ORKUSTOFNUN
NATIONAL ENERGY AUTHORITY
GEOTHERMAL DIVISION

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GEOTHERMAL LOGGING

I

An introduction to techniques and interpretation

OS-80017/JHD-09
Reykjavík, January 1990

Third edition

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ABSTRACT

The aim and purpose of geophysical logging in geothermal investigation is described and comparison made between petroleum and geothermal logging. Logging parameters in geothermal investigations are listed and the principles for some logging equipment described. Practical application of well logging in geothermal drilling operation is emphasized and examples shown of this application. Detailed description of various temperature profiles is made, and the interpretation of these is discussed. The information gained by pressure logs is discussed and various examples of pressure measurement are shown. A brief description is given of the lithological logs: natural gamma ray, gamma-gamma density, neutron-neutron porosity, and resistivity logs. The interpretation of lithological logs in igneous rock is discussed.

PREFACE

Geothermal science is a young discipline, and its place and boundaries have hardly been defined yet. Textbooks and instruction material in this field are scarce.

This report was compiled to meet the need for a reference manual for the Geothermal Training Programme at the United Nations University in Reykjavík, as well as for the staff of the Icelandic National Energy Authority.

Well logging and reservoir engineering are two disciplines within geothermal science which can be regarded as newcomers to the field. Every attempt to put together a summary to be used for teaching purposes has to be regarded in the light of these circumstances.

The material in this text relies heavily on the geothermal experience gained in Iceland during the last few years. It is, however, considered to be of general interest, partly because various types of geothermal systems occur in Iceland and partly because we consider geothermal systems to depend more on physical processes than geographical settings.

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the well looks like" at depth, or as a safety tool to prevent the drill string from getting stuck or similar risks. Many logging methods, like temperature, caliper, bond log, casing collar locator, perforation, free point location, downhole photography, and directional survey are either directly designed for this purpose, or can be used to obtain indirect information.

The advantage of this kind of logging is usually immediate. In some cases, however, as in carrying out a caliper log (measures the diameter of the well) immediately after the completion of a geothermal well and before the start of flow, the result is to be regarded as a reference value for further operation of the well.

Even though we have here stressed the importance of considering the objectives of logging, the rule seems to be that too little geothermal logging is done.

1.2.2 Information on geothermal systems

Obtaining this type of information is usually the main objective of geothermal logging. This is quite natural from the economical point of view as we regard the geothermal system or the geothermal reservoir as the resource to be utilized, and the properties of the resource are of greater importance than the condition of a single well.

What do we want to know about the geothermal system?

In general the following:

- The geological construction of the geothermal field
- The size of the reservoir
- The boundary conditions of the reservoir
- The lifetime of the resource
- Chemical, physical, and structural properties of the reservoir rock
- Chemical and physical properties of the fluid
- Chemical and physical processes within the geothermal system.

The geothermal logs do not give an unambiguous answer to these questions, but are instead a sequence of different parameters recorded in the wells, parameters representing values inside or very close to the well. Conditions there are usually not the same as in the undisturbed geothermal system before the well was drilled. Interpretation of the logs will therefore include elimination and correction for some of the effects inferred by the well.

Observation in a single well will only show a one-dimensional array of the logging parameters. If many wells are observed a three-dimensional picture of the geothermal reservoir can be drawn. Repeated measurements will finally complete the picture and show the time behaviour of the reservoir.

1.3 Comparison of geothermal and petroleum logging

In the petroleum industry well logging is a well developed discipline that has matured over five decades (see Well Logging 1971, Schlumberger 1972 and 1974). Geothermal logging apart from temperature logging is on the other hand only few years old.

Like geothermal drilling, geothermal logging has developed from petroleum logging and relies to a great extent on the latter's experience and development. However, there are important differences between these two types of logging. These differences concern objectives, operation and interpretation.

1.3.1 Logging objectives

The most important objective of petroleum well logging is the determination of porosity and hydrocarbon saturation. For this reason the bulk of research activity related to petroleum logging concerns the accurate determination of these parameters. Petroleum reservoirs are mostly of the intergranular type, whereas the majority of geothermal reservoirs are fractured rather than intergranular. The techniques of detection and quantification of the characteristics of fractures is relatively undeveloped in the logging industry. It is therefore clear that there are differences in the basic objectives of petroleum and geothermal logging, and the petroleum logging knowhow cannot be transferred to the geothermal logging unchanged.

The assessment of reservoir lithology and permeability is common to both types of logging. Here again basic differences occur. The majority of petroleum reservoirs, but very few geothermal reservoirs, are found in sedimentary rock apart from those in the Imperial Valley, California and Cerro Prieto, Baja California (Davis & Sanyal 1979). The permeability in geothermal reservoirs is largely controlled by faults and fractures, and the techniques of measuring it are far behind those used in intergranular reservoir engineering.

1.3.2 Logging operations

Standard well logging instrumentation in the petroleum industry is capable of working at temperatures up to 150 - 180°C, too low for most of geothermal logging, in which temperatures up to 350°C have been encountered. At present this problem is often circumvented by cooling the wellbore down to temperatures suitable for standard petroleum tools. This operation is, however, expensive unless the logging is performed immediately on completion of drilling. Furthermore, the cooling can cause undesirable thermal stress on the casing. This method can, however, neither be used in dry steam fields nor during well flow. Investigation of flowing conditions is, however, very important for the understanding of any geothermal system.

Progress in the development of high temperature logging tools has been made during the last decade. Most of these are, however, at the prototype stage (Veneruso & Stoller 1978, White 1979). In wells hotter than 170°C measurements are therefore carried out with Amerada or Kuster logging tools. Measurements of temperature pressure, and flow rate, can be performed by these tools as well as fluid sampling.

1.3.3 Logging interpretations

The petroleum logging industry has developed relatively sophisticated interpretation methods. These are designed for petroleum investigations and depend on the geological environment common in petroleum wells. As geothermal systems usually occur in different types of geological environment the lack of calibration is one of the major difficulties in geothermal log interpretation.

1.3.4 Case histories

As a result of the infancy of geothermal logging, very few case histories exist today where other parameters than temperature and pressure have been registered. The situation is quite different in the petroleum industry where the number of case histories is many times greater than in the geothermal development field. Furthermore, the interpretation methods used in petroleum logging seem to rely more on empirical relations than on theoretical considerations. This state of affairs only reflects the fact that the case histories in the petroleum industry have been used to improve the interpretation methods. The high temperature geothermal fields which have been utilized for a long time are:
Larderello, Mt Amiata and other dry steam fields in Italy, Otake and Matsukawa fields in Japan, Wairakei and Kawaran fields in New Zealand, Cerro Prieto field in Mexico, Ahuachapan field in El Salvador, the Geysers field in USA and the Námafjall field in Iceland.

Ideally, the predicted performance based on interpretation of logs could be compared to the actual production performance of the fields. Much remains to be learned about the effectiveness, the strong points and the weak links in the geothermal log interpretation. Even, so-called negative case histories, where log analysis did not contribute to the resource assessment of geothermal fields are of value, because they can point out specific needs for the development or improvement of geothermal logging interpretation.

Unfortunately, logging data on parameters other than temperature and pressure are not available from the fields which have been in operation for a long time, mostly because other parameters have not been recorded. There are, however, exceptions from this rule, i.e. as regards the East Mesa and Cerro Prieto fields. These fields are, however, also exceptional in the sense that the geothermal reservoirs are situated in sedimentary rock. This might also be the reason why the petroleum methods have been found useful there.

1.3.5 Summary

Even though it has been stressed here that there are many basic differences between geothermal and petroleum logging it should be pointed out that the similarities are perhaps greater than the differences. Geothermal logging can and should take advantage of the experience gained in petroleum logging, but in the meantime it has to develop its own methods and technology which can be applied to geothermal problems.

At the end of the report is an appendix presenting a list of companies selling logging equipment.

2 LOGGING EQUIPMENT AND LOGGING PARAMETERS

There is a great variety of logging tools presently in use in geothermal logging. In general all logging equipment consists of three parts, viz. the downhole sonde, transmission line, and the registration unit. Such units vary in sophistication. A downhole sonde can be one resistor or a very complicated electronic instrument, and the registration unit can be a mini-computer or simply a notebook and a pencil. The transmission line is usually a logging cable, which is a cable with one, four or seven conductors with the bearing unit, the armour, wound on the outside of the conductors. On the lower end of the cable is the cable head, and different sondes can be connected to the cable. At the surface, the logging cable is connected to a slip ring which makes it possible to get continuous registration while the cable drum rotates and the sonde is moving in the well.

As most of the instrument functions of the logging tools depend on the logging speed it is necessary to have the cable drum motorized to achieve constant logging speed. Hydraulic draw-work is usually preferred at least for logging deep wells (>1000 m).

There are different surface instruments for each sonde. The logging data is recorded on an analog recorder, where the recorder paper is fed by the deptometer. This registration technique is, however, being gradually changed to electronic memories like magnetic tapes, in order to have the data accessible for direct computer interpretation. In some cases there is even a mini-computer in the logging truck for immediate processing of logging data.

As has been pointed out before, the conventional petroleum logging technique is so far only applicable to relatively low temperatures. For higher temperatures one has to use tools which register the logging data mechanically downhole inside the logging sonde. In such cases the transmission line is replaced by a steel wire and the registration is in analog form whose accuracy is in most cases lower than that of a surface electronic registration.

The following discussion of logging parameters and methods is in no way intended to be complete, but the parameters and methods most frequently used to-day will be mentioned.

2.1 Temperature

The fundamental parameter in geothermal investigation is the temperature. Throughout the history of logging many types of thermometers have been used.

Mercury thermometers used to have a wide application in geothermal investigation. As transmission of this measurement is impossible the so-called maximum thermometers were used, and one temperature reading taken during each run. Although the accuracy of the thermometer itself can be quite good ($\simeq$0.01°C) the confidence in the temperature profile measured cannot be high as it is difficult to register points of inflection in the profile. The thermometer will also be exposed to mechanical shocks when taken out of the well. These shocks will tend to lower the temperature readings. Due to this inaccuracy and the long logging time involved for many measuring points, the application of mercury thermometers is insignificant at present.

Resistivity thermometers are the temperature sensors most frequently used in well logging to-day. They have the advantage of small size and ease of transmission from the measuring point to a surface recorder. This is generally done through an electric cable, and the measuring value is obtained either directly by a simple resistivity measurement, or indirectly by coupling the sensor into a resonant circuit. The data information is then fed through the cable as a pulsed signal where the temperature is given by the frequency of the pulses. Pulsed logging is far less sensitive to electrical leaks in cable and cablehead than dc. logging. Neither is it affected by the changing resistivity of the cable due to temperature variations.

The resistivity temperature sensors most commonly used in logging are platinum sensors, which have a fairly linear temperature resistivity relation, and semi-conductors (thermistors), which have a unlinear temperature resistivity relation. Furthermore, the resistivity of thermistors decreases as the temperature increases.

The sensitivity of the resistivity thermometers can be better than ± 0.01°C depending on calibration, but due to the time dependent drift of their electrical properties they need regular recalibration.

Although resistivity thermometers are those most frequently used in geothermal investigations their operation temperature is limited. Problems with ordinary types of electric insulation, and electronic components arise at temperatures above 180°C. Special electrical insulators (teflon) are available for temperatures up to 250°C but max. operation temperature of commercial high temperature electronics is still well below 200°C. At such temperatures the electrical leakage of ordinary cableheads also becomes too great for any serious application of the dc. method. At temperatures above 150 - 200°C thermometers of far less quality are used.

Mechanical thermometers are mainly used in high temperature wells. The data are not transmitted to the surface, but recorded inside the temperature probe on a clock-driven recorder. Several measuring points (20-30) can be recorded during one run.

Two types of temperature sensors are used for mechanical thermometers. These are the bourdon tube (Amerada-gauge) where the boiling pressure of a special fluid is recorded, and bimetal (Kuster-gauge), where the temperature expansion of the bimetal indicates the temperature.

Both sensor types drift with time and need to be recalibrated regularly. Higher accuracy than ± 1°C should not be expected for commercial mechanical thermometers, but at high temperatures they are superior to other thermometers and can be operated up to 350°C, which is close to the highest temperature so far measured in a geothermal well.

2.2 Pressure

It is common in geothermal investigation to use the water level, or the wellhead pressure if the well is artesian, to indicate the pressure potential of the geothermal system at the well site. This is a rather good way of determining the pressure if the temperature is uniform from the water level/wellhead down to the main aquifer of the well, and no water flow or boiling is present inside the well.

In other cases, especially at high temperatures when the density of water depends strongly on the temperature, water level or WHP can give quite erraneous results. In such cases the pressure can either be determined by actual pressure logging of the well or by lowering a small pipe from the well head down to the main aquifer. The pipe is open at the lower end, and the pressure there can be determined by a pressure sensor situated at the upper end of the pipe.

Pressure logging of geothermal wells is widely used in high temperature wells (T>150°C). The use of electrical logging sensors (like piezo-electrical crystals) is not possible at such temperatures, and mechanical pressure gauges are used instead. These gauges are quite similar to the bourdon tube thermometers except that in the pressure gauge the bourdon tube is not sealed from the well fluid, and the gauge therefore senses the pressure in the well at the measuring point.

As in the temperature gauge the pressure is recorded on a clock-driven recorder inside the measuring probe.

The accuracy of the pressure gauges is ± 0.1 - 1 bar and like the temperature gauge it needs to be recalibrated regularly.

2.3 Diameter of the well

The log of the diameter of the well, or the caliper log, which is the usual name for it, is of great importance in well log analysis. Several types of measuring sondes exist. The ordinary type is a three arm caliper, but tools with one up to 60 arms are available. The arms are in all cases motorized, i.e. an electrical motor is present inside the caliper tool. The logging cable makes it possible to control this motor and open and close the arms at demand. The arms will centralize the tool in the well, and the position of the arms is sensed through a variable resistance. A caliper log is measured continuously from bottom to top.

Because of the electrical cable and the downhole electronics, high temperature wells can only be caliper-logged with this technique after they have been cooled down by quenching with cold water. Caliper tools with mechanical downhole registration similar to Kuster and Amerada gauges have been in use for a long time in New Zealand for casing inspection.

These tools can operate at high temperatures.

Go devils are frequently used in high temperature wells. They are in fact sinker bars of different diameters, and therefore show the maximum depth of each clearance in the well, and are mainly used for distinguishing between well deposits and casing damages.

2.4 Formation resistivity

Geoelectrical surveys play an important role in the geophysical investigation of geothermal fields. Low resistivity anomalies are used to map the boundaries of the field, and the location of promising drill sites is for instance often more or less based on the structure indicated by a resistivity map of the field, especially the location of the first well in a field.

Resistivity well logs are the best method available to check the results of the geoelectrical surveys, and are therefore of great importance in geothermal investigation. Because of the difference in electrical properties between different formations the resistivity log will show lithological variations clearly.

There is a great variety of measuring techniques for recording resistivity logs in use to-day.

Here, only one of these techniques, the normal log, will be described briefly.

The normal resistivity log is a four-electrode array with two electrodes fixed on the logging sonde in the well. The third electrode is placed at surface, but the armour of the logging cable is usually used as the fourth electrode, as shown in fig. 2.1. During logging a constant current I is driven between the electrode A on the sonde and the cable armour, and the voltage V between electrode M and the surface electrode N measured. For the normal electrode array the resistivity of an infinite homogeneous medium is given by the relation:

$$\rho = 4\pi \cdot \overline{AM} \cdot \frac{V}{I}$$

where $\overline{AM}$ is the distance between the two electrodes fixed on the logging sonde. In oil well logging the standard values used for $\overline{AM}$ spacings are:

$$\overline{AM} = 16'' \text{ and } \overline{AM} = 64''$$

In a non-uniform medium the resistivity defined by the above relation is an apparent resistivity. The normal resistivity will therefore show the apparent resistivity variations of the medium surrounding the sonde, and will therefore include the well itself. The determination of the true rock resistivity will therefore include elimination of well effects (fluid resistivity and well size) as well as the effects of limited bed thickness of the adjacent lithological units.

Resistivity logging can only be done in the uncased part of the well below water level. The maximum operation temperature is 150 - 200°C depending on cable and cablehead used.

2.5 Natural radioactivity of formation

The natural radioactivity of the rock formation is due to the presence of radioisotopes in the formation. The isotopes that are mainly responsible for the radiation are potassium (^{40}K isotope) and those involved in the decay series of uranium and thorium. Although these isotopes are only found in very small quantities in rock their radiation is detectable. Due to the short penetration length of alpha and beta particles it is the gamma radiation that is detected, and the corresponding log is called "the natural gamma ray log". The detectors used are both Geiger-Müller and scintillation counters. The GM-counter measures the total gamma intensity, but the scintillation counter can register the energy spectrum of the gamma radiation. The count rate measured by a gamma ray tool at each depth in a borehole is related to the concentration of the radioisotopes ^{40}K, ^{238}U and ^{232}Th in the formation outside the well, and defines a quantity that is called the radioactivity of that formation. As the efficiency of different counters differs, calibration is necessary to make radioactivity data comparable from one log to another. In the first years of gamma ray logging (1940 - 1950) each logging company had its own calibration system. Since then a standard calibration unit has been established. This standard is the API γ ray unit (API: American Petroleum Institute). It is defined as 0.5% of the difference in count rate registered between zones of low and high radioactivity in a test pit situated at the University of Houston (Texas, USA).

A simplified sketch of this pit is shown in fig. 2.2.

The radioactive concrete, giving about 200 API gamma units, contains approximately 4% K, 24 ppm Th, and 12 ppm U.

Gamma ray logging can be performed in cased as well as open wells, above and below the water level. Maximum operation temperature is 100 - 150°C.

2.6 Formation porosity

Neutron logs are used in porosity investigations. Actually the log records the ability of the formation material to slow down fast neutrons. The life history of a typical neutron emitted into the formation can be described in the following way. The neutron will be slowed down through several collisions with the nuclei of the formations material until the thermal state is reached ($E=k \cdot T$ where k is the Boltzman constant and T is temperature in degrees Kelvin). In the thermal state the neutron will be captured by a nucleus and the capture will be accompanied by emission of gamma radiation.

As is well known from the collision theory the slowing down effectivity has a prominent maximum when particles of equal masses collide. The slowing down of neutrons is therefore primarily controlled by the abundance of hydrogen. In rock formations most of the hydrogen is in the formation fluid (water, oil), so the neutron logging method can be related to the porosity of the formation.

The neutron logging tool consists of a neutron source (Americium-Beryllium or Radium-Beryllium) and a detector, either a slow neutron detector (He^3) for the detection of thermal neutrons or a gamma detector (GM counter) which detects the gamma ray intensity emitted upon the capture of a neutron. The spacing between the source and the detector is in both cases of the order of 0.3 - 0.4 m.

As for the gamma ray tool a standard calibration is used for this system. It defines an API neutron unit as a part of the difference between two porous layers in a calibration pit at the University of Houston. A sketch of this pit is shown in fig. 2.3.

The neutron logs can be performed in both cased and open wells, filled the liquid. Maximum operation temperature is 100 - 150°C.

2.7 Formation density

Information on formation density is recorded on gamma-gamma logs. Density logging was introduced to obtain data for gravity studies. Today, however, density logging is intensively used to distinguish between different lithological units in conjunction with neutron and resistivity logs.

A γ-γ logging sonde consists of a gamma radiation source and a gamma detector. The spacing between the source and the detector is of the order of 0.4 m. The log measures the ability of the environment of the sonde to compton scatter the gamma rays. This ability is proportional to the electron density which is closely related to the mass density of the medium.

Density tools have to be calibrated in test pits and the log corrected for well size and variations of well diameter.

2.8 Miscellaneous logs

Numerous additional logs and logging operations are utilized in geothermal logging. Only a brief description will be presented here.

Directional survey is of importance in localizing the inclination and direction of a well. The direction of a well is determined either by a magnetic or a gyroscopic compass.

A sonic log measures the velocity of the compressive sonic wave in the formation. The velocity depends both on the rock type and the porosity of the rock.

A sonic bond log measures the attenuation of the sonic wave. Measured in the casing, the amplitude of the wave is proportional to the quality of the cement bonding of the casing to the formation.

A borehole televiewer measures the size and orientation of fractures in the walls of the hole. Its operation is based on acoustic reflection from the walls of the hole.

A spontaneous potential measures the natural potential as a function of depth in the well.

A sampling of fluid at various depths as well as the sampling of rock fragments is furthermore performed by logging equipment.

2.9 Summary of logging parameters

In Table 1 there is shown a summary of the various logging parameters, which are measured or can be measured in geothermal wells.

TABLE 1

Logging parameters

Type of log	Parameter measured	Type of detector	Information obtained
Temperature log	Temperature	Resistor, bourdon tube or bimetal	Reservoir temperature, location of aquifers, temperature gradient, heat flow
Differential temperature log	Temperature difference between two locations in well	Resistor and delay	Location of aquifers
Caliper log	Hole diameter	Movable arms	Location of cavities in well, casing damages
Nat. gamma ray log	Total gamma radioactivity of rock	GM-tube or scintillation detector	Differentiation of rock
Gamma-gamma log	Scattered and attenuated gamma radiation	GM-tube or scintillation detector	Bulk density of surrounding rock sensitive to hole diameter
Neutron-neutron log	Neutron slowed down and scattered by hydrogen	^{3}He neutron detector	Porosity of surrounding rock sensitive to hole diameter
Spontaneous potential log	Natural electrical potentials	Electrode	Probable streaming potential in well
Resistivity log	Resistivity of hole and adjacent rock	Electrode	Porosity of rock. Salinity and temperature of fluid
Sonic velocity log	Vertical component of compressional sonic wave	Hydrophone	Porosity of rock. Rock type
Pressure log	Pressure	Crystal or bourdon tube	Pressure in reservoir. Time dependent pressure gives information on permeability. In some cases flow direction. Response of field to utilization
CCL log	Differential magnetic permeability adjacent to sonde	Perm. magnet and two coils	Location of joints of casing. In some cases casing damage can be localized
Sonic bond log	Attenuation of sonic wave	Hydrophone	Quality of cement outside casing. In an open hole it can give density of fractures in the well
Directional survey	Dip and direction of well	Pendulum and compass	Three dimensional location of the well
Flow meter log	Fluid velocity in well	Spinner	Flow and flow direction in well. Location of aquifers
Fluid sampler	Sample of fluid	Bottle	Composition of fluid at various depths
Side wall core gun	Sample of rock	Piston cylinder	Composition of rock at various depths
Borehole televiewer	Reflective acoustic wave from walls of the hole	Sonic detector	Fractures in the borehole walls
Magnetometer log	Vertical or total magnetic field	Fluxgate or NMR	Magnetic polarity of geological units transversed
Free point log	Differential extention or torsion of the drill-string	Extensio meter or torsion meter	Highest free point of the drill-string

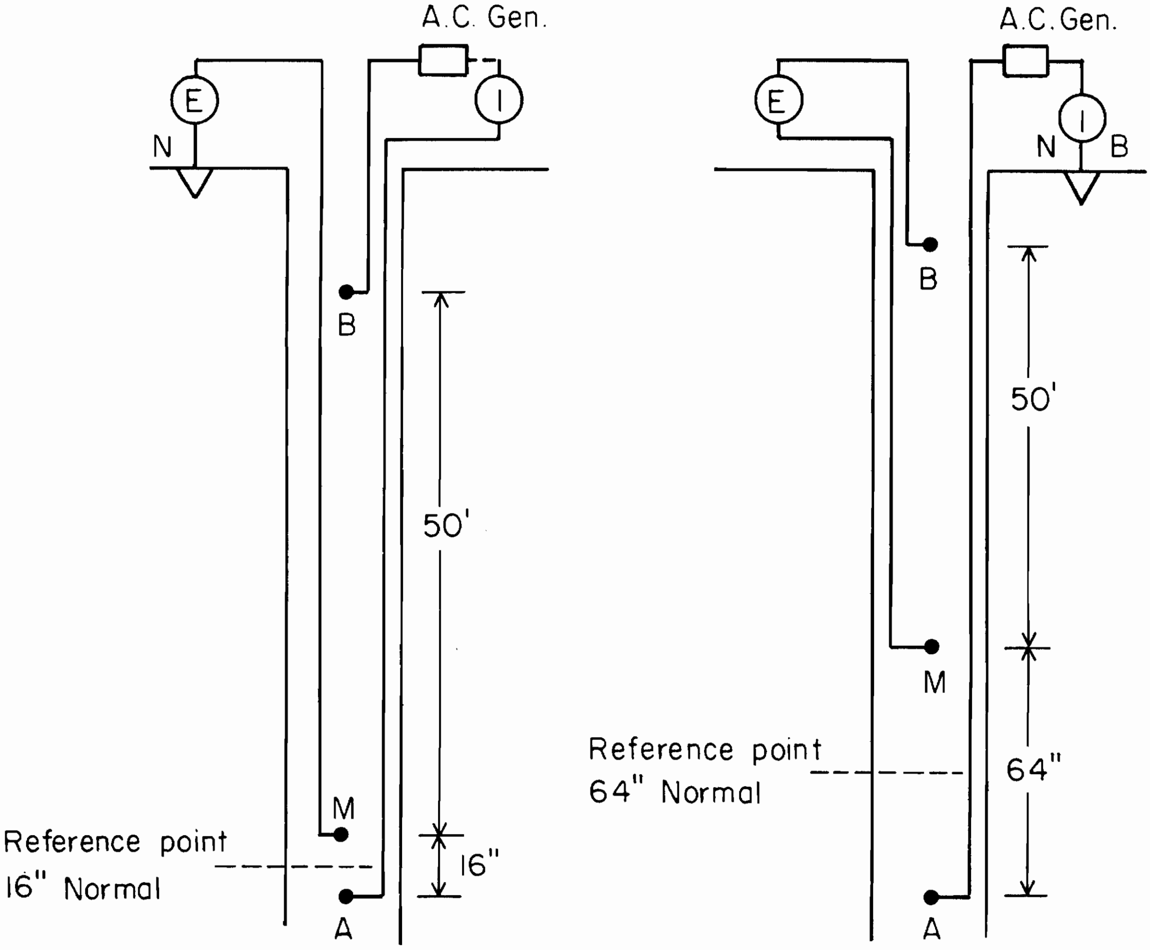


Fig. 2.1 Electrode arrangements for the 16 and 64 inches normal resistivity log.
From Keys and McCary 1971.

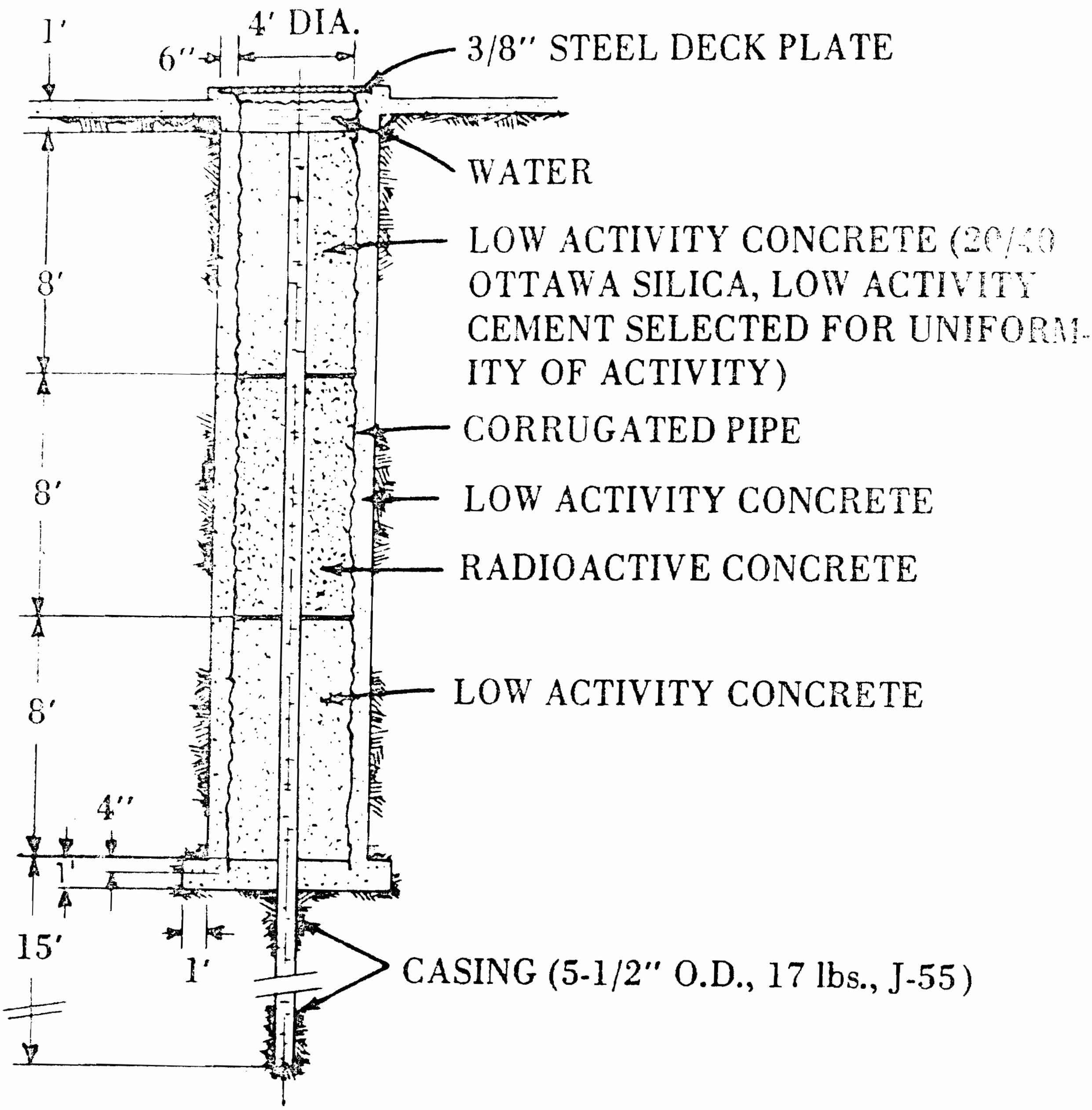
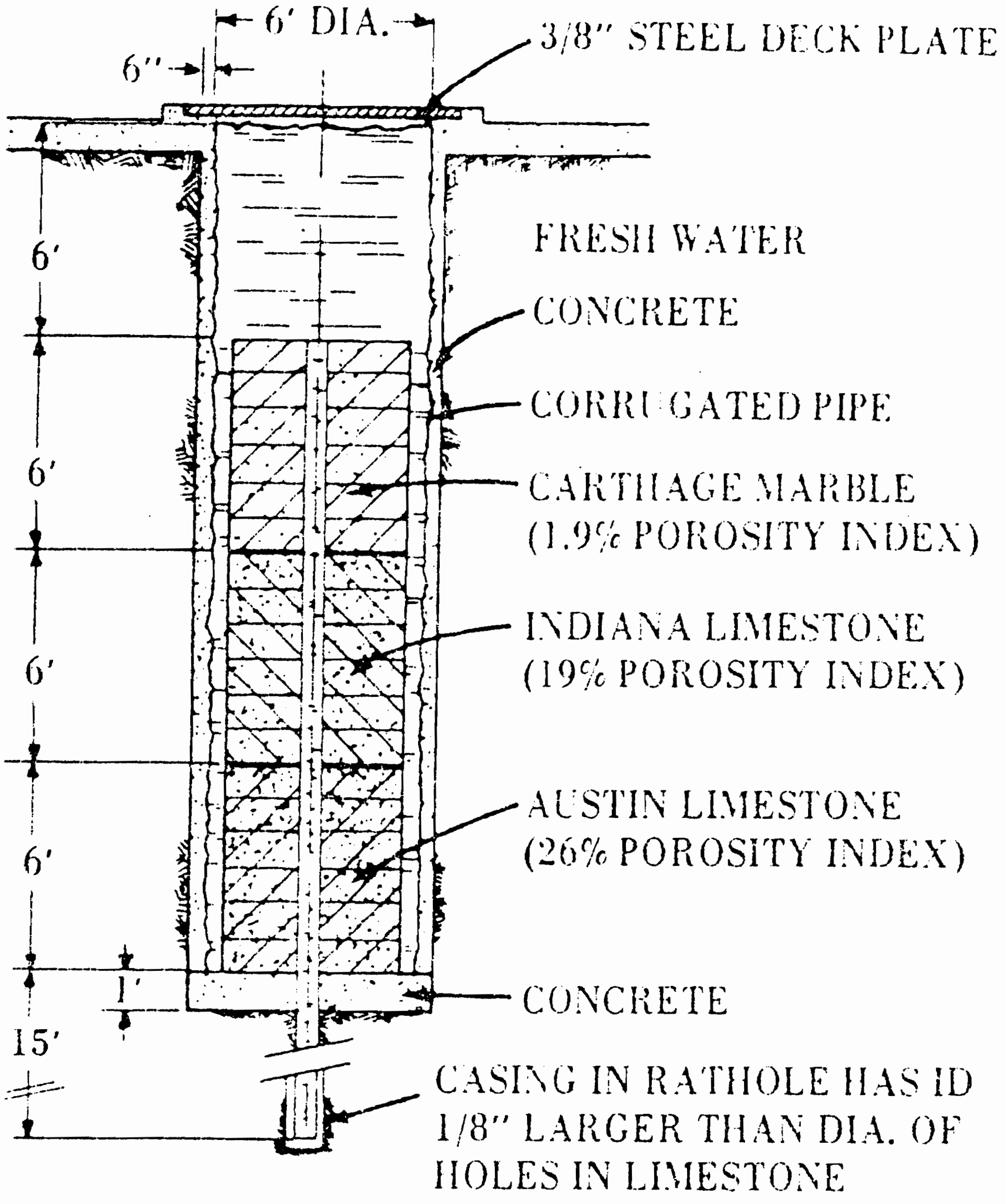


Fig. 2.2 The American Petroleum Institute (API) gamma ray calibration pit located at the University of Texas in Houston. From Dresser Atlas 1977.



Carthage marble, Austin limestone, and Indiana limestone sections are each composed of 6 regular octagonal blocks, 5 ft. across, 1 ft. thick, with 7-7/8" (±1/16") center bore hole.

Fig. 2.3 The Americal Petroleum Institute (API) neutron calibration pit located at the University of Texas in Houston. From Dresser Atlas 1977.

3 PRACTICAL APPLICATION OF WELL LOGGING IN DRILLING OPERATIONS

The well logging technique provides a powerful tool for the mapping of the characteristics and conditions of a well. Logging methods are for instance extensively used to locate zones of circulation losses or water entry, well diameter and direction, in the inspection of casings and in estimating the quality of cement behind casings and so on.

During drilling, information gained from logs on what is happening in the well can often help the drilling engineers to choose the best operation, either to prevent difficulties or solve drilling problems. Because of rigtime cost such information will immediately show its economical value.

In planning the logging operation all available information on the well should be collected in advance. Information such as total depth drilled, diameter of drill bits used, diameter of casings and their depths, together with information on the behaviour of the well before the survey was done, and finally older logs if available.

The purpose of the logging operation should be written on the log together with all information necessary to reconstruct the situation in the well during logging. This will preserve the logging information so it can be used not only immediately after the survey but also as a reference at later stages in the lifetime of the well.

