HYDROGEOLOGY OF THE TIANJIN AREA, CHINA AND SOME SELECTED AREAS IN ICELAND

Chen Zhenxia*
UNU Geothermal Training Programme,
National Energy Authority,
Grensasvegur 9, 108 Reykjavik,
ICELAND.

*Permanent address:
Tianjin Bureau of Geology and Mineral Resources,
261 Yingkou Road, Tianjin,
PEOPLE'S REPUBLIC OF CHINA.

ABSTRACT

The geological and hydrological conditions in the Tianjin area, China, are described and the water level drawdown encountered during exploitation is discussed. Examples are given of the Icelandic experience of dealing with cooling of low temperature systems, drawdown of water levels, and stimulation of aquifers by injection packers.

The hydrology of the low temperature areas at Urridavatn, Selfoss and Glerardalur Iceland is described. During utilization in the former two areas cooling has been observed. In order to minimize the effect of cooling it has been tried to intersect the aquifers at deeper levels and to case carefully off the uppermost sections of the drillholes to prevent inflow of surface water into the geothermal systems. The chloride content of the water has been found to be very useful in detecting mixing of cold groundwater (low in chloride) with the thermal fluid (high in chloride). This is because change in the chloride content can be detected much earlier than any change in the temperature. Drawdown of the water level has been observed significantly during utilization of the thermal reservoir at Glerardalur. Accordingly a careful monitoring of the wells is necessary.

Stimulation by injection packer has been a routine completion procedure for low temperature drillholes in Iceland since 1970. The aim is chiefly to reopen aquifers that have been sealed by drill-cuttings and other circulating materials during drilling and also to open up new aquifers. A description of the stimulation process performed after drilling of THG-10 in Selfoss is given. It is shown that the stimulation increased the production of the well considerably, from what it was at the end of drilling.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

1 INTRODUCTION

1.1 Scope of work

This report represents the final outcome of the training of the author from April to October 1985 at the UNU Geothermal Training Programme, National Energy Authority in Reykjavik, Iceland, under a Fellowship from the UNDP.

The training programme started with a five week introductory lecture course on relevant aspects of geothermal energy. Furthermore the author attended specialized seminars and fieldwork for about two weeks in geophysical logging, reservoir engineering, drillhole stimulation and hydrogeology. In addition a field excursion for one week was carried out to an extinct and deeply eroded central volcano in SE Iceland. A second field excursion to visit most of the geothermal fields in Iceland lasted 2 weeks. During the excursion, the author received lectures and seminars in each respective area. It made a lasting impression on the author, that Iceland is very rich in geothermal resources and utilizes geothermal energy to a great extent. A third field excursion was made to eastern and northern Iceland to study hydrogeological conditions and some problems encountered along with the exploitation of the geothermal water in Icelandic low temperature areas.

The rest of the period in Iceland was used for specialized training and the writing of this report. The report deals partly with hydrogeological conditions of the Tianjin area in northern China and some problems encountered with the exploitation of the area. Experience to be learned from the exploitation of Icelandic low temperature areas is also included. This can be divided into three aspects: a) Methods for the detection and prevention of inflow of cold groundwater into geothermal reservoirs under exploitation, with examples from the Selfoss and Urridavatn geothermal areas. b) Hydrogeological conditions of a low temperature area characterized by narrow, vertical aquifers and large drawdown in wells, with an example from the

Glerardalur thermal area. c) Drillhole stimulation with an injection packer,with an example from the Selfoss low temperature area.

The figures, maps and data used in this report were mostly obtained from the Tianjin Geological Bureau and the National Energy Authority of Iceland.

2 THE TIANJIN LOW TEMPERATURE AREA

2.1 Introduction

Tianjin city is located in the north-eastern sector of the North China plain about 100 km from the Bohai Gulf and 137 km SE of Beijing (Fig. 1). It is the third most important city in China after Beijing and Shanghai. The terrain of the area is low and flat and the nearest mountains are the Taihang mountains which are situated 150 km west of the city and the Yan mountains 120 km to the north (Fig. 1).

The Tianjin thermal area is of the low temperature type where the water is considered to be heated by thermal conduction. It has been divided into the following three geothermal fields: the Wang-Lan-Zhuan geothermal field, the Shan-Ling-Zi geothermal field and the Wan-Jia-Ma-Tou geothermal field (Fig. 2). The average geothermal gradient in the former two areas is 40°C/km, but the Shang-Ling-Zi field has not yet been drilled into. According to geochemistry, the water is of meteoric origin (Yao, 1980).

The distribution of the geothermal fields of the North China plain is closely related to the uplift and subsidence of the basement. Available data show that shallow anomalies are distributed mainly in the uplifted part of the basement.

Two types of geothermal systems are present in the Tianjin area. One is a pore-water layer which is confined to the Tertiary silt and fine grained sand, and the other is a fracture-karst water within the bedrock which is mainly confined to limestone of Ordovician and Sinian age (Lu Run, 1983).

2.2 Geological and tectonic features

2.2.1 Structure

The Tianjin area is situated at the northern end of the Cang-Xian uplift, which is within the subsidence zone of the North-China plain and belongs to the Neocathaysian structural system, with its south-east side and north-west side adjacent respectively to Huang-Hua and the Ji-Zhong grabens.

There are two groups of structural zones in the area. One has a NNE direction and is composed of uplifts, subsidences and parallel fractures, and the other has a WNW direction, and is composed of parallel fractures (Fig. 3).

Another characteristic feature of the area is the morphology of the horsts. Their easterly slopes are steep whereas the westerly ones are more gentle. Fractures of large dimensions are mostly on the steeper side.

Still another feature is the new tectonic movement of the Bai-Tang-kou fracture (Fig. 3). From 1971 to 1973 it was basically firm and stable, but in 1973 the east wall began to rise gradually and has since been active. The upper wall has already attained a height difference of more than 10 mm relative to the lower one.

2.2.2 Stratigraphy

The geological succession is made up of a crystalline basement overlain by sedimentary formations dating from Sinian to Quaternary.

A. Sinian:

The normal thickness of the Sinian rocks can be up to thousands of meters. It is composed of dolomite limestone and siliceous limestone interbedded with mudstone and sandstone.

B. Palaeozoic

The Cambrian system: It is mainly composed of mudstone and argillaceous limestone with thin layers of limestone. Generally the thickness is about 150 to 300 m.

The Ordovician system: The normal thickness is about 300 m and the lithology is characterized by limestone, interbedded with mudstone and dolomitic limestone.

The Carboniferous system: Drillhole No. 1 has revealed that this system is composed of 42 m thick carbonaceousmudstone with thin layers of fine-grained sandstone and a coal layer, with hematite and bauxite at the bottom.

C. Cenozoic

The Tertiary system: The thickness is 500-600 m. This system has been divided into the following formations:

Ming-Hua-Zhen formation: The lower part is composed of sandstone and mudstone in alternating beds and the upper part is composed of silt.

Guan-Tao formation: This is composed of psephitic sandstone interbedded with mudstone.

The Quaternary system: This system is mainly composed of a series of sand and clay soil with a thickness of about 550 to 600 m. Most of the system belongs to continental facies, while the coastal plain belongs to both marine and continental facies.

2.3 Hydrogeology

On basis of available data, two main types of aquifers have been identified in the Tianjin area, namely,the pore water of the Tertiary system and the fracture-karst water of the Ordovician and Sinian system (Fig. 4 modified from Tianjin Geological Bureau).

Fig. 4 shows the model of the groundwater flow both in the Tertiary aquifer unit and in the lower Paleozoic-Sinian aquifer unit. Due to the karstic features of the carbonitic and dolomitic formations, the hydraulic conductivity of the lower Paleozoic-Sinian aquifer is much higher than that of the Tertiary one.

The recharge area is represented by the Yan mountains in the north where the Sinian formations crop out. According to Yao (1980) the thermal water reaching the surface is a mixture of hot parent water and cold groundwater. He estimates that the temperature of the thermal water before mixing is about 140°C. As the water is considered to be heated by thermal conduction it must have penetrated down to 3500-4000 m depth to gain such a high temperature. The rain water infiltrates into the outcrop and into the carbonitic formations and reaches the Tertiary sediments. The main flow is divided into two parts where one is feeding the Tertiary reservoir and the other the Paleozoic-Sinian reservoir.

2.3.1 The pore-water of the Tertiary system

The depth of the Cenozoic aquifers ranges from 600 to 1000 m. The lithology of the aquifers is characterized by fluviolacustrine silt and fine sand. The thickness of the reservoir strata is 100 to 250 m, and the temperature is 30-63.5°C. The water level is now about 50-70 m and the output of a single well is 30-75 m3/h. This aquifer contains good quality water as is shown in Table 1

2.3.2 Fracture-karst thermal water within the basement

The depth of the aquifer ranges from 800 to 1400 m and it is mainly within the limestone of Ordovician and Sinian age. The water temperature is 50-98°C. The hydraulic head is generally 2-40 m and the outputof a single well is 60-120 m3/h. The characteristics of the thermal water is shown in Table 1.

TABLE 1: Hydrochemistry of the underground thermal water of the Tianjin geothermal area

Type of water	Hydrochemistry	T.D.S. (g/l)	Total hardness G.D.	Alkalinity G.D.	Fluorine content (mg/l)	pH value
Tertiary system thermal water	HCO_3-Na HCO_3-Cl-Na	0.6-1.0	0.7-1.0	20-25	3-5	8-8.5
Ordovician system	Cl-HCO_3 (SO_4)-Na	2-5	9	25.88	10.40	7.116
Sinian suberathem	Cl-HCO_3-Na	1.8-2.0	5-7	17-20	6-10	7.5-8

2.4 The drawdown of the water level

Prior to 1972 all wells were artesian. Because the extraction volume of geothermal water of the Tertiary system has been increasing steadily, drawdown of the water level has occured (Fig. 5 from Tianjin Geological Bureau).

The Tertiary aquifer has been divided into two different units: a) Upper aquifer (500-700 m) from which 90 % of the water is extracted; b) Lower aquifer (750-1300 m) from which 10 % of the water is extracted.

The cumulative production from the Tertiary reservoir from 1970 to 1982 is shown in Table 2 (from the Tianjin Geological Bureau, 1977, 1982).

TABLE 2: Extraction rates from Tertiary reservoir in Mm3/y

Year	Upper Aquifer	Lower Aquifer	Cumulative
1970	3.527.400	693.000	4.220.400
1971	5.449.400	1.387.600	6.837.000
1972	6.993.000	1.904.300	8.897.300
1973	13.956.000	2.493.100	16.449.100
1974	15.143.500	3.444.600	18.588.100
1975	17.272.300	4.102.400	21.374.700
1976	15.833.700	3.598.100	19.431.800
1977	17.787.700	3.342.700	21.130.400
1978	17.693.300	3.822.000	21.515.300
1979	16.220.600	4.830.600	21.051.200
1980	19.274.200	4.927.100	24.201.300
1981	20.856.600	4.804.100	25.660.700
1982	13.493.200	5.811.400	19.304.600

As a result of the extraction rate, the Tertiary aquifers both the upper and the lower, were subjected to a decrease of the hydraulic head. The trends of the drawdown in the two aquifers are very similar and indicate a close hydraulic connection between the two (Fig. 6 from Tianjin Geological Bureau, 1982). The drawdown of the water level of the Tertiary upper aquifer has been noticed since 1975. In recent years, it has increased at a rate of 3.0 to 3.5 m/year.

Fortunately, the exploitation has not caused any drop in temperatures nor any change in water quality. This is thought to be because the depth interval of the cold groundwater in the wells is carefully cased off and also because of the presence of an aquiclude between the groundwater system and the thermal reservoir.

So far, the fracture-karst water from the Ordovician and Sinian basement has not yet been extracted on a large scale. The water level in all wells is still artesian. However, the water level is decreasing with time, even without production.

3 EXPERIENCE TO BE LEARNED FROM ICELAND

3.1 Introduction

Despite the different geological conditions in China and Iceland similarities are recognized regarding geothermal activities. The heat source of the low temperature areas in both countries is for example considered mainly to be thermal conduction from the regional heat flow. The flow paths are thought to be fractures and faults as well as horizontal aquifers, though the latter are presumably more abundant in China than in Iceland. Natural hot springs are frequently observed on the surface near the intersection of the tectonic features. Furthermore both countries are tectonically active causing new fractures to form and the reopening of older ones that have been sealed by secondary minerals.

