water comes into boiling conditions. This boiling sustains the steam cap located around wells SG-2, SG-3 and SG-10. The effect of the boiling is therefore to increase the temperature of the steam cap. The temperature of the steam zone was about

210-215°C in 1983, but was approximately 190-200°C prior to exploitation of the reservoir. As the largest cooling in the Svartsengi reservoir is observed at a great depth, where the pressure in the reservoir is much greater than the saturation pressure for 240°C, boiling can be excluded as being the cause of the cooling observed in Svartsengi.

7.2 Lateral cold inflow

The fall in pressure has allowed additional recharge fluid, more cold than hot, to flow into the reservoir. The fact that cooling is observed in many wells in Svartsengi favours the possibility of lateral cold inflow into the reservoir. However, the hydrological model used so far to simulate the pressure drawdown in the Svartsengi reservoir assumes the recharge to be only from one direction, and the other three directions are impermeable boundaries to the system. Furthermore, up to 1982 there could not be detected any recharge to the reservoir (Vatnaskil, 1982). If the recharge of cold water had started in 1982, there need not be any discrepancy between temperature measurements and reservoir calcuculations. At present the possibility of cold inflow is considered to be one of the most likely explanations of the cooling mechanism of the reservoir.

7.3 Episodic cold inflow

The reservoir lies along the main zone of earthquake epicenters on the Reykjanes peninsula, as mentioned earlier. It is probable that fluid recharge occurs from episodic cold inflow of surface groundwaters. Episodic cold inflow into the reservoirin connection with seismic activity is considered a possible explanation for the cooling.

7.4 Decreased lateral inflow of hot fluid

As described previously the temperature distribution in the Svartsengi reservoir indicates a lateral flow in the reservoir at 700-1000 m depth. The direction of flow should be to the SW. If this natural flow of hot fluid is decreasing due to pressure decline in the production field, this could show up as cooling in wells downstream in this flow. The available data do not contradict this description of the cooling, but the result is quite similar to the recharge of cold water.

7.5 Calibration of instruments

Another possible explanation of the cooling in the Svartsengi reservoir could be that the instruments used for temperature measurements were not properly calibrated and that the cooling is simply a measurement error. This possibility has been looked into, and it is found that prior to 1982, the calibration of the measurement tools was not satisfactory and at this time the accuracy was not better than ~ 5°C. However, as many different instruments have been used, the confidence in temperature determination is higher, and an error of the order of 3-5°C should have been detected. After 1982, the accuracy of the temperature instruments used in Svartsengi should be better than ~ 2°C. The cooling in well SG-11 is therefore far from being within the reasonable accuracy of the measuring tools and is therefore considered significant. The cooling in wells SG-7, SG-8 and SG-9 is close to the accuracy of measurements as it was before 1982. This cooling can therefore be considered to be significant. In other wells it is not possible to state that temperature changes have taken place.

In the treatment of the temperature data in this report temperature changes of less than 5°C have not been regarded as significant.

7.6 Discussion

In the previous paragraphs five possible cooling processes have been discussed.

It was found that boiling cannot be responsible for the cooling observed in Svartsengi. All the other processes mentioned can be the cause of the cooling, and it is possible that a combination of all the above mentioned possibilities is the real explanation of the observed cooling.

From the data presented in this report, the possibility of a cold recharge at about 1000 m depth in the neighbourhood of well SG-11 seems to be the most plausible explanation.

8 CONCLUSIONS

1. The Svartsengi reservoir is a liquid dominated reservoir with a temperature of 235-240°C.

2. The main reservoir is below 600 m depth, and a hyaloclastite formation acts as the confined cap rock to the reservoir. Natural discharge to the surface causes boiling above 500 m depth, and a local steam zone at shallow level is migrating downward as pressure decreases in the reservoir due to exploitation.

3. Prior to production, temperatures in excess of 240°C were recorded at several places in the reservoir. In 1983 the highest temperatures found in the reservoir are between 235 and 237°C.

4. Between 1982 and 1983 significant cooling is recorded in well SG-11 and almost significant cooling in wells SG-7, SG-8 and SG-9. The cold water inflow seems to be at around 1000 m depth near to well SG-11.

5. The pressure drawdown in the Svartsengi reservoir in 1983 is about 9 bar and the total mass withdrawal from the reservoir from 1976 to 1983 is 4.10^{10} kg. A simple relation has been established between the total mass withdrawal and pressure decline in the Svartsengi reservoir.

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