The variety of logging methods and the variety of conditions where logging is applied make it impossible to give definite rules for when and which logs should be run. Each case must therefore be treated individually and the choice of logging procedure based on experience and sound understanding of the operation principles of the logging method selected.

This section describes some of the applications of well logging as an aid in drilling operation and in determining well characteristics, by considering several logging methods separately.

3.1 Temperature log

Temperature logs very seldom show the true rock temperature in the well. During drilling the circulation fluid will change the temperature considerably. If circulation is stopped the disturbances will start to die away, but even though the well is kept circulation free for a long time there is no guarantee that all the disturbances will disappear. Disturbances caused by circulation, injection of water and other heat transfer operations give on the other hand valuable information on the locations of water entries and zones of circulations losses. In fig. 3.1 four examples of disturbed temperature profiles for a three aquifer well are shown. For each example a linear rock temperature profile is used as a reference. Both cases A and B can be observed in wells during injection, depending on whether the injected fluid is lost at the aquifers or whether there is an additional fluid entry at some of the aquifers. A fluid-loss zone is seen in the temperature log as a change in the temperature gradient whereas fluid entry appears as a discontinuous jump in the temperature itself. A quantitative estimate of the amount of fluid lost or gained at the aquifers is possible if the heat flux through the walls of the well can be considered constant throughout the well (the heat flux together with the flow defines the temperature gradient between two loss zones) or if the original temperature of the fluid entering the well at an aquifer is known.

In case of a fluid entry, see figs. 3.2 and 3.3, the inflow q at a temperature T_1 is given by the formula:

$$q = Q_o \cdot \frac{T-T_o}{T_1-T}$$

where Q_o and T_o present the flow and temperature above the inflow aquifer respectively, and T is the temperature below the aquifer.

In case B in fig. 3.1 it should be noted that the inflow at the aquifers a and b will not stop immediately and the thermal recovery will be governed by flow between aquifers at least at the beginning of the warm-up period.

The above equation also applies to free flow from a well (case C and fig. 3.1 if the words <u>below</u> and <u>above</u> are interchanged in the definition of T and T_o, Q_o). The temperature disturbances below the deepest aquifer on

3.1.C will die away during recovery and the temperature align itself to the true rock temperature.

Finally fig. 3.1.D shows that aquifers can be seen in the temperature profile of a closed well free from fluid flow either as a positive or a negative anomaly in the temperature log.

The location of aquifers is of general interest in geothermal investigation. The location of loss zones together with the amount of fluid lost will, during drilling, be a crude measurement of the success of the drilling operation, and may in some cases determine the final depth of the well.

Aquifers are also of interest in the cased part of the well as it is usually preferred to cement all such major loss zones off before the casing is sunk into the well and cemented. This is done to minimize the risk of bad cementing of the casing.

Although the use of temperature logs during drilling has so far only been mentioned as a tool to localize aquifers, the temperature itself can be of interest, as the two following examples will show.

1. The lubricator used in ordinary drill bits cannot stand higher temperatures than 100-150°C. If the well cannot be cooled by a cold water injection (f.ex. after the cementing of the casing), a temperature log will show how deep into the well it is safe to sink the drill bit before it is necessary to slow down and start cold water circulation to protect the drill bit.
2. The BOP valves (blow-out preventor) cannot be applied for one or two days during the sinking of a casing or a liner into a well. Hence there is a potential blow-out risk. If the temperature response of the well is studied before the drill string is taken out of the well the blow-out risk during the casing operation can be estimated.

3.2 Caliper log

The caliper log gives the location of cavities in the well. During drilling cuttings will accumulate in all major cavities and cause a potential risk of the drill string becoming stuck in the well. Before the situation develops that far the geologist who analyses the cuttings has usually noticed the problem so proper precautions can be taken. These include running a caliper log of the well to localize the washout zones and to define the size of the problem. If big cavities are found it is usually preferred to cement them off, unless a big aquifer is at stake, then a fake casing may solve the problem. In fig. 3.4 a caliper log of a well before and after cementing of a washout zone is shown.

Caliper logs are also commonly used to inspect casing for damages either during drilling or later in the lifetime of a well. Depositions in wells are also clearly seen on caliper logs (see fig. 3.5).

3.3 Sonic bond log

Cementing of long casings in geothermal wells is a delicate operation, and problems arising from poorly cemented casings are far too common. A log of the quality of the cement behind the casing is therefore of a great interest in distinguishing between different cementing techniques and in defining which steps should be taken to improve the cementing of the casing in the well logged. The sonic bond log is designed for this purpose, it shows how well the casing is bonded to the formation, and therefore shows the top of the cement outside the casing and water pockets in the cement (see fig. 3.6). Water pockets between inner and outer casings in a geothermal well cause casing collapses when the well warms up. Such water pockets can be neutralized by perforating the casing at that depth.

Perforation is also a method widely used when the cement does not reach the surface outside the casing. The part of the casing perforated in that case is at the top of the cement and the cementing operation can then be repeated from that level.

3.4 Free point log

This log is commonly run in oil well drilling when the drill string is stuck. It determines the point at which the string is stuck. The string can then be backed-off at this level and the rest recovered either by jarring it out of the well or by drilling round it before recovery is made.

3.5 Directional survey

Geothermal wells are by no means vertical and inclination up to ten degrees is common. The inclination depends both on the geological structure penetrated and the drilling technique used, and can by "careful" drilling be kept within certain limits. In general this will mean a slower penetration rate.

The usual compromise is therefore to try, during drilling, to avoid rapid changes in the inclination of the well by measuring the inclination regularly throughout the drilling period (at least every 100 m). Such changes in inclination occuring on short intervals in a hole can result in a key-hole formation, where the drill string may get stuck when pulled out of the well.

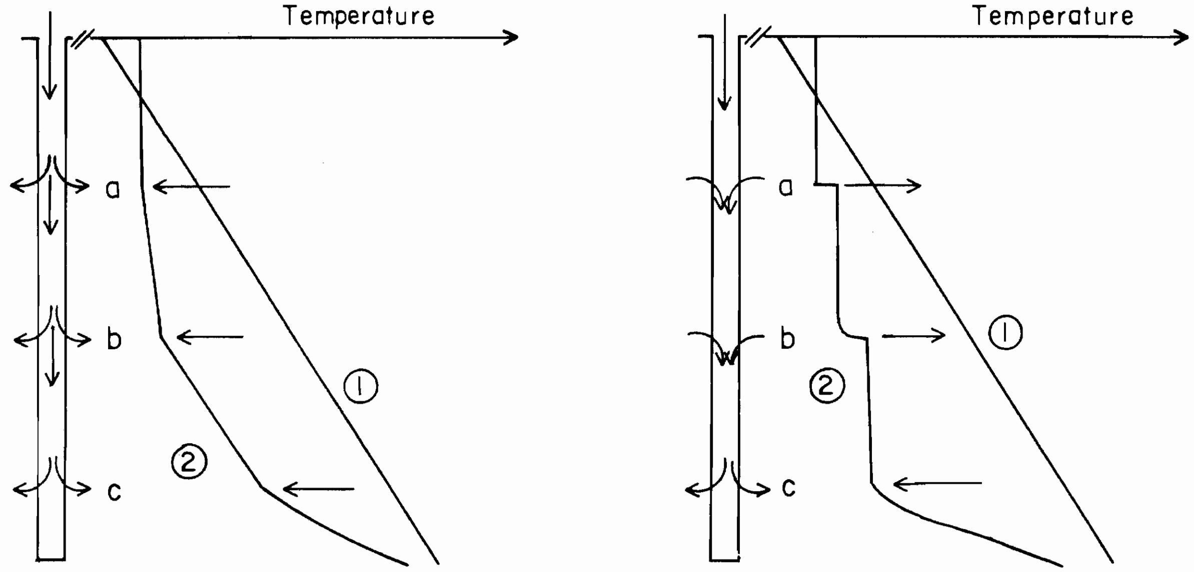
When the well is completed a directional survey is necessary to obtain an exact location of the different parts of the well. An example of a direction log is shown in fig. 3.7.

3.6 Casing collar locator

The CCL log shows the variation in the amount of iron in the vicinity of the CCL tool. It can therefore be used to locate casing joints. Casing damages can also usually be seen. Fig. 3.8 gives an example of this use of the CCL log.

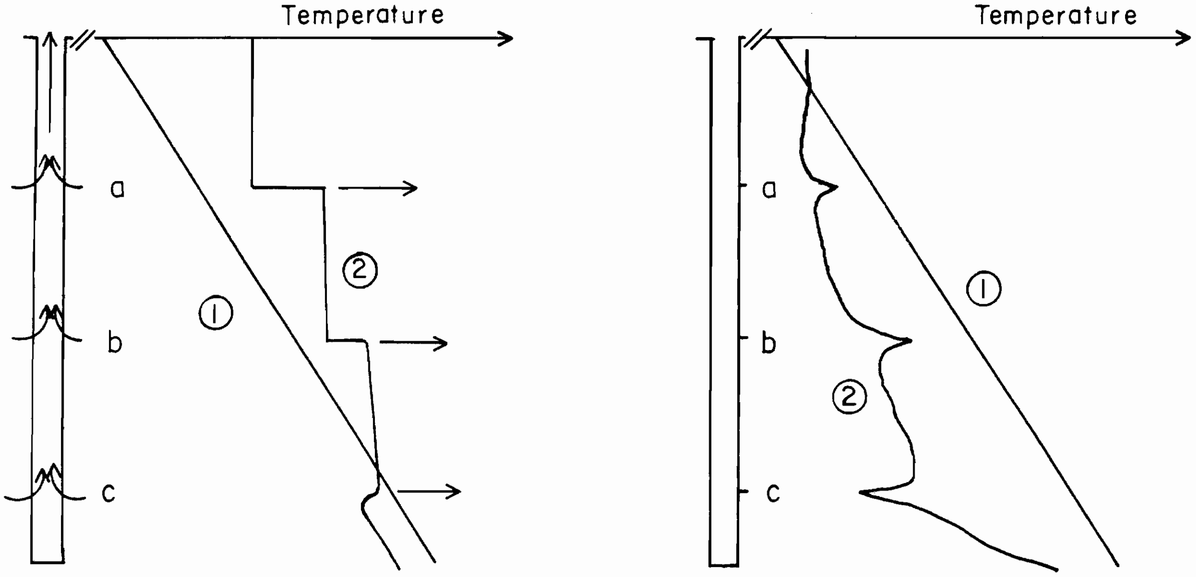
3.7 Downhole photography

In all cases of casing damages it is of great benefit to have a photograph of the damage to find out its cause and to choose the best way of reparation. For this reason a downhole camera should be a standard item in every geothermal well logging outfit.



A.
Water injected into the well

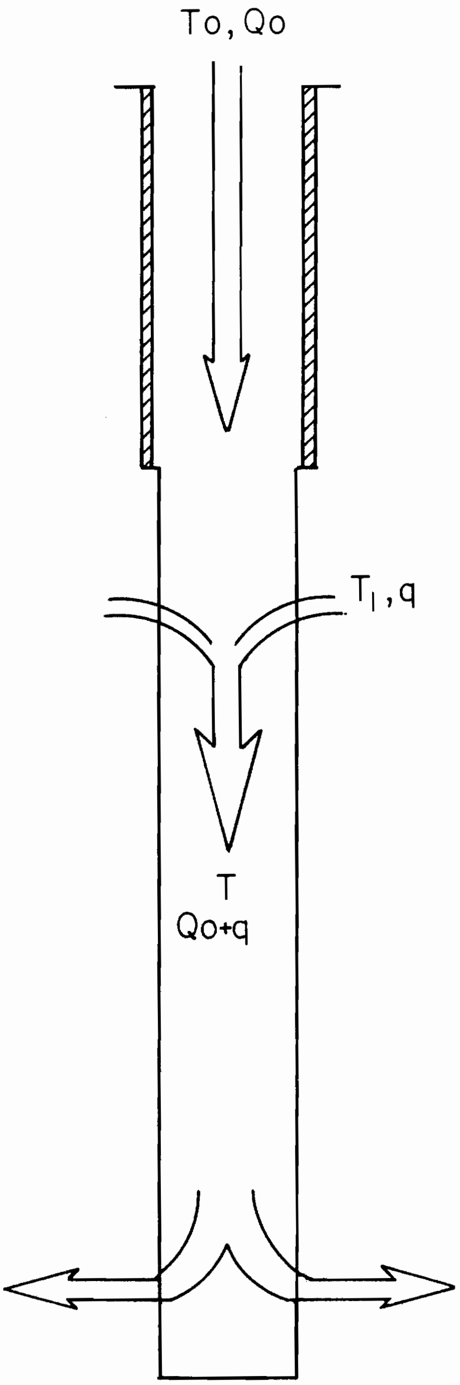
B.
Water injected into the well (see fig. 3.3)



C.
Free flow from the well

D.
Closed well (no fluid flow)

Schematized picture of temperature profiles of a well with aquifers at the depths a, b, and c. Curve ① denotes the true rock temperature and curve ② shows the temperature shortly after drilling. Arrows indicate direction of fluid flow.



To, Qo : Temperature and fluid flow above the water entry

T_l, q : Temperature and amount of fluid entering the well at the aquifer

T : Temperature below the water entry

The conservation of mass and heat gives

$$(Qo+q)T = Qo \times To + q \times T_l$$

$$\downarrow$$

$$q = Qo \times \frac{T - To}{T_l - T}$$

Fig. 3.2 Schematized picture showing a water entry into a well during injection at the top of the well.

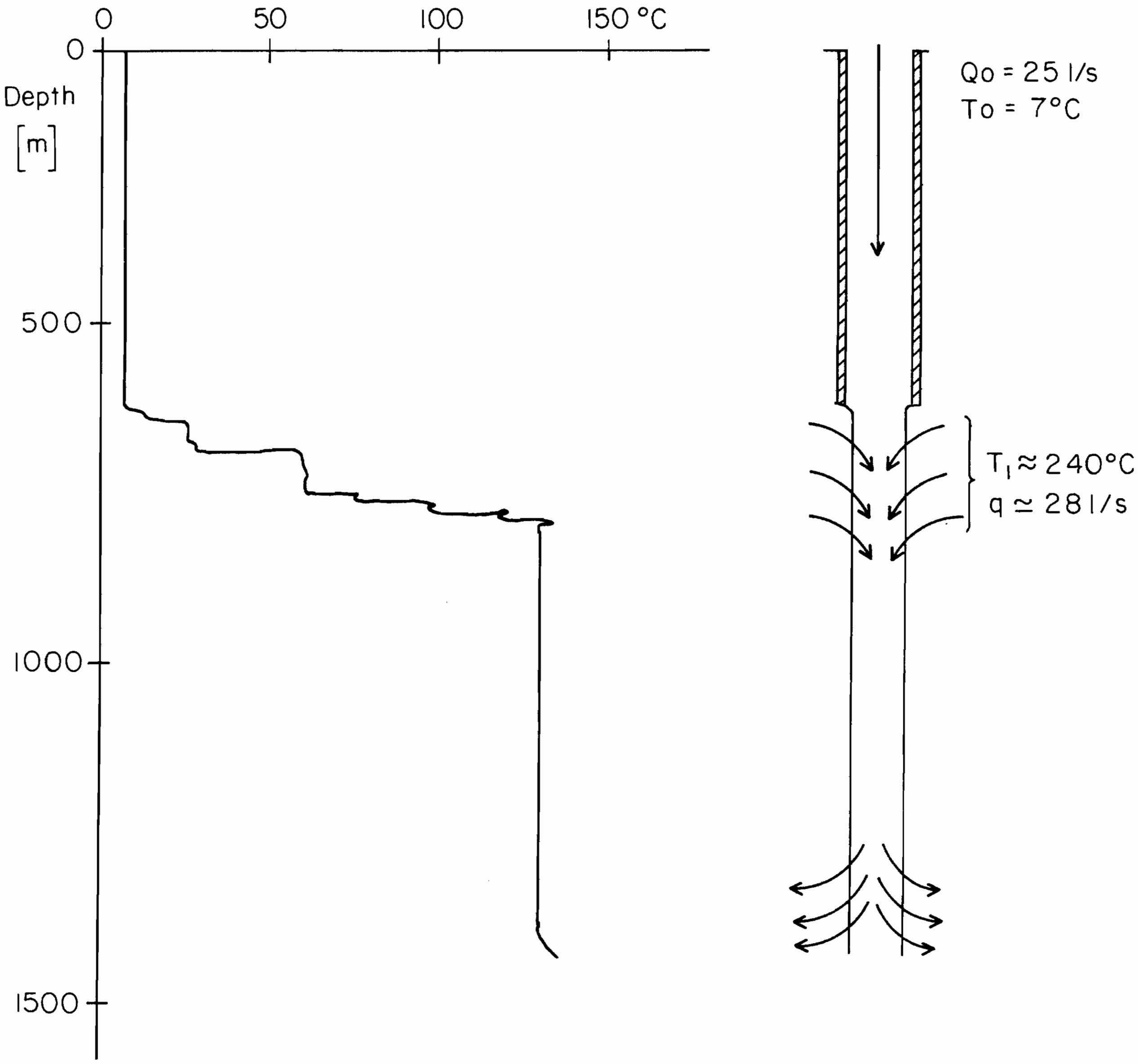


Fig. 3.3 Measured temperature profile during injection in well No. SG-7 in Svartsengi, Iceland. Reservoir temperature in Svartsengi is appr. 240°C and the calculated inflow in the well is 28 l/s when 25 l/s is injected at the top of the well.

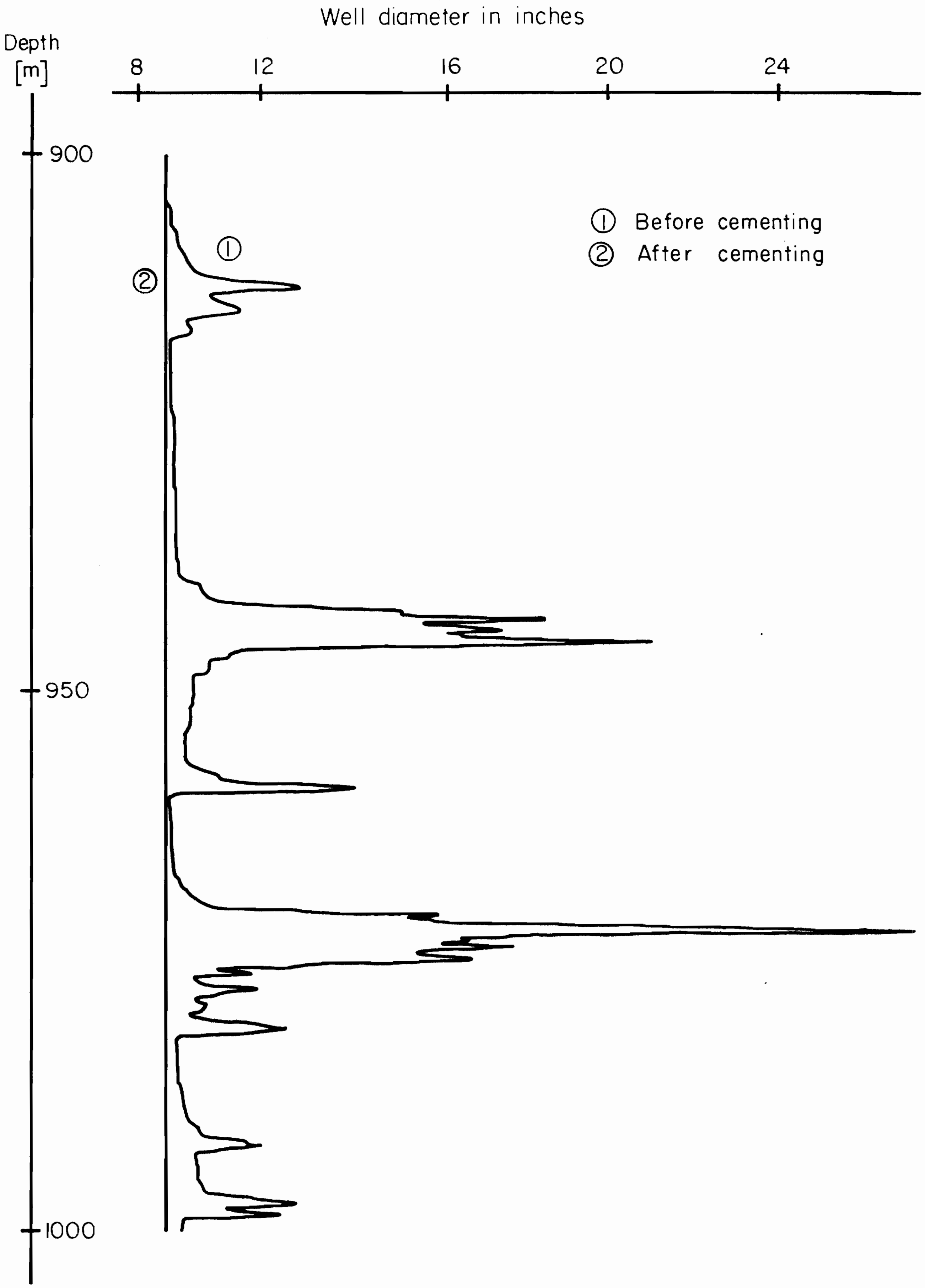


Fig. 3.4 Caliper logs of well No. LN-12 at Laugaland, Iceland. Curve ① shows the cavities formed in the well. Curve ② shows the well diameter after cementing.

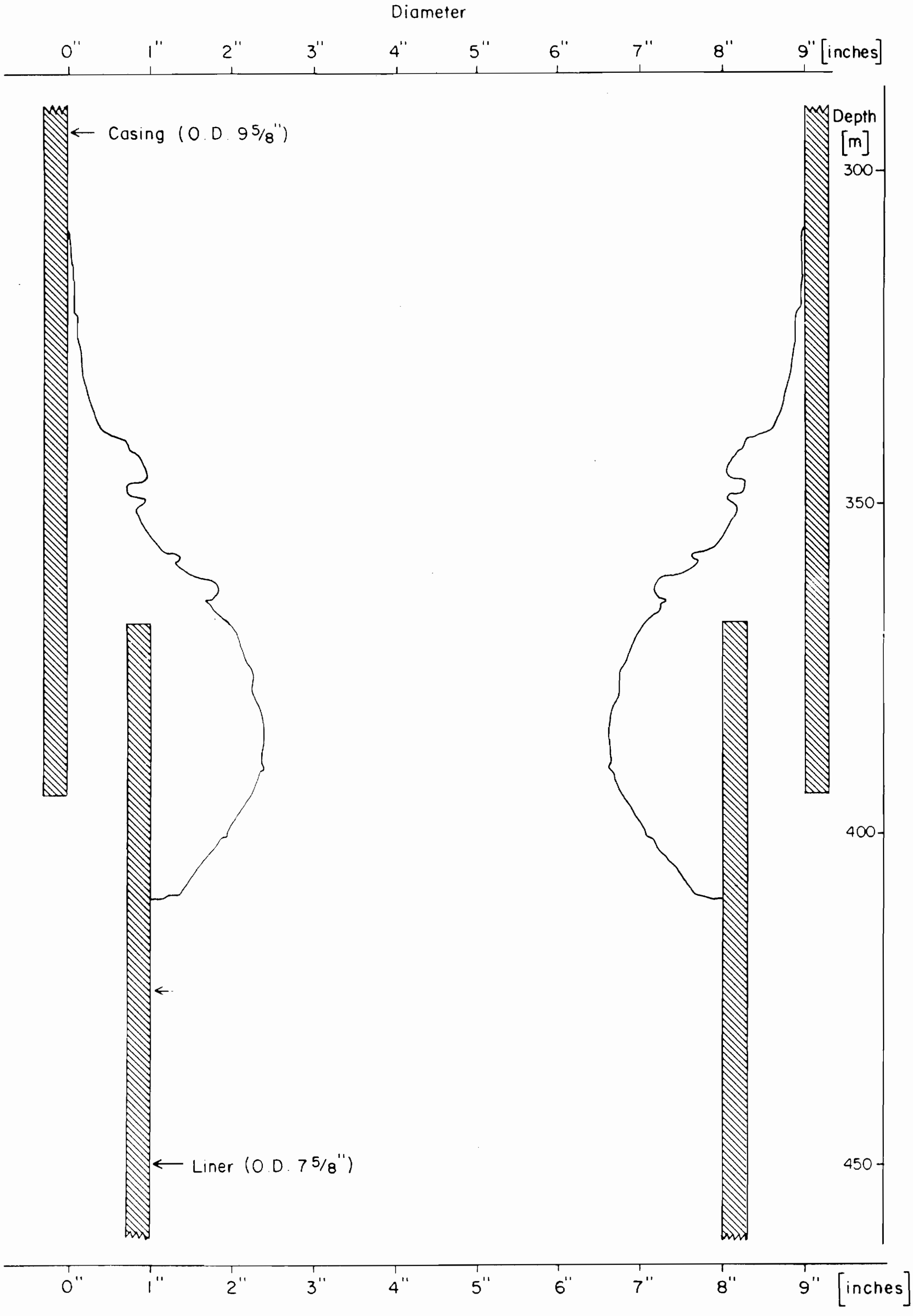


Fig. 3.5 The formation of calcite deposition in well No. 4 in Svartsengi, Iceland. The figure is reconstructed from a caliper log run at 78.12.13.

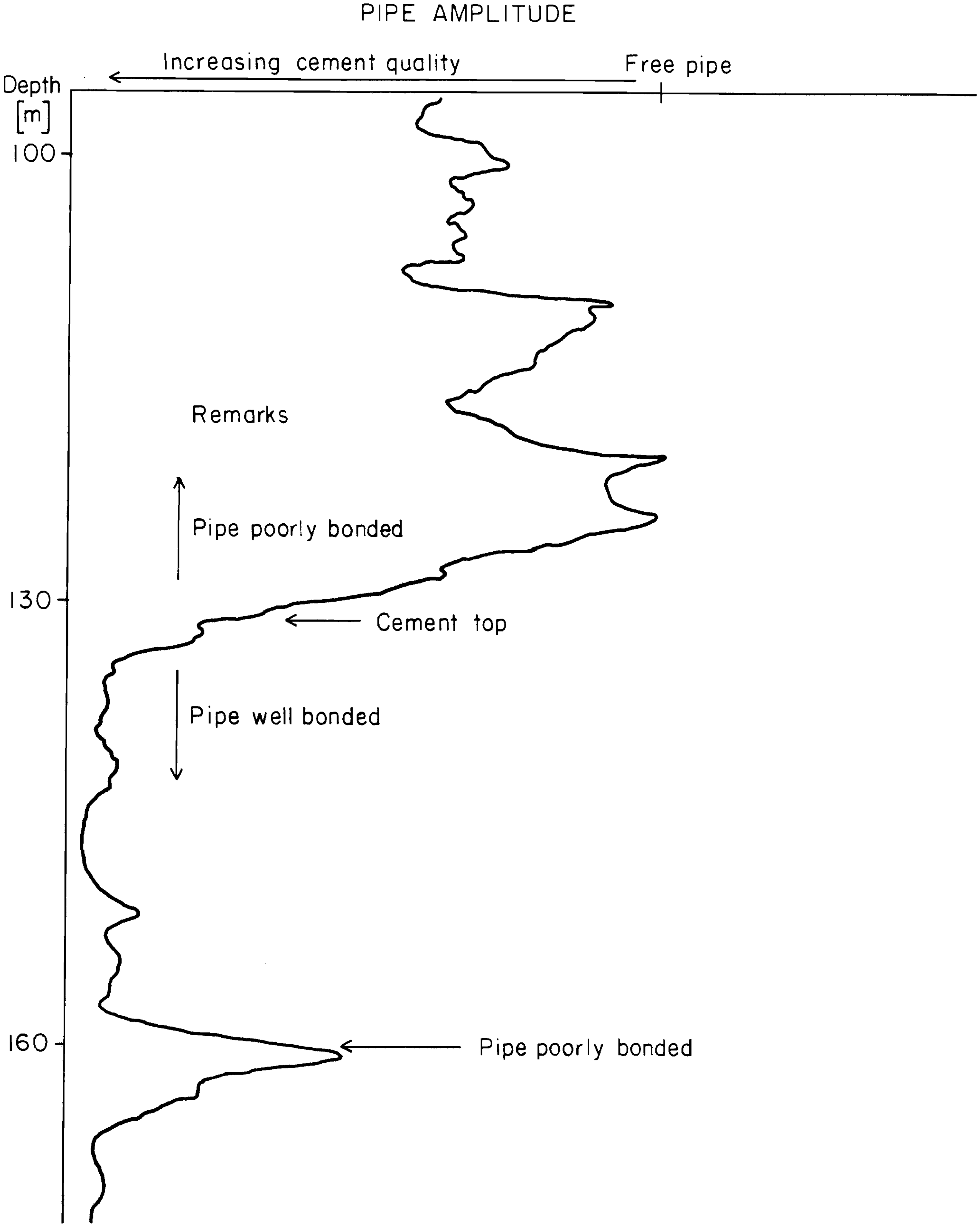


Fig. 3.6 Cement bond log of well KG-12 in Krafla, Iceland. The top of the cement outside the casing is at 137 m depth. The casing was perforated at that depth, and cementing completed from that level to top.

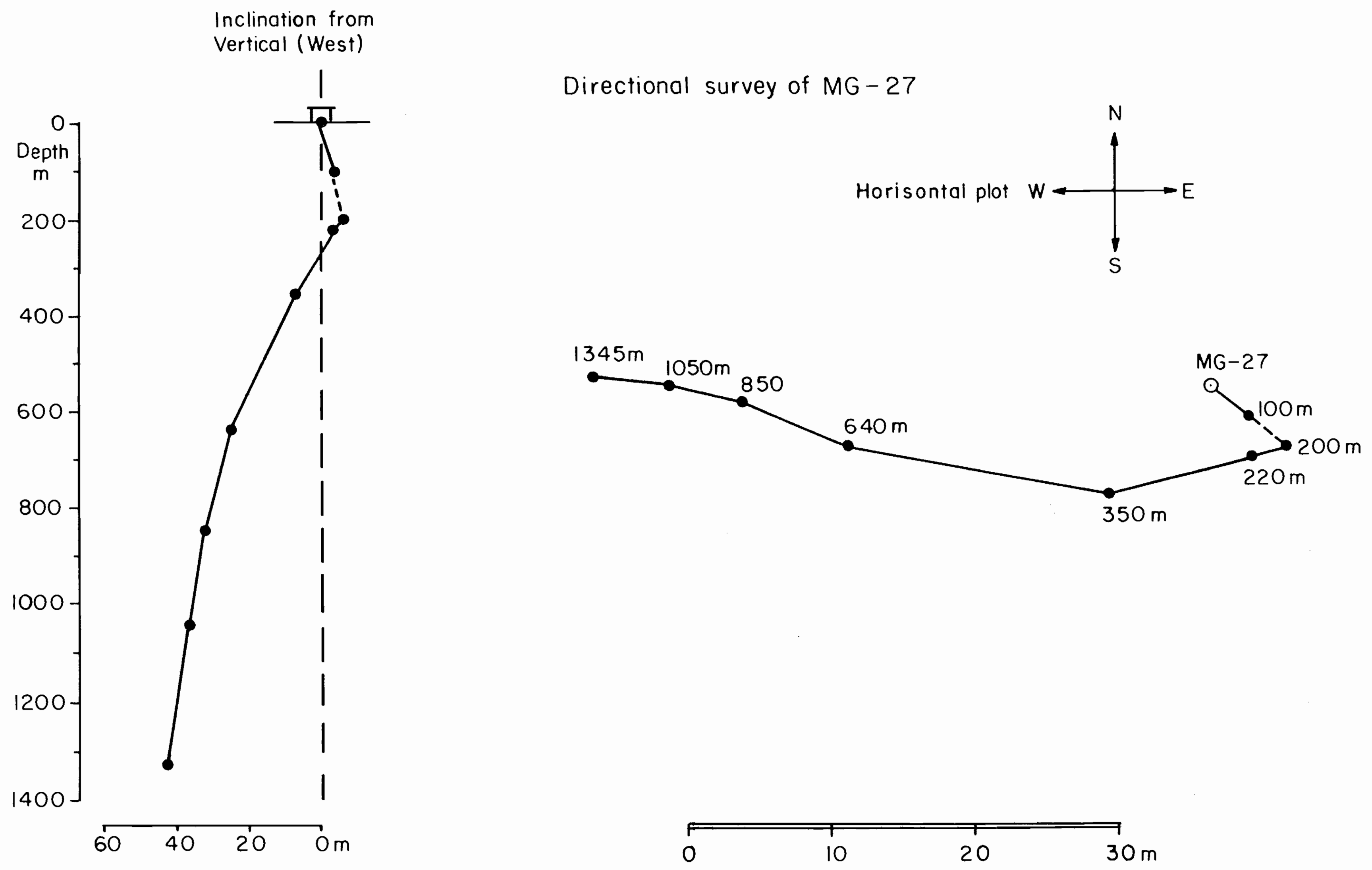


Fig. 3.7 Directional survey of well MG-27 in Mosfellssveit, Iceland. Projection of the well is shown both on horizontal plane and a vertical plane.

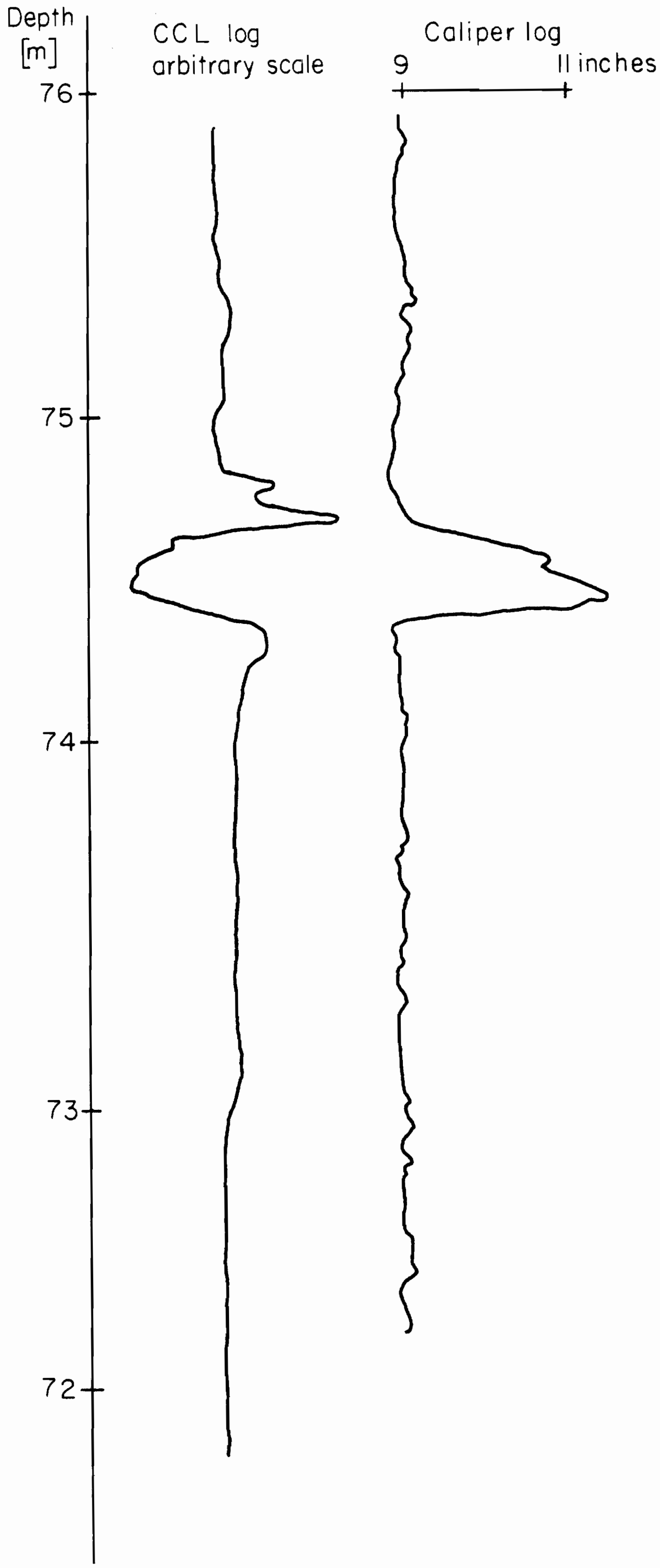


Fig. 3.8 Constant Collar Locator (CCL) log and a caliper log of well KG-3 in Krafla, Iceland. The logs show a 0.4 m gap in the 9 5/8" casing of the well.