Three Icelandic low temperature areas were visited in order to study the hydrology and the problems encountered during exploitation. More specifically the aim was to study the techniques used to: 1) detect changes in the thermal system; 2) predict responce of the area to exploitation; 3) solve the problems encountered.

3.2 The Urridavatn low temperature area

The Urridavatn low temperature field is located within the Tertiary plateau basalt of eastern Iceland (Fig. 7). The area is located in the center of a fissure swarm which belongs to an extinct central volcano, which was active about 8.5 M.y. ago (Einarsson et al., 1982). The landscape is characterized by low hills elongated in N-S direction. Bogs or lakes occur in the depressions between the hills, including Lake Urridavatn.

A geological map of the area is shown in Fig. 7. It demonstrates that the area is transected by a complicated system of faults with a NNE direction. The system is characterized by relatively narrow, almost parallel depressions and uniform platforms in between. The depressions are curved and intersect each other. The dyke density in the area is about 7%. The dip of the dikes is generally about 84° east and their main trend is similar to that of the faults (Einarsson et al., 1982).

The thermal activity is all confined to the bottom of Lake Urridavatn, where the only surface manifestations are gas bubbles and holes in the winter ice. The thermal upflow is connected to a dyke that was detected by magnetic mearsurements and seemed to be the main flowpath towards the surface. Exploratory drilling started in 1963 when two shallow (116 m) wells were sunk into the area. With increasing oil prices in the seventies interest arose again exploiting the geothermal energy at Urridavatn. In 1975 well No. 3 was drilled to the depth of 1453 m, but no aquifers were encountered. In 1977 well no 4 was drilled to the depth of 1600 m and some aquifers were intersected within the uppermost 550 m. Three months of pumping tests showed that the discharge was about 14 l/s of 64°C warm water. During that time a significant reduction in chloride content of the water was observed indicating an inflow of cold groundwater (from the lake) which would most likely cause cooling of the geothermal system. Accordingly it was assumed that cooling would happen in the next 10-20 years.

The Egilsstadir central heating system was initiated in 1979 and then continuous pumping started. The first cooling was observed in the drillholes as early as February 1980. That year well No. 5 was drilled and a year later well No. 6 was sunk into the area. However, the discharge from these wells was both less and colder than from well No. 4 and furthermore the cooling of the thermal water continued. Since 1979 the National Energy Autority (NEA) has been watching changes in the chloride contents of the thermal water to check possible inflow of cold water into the geothermal system (Benjaminsson, 1984; Sigurdsson et al., 1985) (Fig. 8). As chloride takes little or no part in the chemical interactions between rock and water it is often used to measure the mixture of geothermal water with cold ground water, the former having relatively high chloride content compared to the cold ground water. It has been observed elsewhere that when cold water flows into an aquifer the surrounding bedrock cools down very slowly and can give enough heat to maintain the original temperature of the dicharge for many years. Therefore the cooling of the area has a much slower procedure than the mixing with cold water according to the changes in the chloride content (Tomasson and Halldorsson, 1981).

The reason for the cooling was thought to be the absence of a hydrological aquiclude between the reservoir of the geothermal system and the cold water in the lake. Tectonic fractures and dykes which are the main aquifers are quite open up to the surface. When production started, lower pressure in the aquifers presumably caused the cold water in the lake to pour down into the bedrock the same way as the warm water had flown up before. To test this hypothesis a tracer survey was performed by depositing fluorescent dye on the lake's bottom in the vicinity of production wells and it confirmed leakage through the lake's bottom to the shallow production aquifers within 50 hours (Benjaminsson, 1983)

Additional exploration was initiated in 1982 (Einarsson et al., 1982) as previous drillings which were aimed at intersecting aquifers within a dyke, had been unsuccessful. The results of the head-on profiling suggested a vertical low resistivity plane which seems to be the main aquifer in the area. The maximum upflow occurs at the intersection of the fracture and a dyke. These results indicate the existance of a relatively young seismic fracture. Where it intersects the dyke the latter breaks up and becomes a good aquifer within a short distance from the fracture.

Well No. 8 drilled in 1983 is thought to have successfully cut the intersection of the dyke and the fracture, as good aquifers occur at 700-900 m depth. The discharge of the well is now 35 l/s of about 75°C warm water. Water samples that have been taken monthly from the well show a little lower content of some important ions (Na, F, Cl) and a little lower temperature which seem to indicate a significant cooling.

In order to minimise the effects of cooling and to lengthen the production life of the geothermal area, it seems necessary to intersect the aquifers at deeper levels than in the previous wells.

3.3 The Selfoss low temperature area

The Selfoss low temperature area is located in south Iceland about 50 km east of Reykjavik. The geological strata can be divided into three separate formations. The uppermost formation consists of a postglacial lava flow, and is underlain by a tillite sediment. The tillite sediment lies unconformably on top of a Quaternary basement, which consists mainly of basaltic lavas with minor sedimetary intercalations (Tomasson and Halldorsson, 1981).

There are according to Tomasson and Halldorsson (1981), two groundwater systems present in the area. One is a cold groundwater system (5-6°C), which is confined to the postglacial lava flow, and the other is a geothermal system (70-80°C), mainly confined to the Quaternary basement. The tillite sediment acts as an aquiclude between the two ground water systems and as a cap rock for the geothermal reservoir.

Prior to 1949 when the utilization started, the top of the thermal system penetrated up into the cold groundwater layer. This situation was maintained by the higher hydrostatic pressure of the thermal system. A subsequent extraction from drillholes by pumping lead to a pressure drop in the thermal system which in turn resulted in the intrusion of the cold groundwater down into the geothermal system. After two years of utilization the drillholes had to be abandoned due to severe cooling. The leakage of cold groundwater into the geothermal system is believed to be both through faults and fractures which cut through the rock right up to the surface. Some cooling may also take place through drillholes with shallow or cracked casings. The cooling is much more rapid through the drill holes because of faster flow through the wells. Cooling was observed in an aquifer at 130-160 m depth where the temperature dropped from about 80 to 35°C. Gradual cooling on a similar scale has occurred in aquifers down to a depth of 300 m.

Cooling of individual wells has been slowed down considerably by putting deeper casings in the wells at the time of drilling. The first wells which were cased down to 10-20 m depth lasted only for several months, whereas wells with 40-50 m casing lasted for about 15 years. The lifetime of wells with 250-400 m casing is not yet known.

The two ground water systems have very different chloride contents as is shown in Table 3. The thermal water has a relatively high chloride content or 108-502 ppm. The chloride is believed to have originated from seawater which contaminated the system at the end of the last glaciation when the sea level rose to about 100 m above the current sea level. At the beginning of utilization the chloride content of the thermal water was about ten times higher than that of the cold groundwater. Therefore, the change in the chloride content of the thermal water can be used to indicate the amount (ratio) of cold water mixed with the thermal water.

Table 3 shows how the chloride content and the temperature in different aquifers can be used to calculate the ratio of the cold water into the thermal system. It is interesting to note that the change in the chloride content gives much higher ratio of cold water than the temperature ratio. This must mean that the cold water is heated up as it flows down through relatively hot rocks on its way into the thermal system.

TABLE 3: Temperature, chloride content and the amount of cold cold groundwater in the thermal fluid at Selfoss.

Original Cl content	CL content after invasion of cold groundwater	Ratio	Original temp°C	Temp after invasion of cold water	Ratio
500	250	.51	90	81	.11
450	250	.45	81	81	0
500	116	.78	90	55	.41

3.4 The Glerardalur low temperature area

The Glerardalur low temperature field is located just to the south of the town of Akureyri in northern Iceland (Fig. 9). The area lies within a 10 m.y. old Tertiary basalt pile and is transsected by faults and dykes, trending N-N10°E. Most of the region is coverd by thick gravel and moraine from last glaciation and the only good exposures are found within the gully of Glerardalur (Glerargil) below the geothermal area (Flovenz et al., 1984).

Prior to production, natural hot springs occured 150-190 m a.s.l. in Glerargil. The total natural discharge was about 3.0 l/s and the highest temperature about 50°C. The water flowed out along a contact between a dyke and the adjacent lava layers.

In 1965 a 500 m deep hole was drilled in the area. No aquifers were encountered and the temperature was only 50°C.

In 1980 more thorough exploration was initiated as the oil crisis in the seventies had changed the economical situation and geothermal energy had become a more valuable energy source. Geological mapping and head-on profiling were carried out. The geological mapping showed that the dyke which seemed to control the upflow of geothermal water was cut by a major fault just below the geothermal area and could therefore not be the main flowpath towards the surface.

A new model of the area was made which demonstrates that the geothermal area can be divided into high and low resistivity stripes on the surface (Fig. 10), where high resistivity seems to coincide with old faults. The major fault in the gully seems to mark the western boundary of the geothermal area and unfortunately well no. 4 was drilled just outside the geothermal area. Drilling in the area started again in 1981 and since then seven shallow (<300 m) holes have been drilled in the area as well as one deeper hole, which reached 800 m (No. 7).

Onthe 16th of February 1982, the discharge from GY-7 was 12.1 l/s of 59°C warm water, but from GY-5 only 1 l/s. Then well GY-7 was closed for a month for measurements. Pressure became 2.85 bars in well GY-7 and the discharge of GY-5 increased to 3.0 l/s. Pressure was then released stepwise to calculate the coefficient for turbulent pressure drop. Discharge of 6.5 l/s 13.5 l/s and 18.5 l/s was kept in the well for an hour at each step during the release.

On 24th of May 1982, well GY-7 was pumped and the initial discharge was 45-51 l/s but the long term discharge is 30 l/s of 61°C hot water.

Pumping was stopped on the 29th of July 1982 for measurements but restarted on the 10th of August 1982. In that time the water level raised by 108 m. When wells GY-5 and GY-7 were put into production, the natural discharge from the hot spring at Glerardalur diminished and had almost stopped completely in November 1983.

Fig. 11 shows production and the change in the water level of drillhole GY-7 since pumping started on the 24th of May 1982 and a prediction until January 2000. Mean production has been 30 l/s. The drop in water level lowered initially according to what had been predicted but lowered at a higher rate from September, even though pumping had been reduced. The water level fluctuated until April 1983 when it stabilized (Flovenz and Thorsteinsson, 1983).

Table 4 shows the calculated water level of well GY-7 from May 1983 to May 1988 with the assumed production rates of 15, 20 and 30 l/s. The Table shows only broad estimations, because the production time is still too short for such a long prediction. The prediction takes only into an account aquifers in wells GY-7 and GY-5, but not possible production from other wells (Flovenz and Thorsteinsson, 1983).

TABLE 4: Calculations of the water level of well GY-7from May 1983 to May 1988

Date	Time in years	Calculated water level in meters down from the top of the hole		
		15 l/s	20 l/s	30 l/s
May 1983	0	41	149	172
May 1984	1	128	162	239
May 1985	2	145	191	289
May 1986	3	163	217	332
May 1988	4	194	262	404

4 DRILLHOLE STIMULATION AND TESTING

4.1 Introduction

Stimulation by injection packer has been a routine completion procedure for low temperature hydrothermal drillholes in Iceland since 1970. Drillhole stimulations are carried out to stimulate and increase the production of individual wells. The aim of the stimulation is chiefly to reopen aquifers which have been sealed by drill cuttings and clogging materials (sawdust etc.) during drilling. New aquifers may also sometimes open up when vein or fracture fillings are removed, through high injection pressure.

Stimulation is done by injecting water under pressure into the well, either by closing the well at the wellhead or by sealing the well with an injection packer which is located in a predetermined level between two or more producing horizons in the well. Water is then injected through the drill string below the injection packer or above the packer at the well head (Fig. 12).

The position of aquifers can be mapped through packer injection tests by moving the injection packer down to different levels in the drillhole and test different intervals. The best aquifers occur in the depth intervals where pressure build-up is lowest. Injection packers are also used for hydraulic mapping in geothermal areas, especially to determine the depth of aquicludes between different drillholes. This is done by measuring the effects which the injection has on the water level in nearby drill holes, while water is injected at different depth intervals in the test well.

There are two types of injection packers in use in Iceland, one made by LYNES and the other made by TAM. Of the two, the LYNES packer has proved to be more reliable and sits better in the hole after packer setting is completed.

The injection packer consists of a composite iron pipe which is covered by a rubber tube (Fig. 12). LYNES-packer have a plug on the lover end of the ironpipe which is kept closed during setting procedure, while water is injected through the drill string into a cell in between the pipe and the rubber tube. The plug is fastened with a shear pin which yields under certain pressure called packing pressure. The TAM-PACKER is set by squeezing a specially made ball through the packer at a predetermined packing pressure. The packing pressure must always be higher then the injection face pressure. Typical packing pressures are between 100-150 kg/cm2 (Tomasson and Thorsteinsson, 1978).

LYNES-packers can only be set once and have to be taken up to the surface so that a new shear pin and a shear plug can be fitted before they can be set again. It is, however, possible to inject water both below and above this type of packer. This allows the depth interval below and above the packer to be tested in one packer setting, which can be useful if there are two or more large aquifers in the hole.

The TAM-packer can be set several times in the same hole, and does not have to be taken up to the surface between packer settings. This is a big advantage if several aquifers need to be tested in the same well. The TAM-packers have, however, proved difficult to use, as the closing valves tend to leak. This causes pressure drop inside the packer and they become loose in the hole. The weight of the drill string has sometimes been used to push the packer together and plug it into the hole with force. Although this method has worked on several occasions, it cannot be reccommended unless the person performing the packer operation has gained good experience.

4.2 Drillhole stimulation in the Selfoss geothermal area

Thirteen wells have been drilled in the Thorleifskot field in the Selfoss geothermal area. Some of these wells have been stimulated and tested with injection packers. Well THG-10 is taken here as an example to illustrate the stimulation tests in the area. This well was drilled in 1979. The total drilled depth of the well is 1869 m. Fig. 13 shows the casing programme and drilled diameter of the well, and Fig. 14 shows the geological section of the well, along with circulation losses, pump rate and pump pressure during drilling. Stimulation and testing of well THG-10 at Selfoss was carried out in the following way:

(1) Multiple step injection test (MSIT-1): The test was done to estimate the yield of the drillhole at the end of drilling. The initial water level was at 39.6 m below surface and the amount injected was 6.8 l/s from 21:15 hrs to 21:53 hrs (labelled A on Fig. 15). The injection was then increased to 13.6 l/sec. (B on Fig.15) and this amount was injected for one hour. The total amount injected in MSIT-1 was 64.5 tonnes.

(2) Pumping with compressed air (PCA): This test was run in order to clean the hole of drill cuttings and lost circulation material and to stimulate the well by lowering the water level. This decreases the pressure on the aquifers which increases the rate of flow into the well. This is also a short term test of the yield of the well. The drill pipes were put down to 120 m for this test. Fig. 16 shows that the pressure of the air at the well head was 5.5 bar, which means that the water level in the well was at 65 m. It also shows that the pump rate varied from 22-28 l/s and the temperature increased from 37°C to 65°C. The duration of the test was 10.5 hours.

(3) Multiple step injection test (MSIT-2): This test was made in order to learn if the pumping with compressed air had improved the yield of the well (Fig. 15). The initial water level was at 37.2 m below surface. The injection rate was at first 6.8 l/s but was increased to 13.6 l/s for 57 minutes and increased again to 20.3 l/s. The total amount injected in MSIT-2 was 121.9 tonnes.

(4) Injection with a packer in drillhole THG-10: Two packer settings were chosen after the pumping with compressed air. A LYNES-packer was first set at 502 m and then at 1104 m for testing and stimulation. Fig. 17 shows the rate of injection and the injection pressure (measured at the well head).

Packer at 502 m: The packer was first set at 502 m depth and water injected below the packer. The average pump rate was 64 l/s (Fig. 17). The total amount injected was 1824 tonnes. One pressure drop (5 bar) was observed at about 7:00 hrs indicating an opening of aquifers at 502-1869 m depth.

Water was next injected at the well head on top of the packer. The pressure was very low and ranged from 1.6 to 2.7 kg/cm2 (Fig. 17). This indicated open aquifers above 502 m depth (311-502 m).

Water was injected below the packer again with the packer at 502 m depth. As can be seen from Fig. 17 the pressure dropped from 82 to 28 kg/cm^2, and 84 to 30 kg/cm^2 at 18:44 to 19:25, and 20:30 to 20:55 hrs respectively. This was caused by a decrease in pump rate.

Packer at 1104 m: The injection packer was then set at 1104 m depth and water injected through the drill string below the injection packer. The average pump rate was 14.8 l/s and the total amount injected was 395 tonnes. Fig. 17 shows that during the time from 6:00 to 18:55 hrs the pressure dropped from 95 kg/cm^2 to 88 kg/cm^2. As the pumping rate was kept constant during that time this may indicate an opening of an aquifer(s).

(5) Multiple step injection test (MSIT-3): After the injection with the packer, a multiple step injection test (MSIT-3) was performed in order to test the effectof the stimulation with the packer. The water level was at 39 m before the test and the pump rate was 20 l/s for the first hour (Fig. 15). After that the injection was increased to 31.7 l/s and again to 38.7 l/s. After that the injection was increased again to 49.5 l/s and this amount was injected for 25 minutes. The total amount injected in MSIT-3 was 322 tonnes.

4.3 The result of the stimulation and tests

Fig. 18 shows the variation in yield of well THG-10 with different step injection tests. It is obvious that the yield of the well is MSIT-2 > MSIT-1 and MSIT-3 > MSIT-2 and that the stimulations with compressed air and injection packer have increased the yield.

The coefficient of turbulent well losses "C" is calculated for three cases C, C_1, and C_2 according to the formula:

$$C = \frac{\Delta h}{Q^2}$$

where Δh (m) is the drawdown in the well for a certain pump rate Q (l/s). Δh is negative for pumping from the well, but positive if water is pumped into the well. It is a measure of the change of pressure acting on the aquifer.

C is the coefficient of well losses due to turbulence inside the well and in its immediate vicinity, computed from step drawdown tests after stimulation processes are completed. In order to calculate C, we have to know the change of thewater level (Δh) in the well at the time of testing. We also need to know the rate of pumping(Q) into or out of the well. C_1 is the coefficient of turbulent well losses at end of drilling. In this case Δh is the static water level during drilling, and Q is the circulation loss at the end of drilling (Table 5). C_2 is the coefficient of turbulent well losses during drilling. Q is in this case obtained by adding together all increases in circulation losses during drilling (Table 5, Fig. 14) and Δh is the static water level during drilling.

By using numbers from Tables 5 and 7 the following results are obtained:

$$C = 14.56/(49.5)^2 = 0.0059 \ m/(l/s)^2$$
$$C_1 = 39/(10.2)^2 = 0.38 \ m/(l/s)^2$$
$$C_2 = 39/(87.6)^2 = 0.0051 \ m/(l/s)^2$$

TABLE 5: The hydrogeologic parameters of well THG-10 for the Multiple Step Injection Tests

Date of test	Pumping duration (hours)	Depth interval tested (m)	Q (l/s)	Δh (m) (m)	C $m/(l/s)^2$
28.05.79	0.63	311-1869	6.8	5.7	0.123
28.05.79	1.00	311-1869	13.6	26.1	0.141
29.05.79	0.75	311-1869	6.8	0.2	0.0043
29.05.79	0.95	311-1869	13.6	3.2	0.0173
29.05.79	0.78	311-1869	20.3	10.4	0.025
06.06.79	1.00	311-1869	20.0	1.0	0.0025
06.06.79	0.83	311-1869	31.7	5.51	0.0055
06.06.79	0.58	311-1869	38.7	8.77	0.0059
06.06.79	0.42	311-1869	49.5	14.56	0.0061

Improvement ratios (I_1 and I_2) are calculated in order to estimate how the stimulation processes have worked, according to the formula:

$$I_1 = \sqrt{C_1/C} = \sqrt{0.38/0.0061} = 7.9$$
$$I_2 = \sqrt{C_2/C} = \sqrt{0.0051/0.0061} = 0.9$$

TABLE 6: Improvement ratios in well THG-10

Packer depth (m)	Volume injected (m3) beneath	above	total	C $(m/(l/s)^2)$	I_1	I_2
502	3915	1017	4932	0.0061	7.9	0.9

Table 6 shows the improvement ratios I_1 and I_2 after the injection test with the packer at 502 m. The Table shows an eightfold increase in productivity from what it wasat the end of drilling.

Calculation of I_2 (0.9) indicates that most of the aquifers which were blocked by drill cuttings and sawdust at the end of drilling were successfully reopened in the stimulation processes, as this value approaches 1. There is, however, a collapse in the well at 1100 m, blocking off the lover most aquifers (6.6 l/s circulation loss). The I_2 value is therefore about what could be expected, as (87.4-6.6)/87.4 = 0.92.

The injection pressure during injection below the packer is read from a pressure gauge on the stand pipe, before the water goes through the surface equipment (drill hose etc., see Fig. 12). In order to estimate the actual pressure below the packer a correction has to be made for pressure losses due to friction in surface equipment, drill string and packer.

The pressure losses depend on the inside diameter (ID) of the conduit and its length. Data on pressure losses for various pipe diameters can be attained from Drilling Data Handbook.

A correction of this kind is usually not necessary for pumping above the packer if the pressure gauge is placed directly on the well end of the surface equipment after the water has passed through the surface equipment.

The pressure losses in surface equipment, drill pipe and packer were calculated using the following formula:

$$P_2 = P_1\left(\frac{Q_2}{Q_1}\right) \qquad \text{(from Drilling Data Handbook, p.286).}$$

The total pressure loss for the pumping of 64 l/s below the packer at 502 m were 36.4 bar, which means that the pressure acting below the packer was 45 bar (81 bar - 36.4 bar). This means that C(502-1869 m) = 0.11 $m/(l/sec)^2$, and the aquifers are fairly open.

During the pumping of 68 l/s above the packer, the total pressure loss inside the well may have been up to 1.6 bar, making C(311-502 m) = 0.012 $m/(l/sec)^2$. This indicates that the aquifers at this depth interval are open.

During the injection of about 17 l/s below the packer at 1104 m, the total pressure loss was 4.9 bar, making C(1104-1869 m) = 2.91 $m/(l/s)^2$. This gives an indication of poor aquifers for this depth interval.

The C-values for the injection tests can be used to compare the yield of various depth intervals of the well and compare it with the circulation losses during drilling, since we know that the static water level was at 39 m below the surface. This gives Q(311-502 m) = 57 l/s compared to circulation loss of >34 l/s; Q(502-1869 m) = 18.8 l/s compared to circultion losses of 53 l/s; and Q(1104-1869 m) = 3.7 l/s, compared to circulation losses of 6.6 l/s.

TABLE 7: Determination of aquifers in well THG-10 at Selfoss from circulation losses and temprerature logs

Depth m	Circulation loss (l/s)	Increase in loss (l/s)	Seen in temp-log	Lithology
400	>34	>34	yes	hyaloclastite
552	18.0	13.2	yes	basalt
621	10.2	5.1		-
760	12.0	3.2		-
867	10.9	3.1	no	fine grained intrusion
944	10.2	1.0	yes	dolerite intrusion
1023	>21.2	>21.2		basalt
1175	17.8	6.0	yes	dolerite intrusion
1626	9.6	0.0		basalt
1731	10.2	0.6	no	basalt

Remarks: Aquifers below 1100 M are blocked by collapse in well and packer left at 1108 m.

5 SUMMARY AND CONCLUSIONS

In the Tianjin area a cold groundwater system covers the two geothermal systems. This is a similar hydrogeological condition as in the geothermal areas of Urridavatn and Selfoss in Iceland, and although cooling has not yet been experienced, precautions must be taken. The most useful method for detecting mixing is to analyse both the cold groundwater and thermal water for chloride. It is also very important to case off carefully the drillholes at the depth interval of the cold groundwater.

The cooling problem

The geothermal areas of Urridavatn and Selfoss are experiencing a gradual cooling because extractions from the drillholes by pumping have led to a pressure drop in the thermal systems, and cold water has intruded the thermal systems. It is possible to use the concentration of chloride to detect the cold water intrusion into the thermal reservoir before any temperature change has taken place.

The drawdown of the water level

The water level drawdown encountered in the geothermal systems in both Glerardalur and Tianjin, indicate that the geothermal reservoirs are over-exploited.

In the Tianjin area the recovery of the hydraulic head cannot be considered sufficient, as the withdrawal is still higher than the possibility of lateral recharge. Therefore, it is necessary to decrease the pumping rate in order to minimize the water level drop. In addition, the reinjection hypothesis must be studied carefully taking into consideration the constraints concerning the water quality and water temperature. Also, in order to prevent interference among production wells, a suitable distance should be kept between the wells.