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4 TEMPERATURE LOG

In this chapter we will look at various temperature logs and their interpretation.

Firstly, remember that the temperature log shows the temperature inside the well, and the value recorded need not be that of the surrounding rock. As shown in fig. 4.1 the temperature usually increases with depth, but quite different profiles can occur. We will examine these types of temperature profiles and see what they can tell us.

4.1 Constant temperature gradient

This type of temperature log is probably globally the most common temperature profile measured (see fig. 4.2). Such temperature profiles are interpreted as being the result of heat conduction in the crust, and that the heat flow is governed by heat conduction alone. The heat flow then follows the equation:

$$Q = K \cdot \frac{\Delta T}{\Delta Z} \tag{1}$$

As the thermal conductivity K of rock is fairly constant, the temperature will be a linear function of depth:

$$T = T_o + \alpha \cdot Z \tag{2}$$

where Q = heat flow
T = the temperature
T_o = annual mean temperature at surface
Z = depth
α = the temperature gradient = $\frac{\Delta T}{\Delta Z}$
K = the thermal conductivity

In order to use the temperature gradient for heat flow estimates the thermal conductivity K must be known for instance from drill cores.

Most of the heat flow values for the ocean floor are calculated from temperature logs and core data, and big areas on land have been mapped in the same way. See figs. 4.3 and 4.4.

Heat flow or temperature gradient anomalies have for a long time been used in exploration of geothermal resources. First the heat flow in Eastern Iceland is examined (fig. 4.3). When a deep hole was drilled there in 1978 it was found that the temperature profile followed the pattern shown in fig. 4.5. From these temperature logs it is clear that the heat flow in the area is controlled by heat conduction only in the uppermost 600 m. Below that level the temperature profile is non-linear with a relatively low average gradient. Therefore heat flow below 600 m must be governed by vertical hot water flow and not heat conduction. This water flow also explains the heat flow anomaly in the area, as fig. 4.6 demonstrates. Therefore, it is quite natural to assume that anomalous temperature gradient or heat flow values are due to vertical water flow in the upper crust. These anomalies can be both higher and lower than the regional values. Fig. 4.6 shows the general effect of circulating water on the temperature gradient measured near the surface.

In fig. 4.1 an example of downflow in or in the neighbourhood of a well is shown in the profile marked Kaldársel.

Further, it can be mentioned that local anomalous low heat-flow values measured on mid-oceanic ridges are interpreted as down-flow regions of hydrothermal systems at the ocean floor.

4.2 Temperature profiles in geothermal wells

This is one of the most important geothermal logs, and will be dealt with in detail. Some effects commonly occurring in geothermal logs will be considered, including the effect of time on the measured temperature.

4.2.1 Warm-up period

As the well and the surrounding rock are cooled down during drilling, it takes the well some time to recover its initial temperature. It depends on the properties of the well whether the aquifers warm up more rapidly than the "dry" rock part of the well.

When a well is not flowing the aquifers usually warm up more slowly than the rest of the well. If on the other hand a fluid flow or boiling exists in the well the reverse situation can easily occur. In fig. 4.7 an example of a well where the aquifers at 290 m and at 450 m depth warm up faster than the lower part of the well is shown. The well is flowing and the temperature above the aquifers is disturbed by the water flow.

When no flow is in a well the aquifers usually warm up more slowly than the impermeable rock. An example of this is shown in fig. 4.8. This behaviour is explained by the penetration of circulating fluid, during drilling, into the aquifers (more permeable) causing more effective cooling there than in the impermeable rock. Provided that the cold water does not flow back into the well, the heat in the surrounding rock is needed to warm up the cold water. Hence, the aquifer warms up more slowly than the impermeable rock.

If the wells in fig. 4.7 and fig. 4.8 had been allowed to stabilize before a temperature log was run, it would have been much more difficult to locate their aquifers.

This is an example of the use of temperature logs at different times to obtain information on the geothermal system studied.

A related subject is the determination of bottom hole rock temperature during drilling. Several methods have been suggested, but all suffer the disadvantage that the recovery observation time is usually unacceptably long considering rigtime cost. This parameter is therefore only rarely determined during drilling.

We will here confine our treatment to the method used in the hot dry rock experiment in New Mexico (Albright 1976).

The recovery of bottom hole temperature is assumed to be a logaritmic function of time. For an arbitrary time interval, i, which is short compared with the time of total temperature recovery, the temperature curve for the i - the interval (recovery of temperature) - can be described by the equation:

$$\frac{\Theta_\infty^i - \Theta_t^i}{\Theta_\infty^i - \Theta_o^i} = e^{-c^i \circ t}$$

where

Θ_o^i = the temperature at the beginning of the time interval

Θ_t^i = the temperature at the time t later in this time interval

Θ_∞^i = the estimated equilibrium temperature for the time interval i

c^i = a constant

Solving the equation for each interval gives a series of pairs (Θ_∞^i, c^i) as seen in fig. 4.9.

When the temperature recovery is total the true rock temperature is $\Theta_\infty^\infty = \Theta_\infty^i$ and $c^i = 0$.

When only a small part of the thermal recovery curve is known, Albright suggests the use of a linear relation between Θ_∞^i and c^i. Extrapolation to $c^i = 0$ will then give the estimated rock temperature Θ_∞^∞ (see fig. 4.10).

4.2.2 Flow between different aquifers

Flow between different aquifers is common in closed wells. Usually it is a downward flow from an upper aquifer to a lower one. The temperature profile in such cases is characterized by a fairly constant temperature over a large interval in the well.

An example is shown in fig. 4.11, where various temperature profiles, measured both during the warm-up period and after the well had been discharged, are drawn.

The constant temperature from 400 to 1100 m depth in this well has always been found to be below 185°C when the well is closed. During discharge the temperature, however, rises to 195°C. The interpretation is that when the well is closed the 185°C water from the aquifers between 300-400 m depth flows down to the aquifer at 1100 m depth. When the well is discharging the 195°C aquifer at 1100 m depth contributes to the flow.

4.2.3 Boiling effects observed in temperature profiles of closed wells

When there is no flow between aquifers, the temperature in the well will usually reach equilibrium with the surrounding rock as described in 4.1. However, processes like boiling accompanied by one-dimensional convection can disturb the temperature profile in the well.

All high temperature wells tap reservoirs of higher temperature than 100°C. Boiling and steam accumulation will therefore always be present in these wells during discharge and sometimes even when they are closed.

The boiling point of water is defined by two parameters, temperature and pressure. At atmospheric pressure water boils at the well known temperature of 100°C. If the pressure is higher a higher temperature is needed to reach the boiling point. Fig. 4.12 shows the boiling point curve of water up to critical temperature and pressure.

It is common in temperature log interpretation to compare the temperature profiles measured in closed wells with a boiling point curve or more correctly with a boiling point profile. This curve (profile) (see figs. 4.13 and 4.23) is derived from the data in fig. 4.12 by assuming that the water column in the well is at boiling point temperatures from the water level down to the bottom of the well. The comparison shows immediately where boiling can possibly occur in the well.

In fig. 4.13 we show two types of temperature profiles for a well in thermal equilibrium. The first profile, A, shows a relatively constant temperature of 200°C between 300 and 1100 m depth. Below that level the temperature increases rapidly to more than 300°C at 1300 m depth. The other temperature profile of KG-5, B, shows an increasing temperature with depth. At the bottom the temperature is a little lower than in profile A described above, but above 1200 m the temperature values in profile B are higher than in A. After a careful study profile A has been selected as the one showing the undisturbed formation temperature. Pressure logs have additionally showed that below 1200 m depth the water column is at the boiling level.

The reason for the transition from profile A to profile B is a pressure draw-down in the well and the geothermal system due to production from near-by wells. This draw-down (which in this case was 6 bar) lowers the boiling level and intensifies the boiling in the bottom part of the well. Steam bubbles accumulate there, move uphole, condense and warm up the water higher up in the well.

This kind of heat transfer is called one-dimensional convection and has been observed in several wells in Iceland. Fig. 4.14 shows another example of such a well. The boiling occurs in this well at 1100 m depth.

4.2.4 Negative temperature gradient

A negative temperature gradient means that the temperature decreases with depth in a part of the well. This has been observed in high temperature as well as in low temperature geothermal fields. See figs. 4.15 and 4.16.

In some cases there has been disagreement about the interpretation of a negative temperature gradient. However, the most acceptable explanation seems to be the association of the negative gradient with non-vertical water flow in the formation. A negative gradient should exist in parts of a field like Wairakei if the mushroom-shaped model suggested for it is correct (see fig. 4.17). In a laboratory experiment with a two-dimensional convection cell, it can be shown that a negative gradient should be present (see fig. 4.18).

For low temperature fields the horizontal component of flow direction might be even more prominent than in high temperature fields (fig. 4.19).

The negative gradient in wells can be used to determine the horizontal flow direction if there are several wells drilled into the field. In fig. 4.20 the location of several wells in the Hveragerdi high temperature field in Iceland is shown and in fig. 4.21 a cross section from NW to SE of the field.

In the cross section isothermal lines have been drawn. It can be clearly seen that the upflow is located in the northern part of the field and the hot water flows southwards at a fairly shallow level (100-200 m depth).

A similar pattern can be seen in the Cerro Prieto field as shown in fig. 4.22.

4.2.5 Temperature profiles of flowing steam wells

When a steam well in a liquid-dominated field starts flowing, boiling will begin at those well depths where the temperature and the pressure correspond to points of saturation. Until temperature and pressure equilibrium is reached, the boiling level will be moving (generally down the well). At equilibrium the boiling level divides the well into two parts with pure liquid flow in the lower part, and a mixed liquid-vapour flow above boiling level. An example of this kind of flow is shown in fig. 4.24 where both temperature and pressure are shown for a flowing well. According to temperature and pressure profiles boiling level is at approximately 300 m depth (due to draw-down the location of the boiling level will depend on the mass flow). In the two-phase zone above 300 m depth the temperature and pressure are saturated. The decreasing pressure gradient $\frac{dp}{dz}$ indicates the increasing vapour fraction as the mixture flows upwards and flashes to adjust the temperature to the saturation curve.

The vapour fraction can actually be calculated throughout the two-phase zone from either the temperature or the pressure profile, if the well can be treated as adiabatic above boiling level. The adiabatic condition in a well assumes no heat exchange between the well and the formation. In a flowing well heat exchange is only significant at the loci of the different aquifers. So if there is no aquifer above boiling level the vapour fraction is given by the formula:

$$X = \frac{H_o - H_{(T,P)}}{Q_{(T,P)}}$$

where

X is the vapour fraction
H_o is the enthalpy of the fluid at the boiling level
$H_{(T,P)}$ is the enthalpy of the fluid at the saturation point (T,P)
$Q_{(T,P)}$ is the latent heat of evaporation at (T,P)

In cases of near-saturation temperature or low permeability, boiling level will be reached below the deepest aquifer in the well. In this case boiling starts outside the well and both temperature and pressure measured in the well are fairly constant down through the two phase zone. The temperature values are considerably lower than those measured in a stabilized closed well. Similar effects are observed if the reservoir is boiling - that is if there is a two-phase state existing in the undisturbed reservoir, or if the inflow into the well is a liquid phase at one aquifer and a mixed or a pure vapour phase at another. Measurements from the well HGP - A in Hawaii are shown as an example in fig. 4.25. The results have to be interpreted in terms of the above explanations.

A careful study of the well and usually a long-time testing is needed before choosing between the above possibilities.

Fig. 4.26 shows the temperature profile of a well which has been demonstrated to tap fluid from a two-phase reservoir.

One of the characteristics of pure two-phase reservoirs is an increase in the enthalpy of the fluid with time during the first weeks or even months of discharge. The well shown in fig. 4.26, well KG-12 in the Krafla high temperature field in Iceland, started to flow as a liquid dominated well, its discharge consisting of a mixture of steam and water. The enthalpy of the discharged fluid increased continuously and within a week the well was discharging dry steam. The enthalpy continued to increase and the discharge developed into superheated steam as can be seen in fig. 4.26.

Logging of flowing high temperature geothermal wells is not a straight forward procedure. The risk of losing or damaging logging tools is much higher than when logging closed wells. To date this kind of logging has only been successful in wells with relatively little mass flow discharge. The presence of steam or two-phase inflow in wells, which is easily seen in logs from a flowing well can be detected by a careful study of logs made in closed wells.

As was shown in figs. 4.25 and 4.26 the striking characteristic of wells tapping a two-phase flow or steam pockets is the much lower equilibrium temperature inside the well during flow compared with the reservoir temperature. If such a well discharges for a sufficiently long time, and is then closed, a temperature log performed immediately after the shut-in will be influenced by the flowing temperature. If the temperature measured under such conditions is lower than the temperature measured after a long closing period it indicates that the inflow in the well is not tapping a pure liquid phase zone, and the properties of the well as well as the reservoir should be investigated with this in mind. Fig. 4.27 shows an example of such an occurrence.

The measurement from 750812 was done in a closed well but the measurement made 751010 was made immediately after shut-down after almost two months flow. At first glance these results seem to contradict the above statements about the lower temperature just after shut-in. However, the figure shows two effects. One is the cooling of the flow between aquifers when the well is closed, and the other effect superimposed is the cooling effect due to two-phase inflow during discharge. The bottom temperature is lower after the discharge period than in the static well, due to a two-phase inflow at 1600 m depth. In a closed condition water flows from the 200°C aquifer at 900 m down to the much hotter aquifer at 1600 m. An exact determination of the temperature of this aquifer has not been possible, but there are indications that the temperature of the reservoir fluid at that depth is of the order of 300-320°C.

A further example of the effects caused by a two-phase inflow in a well combined with the boiling effects and the flow between aquifers is shown in fig. 4.28.

In this case measurements from 721205, 730202 and 730502 are all made immediately after closure of the well, but apart from that it flowed continuously during this time. The measurement from 730724 was made after two months closure.

The temperature profiles from this single well seem a little confusing, and this is due to the various effects which influence the result. These are:

a) two phase inflow near the bottom of the well during discharge.
b) flow from a water-dominated aquifer at 900 m depth down to the bottom of the well when it is closed.
c) condensation of steam in the well just after closure causes an anomalous temperature transient just above the uppermost water inflow into the well.

Let us look further at these effects. It is assumed that there are two main aquifers in the well. One is liquid saturated at approximately 900 m depth, temperature 270°C, and the other possibly two-phase or vapour dominated, at approximately 1600 m depth, with temperature about 300-320°C. During closed conditions, the water from the 900 m depth aquifer flows down the well to the aquifer at 1600 m depth as can be seen from the measurement from 730724. When the well is flowing and then suddenly closed for temperature measurements, the temperature near the lower aquifer varies due to differences in flowing conditions before closure and the time elapsed from the closing until measurements. Furthermore, the deviation of these three temperature profiles from stabilized conditions is greater at the bottom of the well than immediately below the 900 m aquifer. The temperature peak just above the 900 m aquifer is interpreted as due to condensation of the steam present in the well when it was closed. This temperature peak should be greatest immediately after well closure at which time the cooling effect at the bottom of the well should be most prominent.

Investigation of the three temperature curves measured just after well closure shows greatest cooling at the bottom and the highest temperature peak above the 900 m aquifer 721205. It is therefore concluded that least time has elapsed from closure to measurement 721205.

The information gained from the temperature profiles shown in fig. 4.28 is:

a) there is a 270°C aquifer at 900 m depth which contains liquid water.

b) there is a 300-320°C two-phase flow aquifer at 1600 m depth.

4.3. Temperature in geothermal systems

The temperature at depth in geothermal systems is determined by various techniques, but the most direct one is the measurement of temperatures in wells drilled into the system. We have seen, however, that various effects can disturb the temperature in the well, and quite often the temperatures in the wells are different from the surrounding rock temperatures.

The first precaution is therefore a search for indications of differences between measured well temperatures and rock temperatures. When this has been done it is very useful to draw a vertical cross-section through the wells drilled and draw isothermal lines in the geothermal system. A simple example of this is shown in fig. 4.29. It can be seen in this picture that the upflow zone in this field is expected to be close to wells N-2, N-1 and N-4 rather than elsewhere. Note that a rock temperature in excess of 300°C is assumed in well N-5 even though so high a temperature has not been measured in the well (see fig. 4.28). Further examples of thermal patterns and flow directions were shown in figs. 4.21 and 4.22.

Some of the major questions in modelling high temperature geothermal systems arise if steam zones occur in the systems. Usually high temperature geothermal systems are divided into liquid dominated and vapour dominated systems, as shown in fig. 4.30. However, a whole spectrum apparently exists between these two extremes.

We prefer to look at vapour and liquid dominance as different physical states rather than primary properties of geothermal systems.

As examples of transitional geothermal systems, we can mention:

a) the Olkaria field in Kenya (fig. 4.31) where a thin steam cap exists on the top of a two phase reservoir.

b) the Wairakei field in New Zealand is usually taken as an example of pure water-dominated system. However, the field has developed a steam cap at the top of the reservoir during long exploitation time. Recent reconsiderations of the early measurements in Wairakei (Grant 1979) indicate that the Wairakei field actually had a two-phase zone prior to utilization (see fig. 4.32).

c) the Bagnore geothermal field near Mt. Amiata in Italy has been exploited for more than a decade. Initially it behaved like typical vapour-dominated field, but as the gas content of the fluid decreased with utilization time, many of the wells started to discharge a mixture of steam and water. The field developed into a two-phase system as boundary conditions changed.

The detection of steam in a two-phase system with a hydrostatic pressure gradient needs careful investigation. Recent treatment of this matter (McNitt 1977) indicates that boiling plays a more active role in high temperature geothermal systems than commonly has been considered.

In fig. 4.33 we show an example of a relatively complex geotheraml system. In this geothermal system (Stefánsson 1980) two zones occur. The upper zone contains liquid water at a 210°C temperature, whereas the lower zone is a two-phase system and the temperature corresponds to the saturation curve at this depth interval. The shallowest depth for the top of this zone has been found at approximately 1000 m and there is a connection both to the upper zone and to the surface. The flow pattern of the upper zone has been determined by pressure and chemical investigation, whereas the flow pattern in the lower zone has been determined by the investigation of non-condensable gases in the discharge from the wells.

The construction of a model of such a complex system needs measurements of many independent parameters, and temperature is only one of them. Other important parameters used in the construction of the model of the Krafla geothermal system are: Pressure, enthalpy of fluid, production characteristics of wells, chemical composition of fluid, especially the gas content, etc.

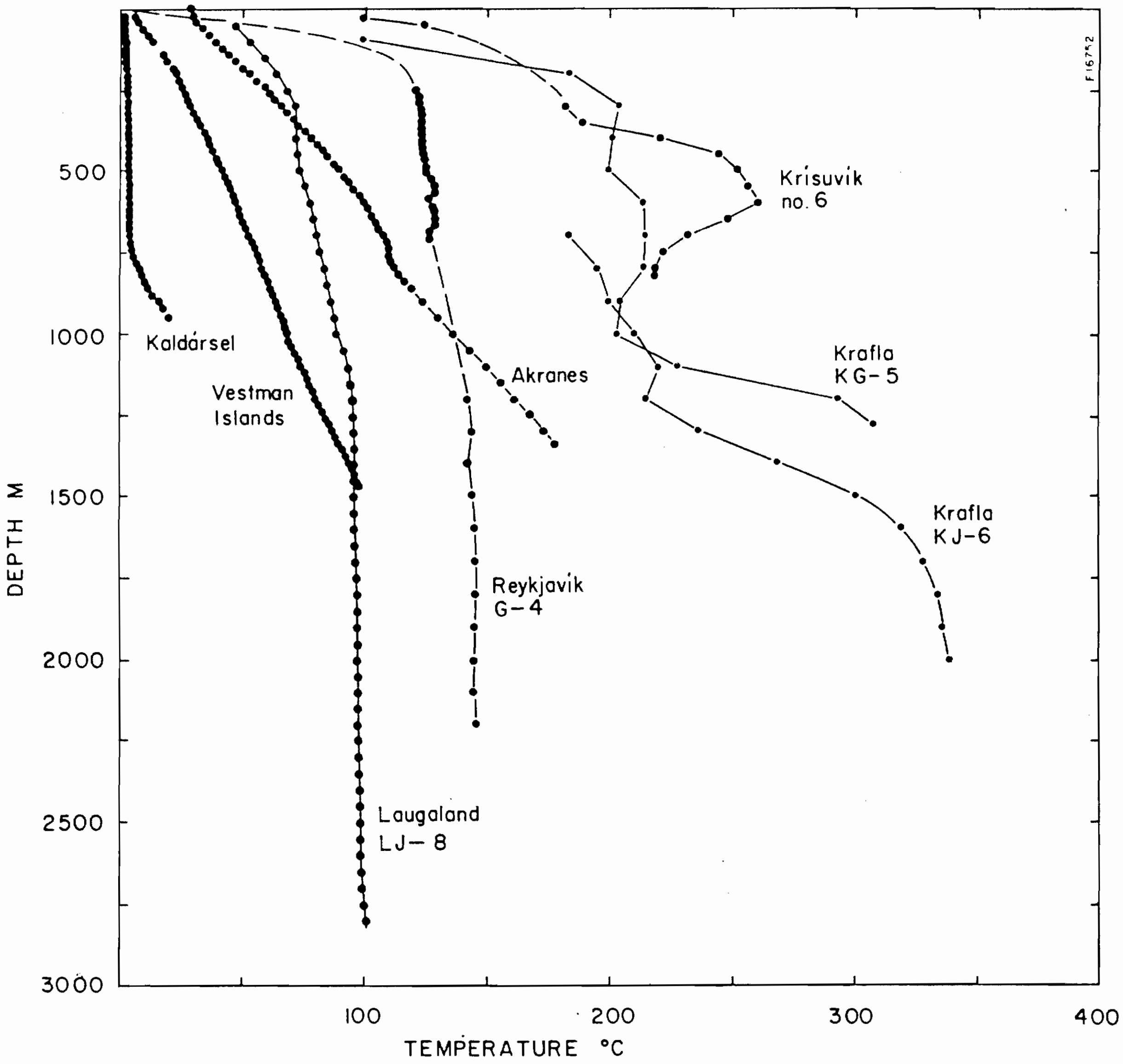

Fig. 4.1 Temperature profiles in deep drillholes in Iceland.

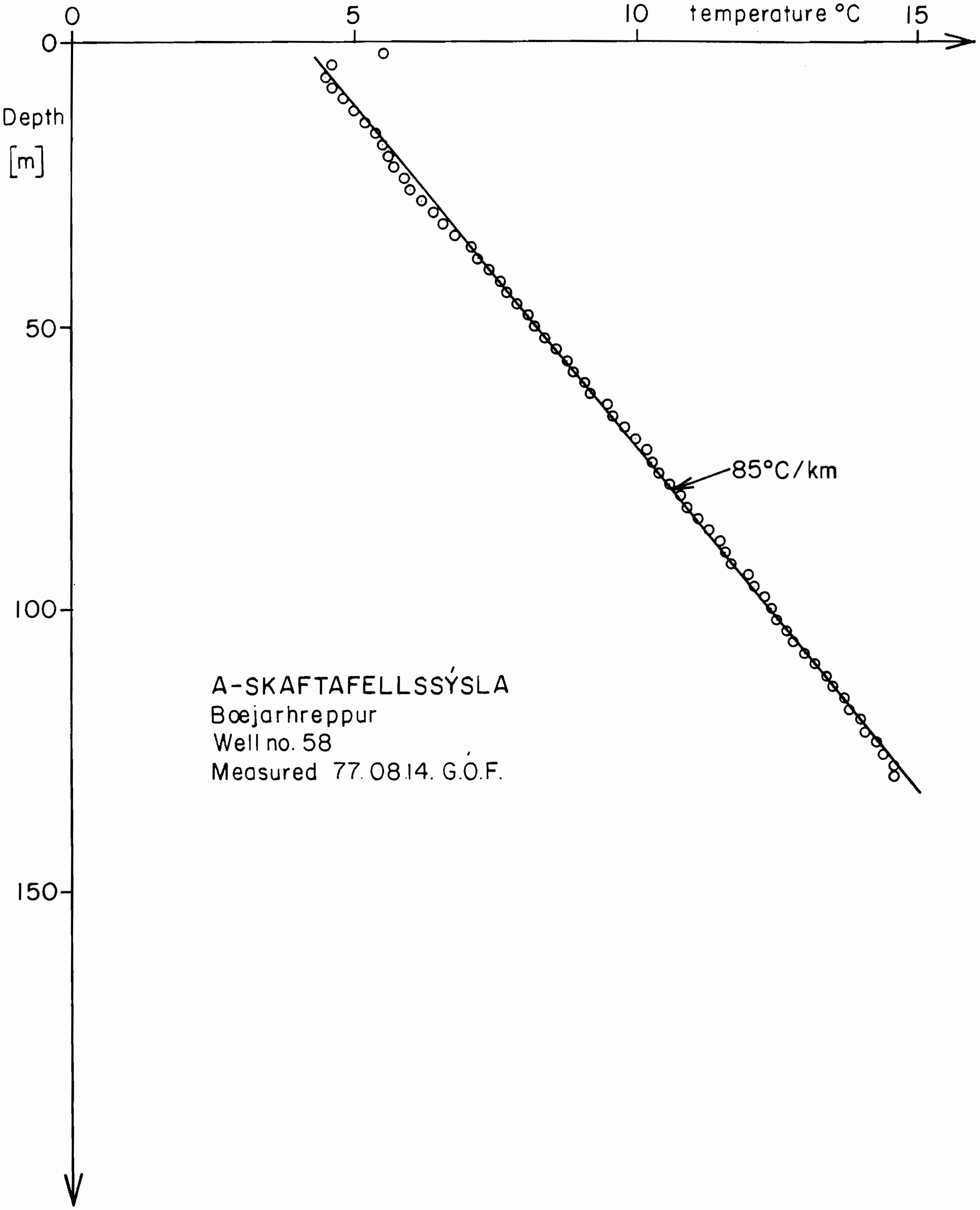

Fig. 4.2 Temperature log in southeastern Iceland. The temperature increases linear with depth giving a temperature gradient of 85°C/km.

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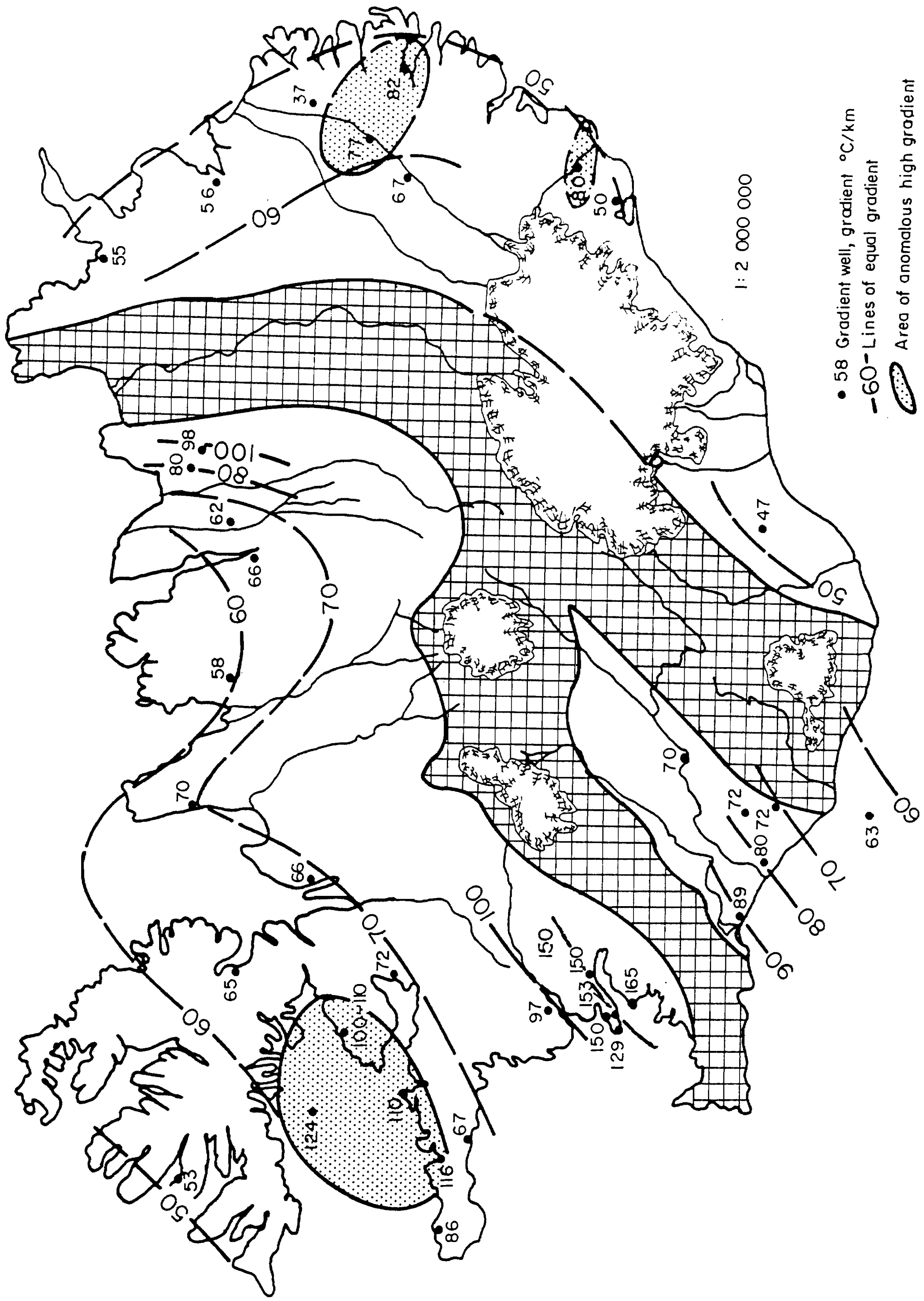


Fig. 4.3 Temperature gradient map of Iceland. Location of temperature gradient wells and measured gradient given. Lines of equal gradient are drawn. Outside the volcanic zones, there are two areas with anomalous high temperature gradient.

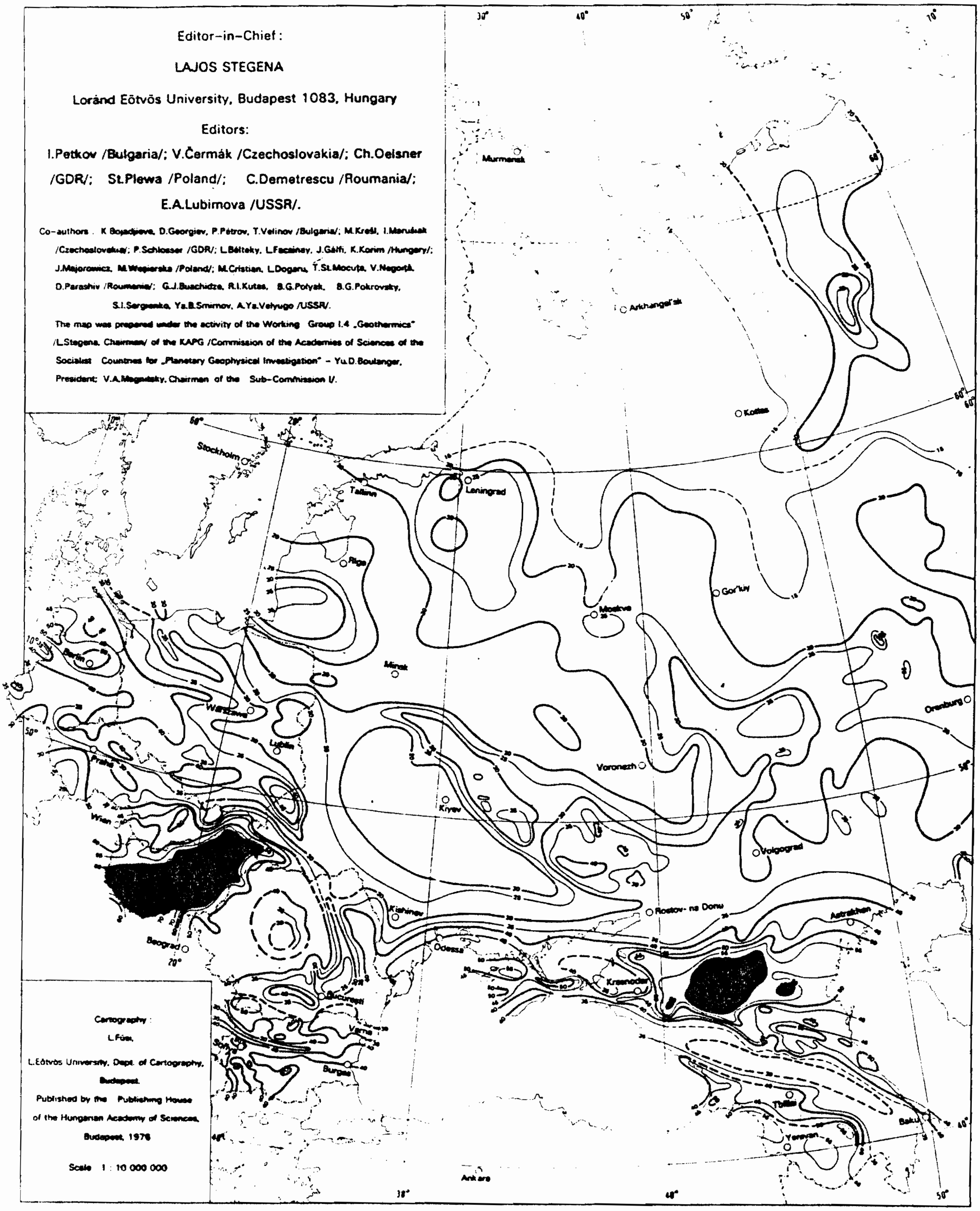


Fig. 4.4 Geoisotherms at the depth of 1 km in Central and Eastern Europe. From Stegena 1976.