Stimulation

The method of drillhole stimulation by pumping with compressed air and injection with or without a packer, has successfully been applied in Iceland since 1970.

The injection packer has also proved to be a valuable tool for determining the hydrological characteristics of individual wells and their connection with other parts of the geothermal system.

In this study well THG-10 was taken as an example and it is demonstrated that the stimulation increased the production considerably from what it was at the end of drilling. Most of the aquifers above 1100 m that were clogged by circulation materials during drilling were successfully reopened in the stimulation process.

Drillhole stimulation could be tried in the Tianjin area in China, especially the pumping with compressed air. Wells with one or two aquifers could also be stimulated by alternating injection directly on the well head, and pumping with compressed air.

ACKNOWLEDGEMENTS

The author learned greatly from the organizers of the 1985 UNU Geothermal Training Programme in Iceland and also from all the lectures on relevant aspects of geothermal energy. The author would like to take this opportunity to express her gratitude to the UNU Geothermal Training Programme in Iceland, especially Dr. Ingvar B. Fridleifsson and Dr. Hjalti Franzson. Mr. Brynjolfur Eyjolfsson and Mr. Sigurjon Asbjornsson have assisted the author in every aspects, therefore the author would like to thank them very much.

The author especially thanks Dr. Arny E. Sveinbjornsdottir for her assistance, and guidance during the training course and the preparation of this report.

Acknowledgement is also due to Mr. Omar Bjarki Smarason for his unlimited patience and assistance during the stimulation study.

In the specialized training on geology and hydrogeology the author is much indebted to Dr. Gudmundur Omar Fridleifsson, Mr. Omar Bjarki Smarason and Mr. Sigmundur Einarsson for their guidance during the trips.

The author wishes to thank Mrs. Olafia Dagnysdottir for drawing the Figures.

REFERENCES

Benjaminsson J.,1983: Jardhitasvaedid Urridavatni Ferlunarprofanir 1983 (The geothermal area in Urridavatn A tracer survey 1983) In Icelandic. OS-85011/JHD-03, 24.

Benjaminsson J., 1984: Jardhitasvaedid Urridavatni. Varmavinnsla og efnainnihald vatns (The geothermal area in Urridavatn. Utilization and the chemical composition of the water). In Icelandic. OS-84114/JHD-50 B, 38.

Drilling Data Handbook, 1978: Editions Technip, Paris.

Einarsson S., Kjartansdottir M., Eyjolfsson B., and Flovenz O., 1982: Jardhitasvaedid i Urridavatni Jardfraedi- og jardedlisfraedirannsoknir 1978-1982. (The Urridavatn low temperature field. Geological and geophysical exploration 1978-1982). In Icelandic. OS-83005/JHD-03, 83.

Flovenz O., Einarsson S., Gudmundsson A., Thorsteinsson Th. and Kristmannsdottir H., 1984: Jardhitarannsoknir a Glerardal 1980-1983. (Geothermal exploration in Glerardalur 1980-1983). In Icelandic. OS-84075/JHD-13, 89.

Flovenz O., and Thorsteinsson Th., 1983: Vatnsoflun Hitaveitu Akureyrar. Stada og horfur i arslok 1983 (Water resource for the Municipal Distric Heating Service of Akureyri. Prospects in late 1983), In Icelandic, OS-84031/JHD-02, 42.

Lu Run, 1983: Stimulation of the water level in the Tianjin geothermal field, N-China. UNU Geothermal Training Programme. Report 1983-10, 69.

Sigurdsson O., Kjaran S.P., Thorsteinsson Th., Stefansson V., and Palmason G., 1985: Experience of exploiting Icelandic geothermal reservoirs. Presented at the Geothermal Resource Council 1984 International Symposium on Geothermal Energy, Kilua-Kona, Hawai, August 26-30, 1985.

Tianjin Geological Bureau, 1977: Observation station of groundwater movement of Tianjin. Report on the hydrogeological conditions and characteristics of groundwater movement from 1966 to 1976.

Tianjin Geological Bureau, 1982: Observation station of groundwater movement of Tianjin. Report of groundwater resource in Tianjin area, N-China.

Tomasson J. and Halldorsson G.K., 1981: The cooling of the Selfoss geothermal area, S-Iceland. Geothermal Resources Council, Transactions, V.5, 209-212.

Tomasson J. and Thorsteinsson Th., 1978: Drillhole stimulation in Iceland. The American Society of Mechanical Engineers, 1-5.

Yao Zujin, 1980: Chemical interpretation of thermal water from Tianjin low temperature area N-China and Yangbe-Jing high temperature area, Tibet, W-China. UNU Geothermal Training Programme, report 1980-6,73.

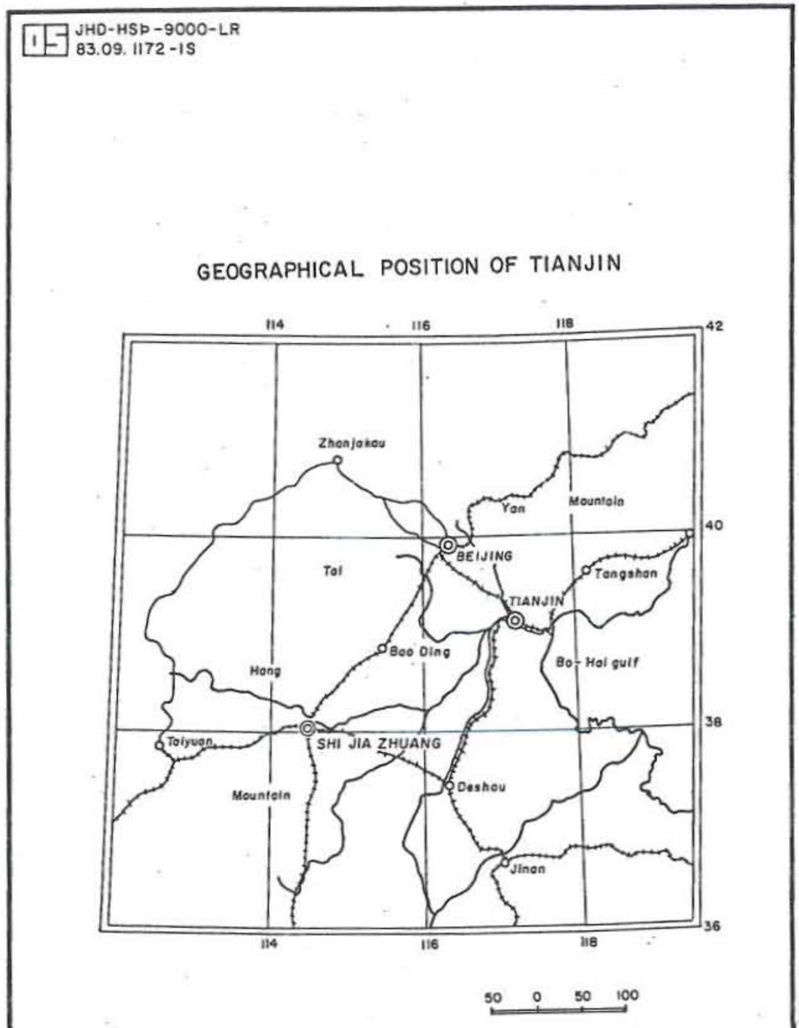


Fig. 1 Location map of the Tianjin area.

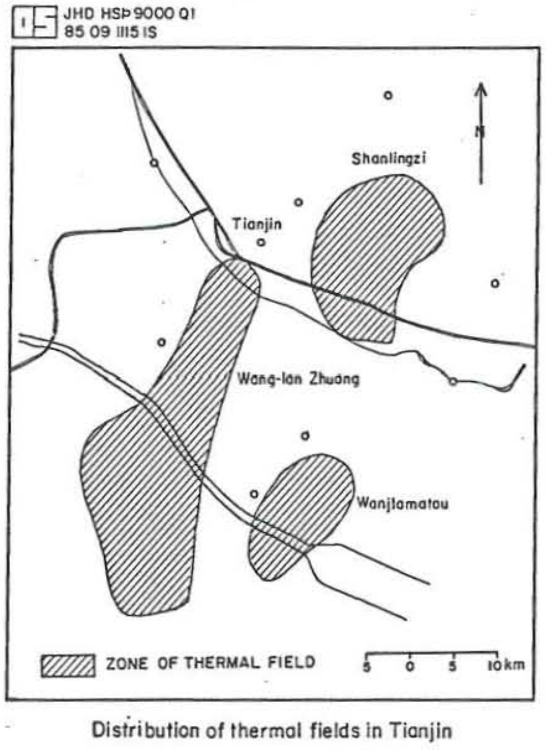


Fig. 2 Distribution of the thermal anomalies in the Tianjin area.

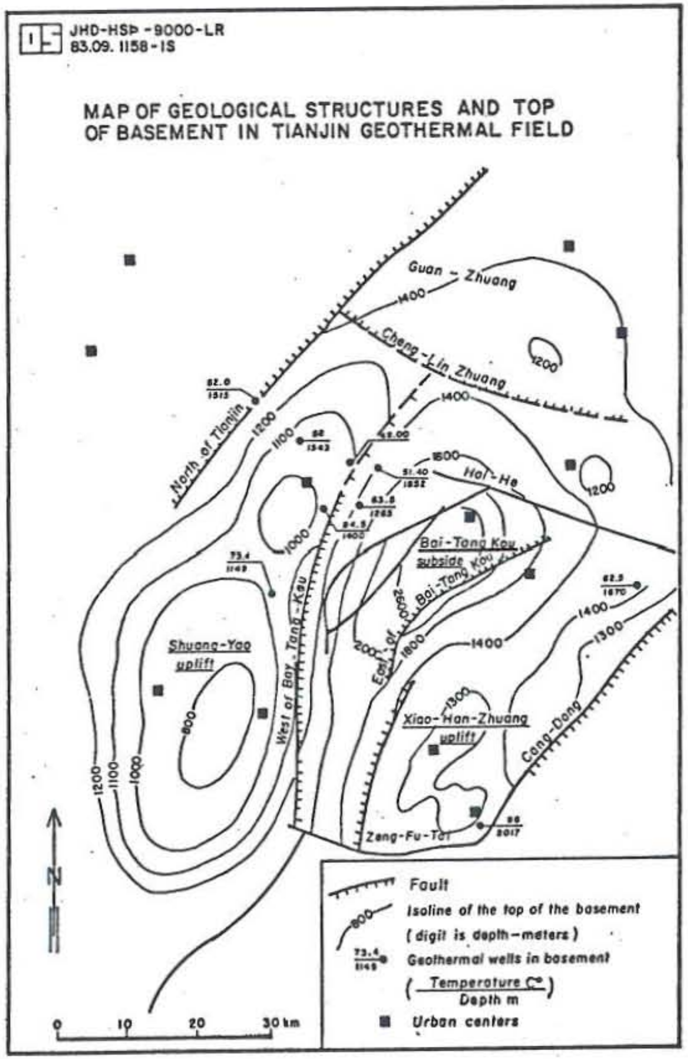


Fig. 3 Geological structures in the Tianjin geothermal field.

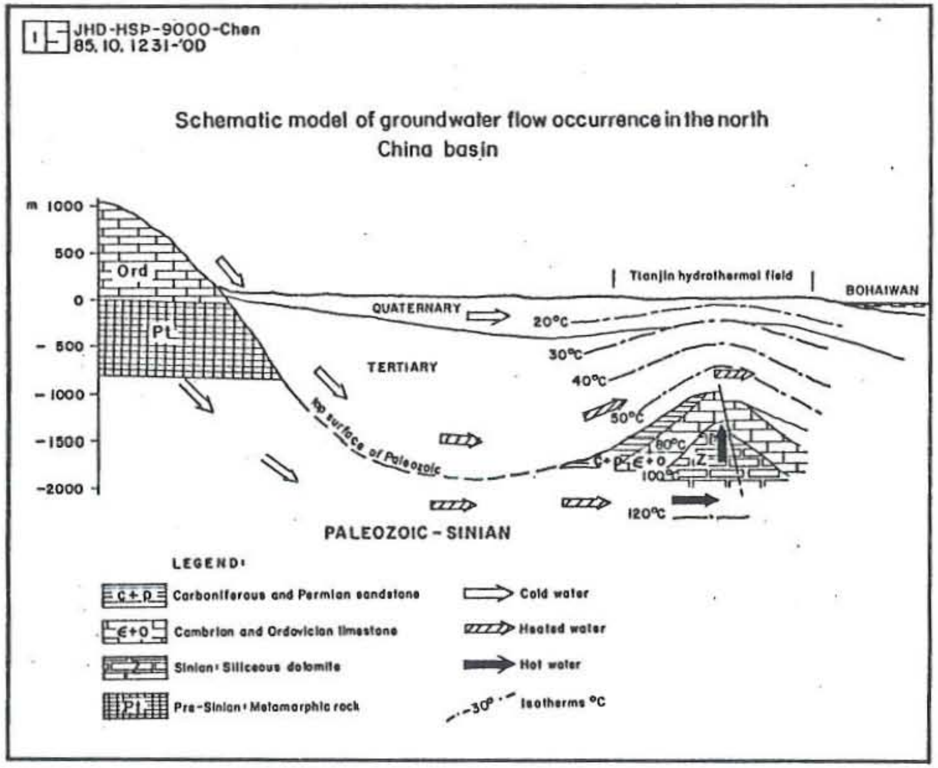


Fig. 4 Schematic model of groundwater flow in the North China basin.

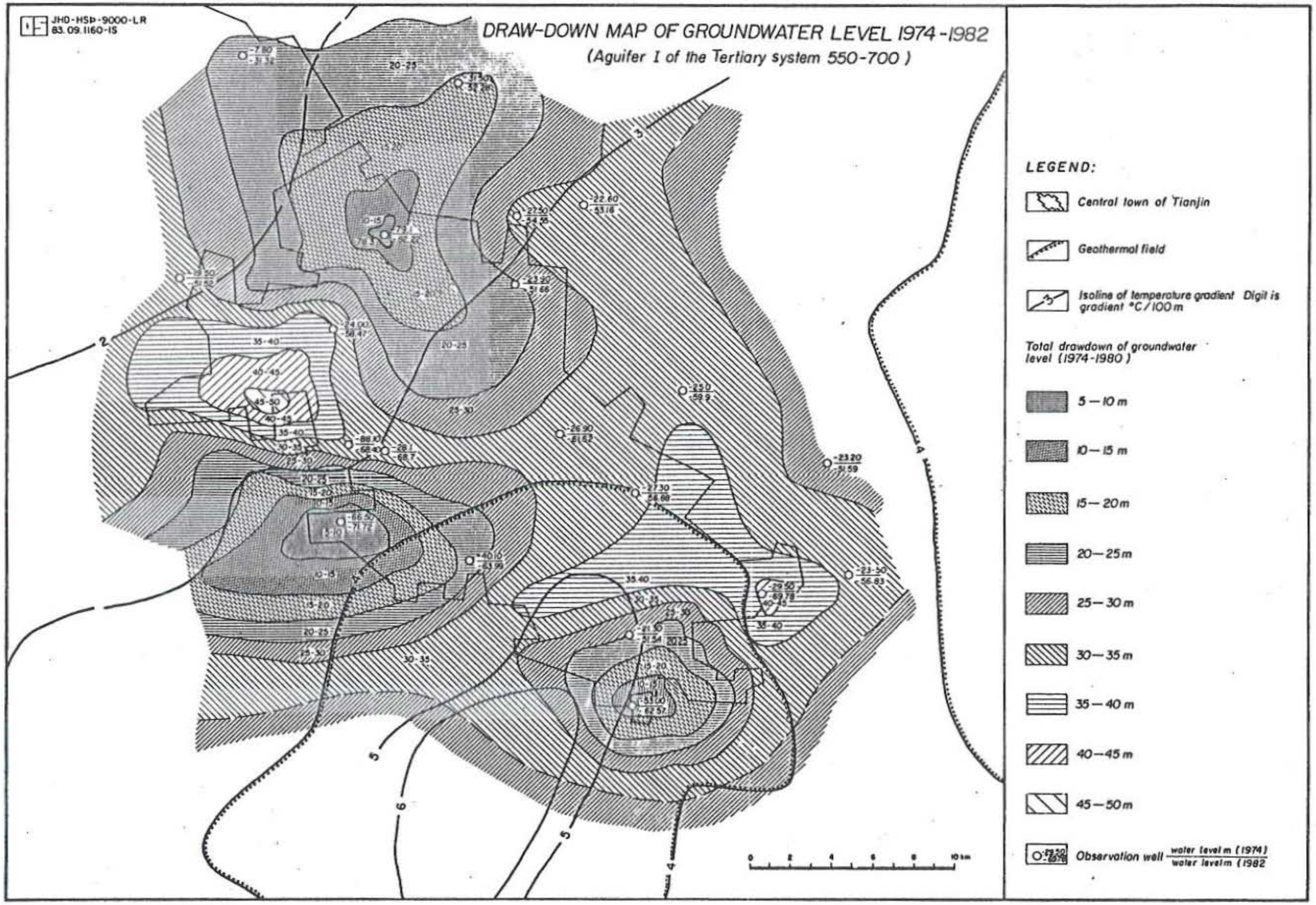
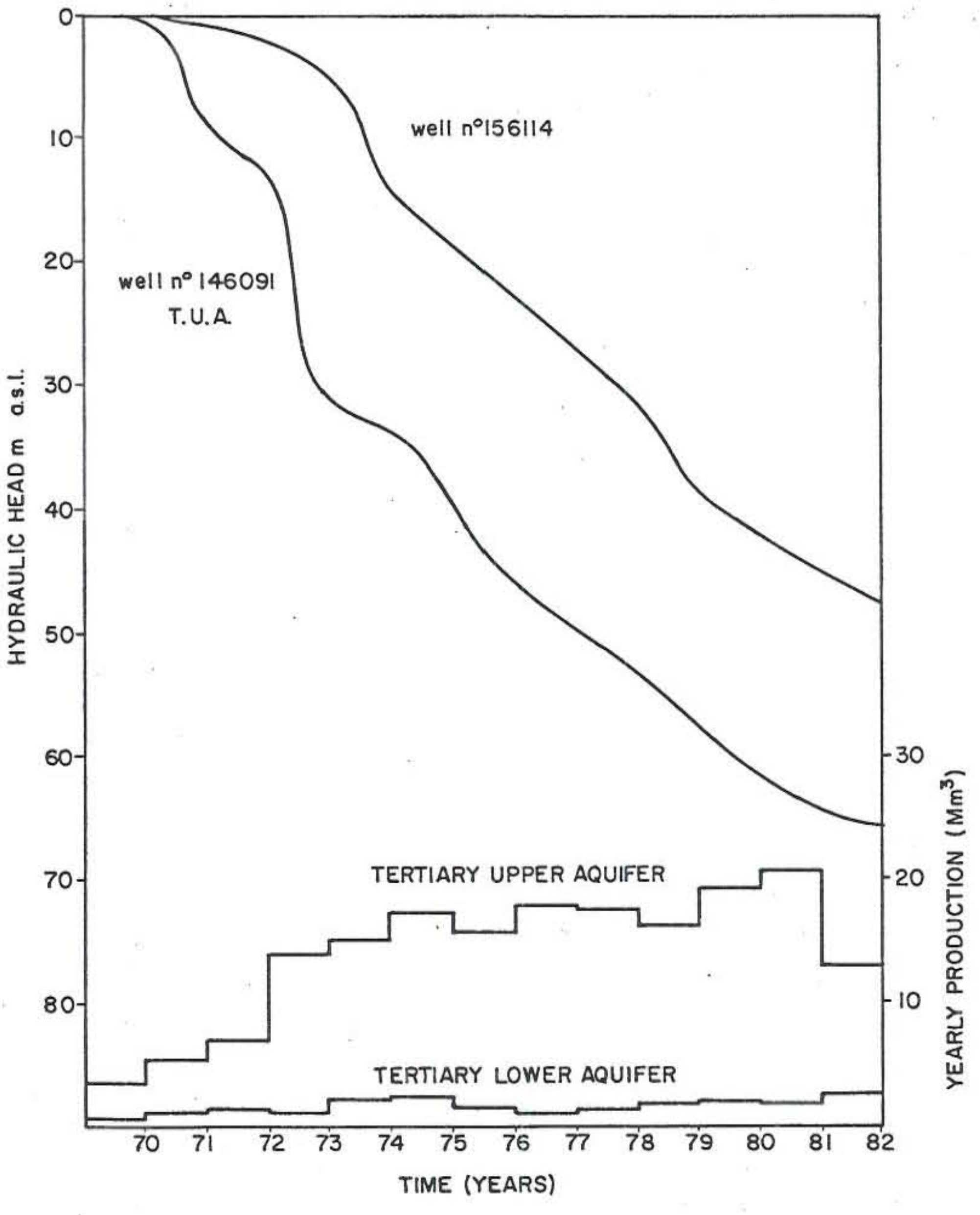


Fig. 5 Drawdown map of groundwater level in the Tianjin area in 1974-1982.

JHD-HSb-9000-Chen
85.10.1232-OD

Fig. 6 – Yearly production of the Tertiary reservoirs and related hydraulic head decline of well 146091 (Tertiary upper aquifer) and well 156114 (Tertiary lower aquifer)



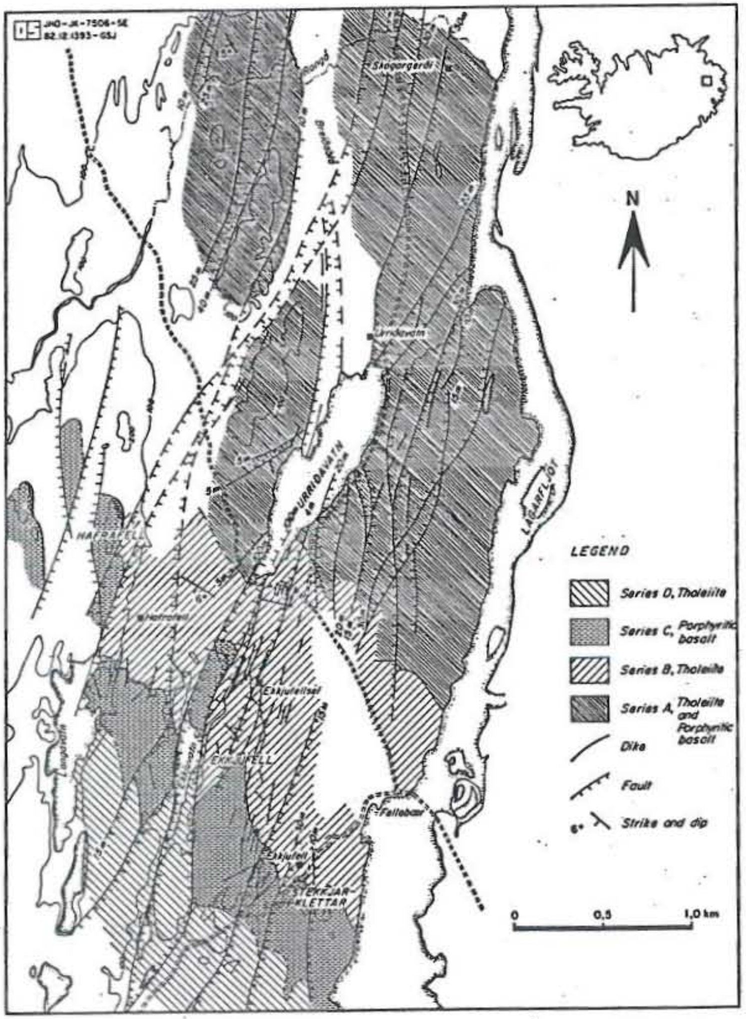


Fig. 7 Geological map of the Urridavatn geothermal area Iceland.