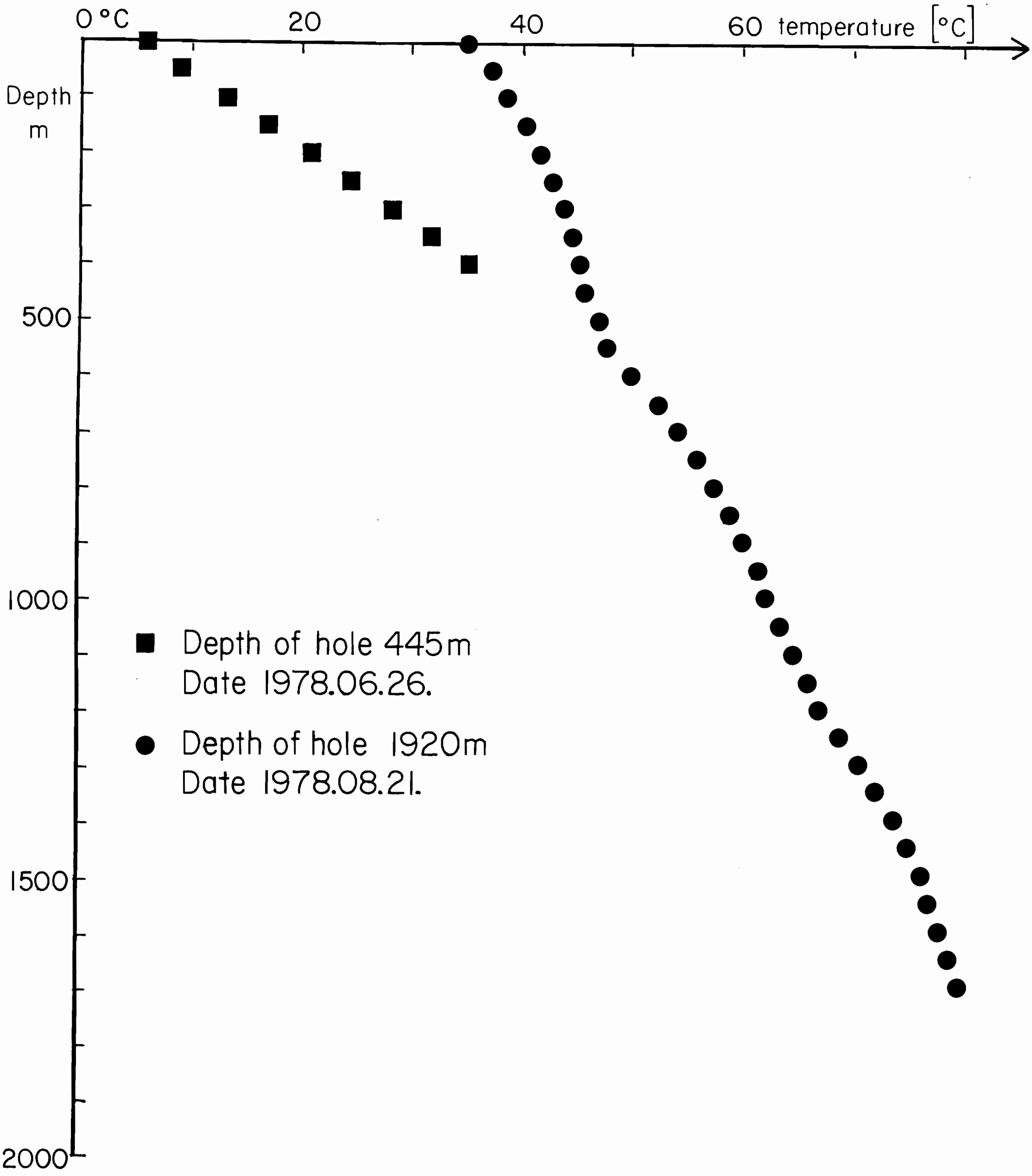


Fig. 4.5 Temperature profiles in the IRDP-hole in Reyðarfjördur, Iceland. When the hole was 445 m deep, the temperature gradient was approximately 80°C/km. This high gradient is caused by 50-60°C warm aquifers at 500-1500 m depth.

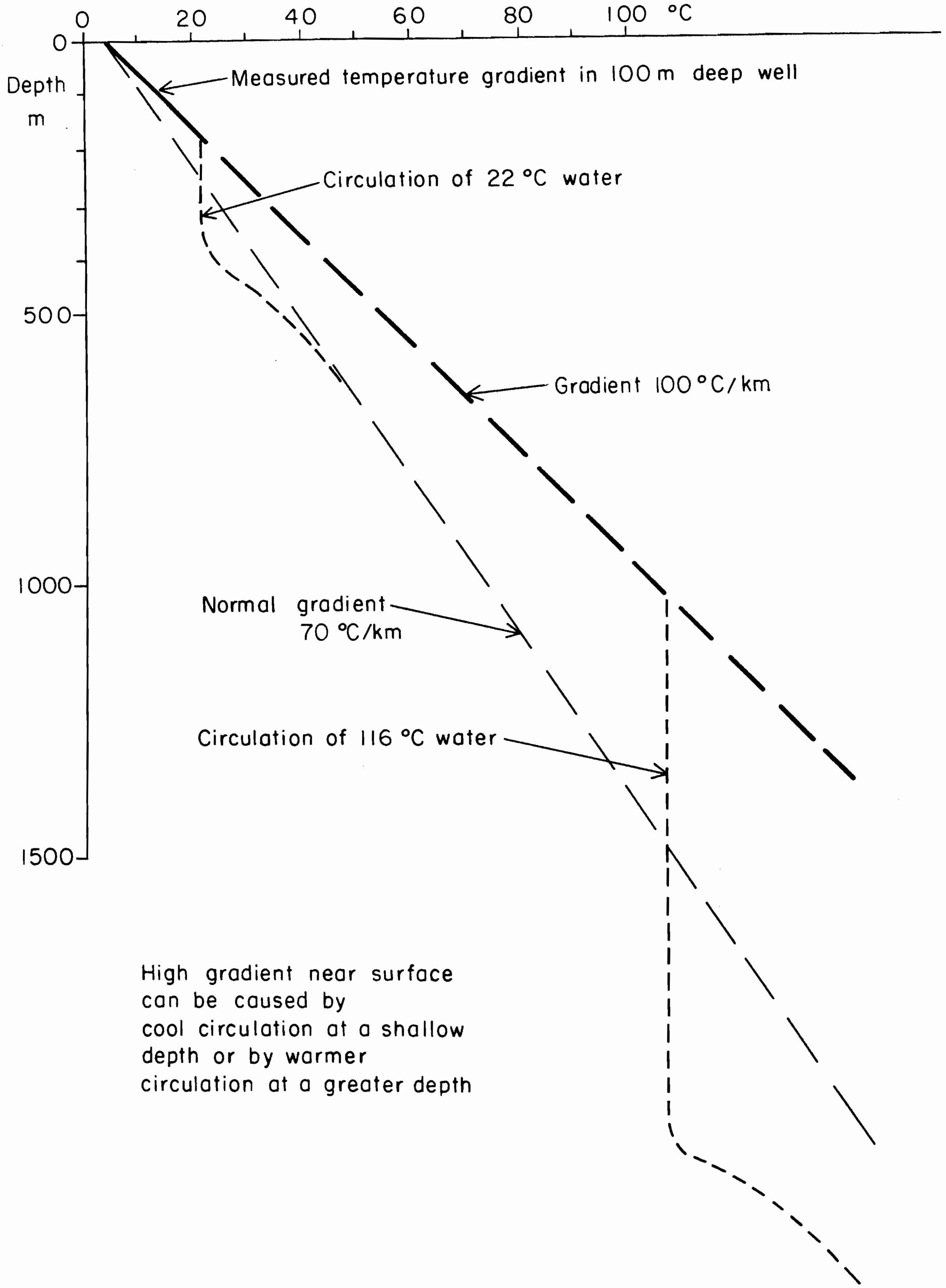


Fig. 4.6 Temperature gradient and circulation of water. High gradient near surface can be caused by cool circulation at shallow depth or by warmer circulation at more depth.

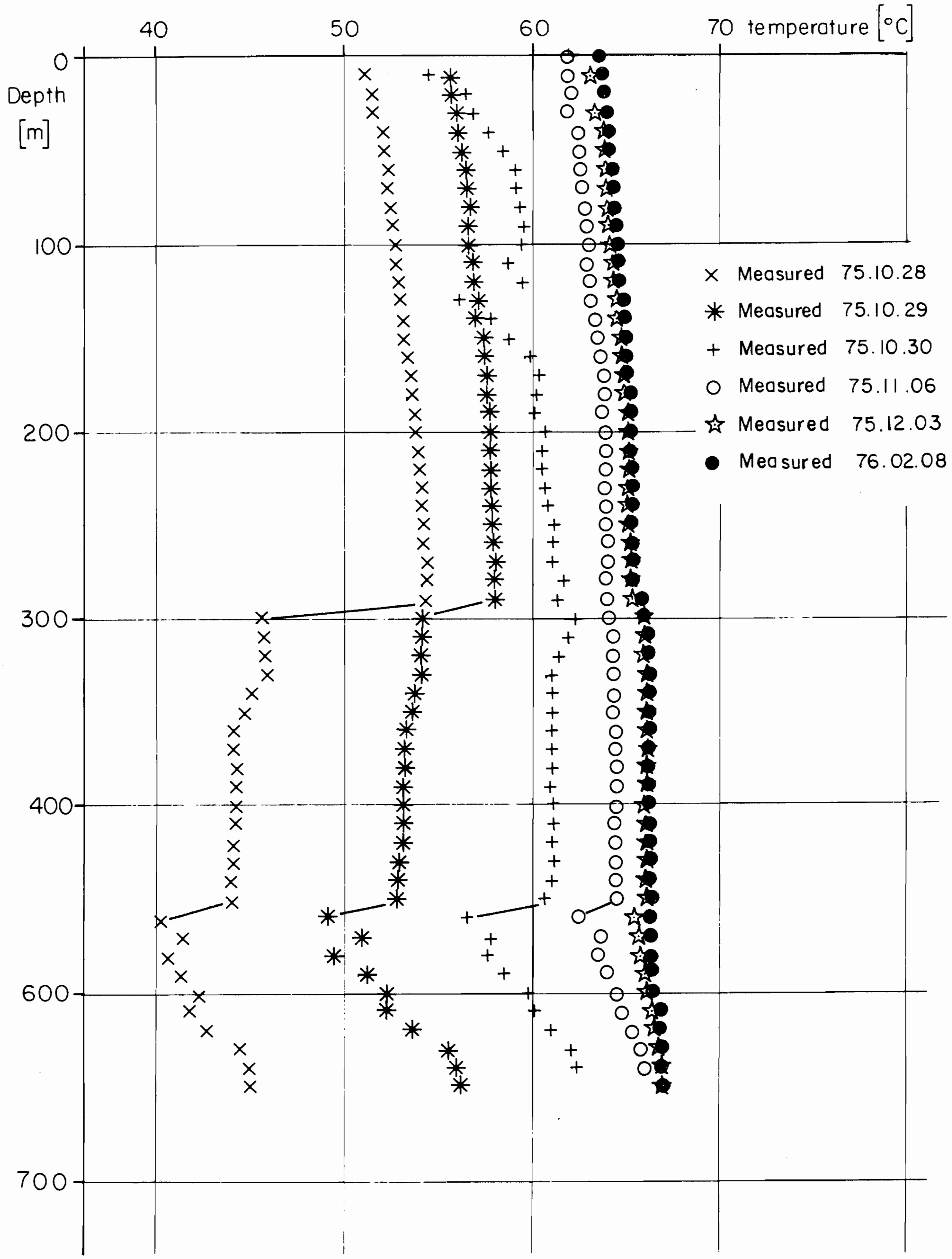
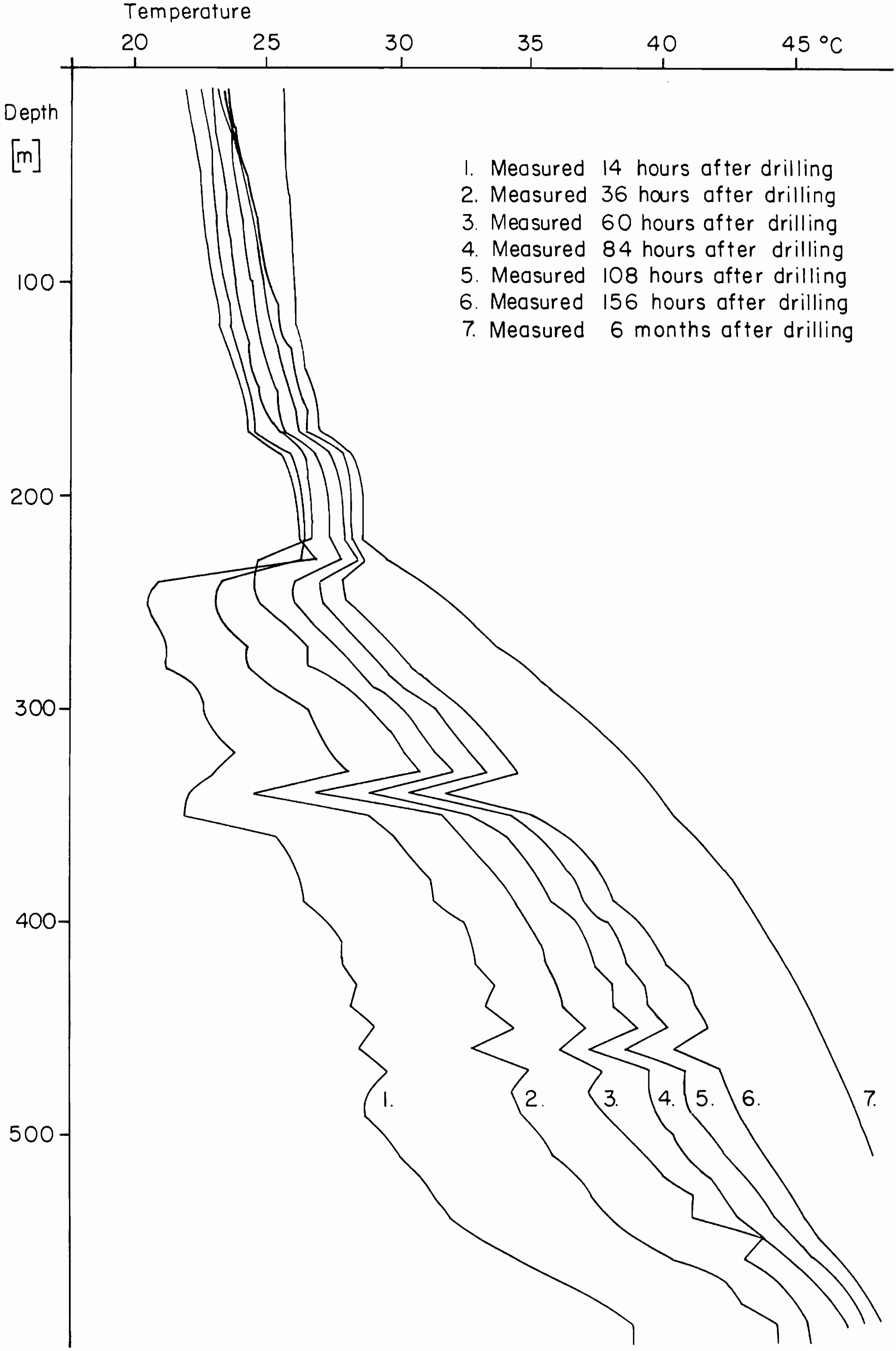


Fig. 4.7 Temperature logs in well No. 2 at Laugar in Súgandafjördur, Iceland. During the warm up period the two aquifers of the well can easily been seen in the temperature profile. Water is flowing from well.



Temperature profiles in well H-2 in Tungudalur, Iceland. The profiles show the thermal recovery after drilling. There is no flow from the well and the aquifers show up

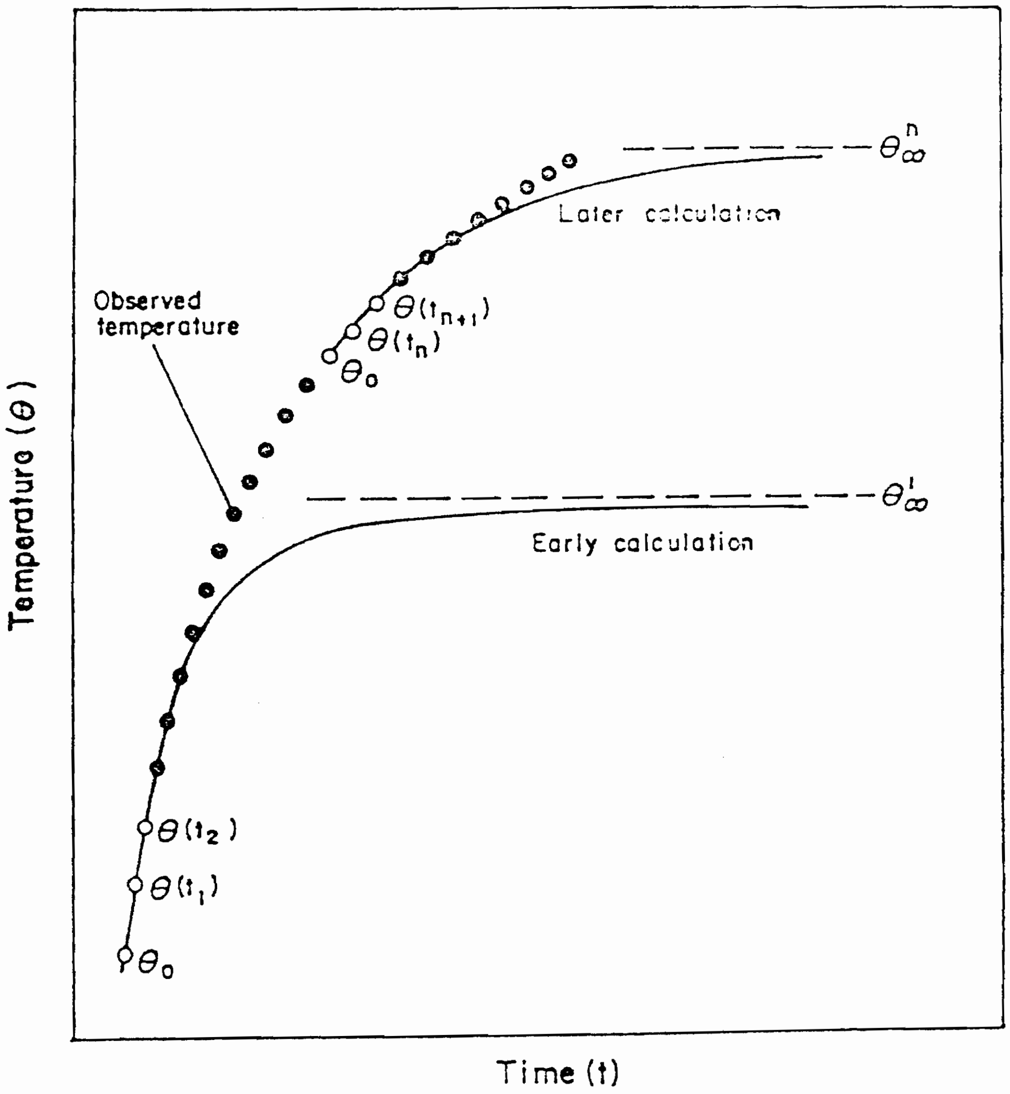


Fig. 4.9 Calculation of thermal equlibrium.

From Albright 1976.

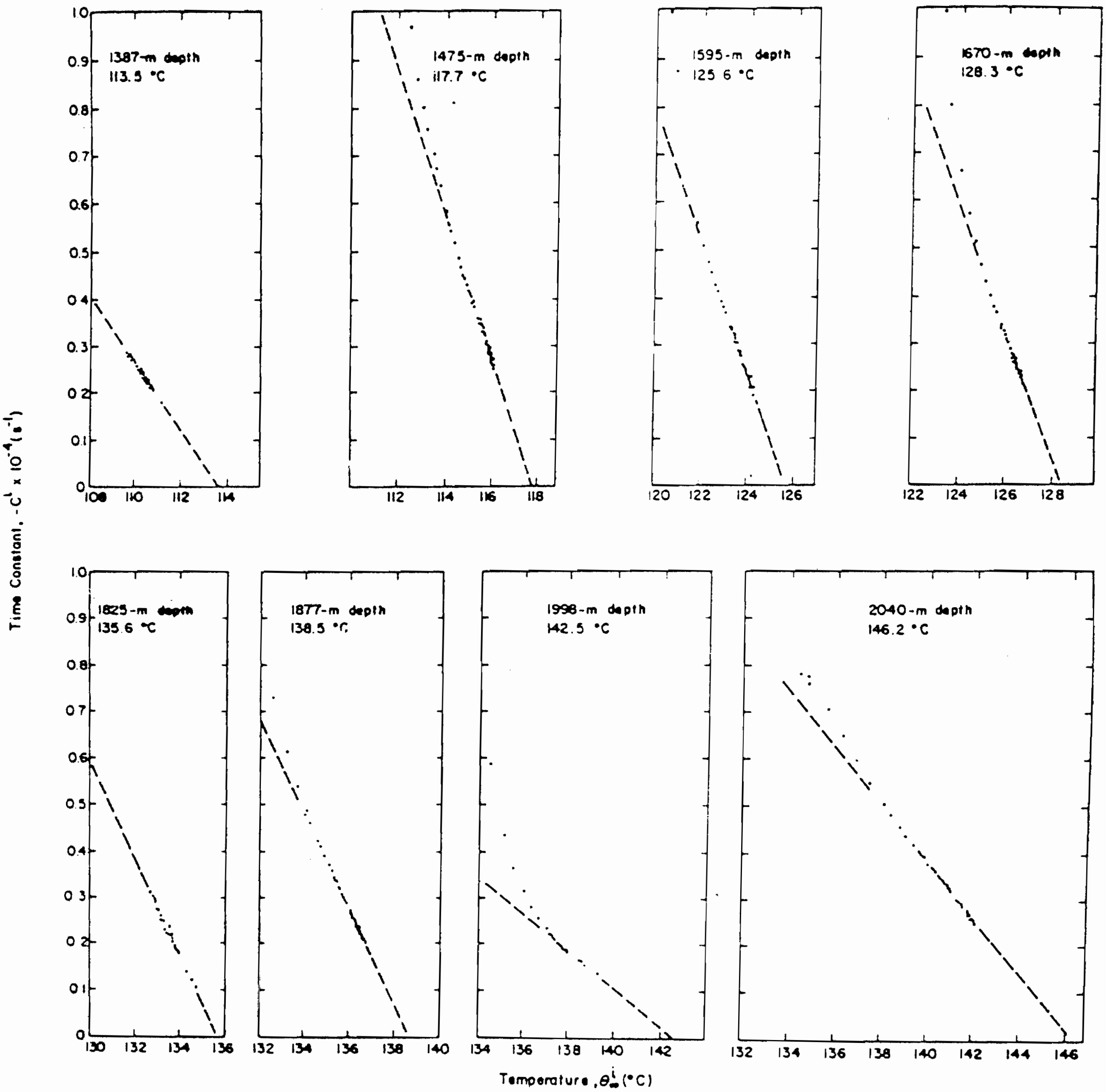


Fig. 4.10 Equilibrium rock temperature determination for various depths of a well.

From Albright 1976.

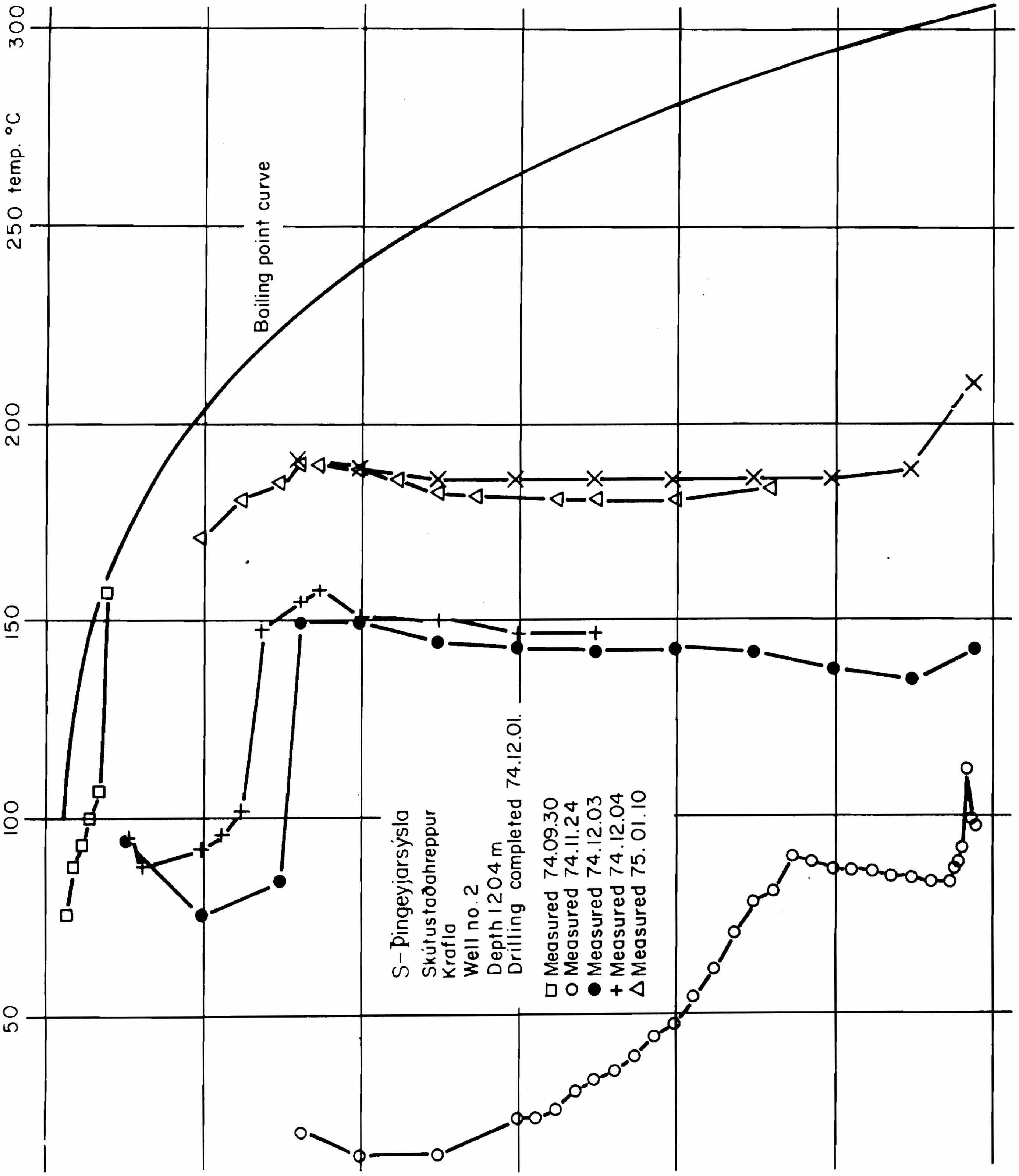


Fig. 4.11 Temperature logs of well KW-2, Krafla, Iceland. When the well is closed water is flowing from 300 m depth down to 400 m depth.

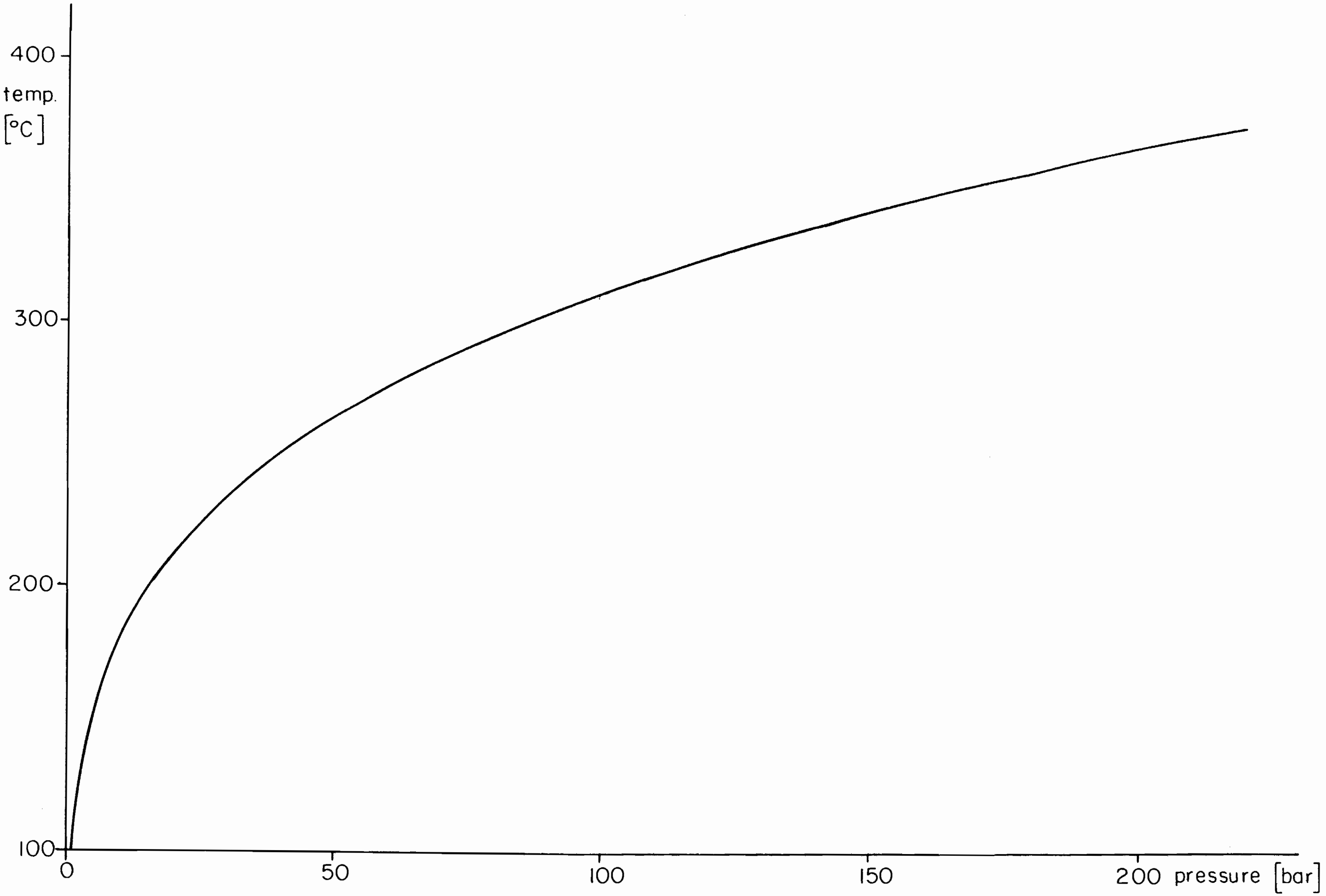


Fig. 4.12 Relation between boiling temperature and pressure for water.

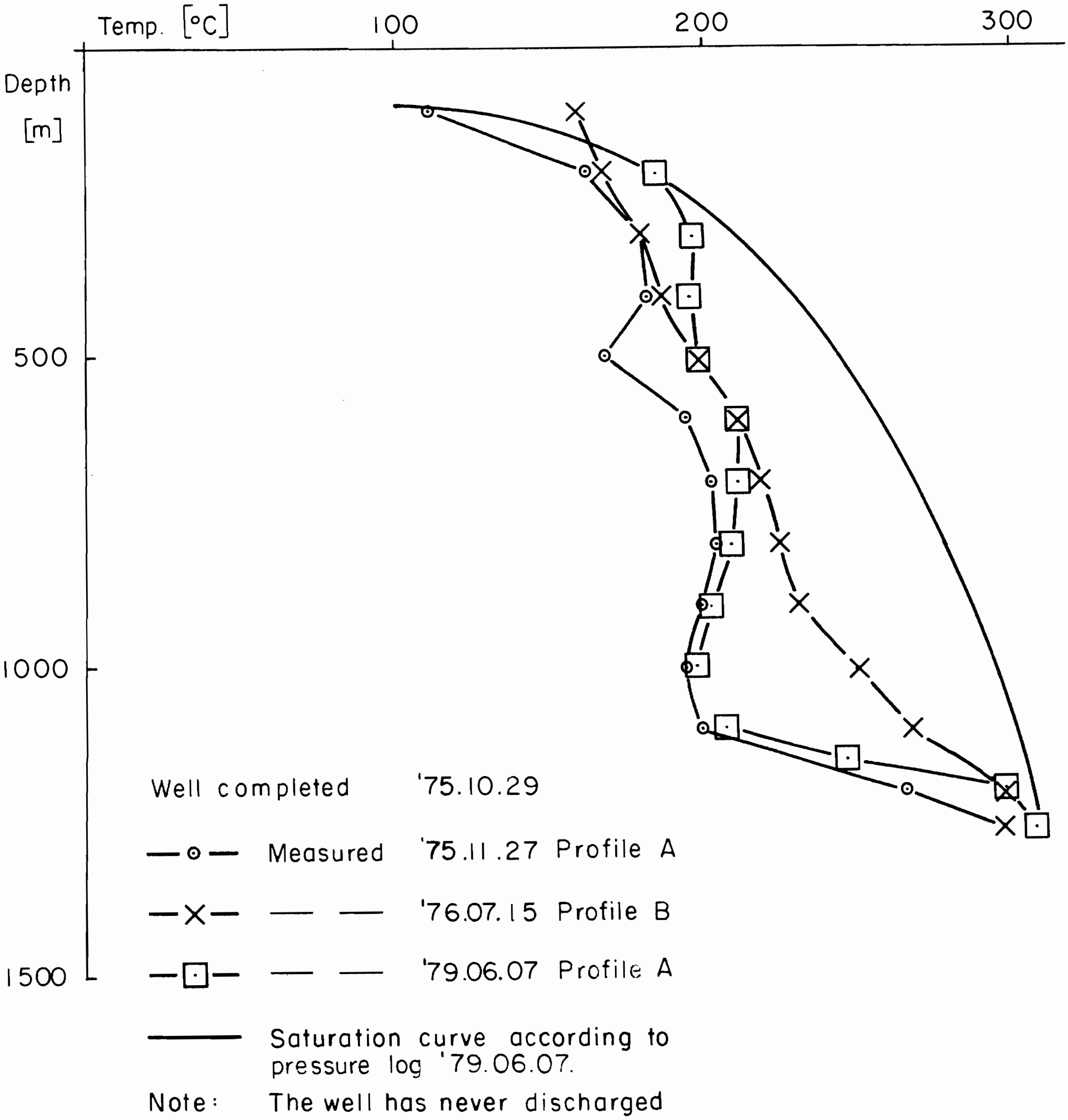


Fig. 4.13 Temperature measurements in well KG-5, Krafla, Iceland. Two temperature equilibrium states in the well are caused by change in reservoir pressure.

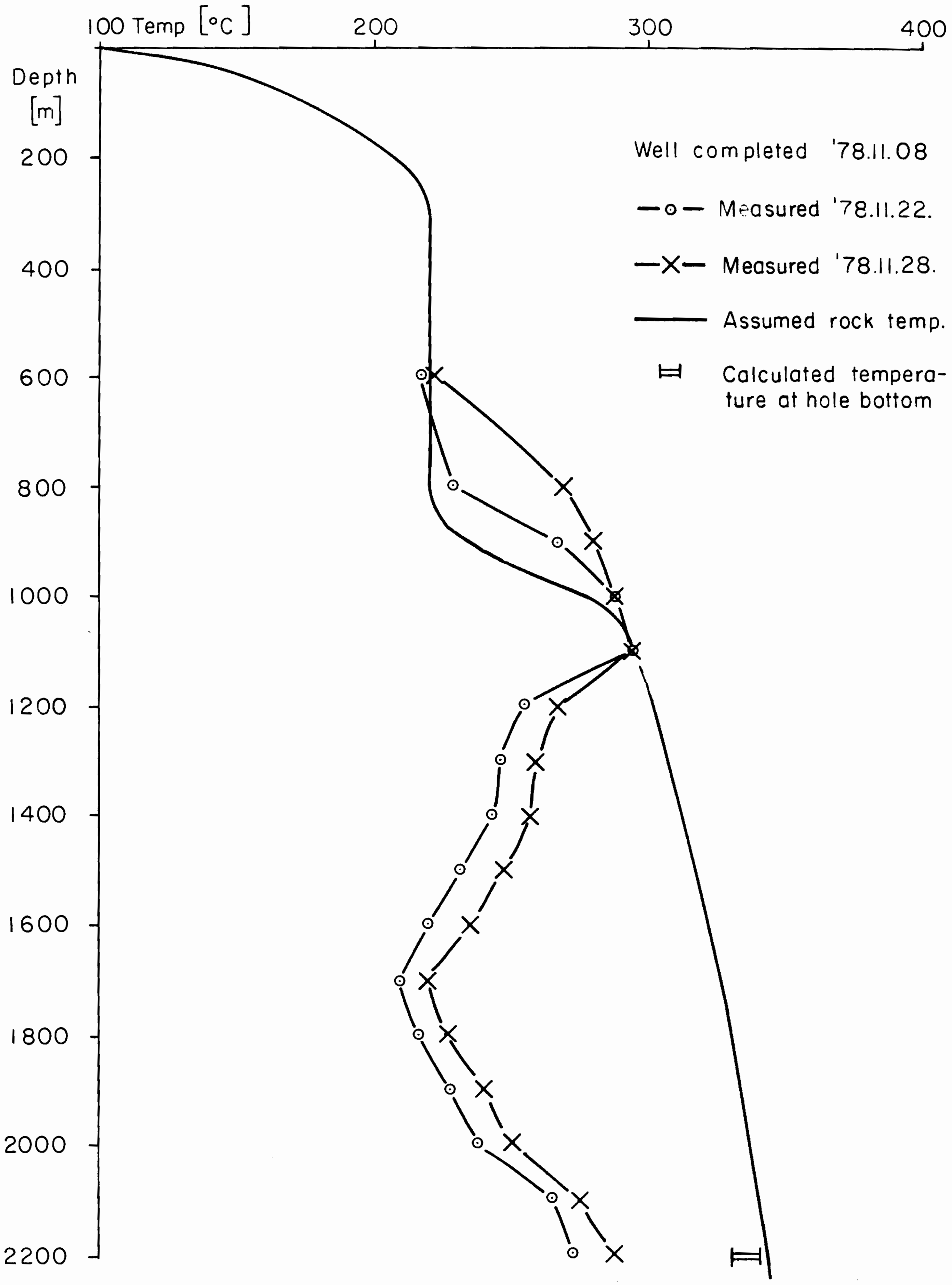


Fig. 4.14 Temperature profiles in well KG-12, Krafla, Iceland. The aquifer at 1100 m depth is boiling during the warm up period, causing the temperature to increase in the well above the

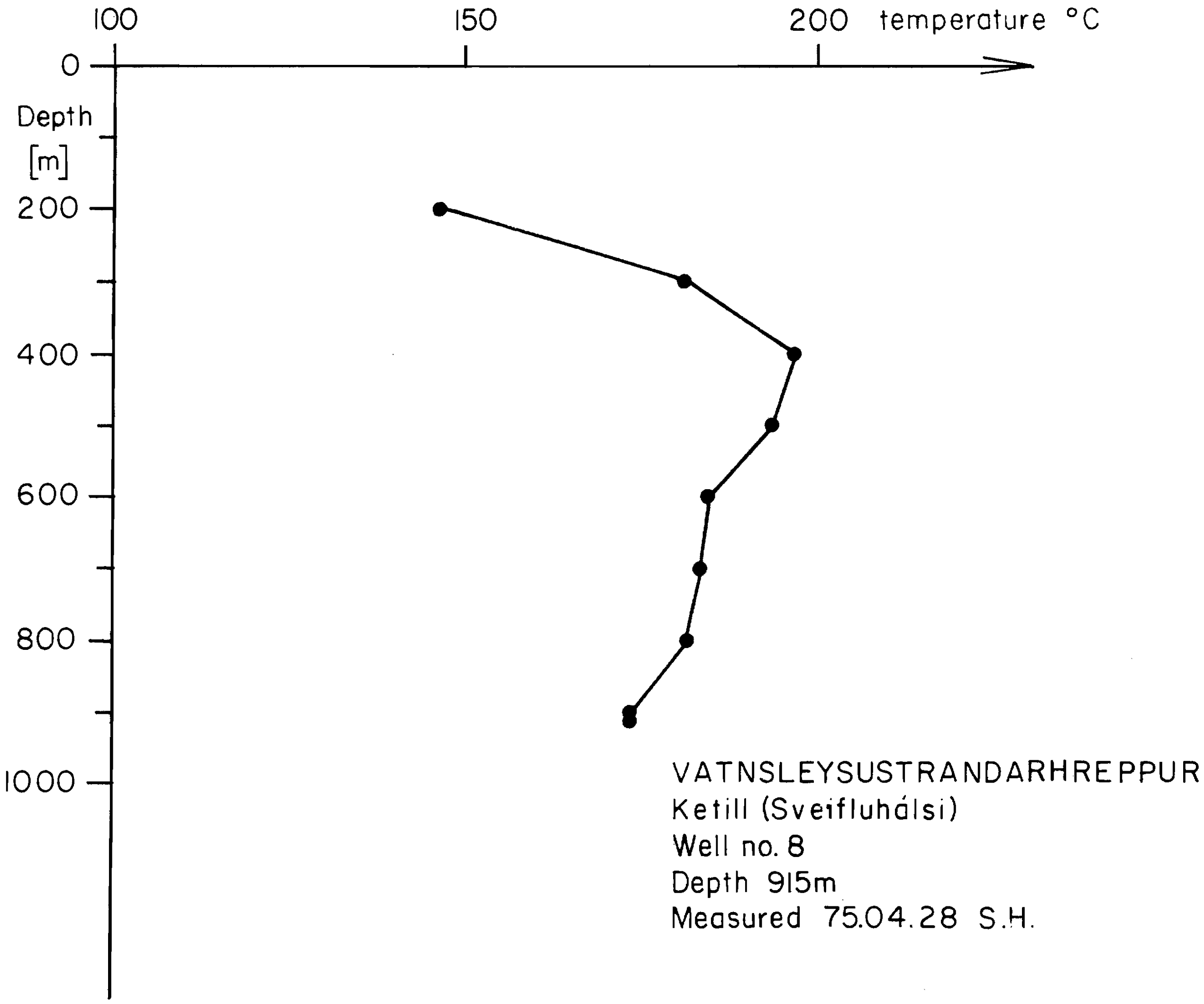


Fig. 4.15 Temperature log in well No. 8, Krísuvík, Iceland. The figure shows a negative temperature gradient.

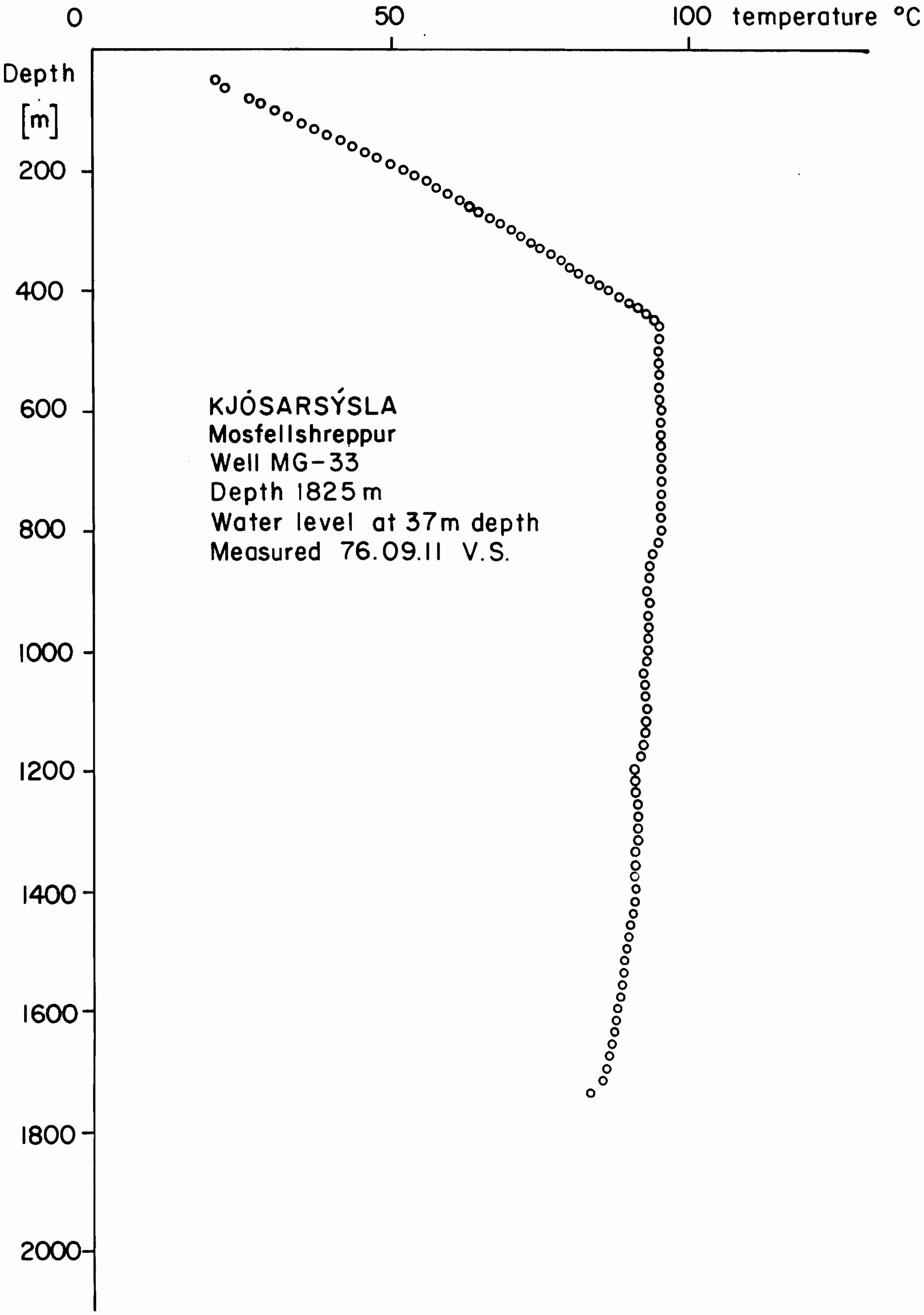
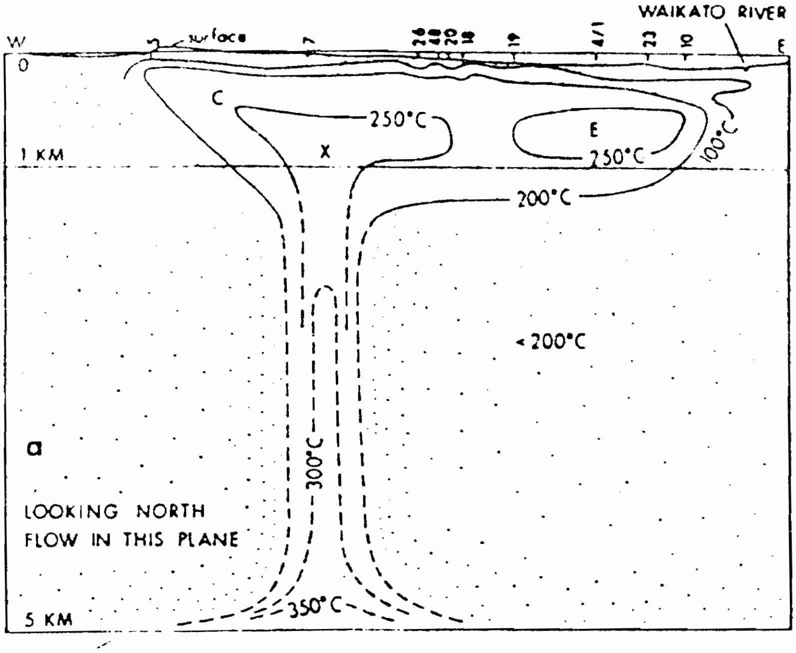


Fig. 4.16 Temperature log in well MG-33, Mosfellssveit, Iceland. The profile shows slightly negative gradient below 450 m depth.



Mushroom - shaped model of the Wairakei field, New Zealand.
From Elder 1965.

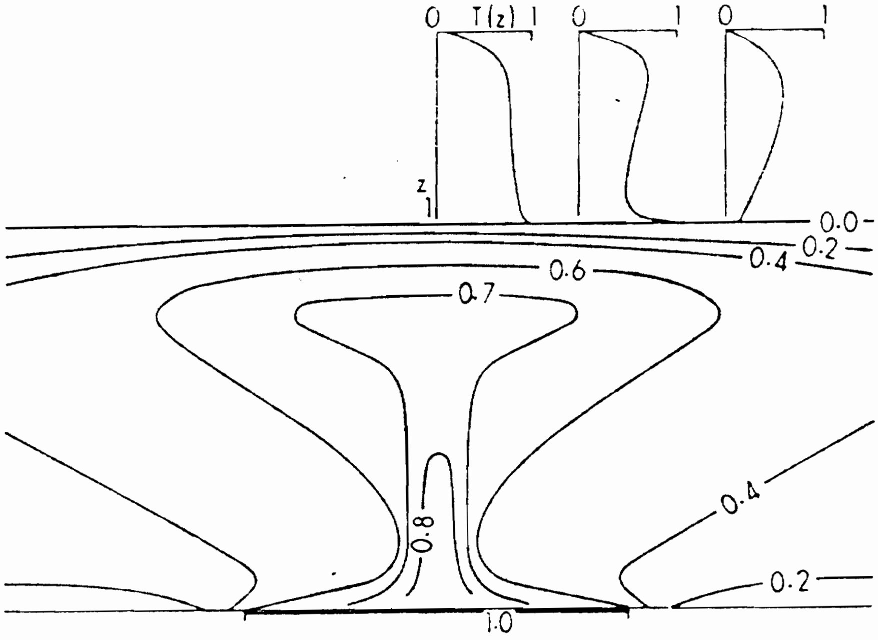
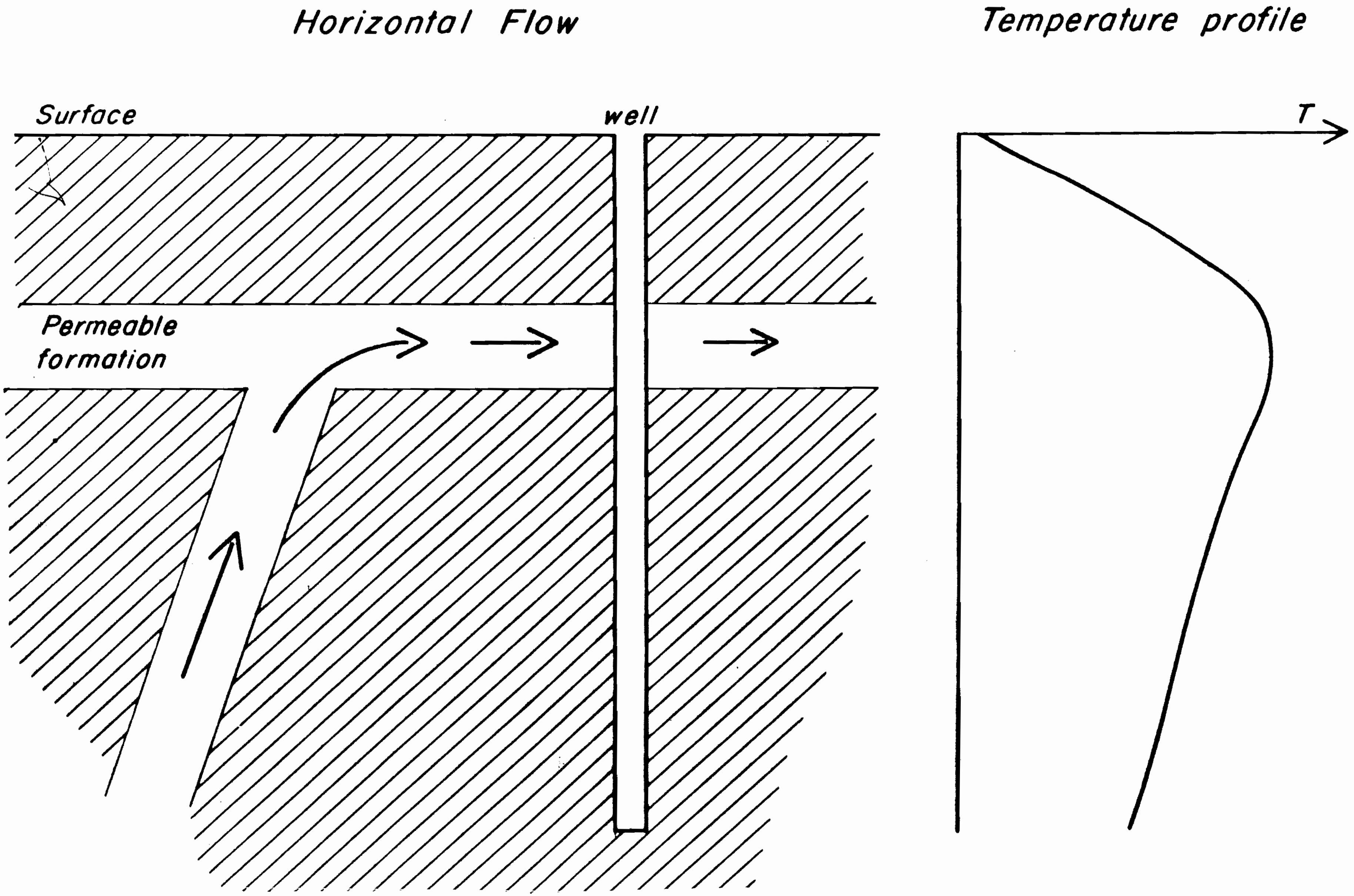
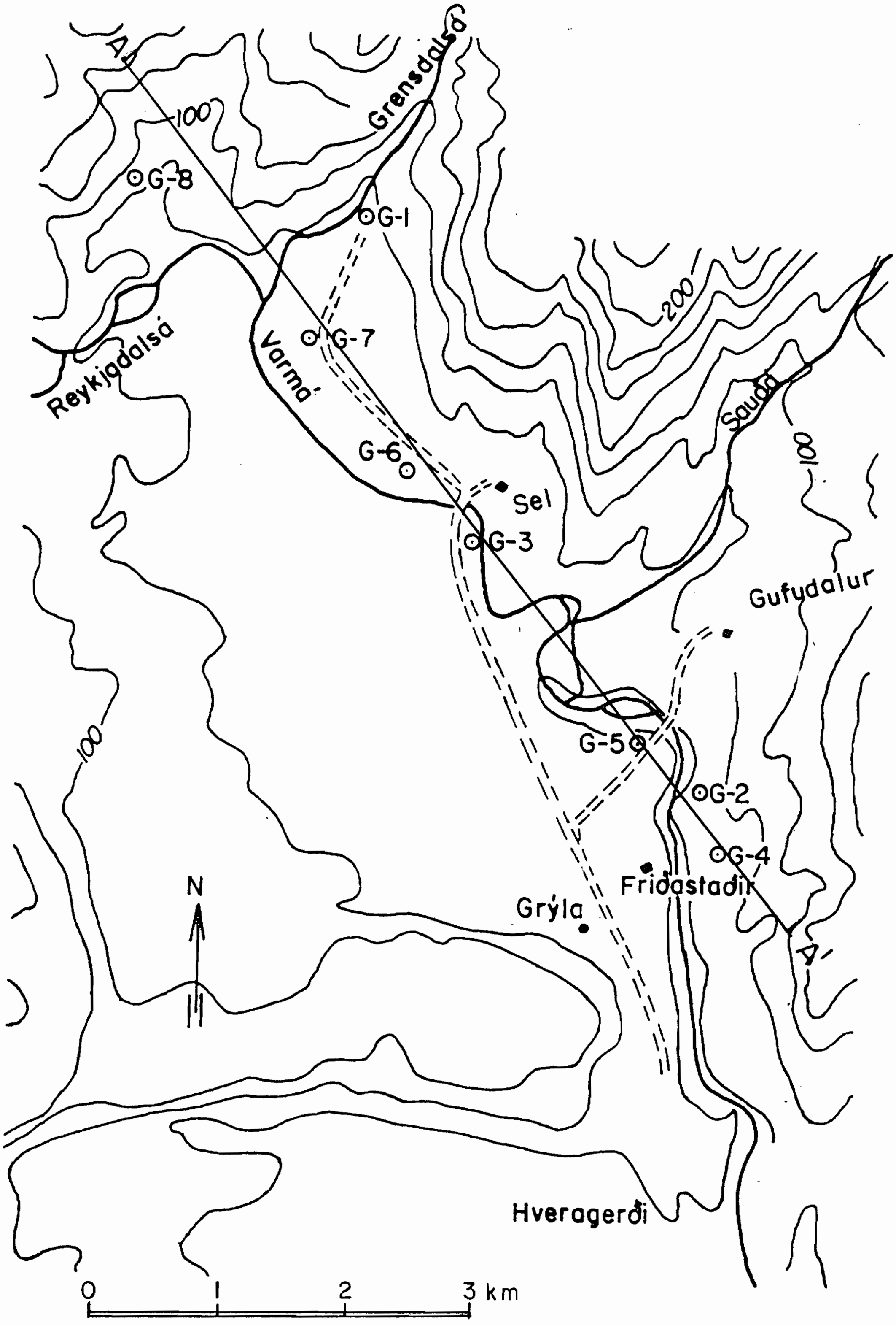


Fig. 4.18 Temperature distribution corresponding to free convection in a Hele - Shaw cell.
From Elder 1965.



A negative temperature gradient caused by horizontal flow.



⊙ Steam wells

Fig. 4.20 The high temperature geothermal field in Hveragerdi, Iceland. The cross-section marked is shown in Fig. 4.21.

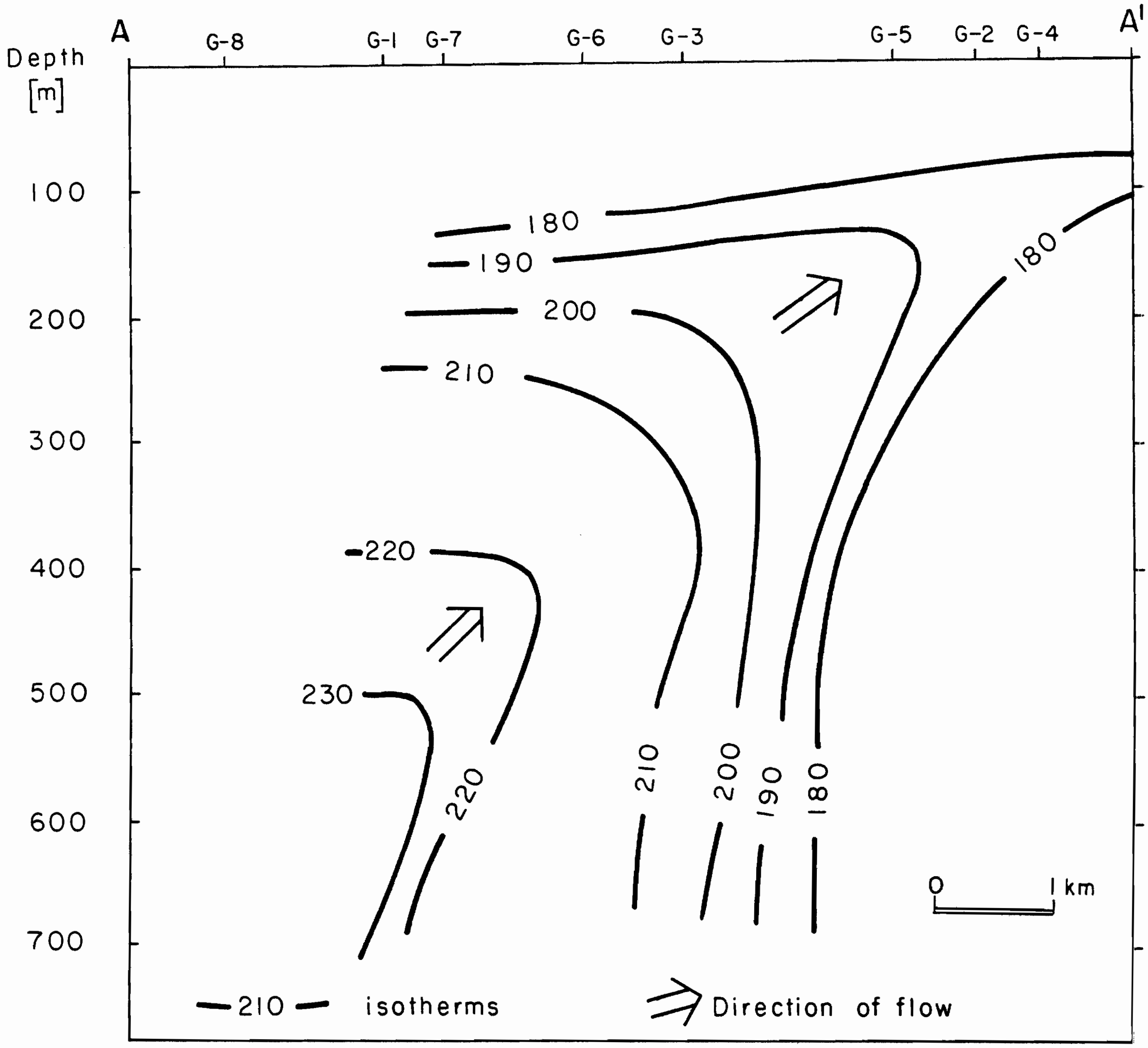
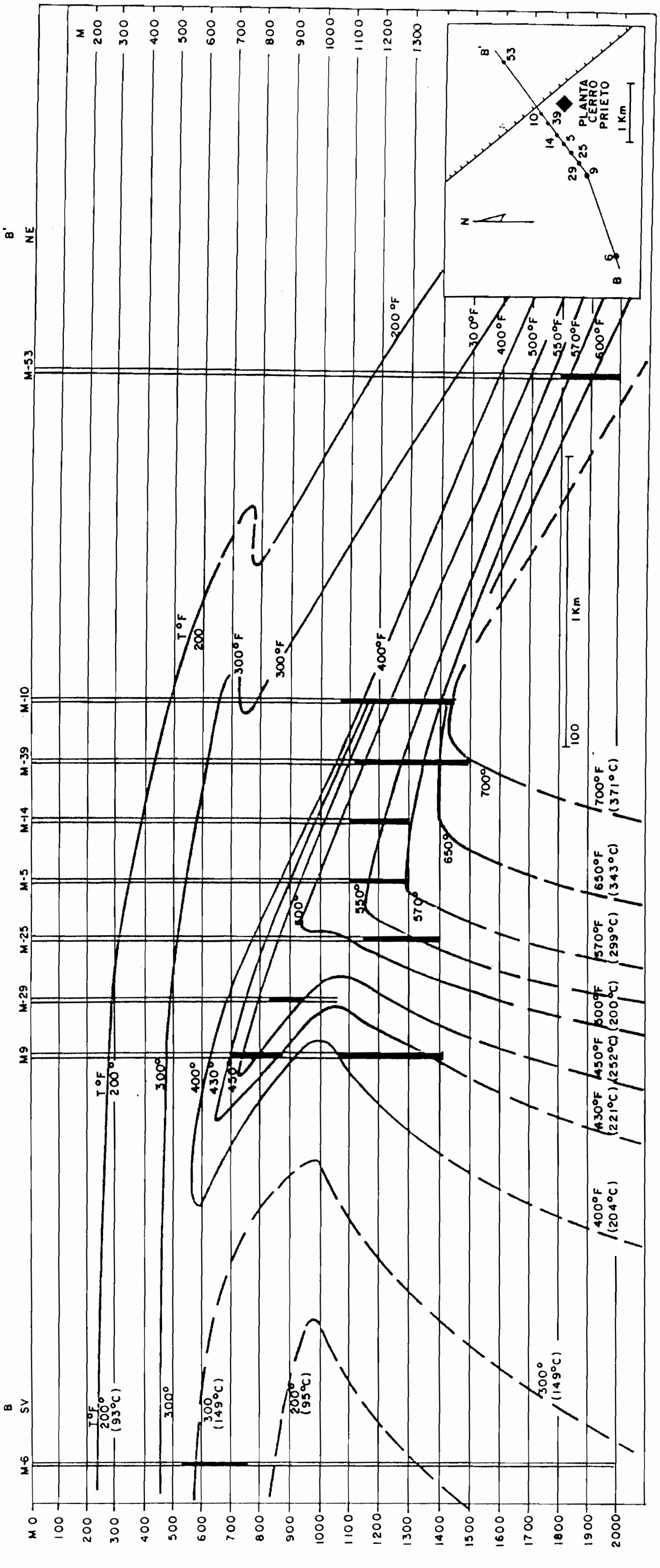


Fig. 4.21 Hveragerdi, Iceland. Temperature distribution in the cross-section of Fig. 4.20.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(200°C)
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(299°C)
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(343°C)
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(371°C)
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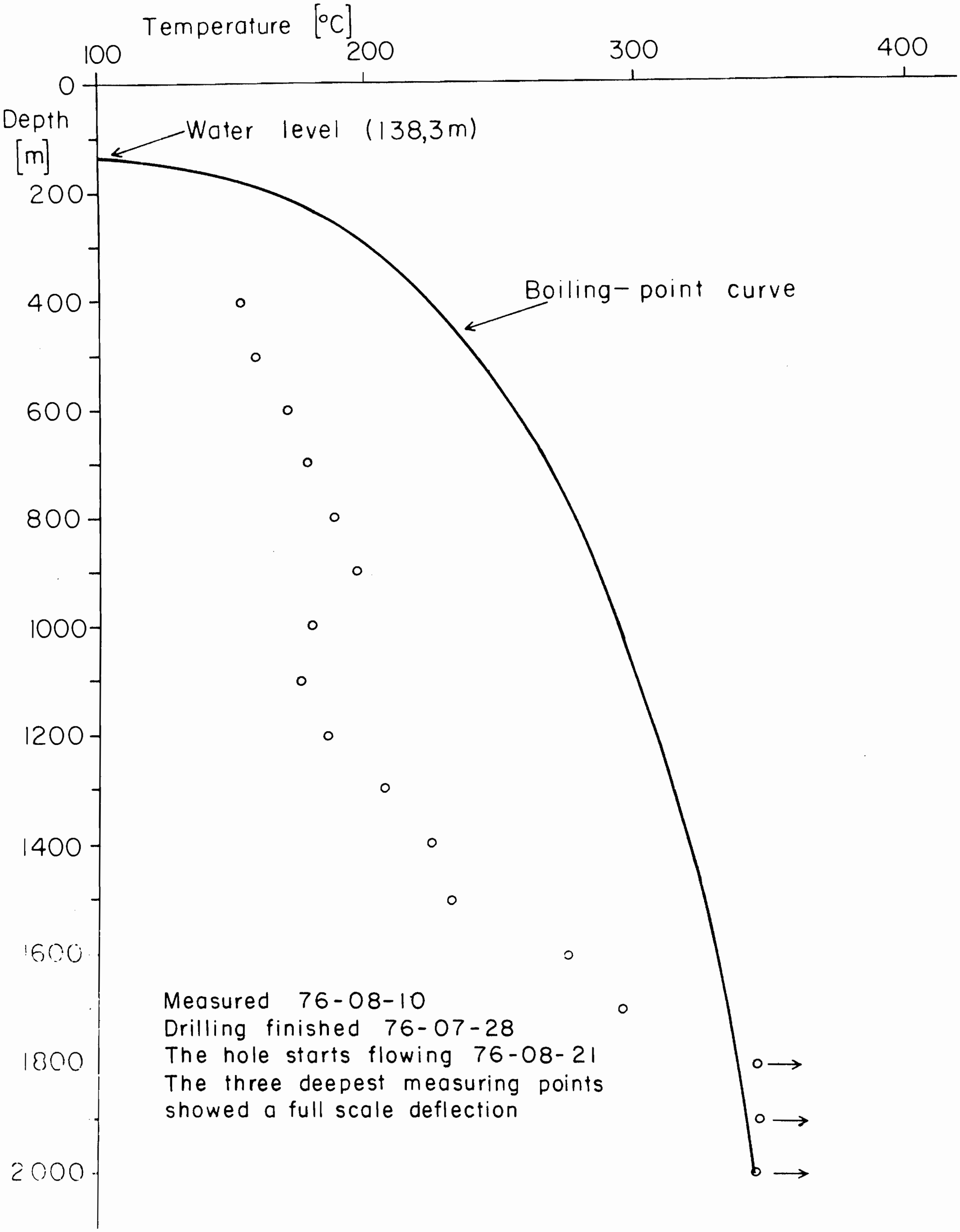


Fig. 4.23 Temperature profile in well KJ-6, Krafla, Iceland.