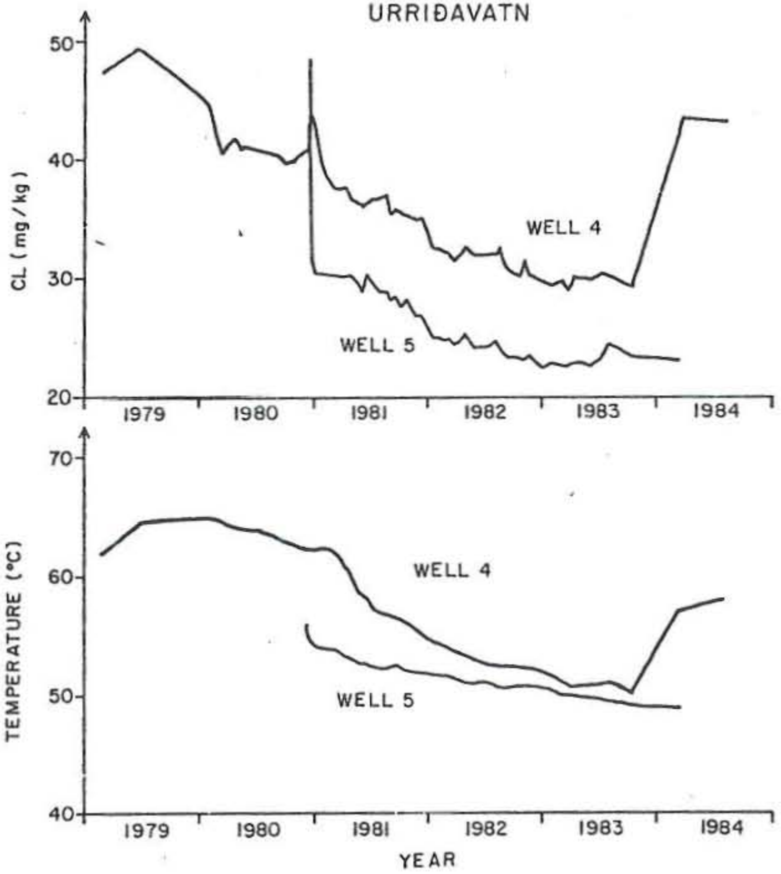


Fig. 8 Variation in temperature and chloride content of wells 4 and 5 in the Urridavatn field.

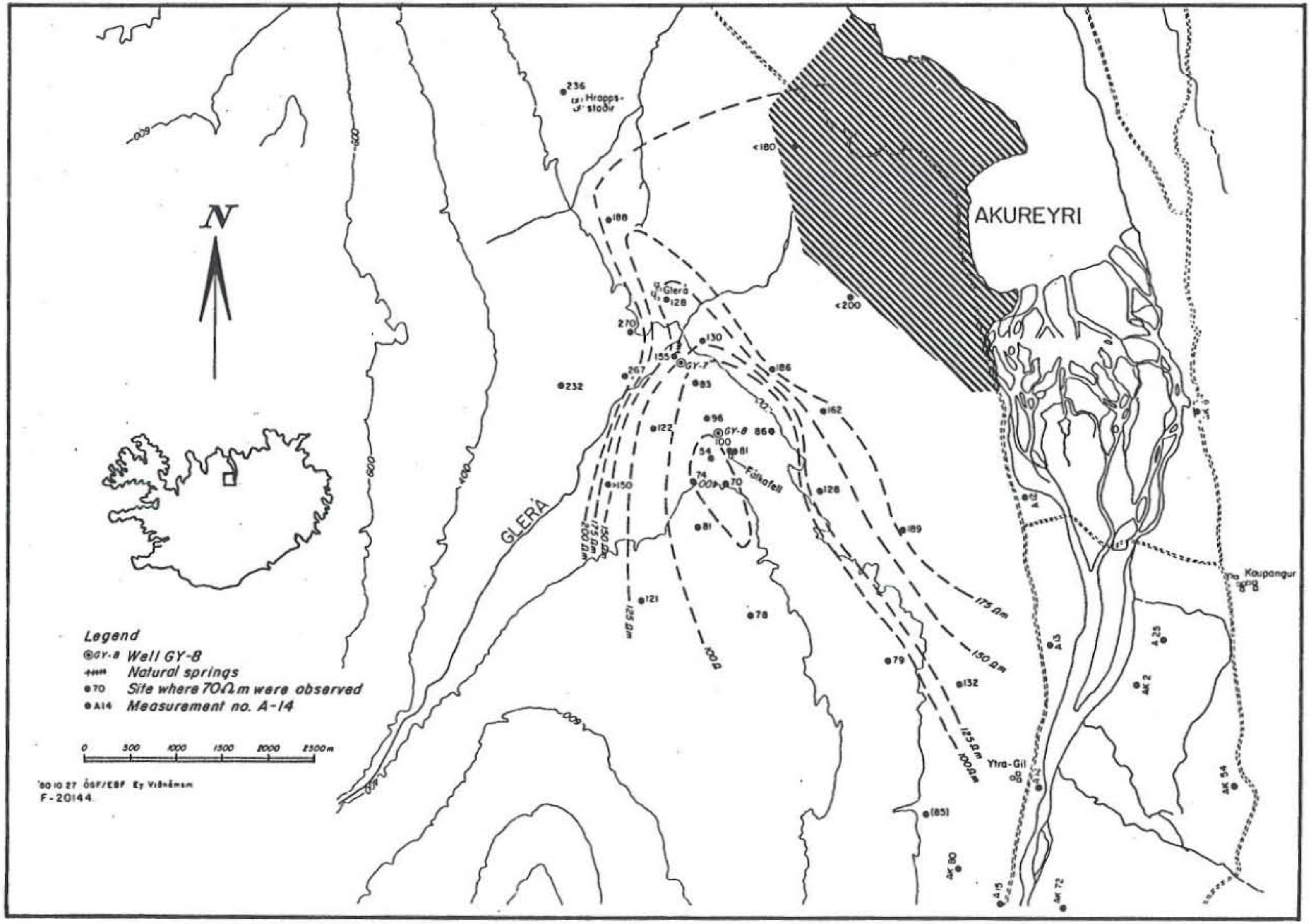


Fig. 9 The Glerardalur geothermal field, north Iceland.

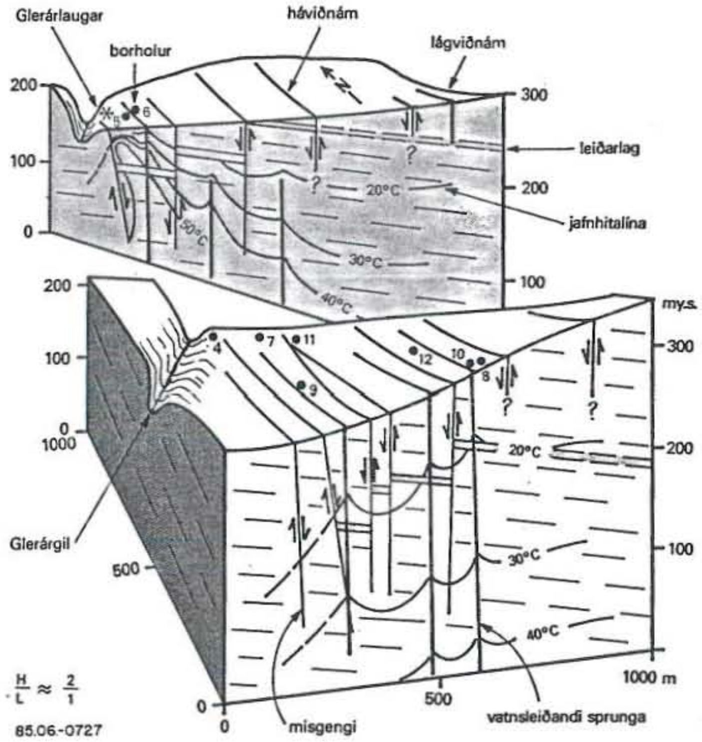


Fig. 10 Geological model of the Glerardalur area.

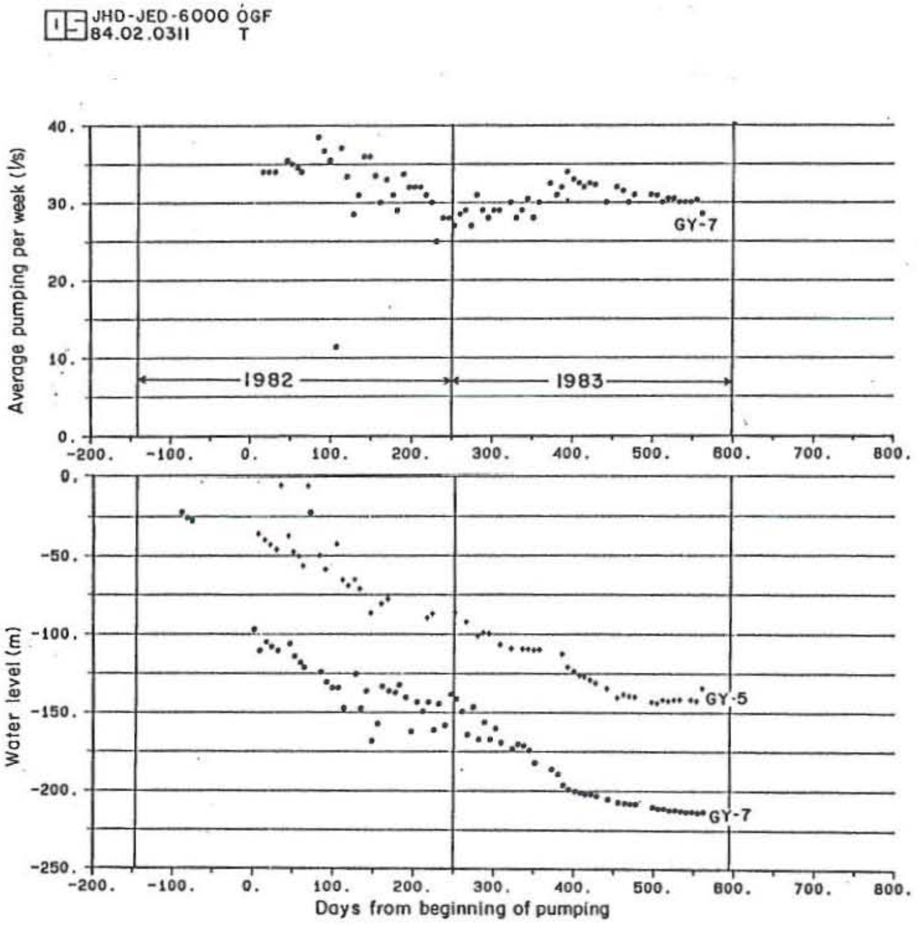


Fig. 11 The water level and pumping of well GY-7 in the Glerardalur field.

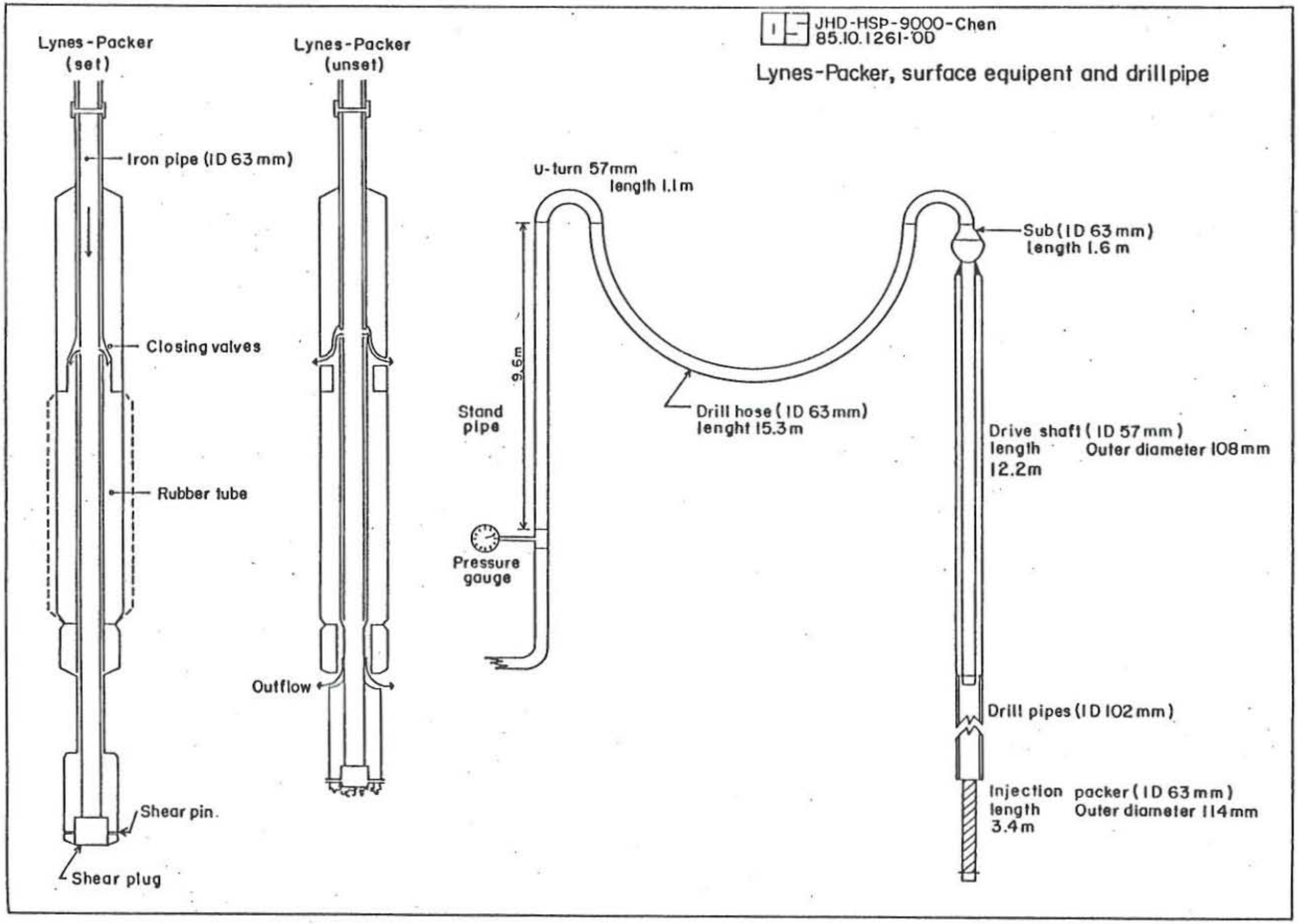


Fig. 12 Structure of an injection packer.

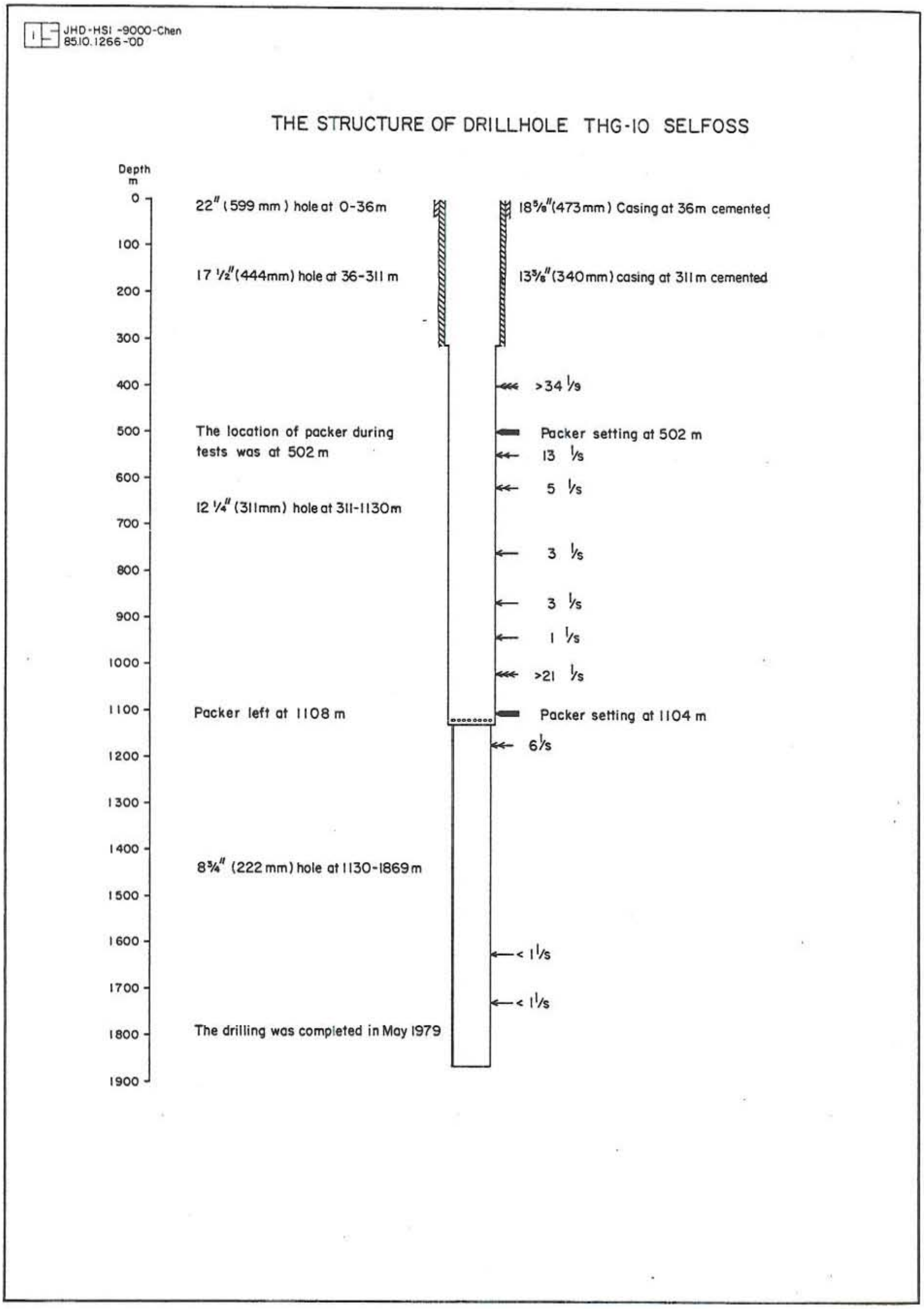


Fig. 13 Structure of well THG-10 in the Selfoss area south Iceland.

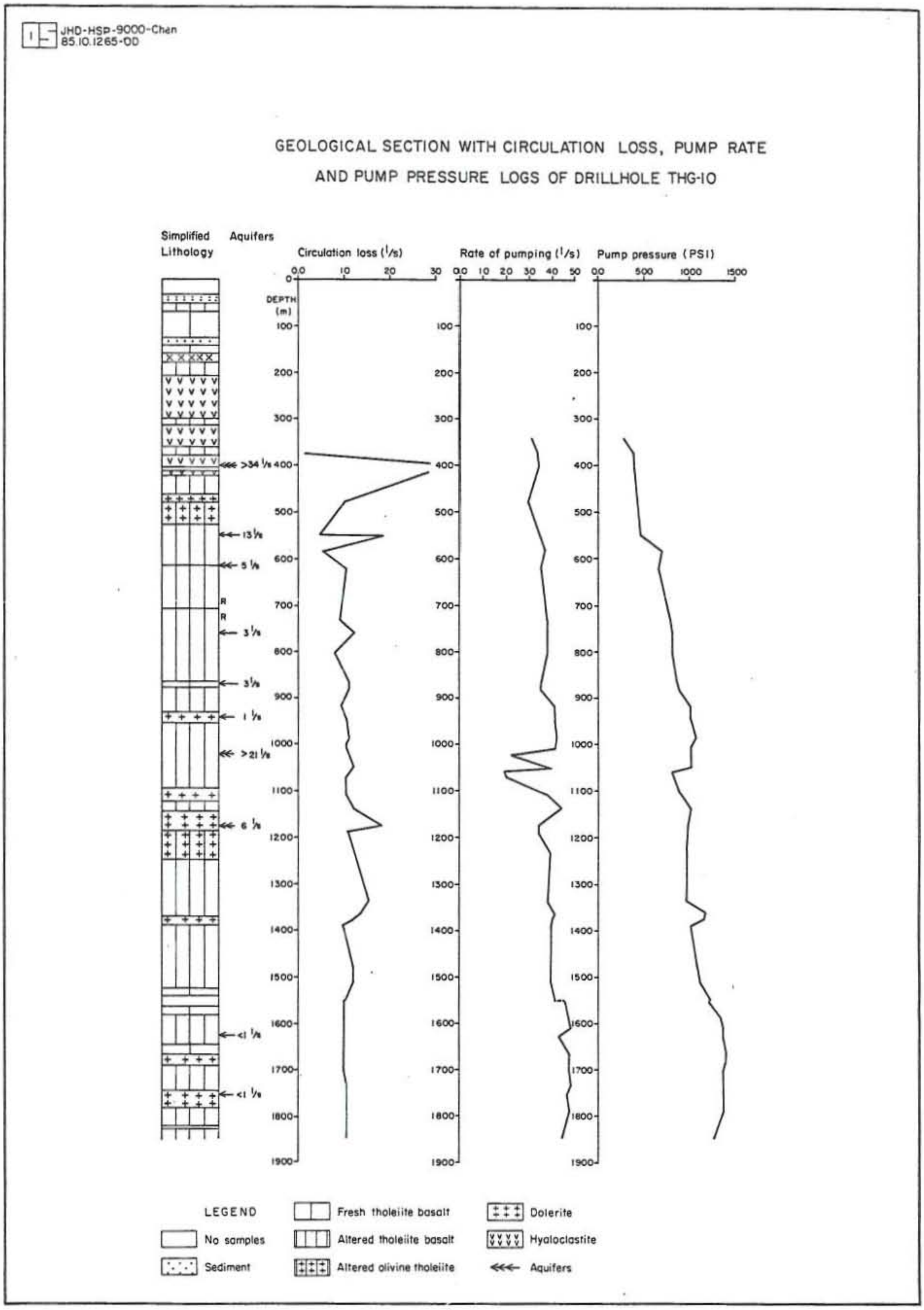


Fig. 14 Geological section with circulation losses, pump rate and pump pressure during the drilling of well THG-10.

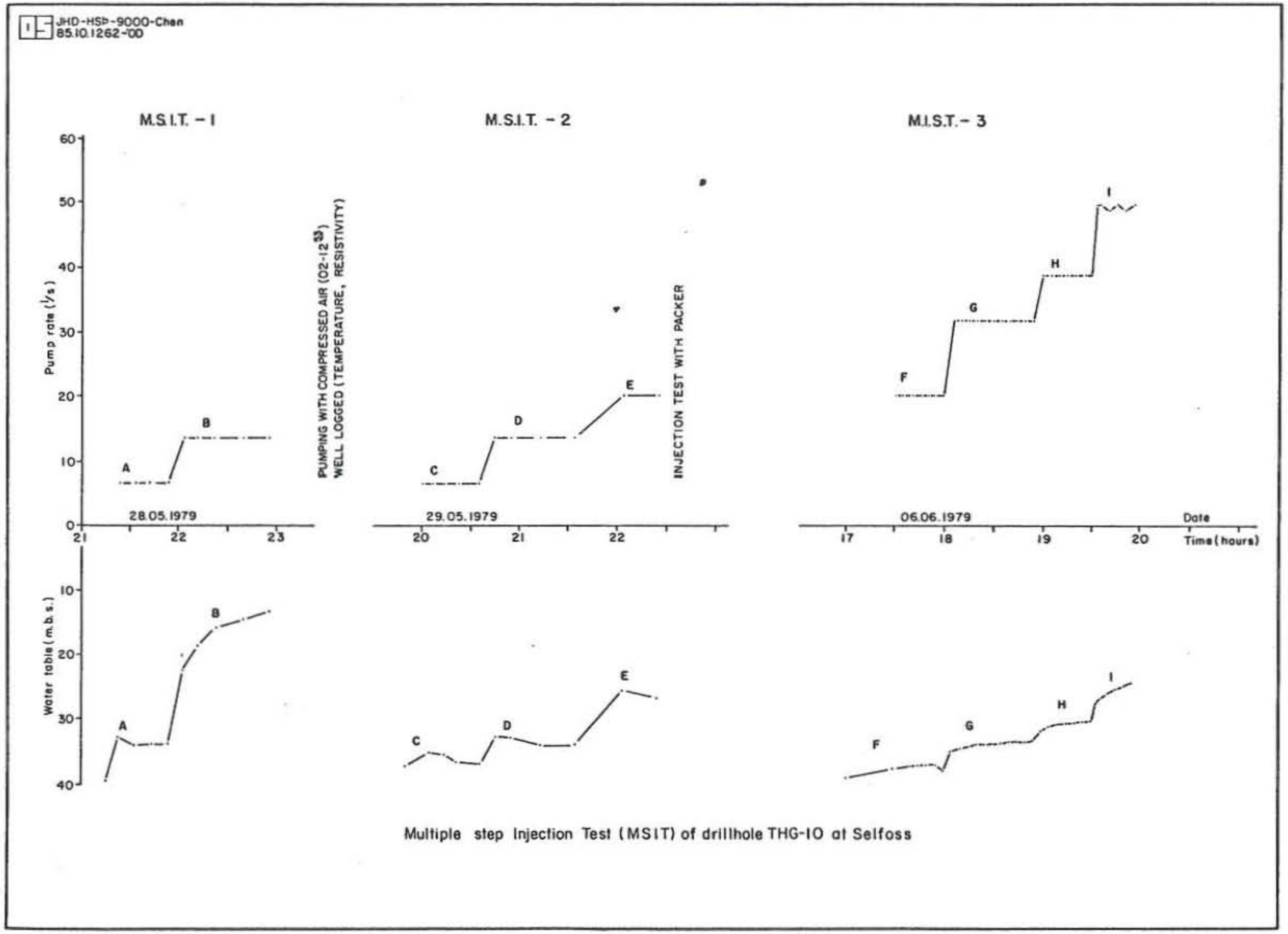


Fig. 15 Multiple step injection test (MSIT V-3) of well THG-10 at Selfoss, south Iceland.