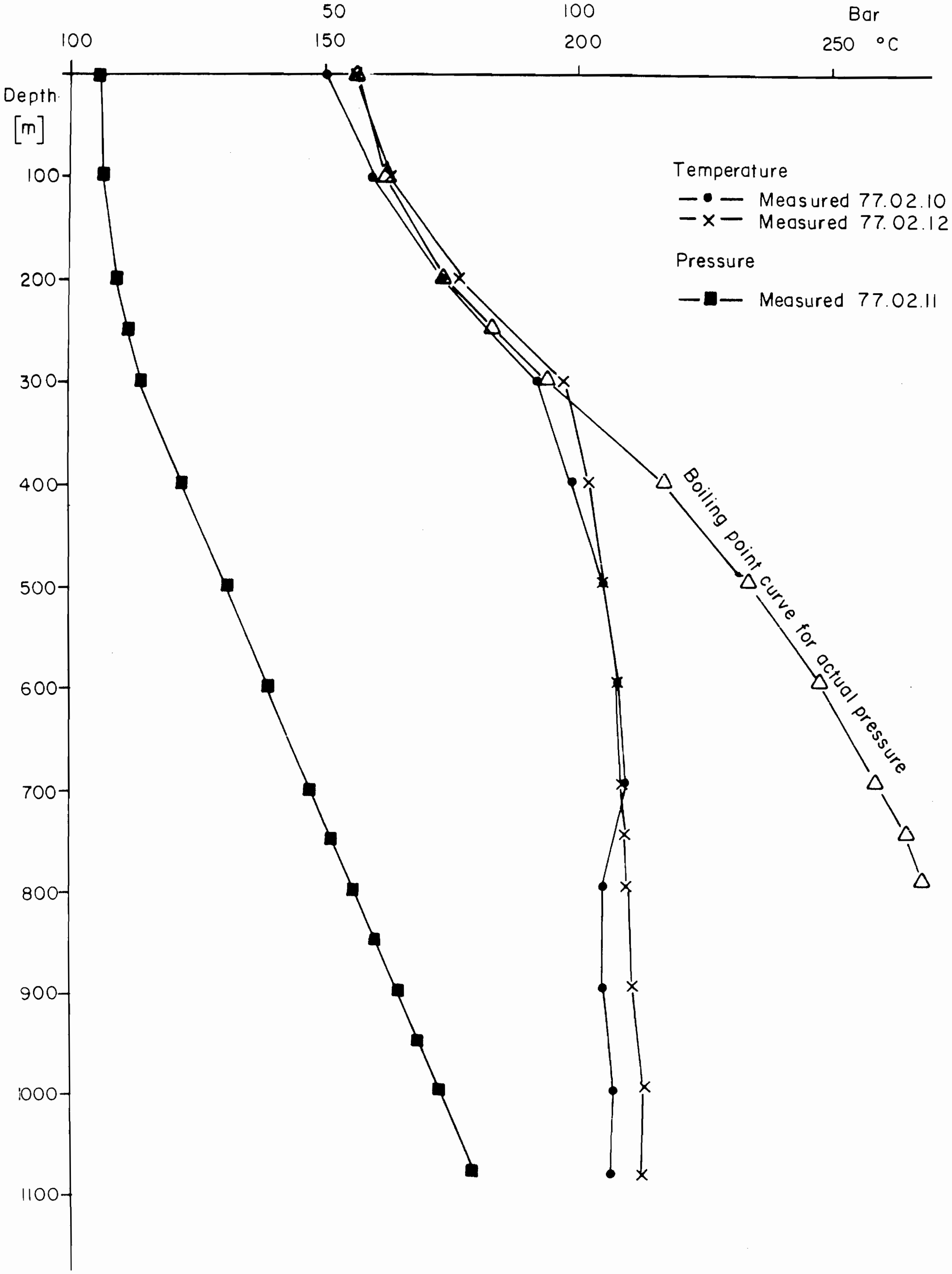


Fig. 4.24 Temperature and pressure measured during discharge of well KJ-9, Krafla, Iceland.

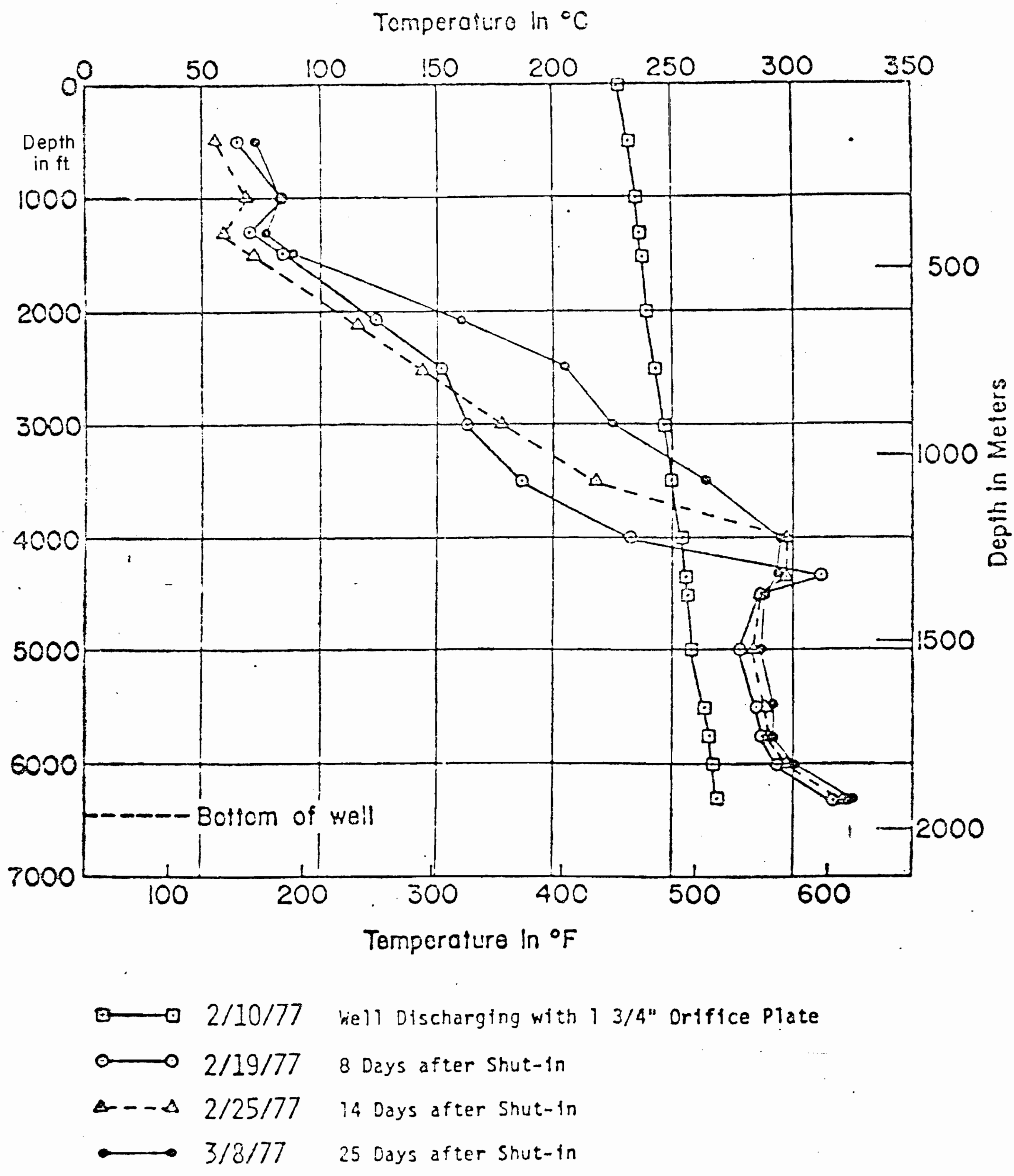


Fig. 4.25 Temperature profiles in well HGP-A, Hawaii, U.S.A.

From Summary Geothermal Energy in Hawaii 1978.

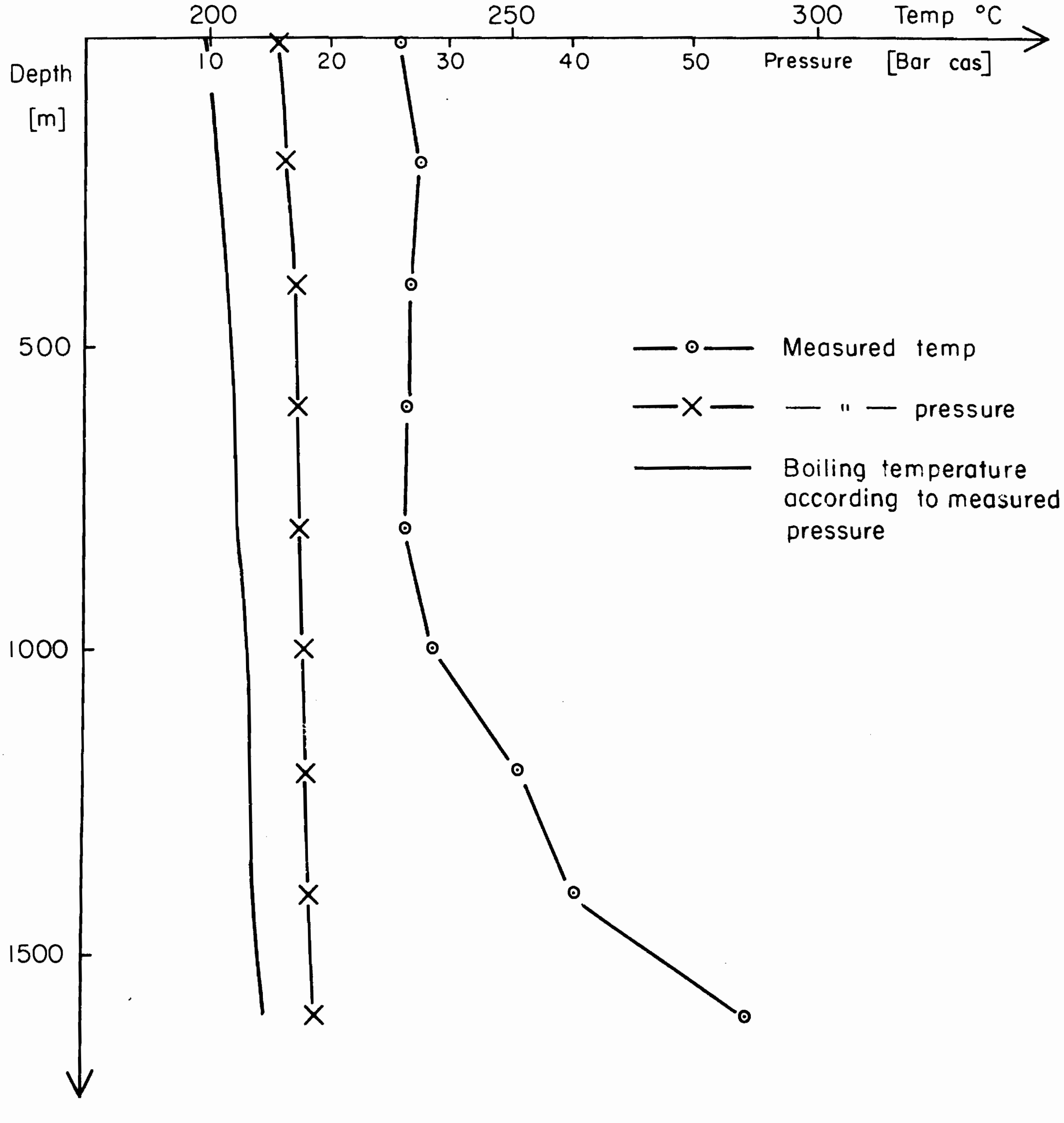


Fig. 4.26 Temperature and pressure measured in well KG-12, Krafla, Iceland , when the well is flowing. The discharge is superheated steam.

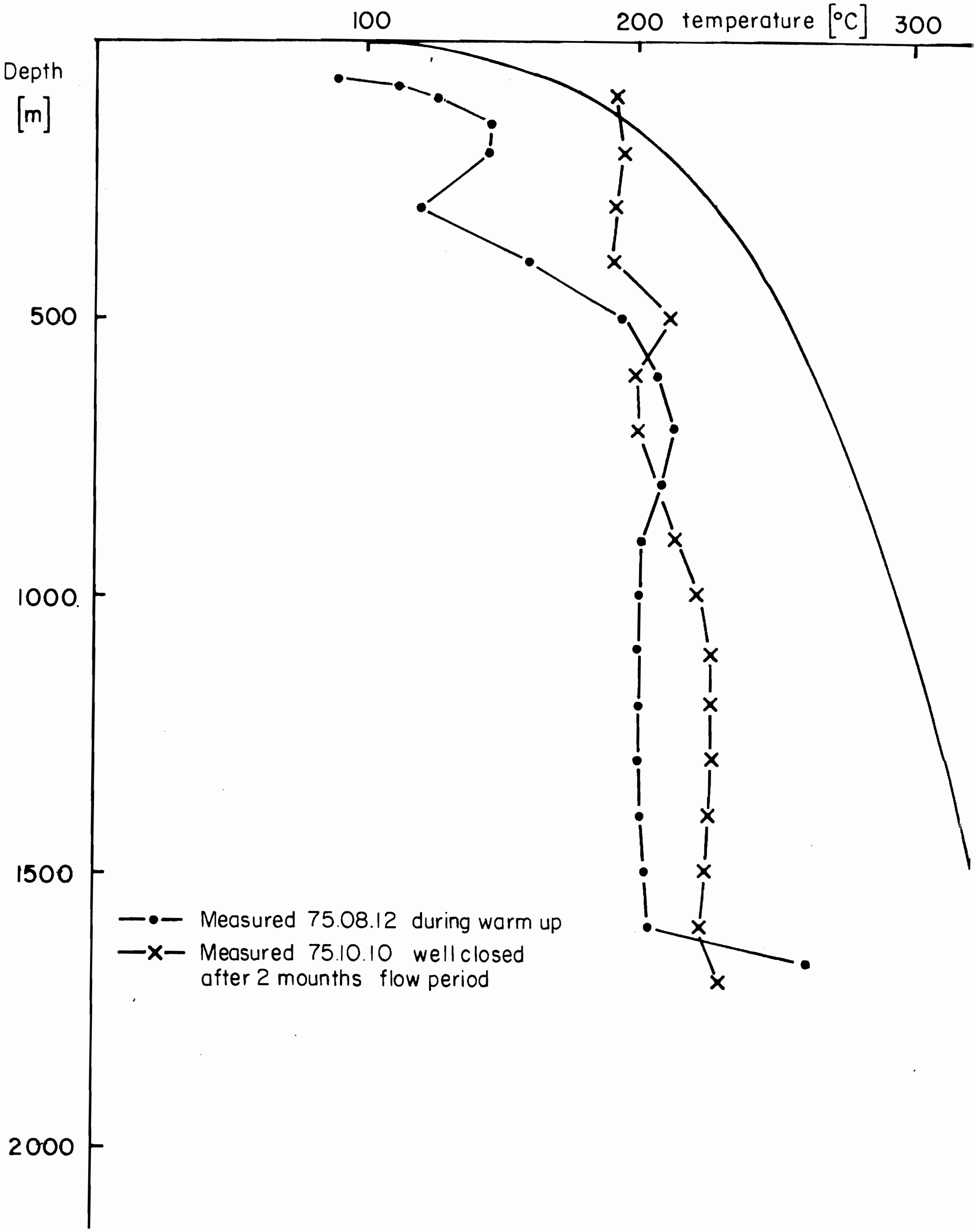


Fig. 4.27 Temperature profiles in well KG-3, Krafla, Iceland. When the well is closed water is flowing down the well from 500 m to 1600 m depth. During discharge the aquifer at 1600 m depth is boiling and the temperature in the well colder than the reservoir temperature.

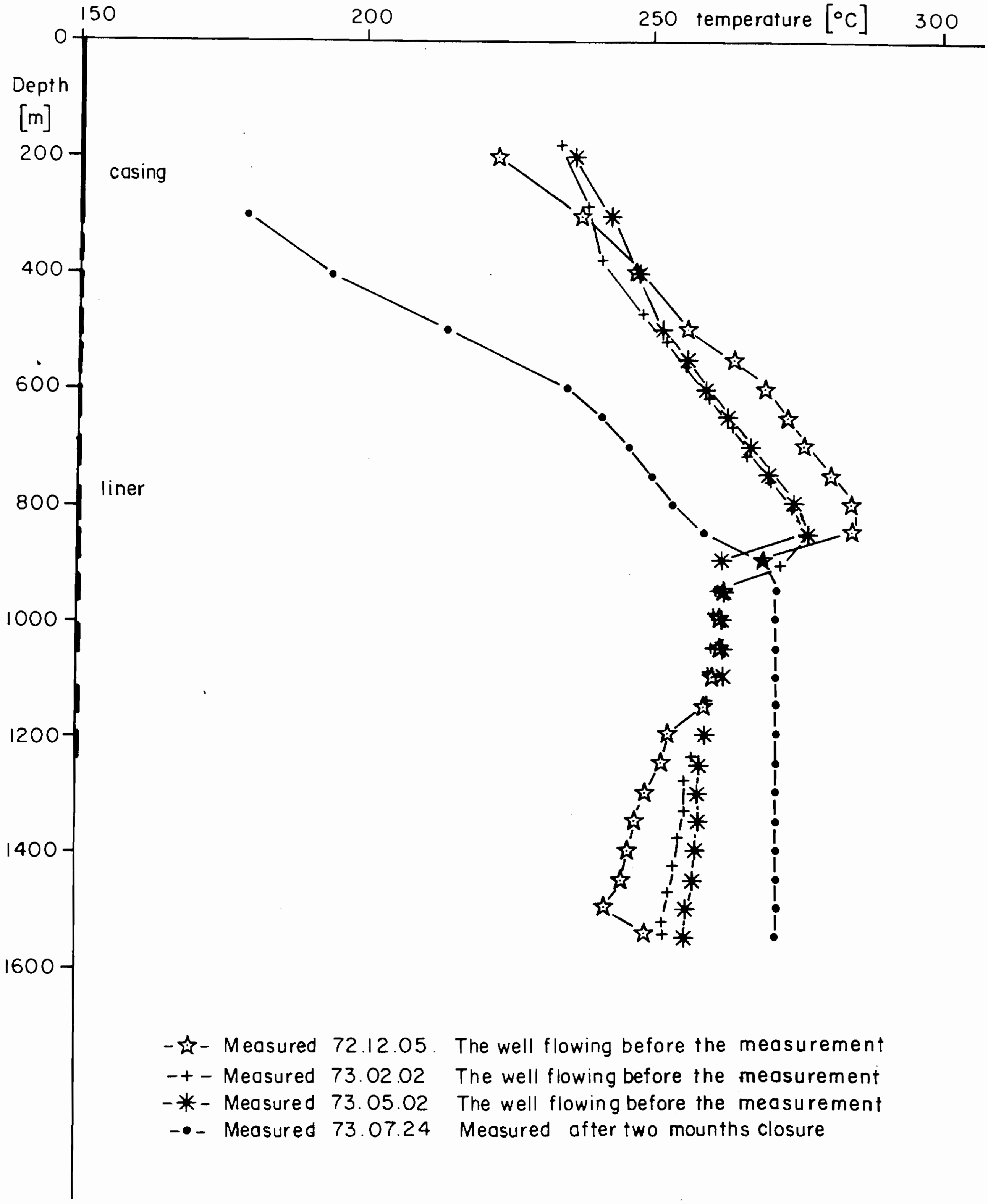


Fig. 4.28 Temperature logs in well N-5, Nesjavellir, Iceland. See text for explanation.

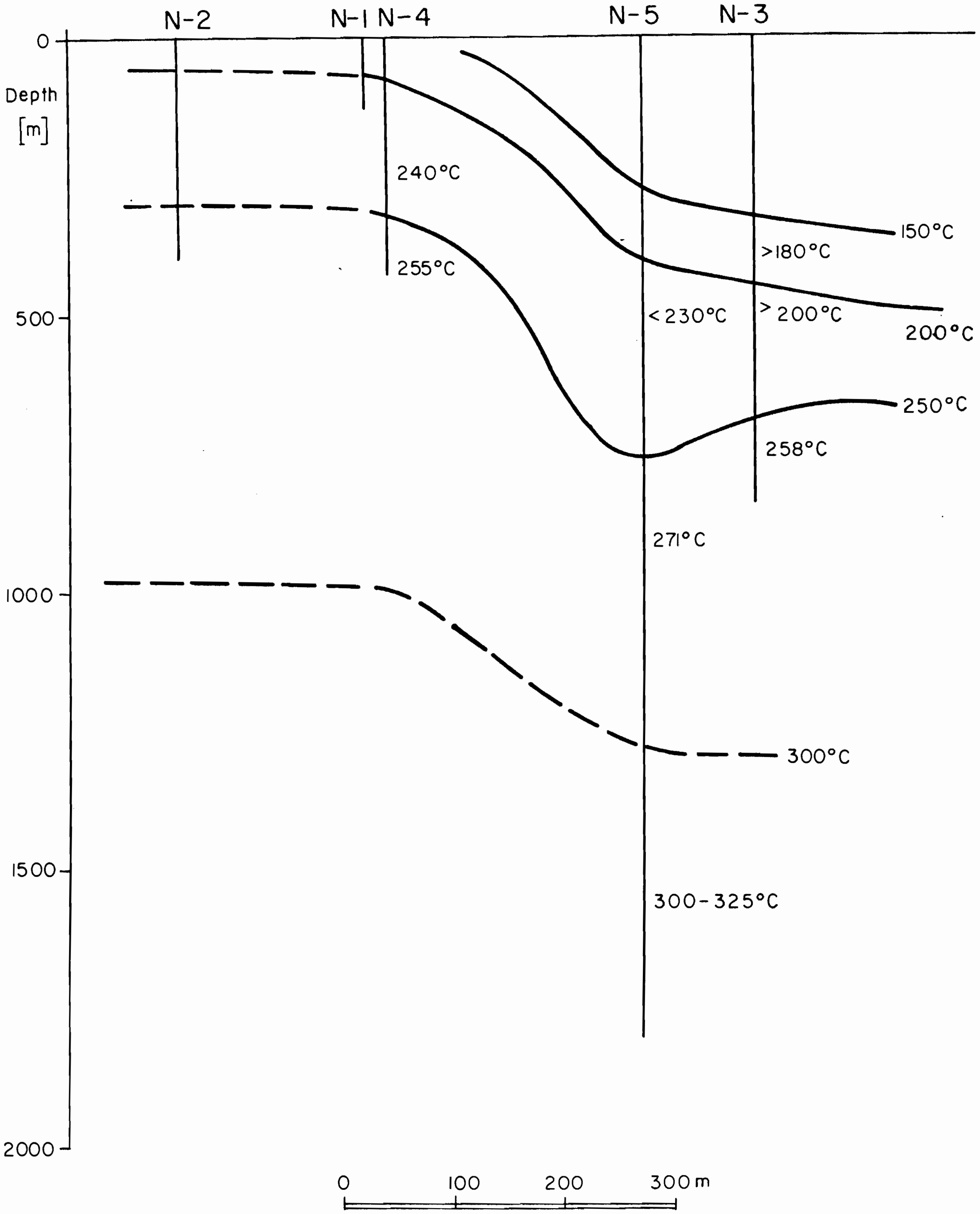


Fig. 4.29 Temperature distribution in the Nesjavellir high temperature geothermal field in Iceland. Cross-section SW-NE.

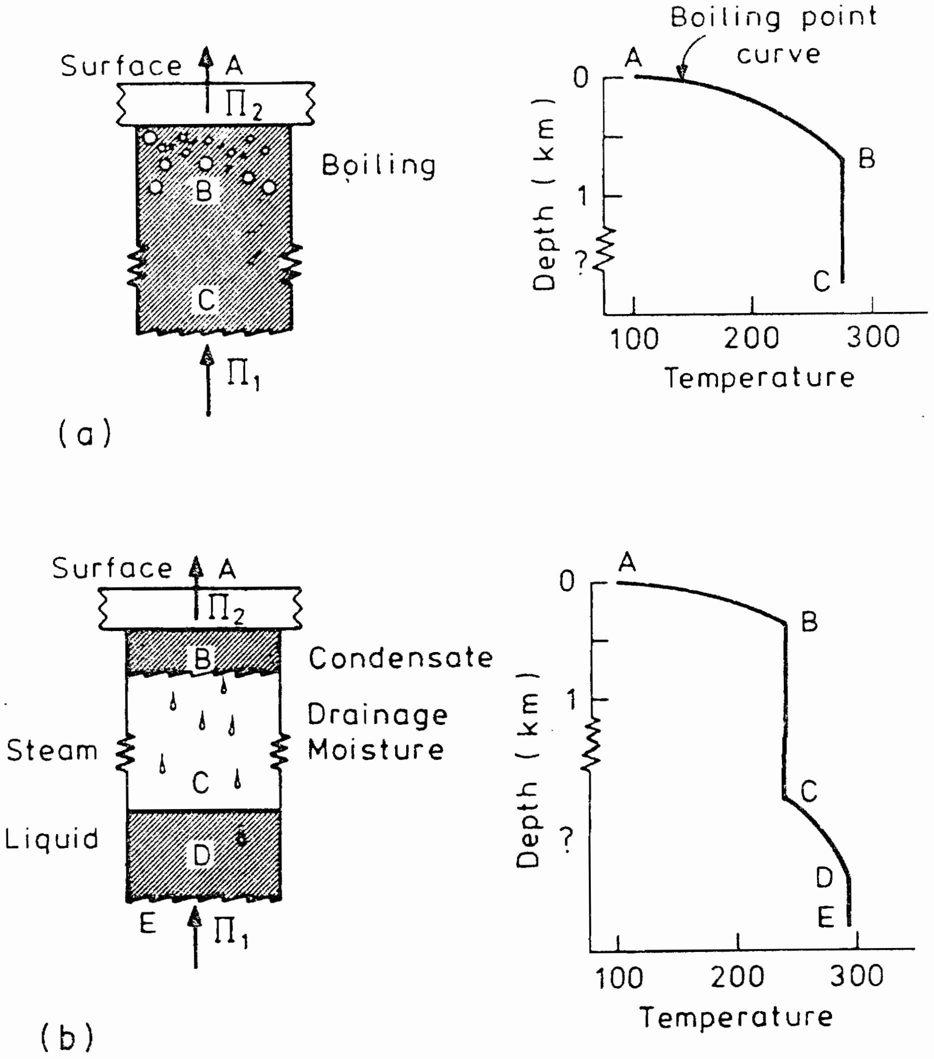


Fig. 4.30 Schematic cross-sections of geothermal systems dominated by hot water (a) and steam (b) in near-surface zones. The temperature versus depth graph for each system is also given. From Ellis and Mahon 1977.

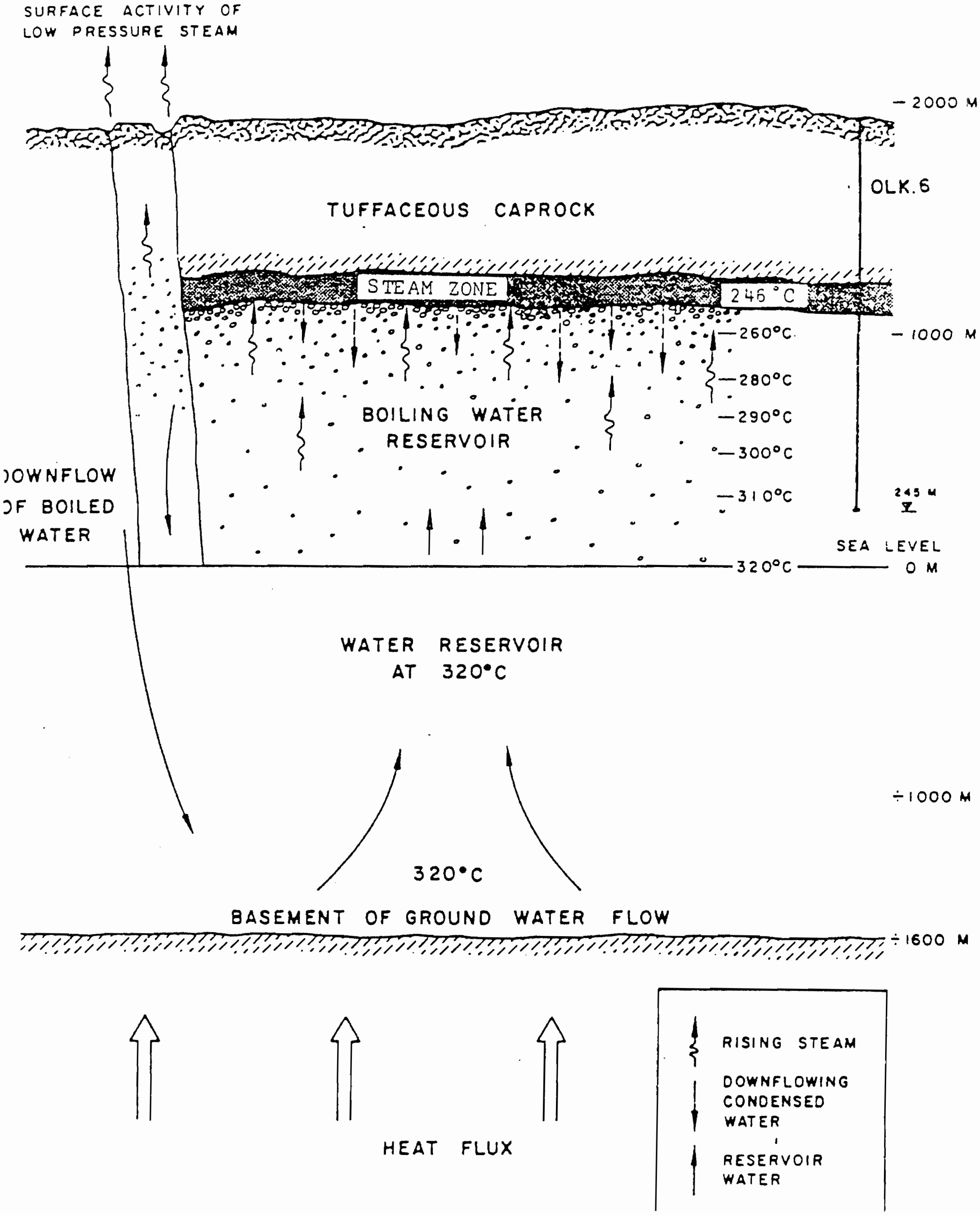
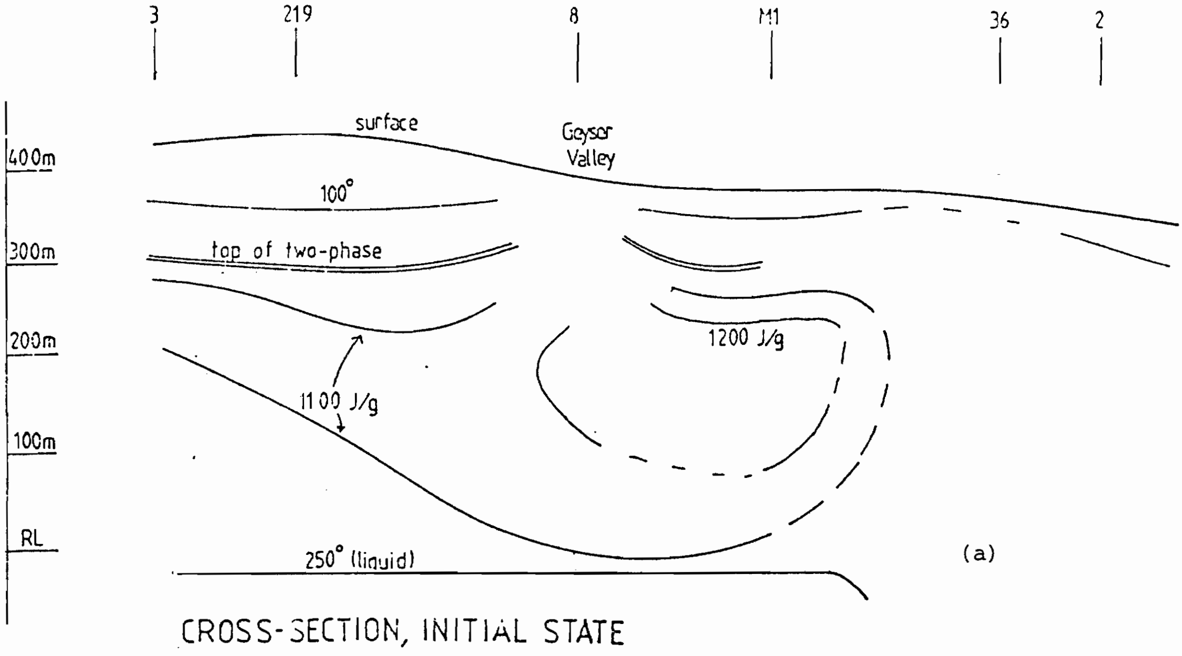


Fig. 4.31 Schematic section of the Olkaria Geothermal Reservoir, Kenya. From Sveinbjörn Björnsson 1978.



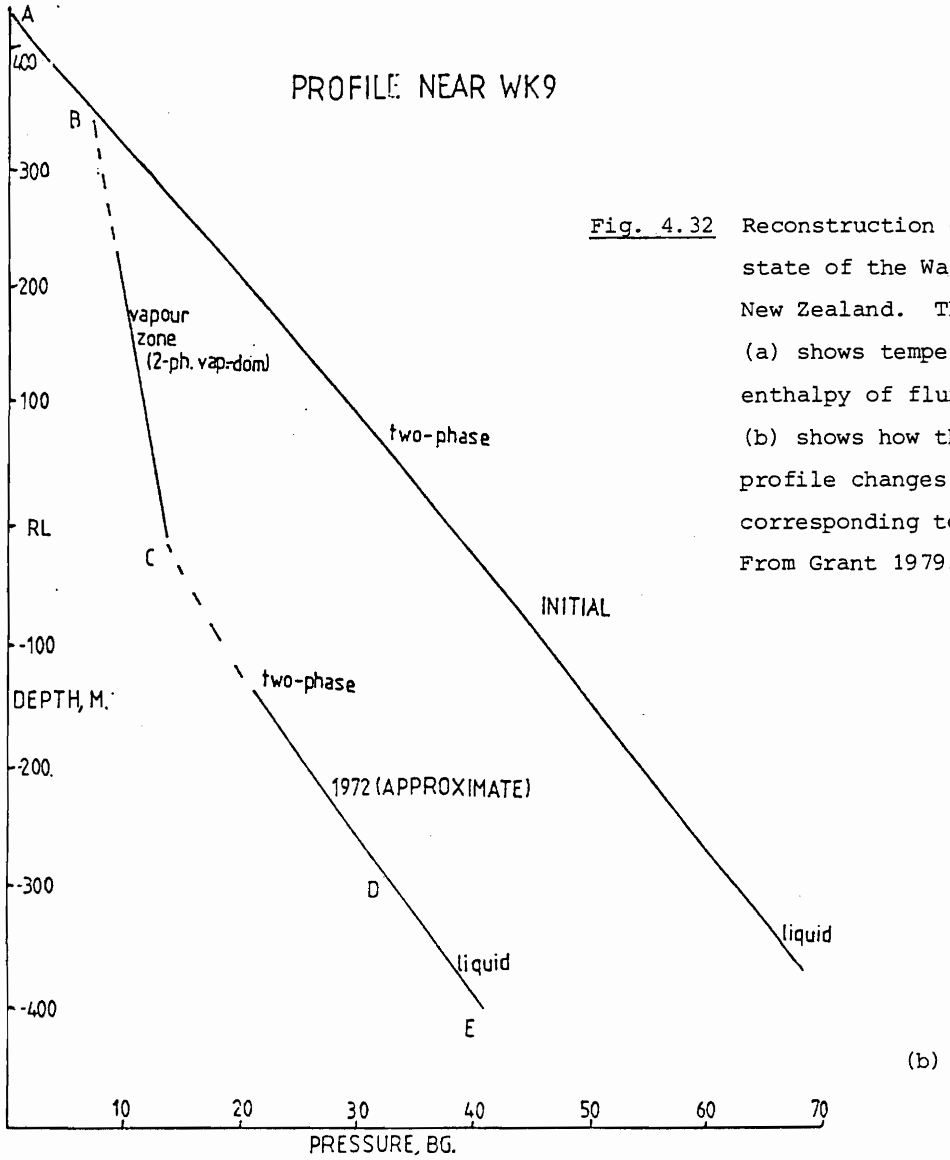


Fig. 4.32 Reconstruction of the initial state of the Wairakei field, New Zealand. The cross-section (a) shows temperature and enthalpy of fluid. The diagram (b) shows how the pressure profile changes in time corresponding to utilization. From Grant 1979.

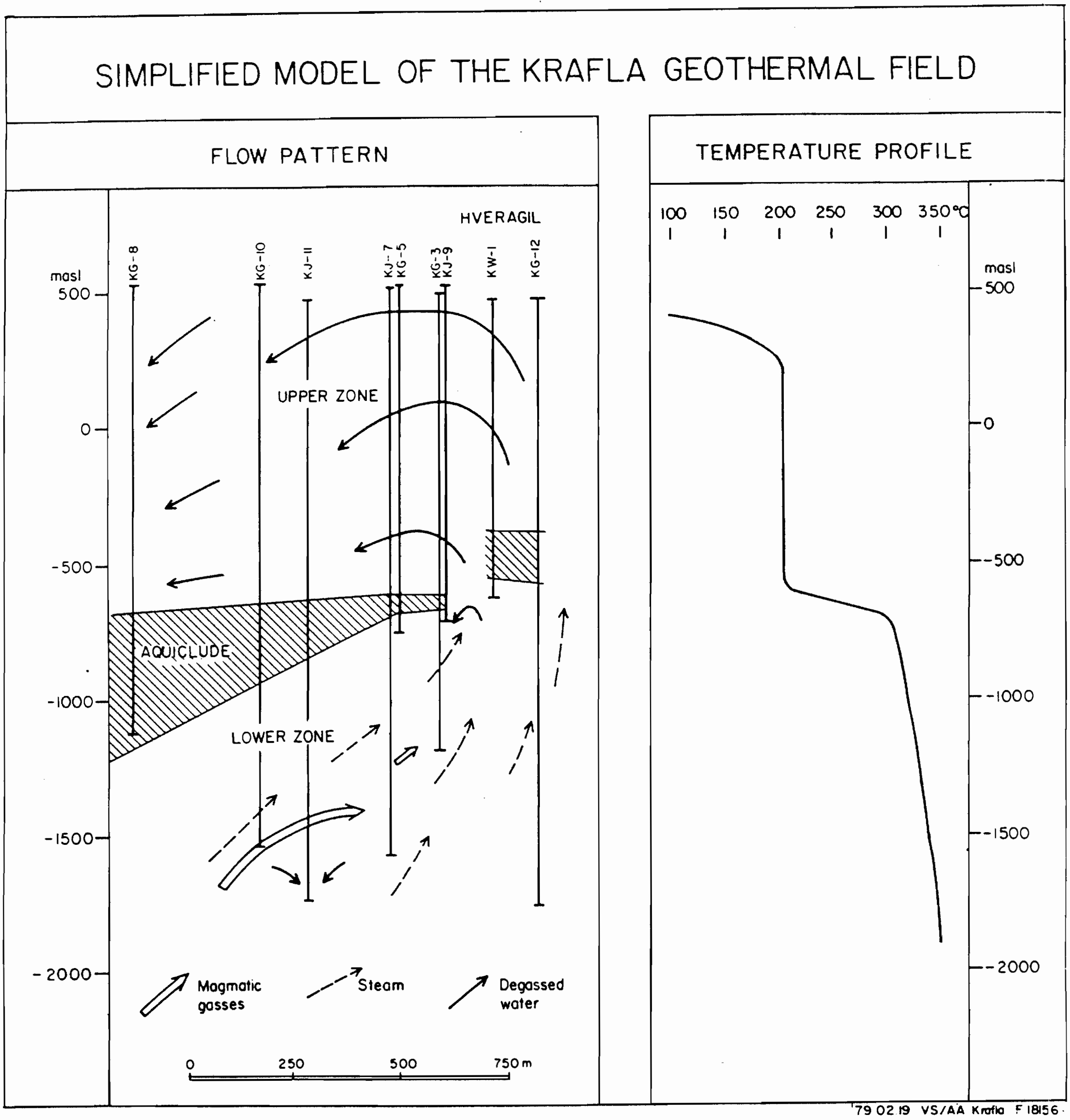


Fig. 4.33 Simplified model of the Krafla Geothermal Field, Iceland. From Stefánsson 1980.

5 PRESSURE LOG

Pressure is an essential parameter in geothermal systems, and in a sense reservoir engineering can be regarded as the study of the pressure distribution in a reservoir.

Because of its nature, pressure logging is usually carried out to get information on the whole geothermal system, rather than the condition or performance of a single well. However, the coupling effect between the well and the reservoir (called the skin effect), which is determined by time dependent pressure measurements, can be regarded as a property of the well as well as of the reservoir.

Here, some of the effects which are revealed by geothermal pressure logs will be considered. Relatively simple examples will be given to keep the material within reasonable limits. But as mentioned before, there is no difference between geothermal logging and geothermal reservoir engineering with regard to measurement of pressure.

5.1 Warm-up period

As with the temperature logs, the registration of pressure during the warm-up period gives valuable information.

Fig. 5.1 shows two pressure logs from the warm-up period of well BJ-11 in the Námafjall field in Iceland. As can be seen in the figure the water level in the well rises as the well warms up. However, at 1400 m depth the pressure does not change with time. This level is the location of the strongest aquifer in the well, and the constant pressure recorded is the undisturbed pressure of this aquifer prior to drilling. The determination of the pressure during the warm-up period is the best determination of the initial pressure potential at this place in the field, a zero point, which is difficult to determine later during the operation of the well.

5.2 Pressure logs in static wells

Determination of the pressure distribution within the reservoir reveals basic properties of the geothermal reservoir. Fig. 5.2 shows the pressure distribution in a cross-section of the Nesjavellir field in Iceland. The figure shows that a part of the field is "overpressurised". The upflow in the field is predicted to be there. See also fig. 4.29 where the temperature distribution is shown.

The combination of temperature and pressure information on geothermal systems is valuable as shown in fig. 5.3. This figure shows the isolines of temperature and pressure at the bottom of the upper zone in the Krafla field in Iceland. The flow directions at this level can be inferred from this picture. Note specially that the isothermal lines tend to be normal to the isobar lines.

With a careful study of the bottom hole pressure during drilling, and the temperature, it has been possible to detect and determine thin steam zones in the geothermal reservoirs. Fig. 5.4 shows the cross-section of the temperature and pressure of the Olkaria field in Kenya.

The reservoir model for the Olkaria field is shown in fig. 4.31.

5.3 Pressure logs in flowing wells

As was demonstrated in chapter 4 both temperature and pressure logs in flowing wells show the flowing conditions of the well (see fig. 4.24). The drawdown in a flowing geothermal well is an important parameter from an operational point of view. Fig. 5.5 shows a measured drawdown in a high temperature water-dominated well. The well flowed for one hour, was then closed and the recovery measured. The drawdown is approximately 23 bar.

As will be shown later this kind of information can be used to determine the permeability thickness of the well.

5.4 Time dependent pressure logs

As has been mentioned before these types of measurements are made with the aim of determining the reservoir properties. Information on the pressure variation and the mass flow either from the reservoir or into the reservoir is necessary for the determination of parameters such as permeability.

In principle, injection and flow tests are theoretically reversible processes and should give similar information on the geothermal reservoir. We will, however, treat them separately, as practical experience has shown that the results are not always in agreement with each other.

5.4.1 Injection tests

Geothermal wells are usually tested at the end of completion by injection tests. The purpose of this operation is to determine the permeability or more frequently the permeability thickness of the well. Water is pumped into the well at a constant rate and the pressure increase in the well measured as a function of time. Fig. 5.6 shows a simple injection test. The pressure change can be found by measuring the water level in the well. The transmissivity is then easily determined by plotting the pressure data on a semilogaritmic paper as shown in fig. 5.7.

5.4.2 Flow tests

There are many methods of measuring the pressure as a function of time when a well or wells are flowing. Fig. 5.5 shows a short time drawdown and a recovery test measured within the well. The transmissivity of the well can be determined by plotting the pressure (see fig. 5.8) as function of logaritmic time as shown in fig. 5.7.

The measurement of pressure in an observatory well is, however, more reliable when another well or wells are flowing. This gives a better value for the general drawdown in the system.

During the operation of a geothermal field the pressure as well as the total mass output is registered regularly. Fig. 5.9 shows the pressure change and mass output for an 8 years period in the Broadlands field in New Zealand. A drawdown of 15 bar is observed in the field, but recovery of the field is also observed during the three years shutdown of the field.

Some effects in pressure distribution are not detected unless a long time flow test is carried out. This includes for example the determination of boundary effects on the drawdown. Fig. 5.10 shows the drawdown in the Svartsengi field in Iceland. The flow rate from the field was constant during the time shown in the figure. The change in drawdown rate is interpreted as due to the boundaries of the reservoir.

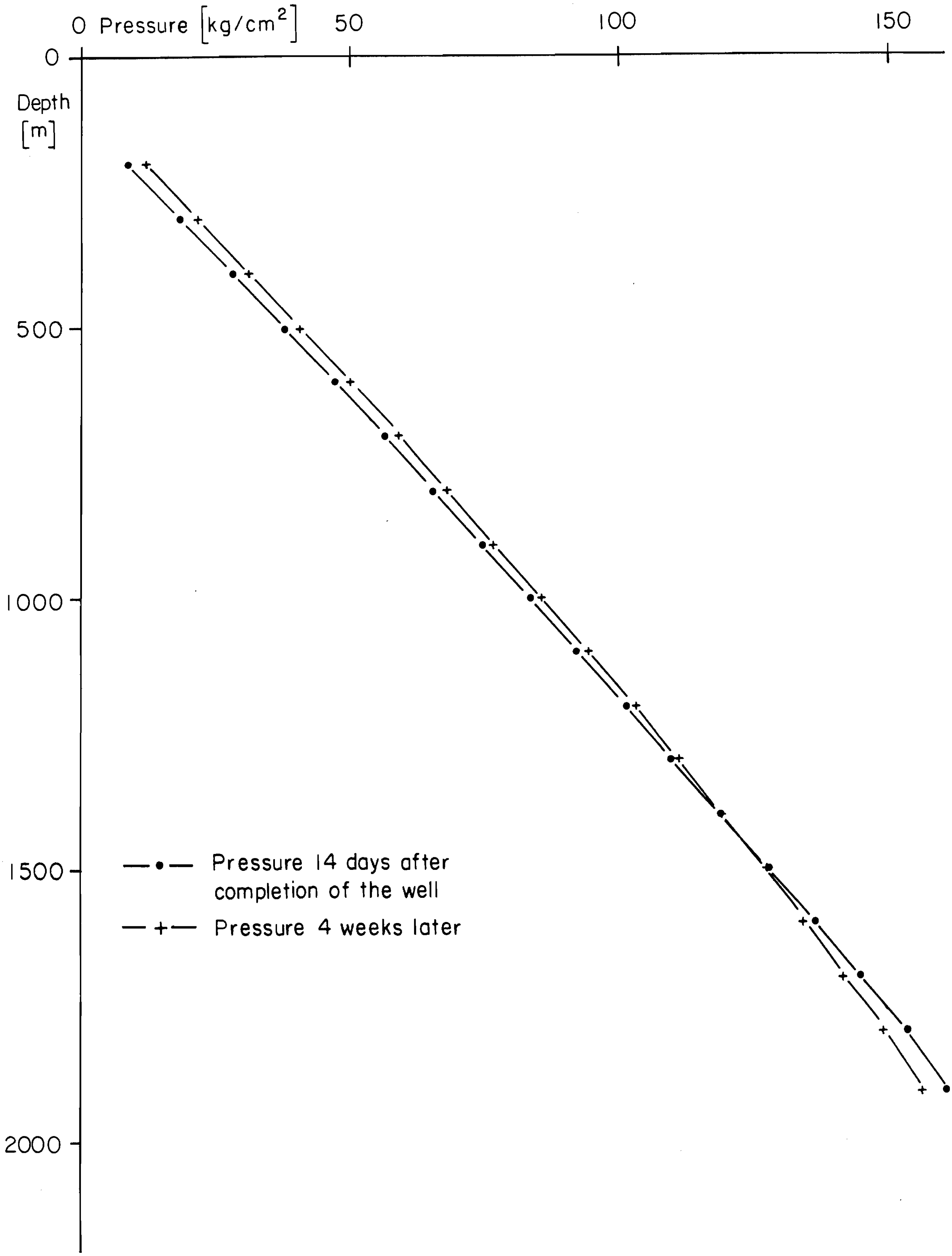


Fig. 5.1 Pressure logs in well BJ-11, Námafjall, Iceland during warm-up period.

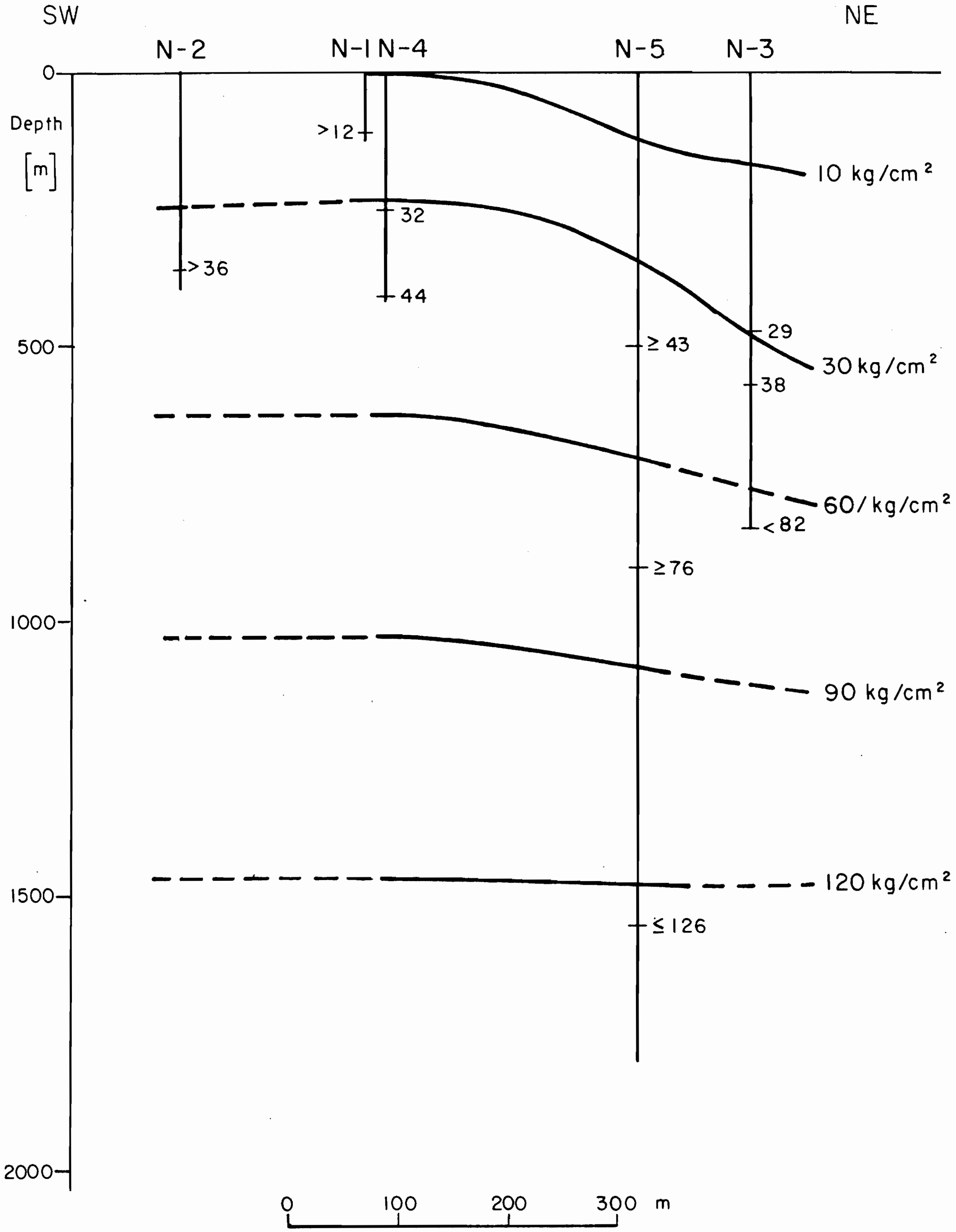


Fig. 5.2 Pressure distribution in a cross-section of the Nesjavellir geothermal field in Iceland.

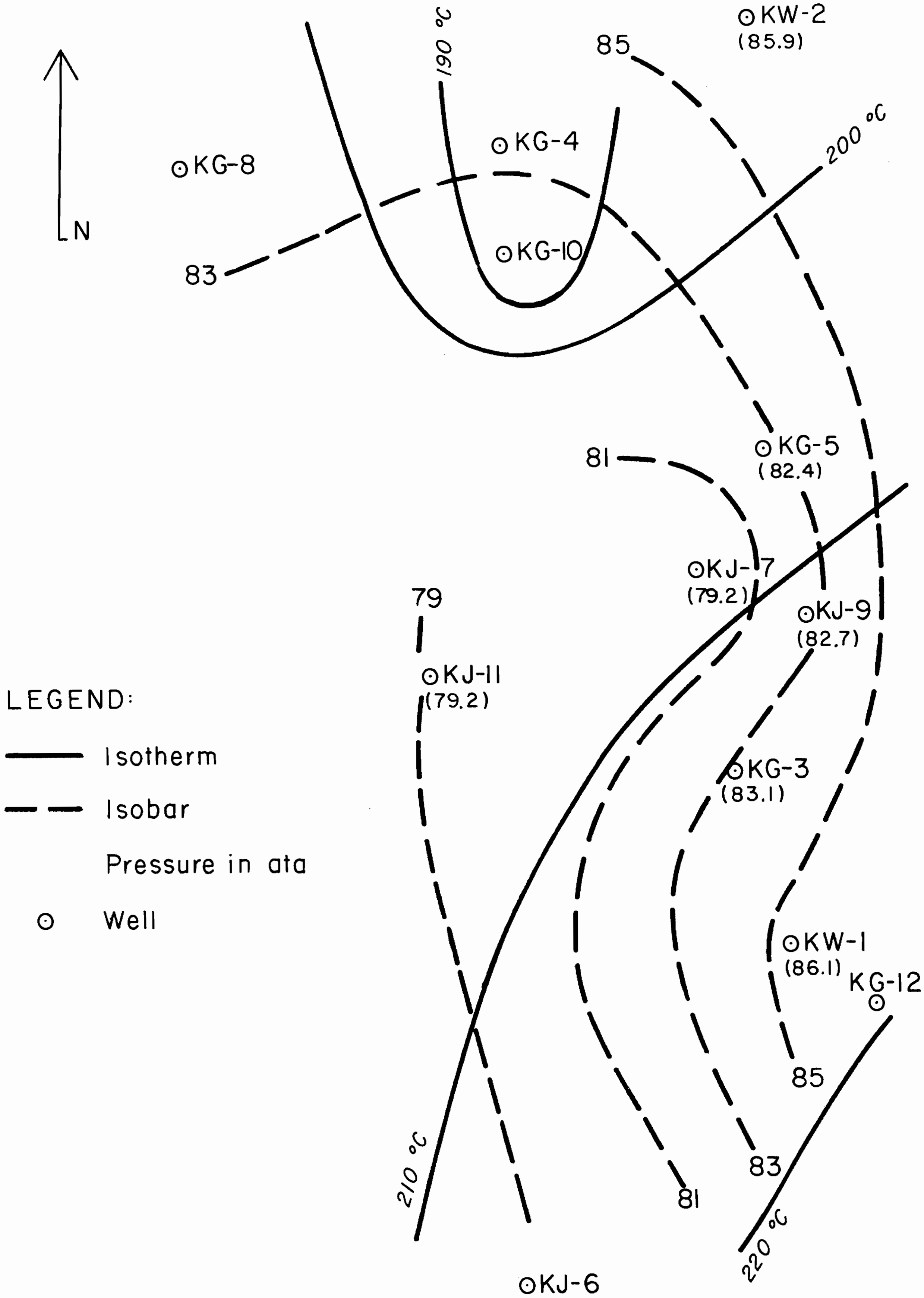


Fig. 5.3 Temperature and pressure at a level 500 m below sea level in the Krafla geothermal field, Iceland.

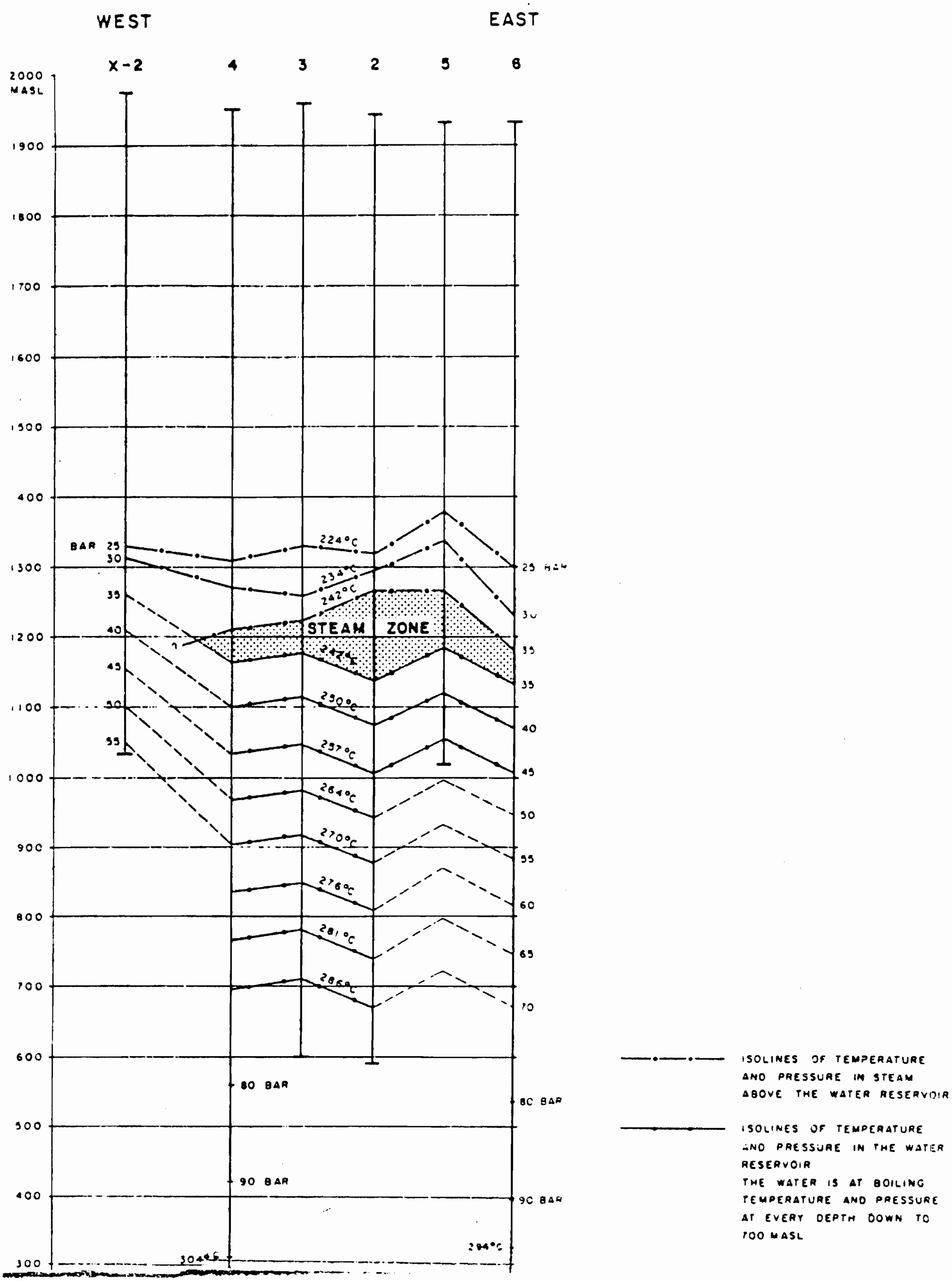


Fig. 5.4 Cross-section of the Olkaria field, Kenya showing both temperature and pressure prior to exploitation.
From Sveinbjörn Björnsson 1978.

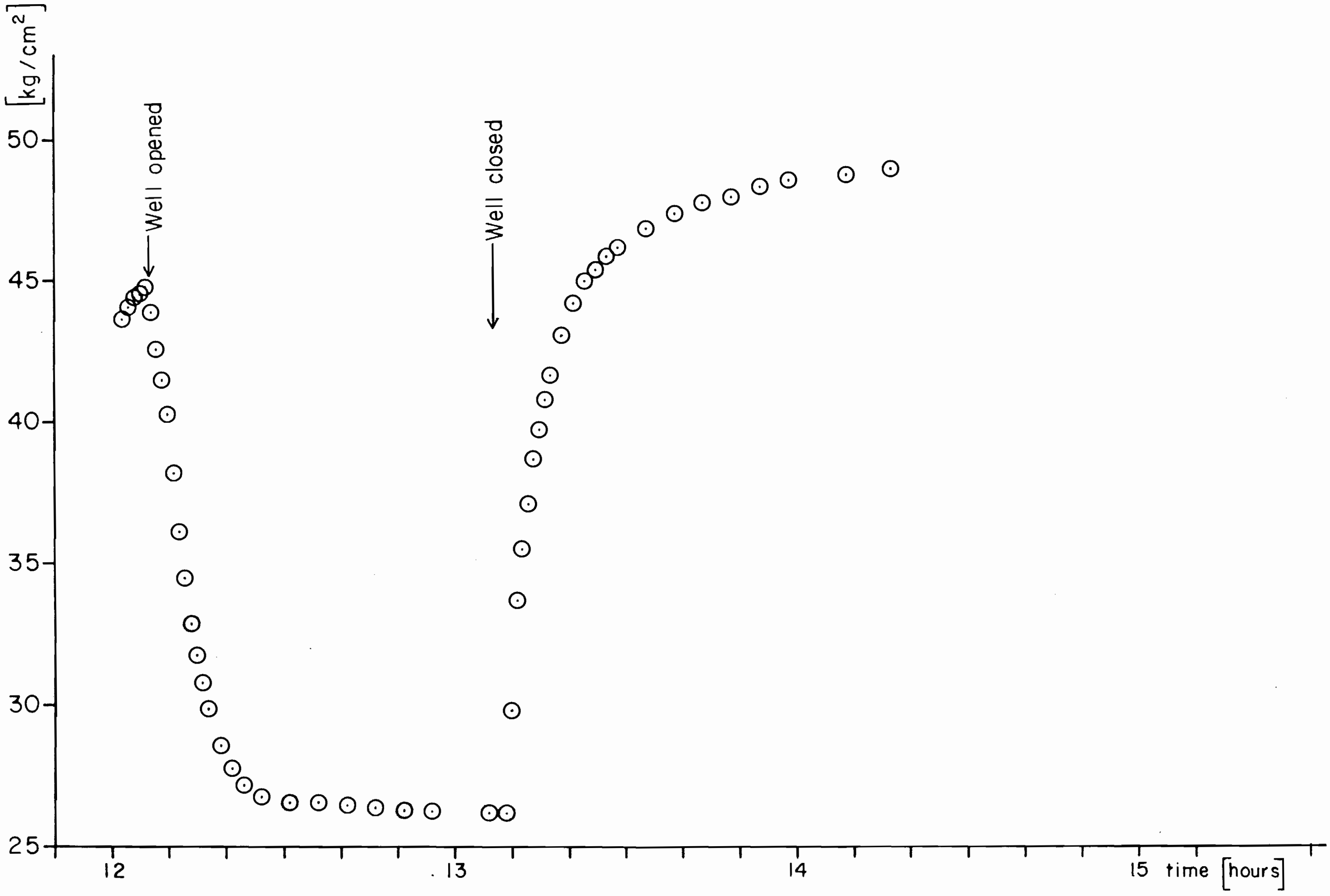


Fig. 5.5 Pressure at 600 m depth in well KG-8, Krafla, Iceland during flow test and recovery.

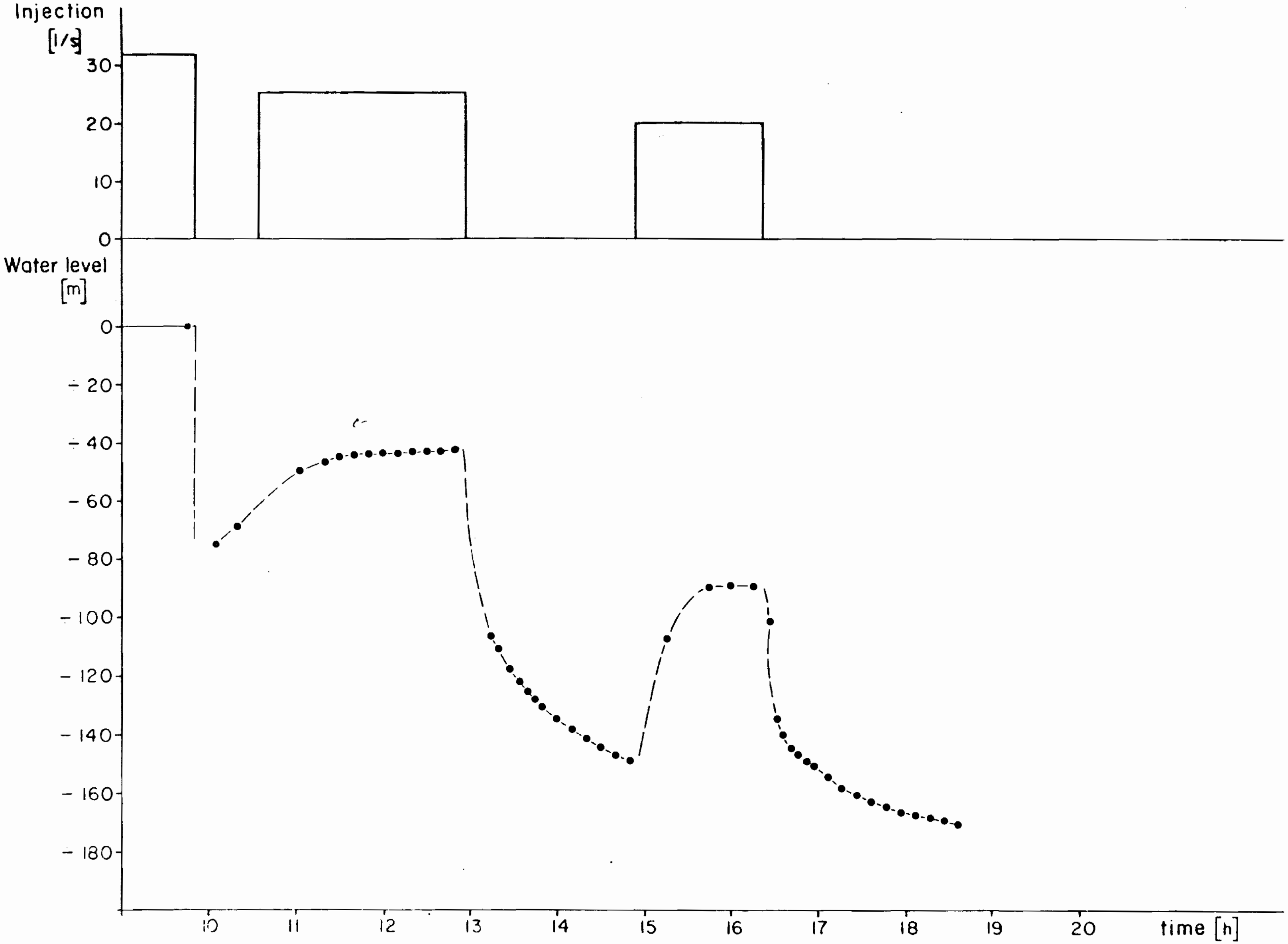


Fig. 5.6 Injection test in well KJ-6, Krafla, Iceland.

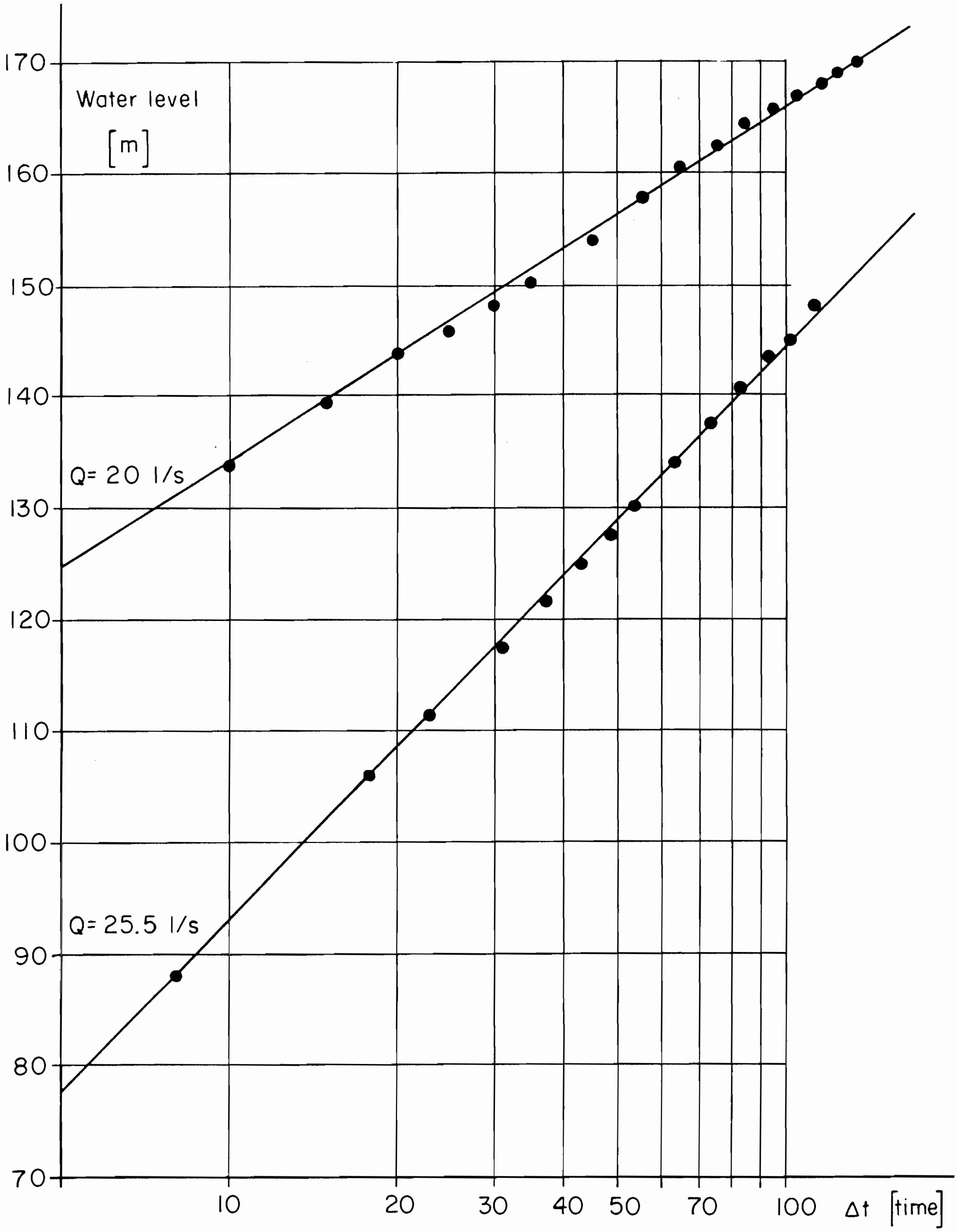


Fig. 5.7 Lin-log plot of the pressure (water level) during the injection test shown in fig. 5.6.