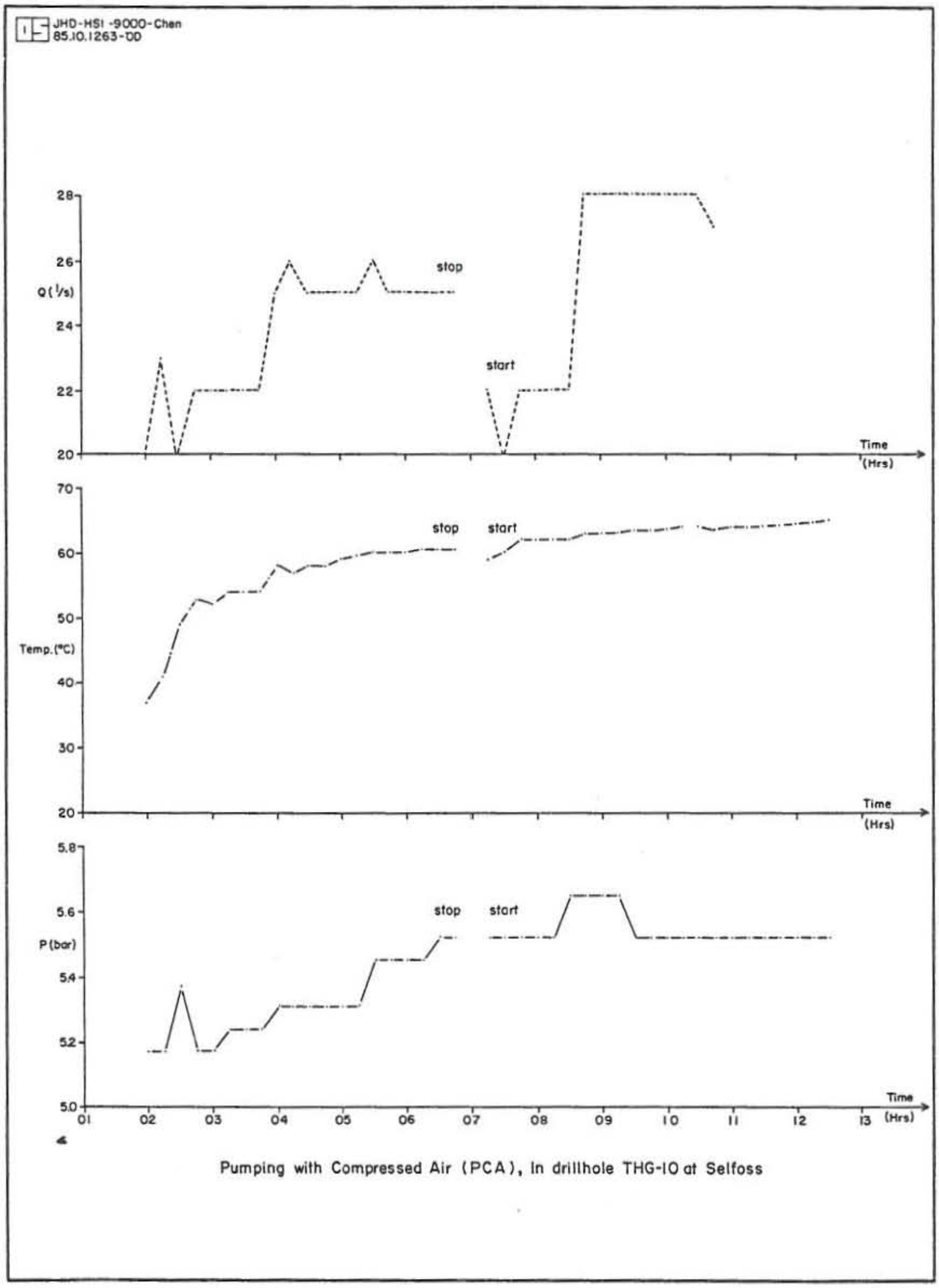


Fig. 16 Pumping with compressed air (PCA) of well THG-10 at Selfoss, south Iceland.

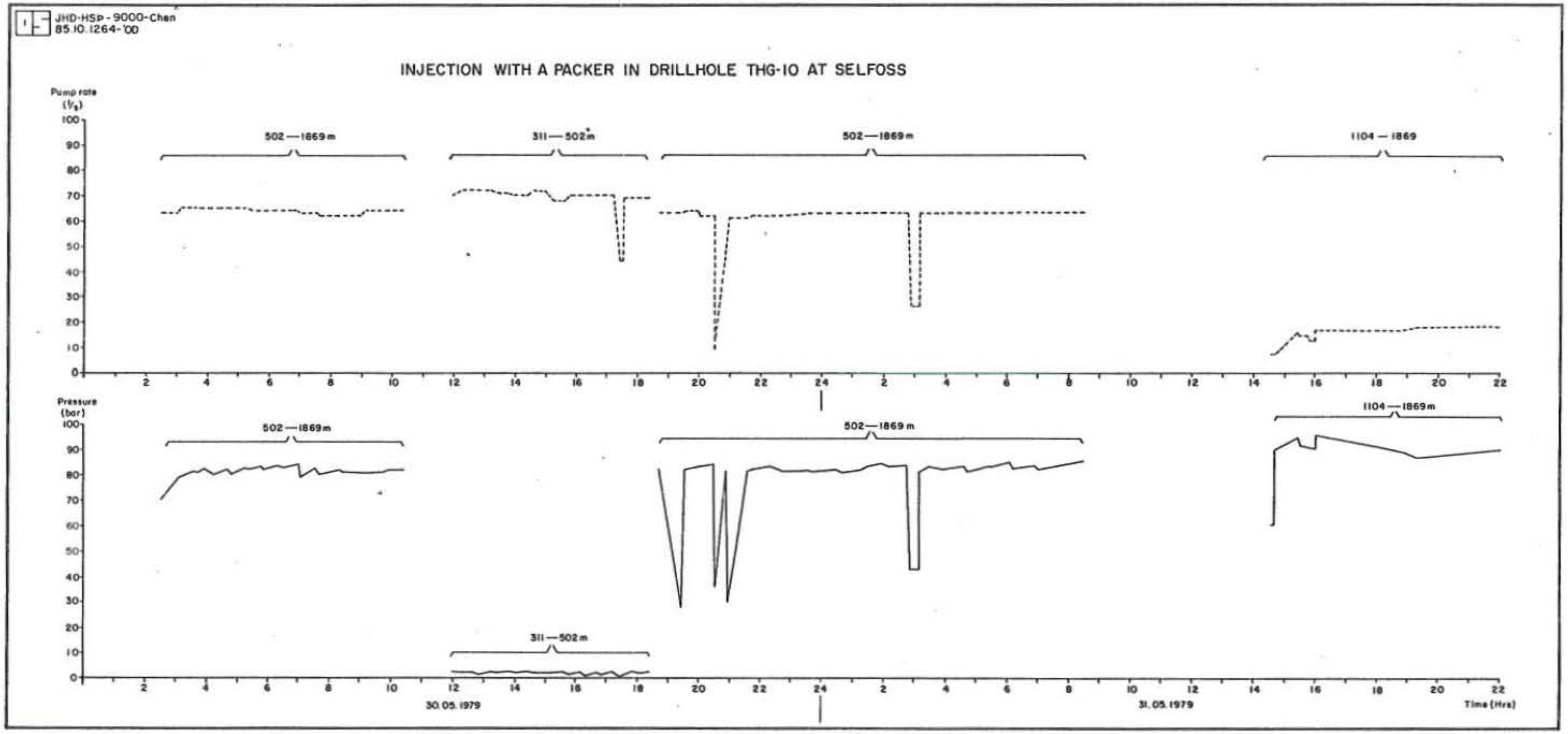


Fig. 17 Injection with a packer of well THG-10 at Selfoss.

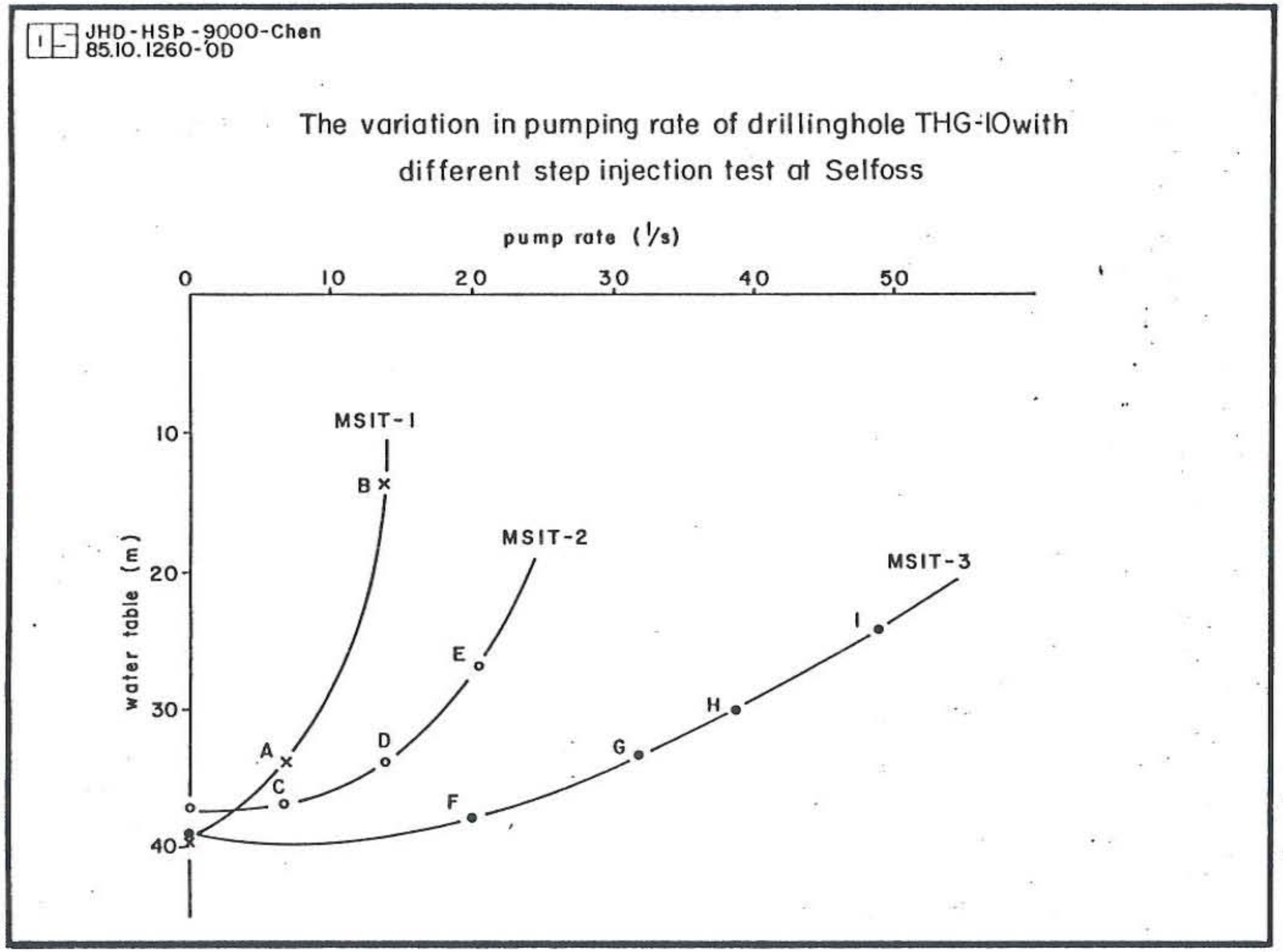


Fig. 18 The effect of varying pump rate on the water level of well THG-10 at Selfoss, during three multiple step injection tests.