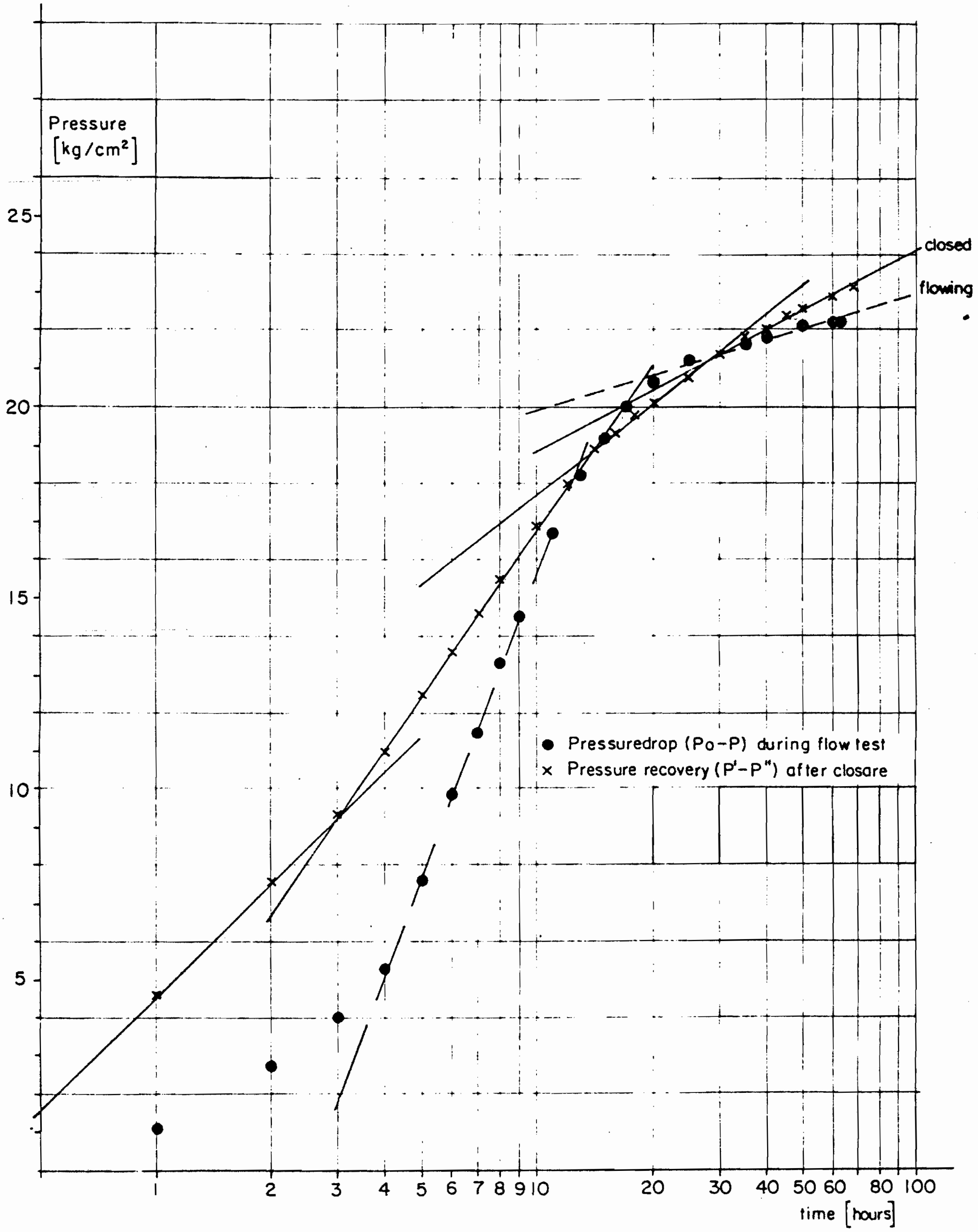


Fig. 5.8 Lin-log plot of the flow test and recovery shown in fig. 5.5.

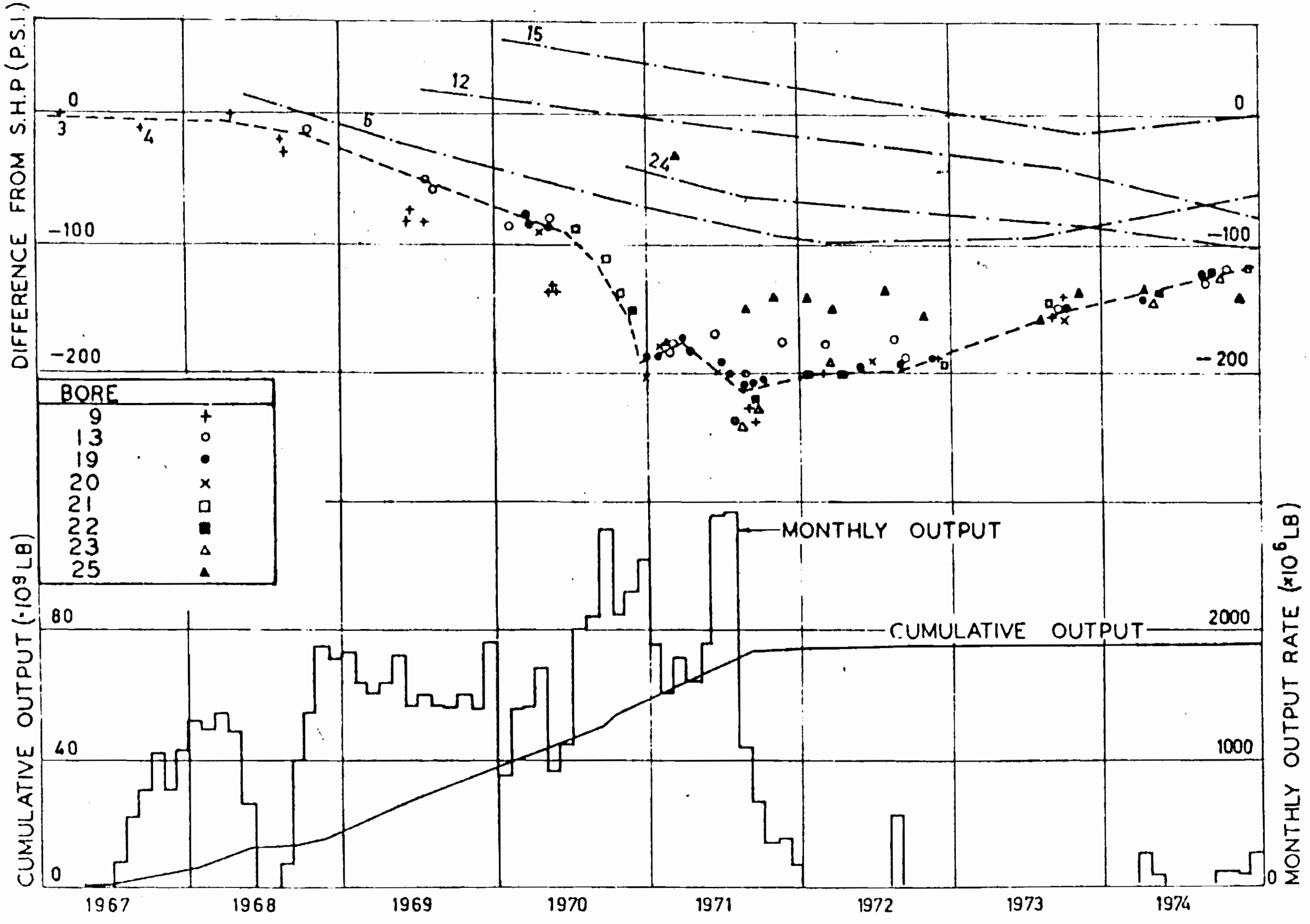


Fig. 5.9 Aquifer pressures and mass withdrawal 1967-1974 in the Broadlands field New Zealand.

From Hitchcock and Bixley 1976.

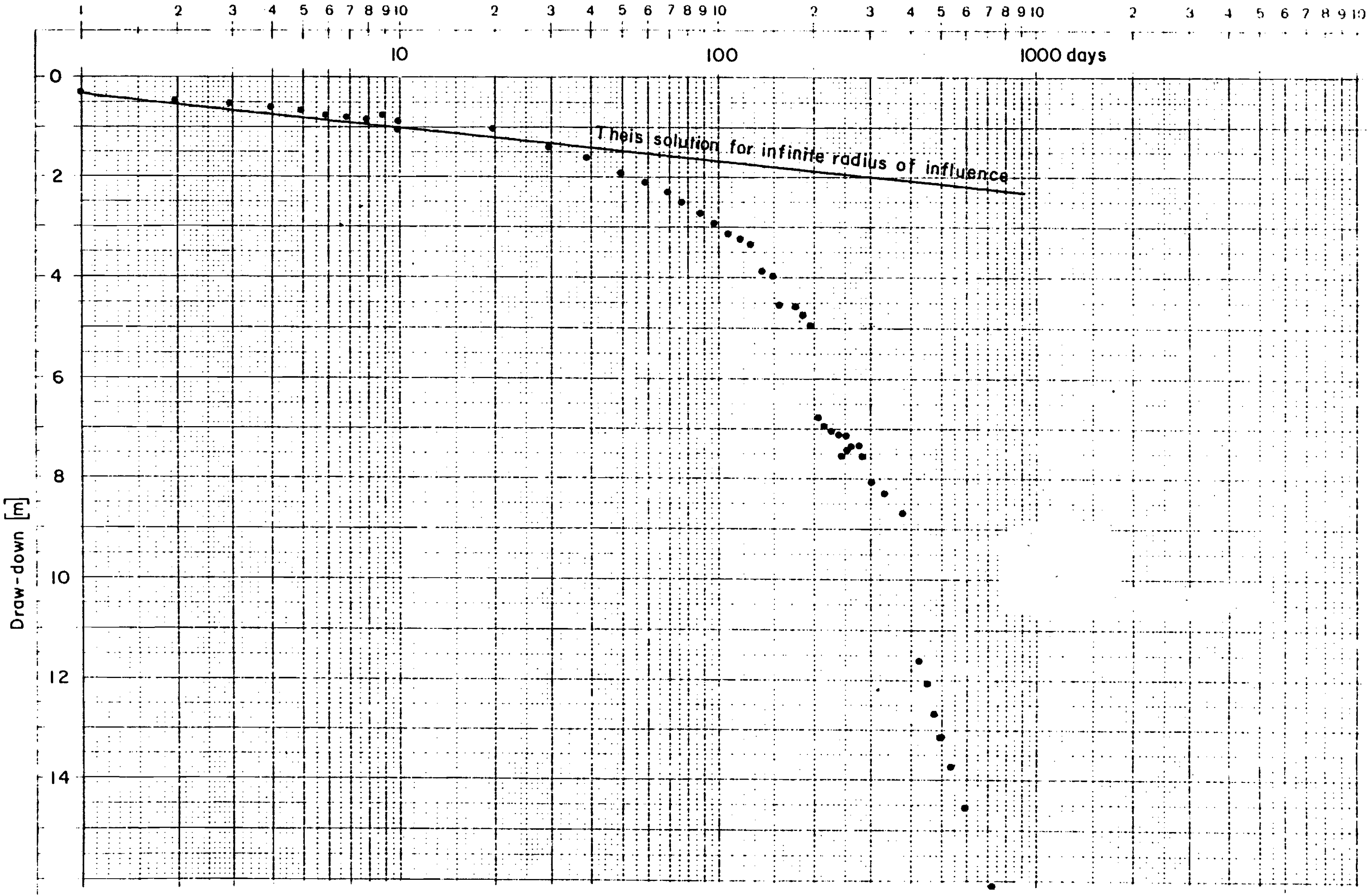


Fig. 5.10 The draw-down in the Svartsengi geothermal field, Icelan
during a mass withdrawal of ca 50 kg/s.
From Snorri Páll Kjaran et al. 1978.

6 LITHOLOGICAL LOGS

Logging methods which give information on physical or chemical properties of rock are here grouped under the name of lithological logs. This includes logs like natural gamma ray, gamma-gamma density, neutron-neutron porosity, resistivity and sonic velocity.

The lithological logging technique has been developed in the petroleum industry during the last fifty years or so, but has only recently been adopted into the geothermal logging family. Although this measuring technique can be transferred directly from petroleum wells to geothermal wells (at least if temperatures are kept below 150-200°C), the same will not apply to the methods of interpretation. The petrophysical properties of the predominantly igneous rocks in geothermal reservoirs, are usually different from those of the sedimentary rocks in oil fields (see Keys 1979). Geothermal well log analysts therefore need to develop a new interpretation technique for lithological logs instead of using the experience gained in the petroleum industry. This development will include things like core analysis plotted against deflection on logs, and crossplotting of different log responses for the same rock type; a job which geothermal well log analysts are just beginning to work on. In due time such work will hopefully result in interpretation techniques giving quantitative information comparable to information obtained from petroleum logs, but until then the application of lithological logs in geothermal investigation will be limited to qualitative uses.

In the following sections the qualitative information that can be gained from four lithological logging methods will be discussed briefly. To keep the material within reasonable limits the quantitative petroleum application of the logs is omitted.

The last section deals with combined uses of different logs, like crossplotting. This technique increases considerably the reliability of the information.

6.1 Geological logs

The point of reference in calibration of geophysical lithological logs is the analysis of geological units penetrated by drilling.

When a core is taken, a direct comparison can be made between geophysical logs and geological units and their chemical and physical characteristics. Geophysical logs have the advantage of measuring certain parameters in situ whereas much more detailed analysis can be done on the core (or the cuttings). In principle the common aim of borhole geology and geophysical logs is to achieve better understanding of the reservoir rock and fluid. Fig. 6.1 shows an example, where geological units found in wells are correlated to surface geology.

6.2 Natural gamma ray logs

As mentioned in Chapter 2 this log is sensitive to the radioactive isotopes within the rock. Three isotopes, ^{40}K, ^{238}U, and ^{232}Th, have been found to contribute most of the natural gamma ray emission in rock. In petroleum logging, the gamma ray log has been found to distinguish between shale and sandstone, which is of importance in sedimentary rock. Any interpretation method for igneous rock or especially young volcanic rock, as is common in geothermal logging, has not been proposed so far. Recent investigation in Iceland (Stefánsson & Emmerman 1980) shows, however, that the gamma ray radioactivity in Icelandic volcanic rock is related to the SiO_2 content in the rock. Geochemical evidence supports this correlation as the content of radioactive isotopes increases when going from basic to acidic igneous rock. In a geological environment like Iceland, where the rock is mainly tholeiitic basalt, the natural gamma ray log will generally show low gamma intensity with a few peaks due to more acid units in the formation pile. In back arc volcanic regions where the rock is generally acid, the gamma ray intensity is expected to be generally high with few minima due to more basic formations or waskout effects. In both cases the gamma ray log will be a valuable guide in interconnecting the different wells and in connecting the formations found in drillholes and on surface, in a similar way as is shown in fig. 6.1. This information, gained in geothermal logging, seems to be of similar importance as in petroleum logging.

6.3 Gamma-gamma density logs

The bulk density registered by the gamma-gamma log is an essential parameter of the reservoir rock. In contrast to sedimentary rock, the matrix density in volcanic rock is regarded as fairly constant. The variation in bulk density is therefore more dependent on porosity in volcanic rock than in sedimentary rock. Experiments done in Iceland indicate that most of the variations in gamma-gamma logs are due to porosity, and a comparison of gamma-gamma and neutron-neutron logs can reveal different geological formations.

As an example of a gamma-gamma log we show in fig. 6.2 a log from a geothermal well in the Raft River, Idaho. The depth interval 1734-1756 m has the density of approximately $3.0 \cdot 10^3$ kg/m^3 and has been interpreted as chlorite schist (Keys & Sullivan 1979).

6.4 Neutron-neutron porosity logs

The neutron-neutron log is sensitive to the density of the hydrogen nucleus in the proximity of the sonde. Water content of the formation is usually the major source of hydrogen, and the log is therefore frequently referred to as a porosity log. It should be pointed out, however, that the neutrons do not distinguish between protons which belong to formation water and water bound in minerals. This is of particular interest in geothermal logging, as hydrothermal alteration is a process of forming minerals with bound water. Furthermore, the water content of secondary minerals which form frequently in fissures in geothermal rock is often high.

The instrument function of a neutron-neutron log is logaritmic, i.e. the variation of porosity for nonporous rock is more easily registered than the variation in porous formations. It has therefore been demonstrated that fissures, totally filled with secondary minerals within a very dense basaltic instrusion can easily be detected by a neutron-neutron log.

The calibration standard for neutron-neutron logs used in petroleum logging is limestone porosity. This reference is of little interest to the geothermal community, but is used as a qualitative reference unit in geothermal logging.

6.5. Resistivity logs

The specific resistivity of the reservoir rock is the result of two different contributions, the resistivity of the rock matrix and the formation fluid.

An igneous rock matrix is generally a poor electrical conductor at geothermal temperatures, with typical specific resistivity values of the order of 10^4-10^6 ohmmeters. With medium conducting formation fluid like geothermal water (1-10 Ωm), the electrical properties of the fluid will define the resistivity of the reservoir rock. This value will therefore in general depend on the porosity as well as temperature and water salinity.

The knowledge of the resistivity of the reservoir rock is of great importance in geothermal investigation and the formation resistivity measured in wells is essential to control the interpretation of electrical survey data. Besides this resistivity logs are used for distinguishing between different rock units in geothermal wells.

In sedimentary rock several empirical relations between porosity and resistivity have been found. One of these is Archie's formula:

$$F = a \cdot \phi^{-m}$$

where

F = the formation factor = $\dfrac{\text{resistivity of formation}}{\text{resistivity of fluid}}$

a = constant,
found to be approximately 1 for sandstone

ϕ = porosity

m = constant,
found to be approximately 2 for sandstone

In geothermal logging, the reservoirs are generally fractured but not of the intergranular type as in petroleum logging. The geometric factors are therefore quite different from those in the petroleum industry, and could be expected to influence relations like Archie's formula.

To our knowledge, the relation between resistivity and porosity has only been determined in one well so far (Keller et al. 1974). The constants a and m in Archie's formula were then found to be the following:

$$F = 18 \cdot \phi^{-1.05}$$

6.6 Combined interpretation of lithological logs

The informational value of lithological logs can be improved considerably by comparing the response of different logs. For instance well effects caused by variation in well size can be distinguished and even corrected for in lithological logs by use of a caliper log.

Another example of a comparison technique is the cross-plot. It is an interpretation method developed and used in petroleum logging, and is a powerful tool in determining the different units of formation crossed by the well.

On cross-plots the responses of two or sometimes even three logs are plotted against each other. The locations of the measuring values on the plots determine the lithology. The three logs most frequently used are:

porosity (neutron), density (gamma) and sonic velocity.

The cross plot will then consist of different combinations of these logging parameters, one of which is shown in fig. 6.3. The application of cross-plots in oil well logging is a straight forward process and supported by great experience. The three most common formations in oil fields are, sandstone, limestone and shale, and the position of each of these formations in the cross-plots is well known to well log analysts, as figure 6.3 shows.

Application of cross-plots in interpreting geothermal well log data is still in a state of infancy. All future developments will include studies of rock types different from those of the petroleum industry, and even other logs have to be included, for instance the resistivity log. We have in fig. 6.4 indicated where we think that two different geothermal rock types should be placed in a cross-plot.

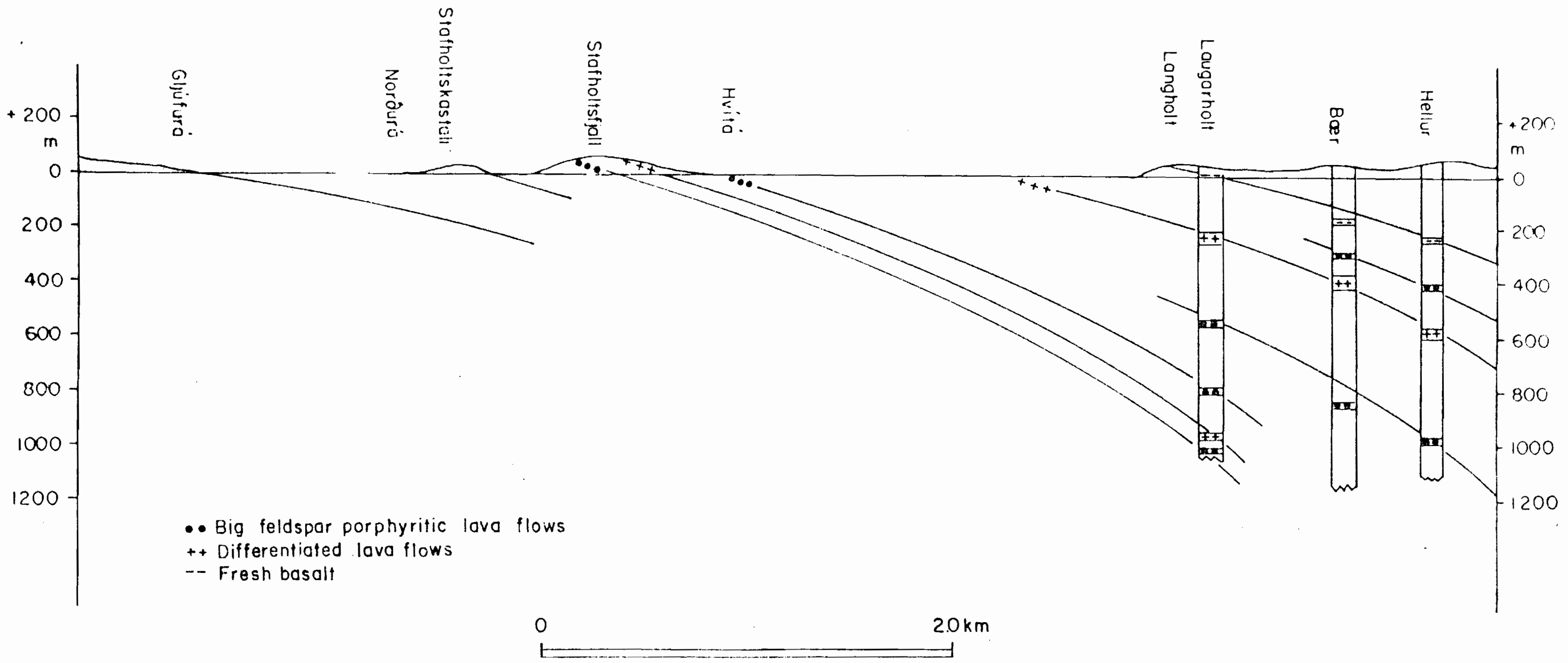


Fig. 6.1 Correlation between surface geology and geological units in borholes in Bær í Bæjarsveit, Iceland.

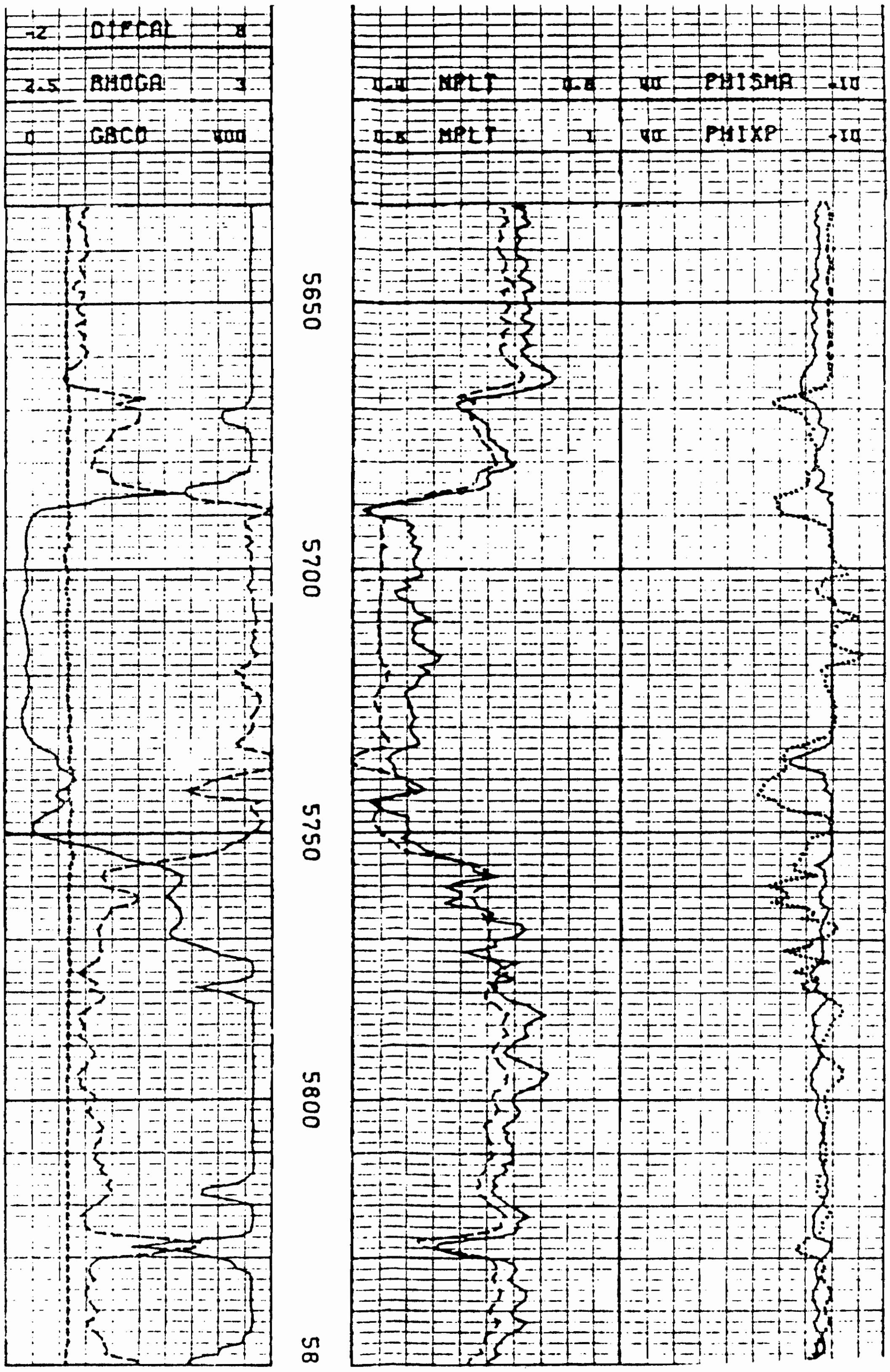
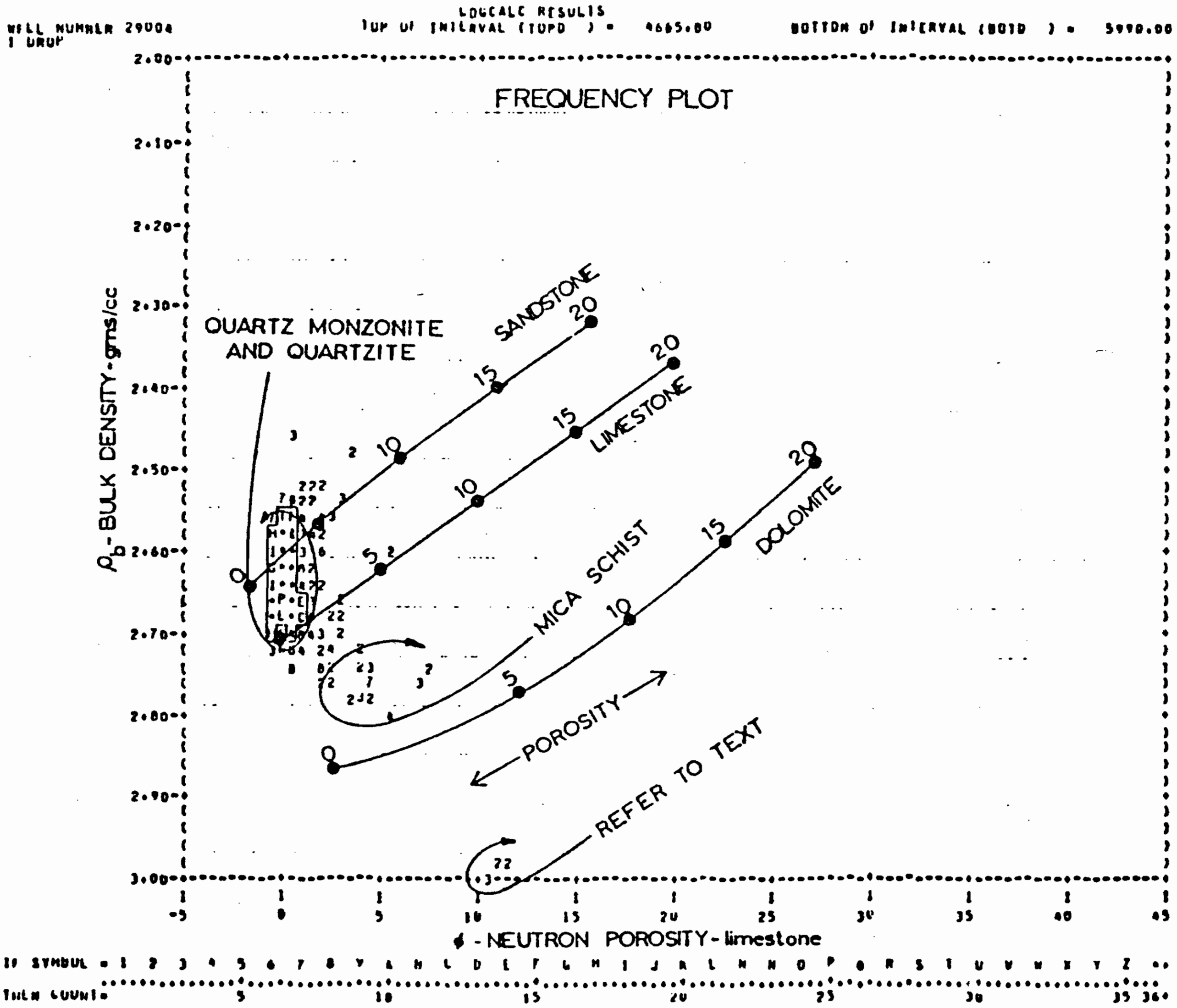


Fig. 6.2 Well RRGE-2, Raft River, U.S.A. Caliper, bulk density, gamma ray, M and N values, sonic porosity, cross-plot density neutron logs. From Sanyal et al. 1979.



<u>Fig. 6.3</u> Density-porosity cross-plot. Geothermal Test Hole GT-2, New Mexico, U.S.A.
From Sanyal et al. 1979.

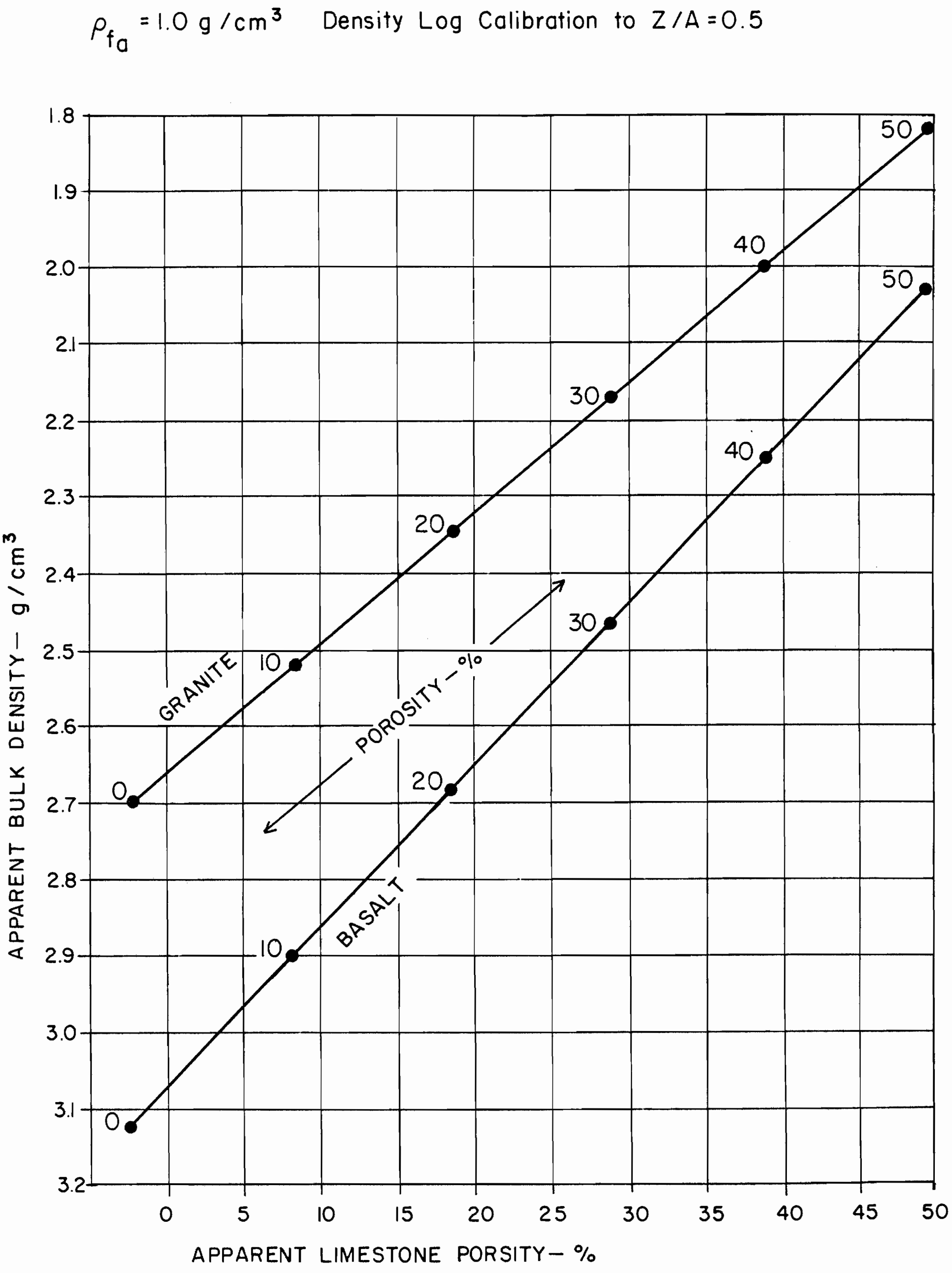


Fig. 6.4 Expected density-porosity cross-plot in volcanic rocks.

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APPENDIX

Companies selling logging instruments

Kuster Company
P.O. Box 7038
Long Beach, California 90807
U.S.A.

Temperature and pressure gauges, Sampling tool, Flowmeter Calibration Equipment (temp. and press.), Survey instruments

Creland Company
P.O. Box 20596
Long Beach, California 90801
U.S.A.

Spinner for Kuster or Amerada recorder

Geophysical Research Corp.
P.O. Box 6248
Tulsa, Oklahoma 74106
U.S.A.

Temperature and pressure gauges

Gearhart-Owen Industries Inc.
P.O. Box 1936
Forth Worth, Texas 76101
U.S.A.

Complete logging trucks with a wide range of logging tools

Prodelco Engineering Ltd.
Newmarket
Auckland
New Zealand

Klyen sampling tool