GEOCHEMICAL INTERPRETATION OF THE THERMAL FLUID FROM THE HRUNAMANNAHREPPUR LOW-TEMPERATURE AREA, ICELAND

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ABSTRACT

The Hrunamannahreppur low-temperature area is investigated using the chemical properties of the thermal water, and the result from the geochemistry with together other investigation used to delineate preliminary modal of the geothermal system.

Composition changes of the thermal fluid with time was considered for some of sampling spot and comparison between different samples made to characterized the chemistry of the thermal fluid.

The chemical composition of the water in surface discharge was used to evaluate subsurface temperatures, and the main upflow zones in the area are identified. The waters from spring shows a chemical characteristic intermediate between cold ground water and hot geothermal water, mixing of the hot water with cold water occurs in the upflow zones. The underground temperature at Flúðir and Reykjaból which are the two major up flow zone of the area, estimated to be of the order of 150°C-170°C. Further application of Silica-enthalpy mixing modal was used to estimate underground temperature of the hot unmixed geothermal water.

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1. INTRODUCTION

1.1. General background

1.1.1. Definition

The term geothermal refers to the internal thermal energy of the earth which is concentrated enough to form an energy resource. In this text however, the term geothermal energy is used rather loosely to refer to the potentially useful thermal energy stored in large rock masses as hot water or steam. A rock-water system were energy is sufficiently concentrated is called a geothermal system. In general a geothermal system consist of three main parts: (1) An energy source (in most case magma). (2) A large rock mass or a favorable geological environment (reservoir). (3) A working fluid (water or steam).

1.1.2. Geothermal exploration

Although there are many places in the world were the existence of a geothermal resource is expected, one can never be certain for the occurrence of the right geological, hydrological, and chemical conditions, without the proper exploration. However, in places which show favorable conditions, geothermal development must be preceded with detailed geological, geophysical and geochemical exploration to establish whether truly exploitable heat exist or not. Detailed investigation of this kind is performed to obtain a realistic model of the geothermal system.

The main objects of geothermal investigation can be summarized as:

-location of the geothermal area and identification of thermal manifestations with in the area

-quantitative evaluation of thermal energy associated with

the field (heat content, temperature, and discharge)

-qualitative evaluation of the discharge (dry steam or steam-water mixture)

-prediction of the futurity of the field (e.g life time, environmental effect, scaling problem and so on).

The role of geochemistry in geothermal exploration, development and utilization is summarized in Table 1 (from Arnórsson 1979., modified).

1.2. Description of the area

The Hrunamannahreppur low-temperature area lies in the northern part of the South lowlands of Iceland (Figure 1), within the South-Iceland low-temperature geothermal area. The area is located just east of the western active volcano zone.

Thermal springs with a hot water temperature ranging from 40°C to nearly boiling are abundant in the area. A numbers of hot water drillholes with average flow rate of 15 l/s are used. The utilization of geothermal water is mainly for greenhouses, gardening and district heating. In addition, there is a small scale industry, a wood drying kiln, that uses hot water for processing. Figure 2 shows the drillholes and nearby springs in the Flúðir farming village.

1.3. The object of the present paper

In addition to their physical properties, which are easily observed from their appearance, thermal fluids are characterized by their chemical composition which is greatly caused by the interaction of the hot fluid to the host rock. Thus, proper application of chemical methods to thermal fluids will give a better understanding of the origin of the

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fluid, and the processes that take place during the transportation of the fluid.

This paper present the project work of the author on the interpretation of the thermal fluid from Hrunamannahreppur low-temperature geothermal area based on chemical data of water samples. For this purpose 9 water samples were collected using appropriate methods. The method used during the collection of the samples are discussed later in this paper. In addition, data from the chemical laboratory at Orkustofnun for previous years were used as well to get a general idea of the geothermal system.

The hot water samples were analyzed using method discussed in section 3.2 and the results were interpreted to meet the following objectives.

1. To estimate subsurface temperatures.

2. To locate up flow zones within the geothermal field, and deduce direction of fluid flow within the field.

3. To evaluate mixing of hot water and cold water in up flow zones during the ascend of the hot geothermal water from depth to the surface as hot springs.

4. To characterized, as far as possible, reservoir water chemistry with respect to the intended utilization.

5. Together with the results of other investigation on the area (geology, and geophysics) to delineate a preliminary model of the geothermal system.

2. GEOLOGY

2.1. Geology of Iceland

The Mid-Atlantic ridge crosses Iceland from southwest to northeast. The neovolcanic zones in Iceland are the landward continuation of the ridge and are characterized by recent volcanism, seismic activity, graben structures, fissure swarms, rifting and high temperature geothermal area.

From detailed geological and geophysical study the crustal structure of Iceland is known. It is almost entirely formed of subarial Cenozoic basalts, with some 10% of acid and intermediate rocks. The crust is overlain be glacial sediments. Figure 3 shows a geological map of Iceland (Sæmundsson, 1979).

Deep drilling in Reykjavik, near Akureyri in northern Iceland, and Reydarfjördur in eastern Iceland has confirmed a minimum thickness of the lava pile about 4 km, and the oldest rock is about 16 m.y. old at the easter most and waster most part of the island. The volcanic pile of Iceland can be grouped in to four series based on climatic evidence from inter-lava sediment or volcanic breccias and on palaeomagnetic reversal patterns. The oldest formation is Tertiary over 3 m.y., then Pile-Pleistocene in the range of 0.7-3.1 m.y, Upper Pleistocene back to 0.7 m.y., and the fourth and youngest formation is Postglacial which cover the last 9000 to 13000 y.

About half of the total area of the country or approximately 50,000 km^2 are covered by Tertiary rocks, which is made up of subaerial tholeiitic lavas and genetically associated intermediate and acidic rocks. The remaining part of the country is covered by the remaining three groups as follow:

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1. Plio-Pleistocene, about 25.000 km^2, cover broad zones intermediate between the Tertiary areas and the neovolcanic zones.

2. Upper Pleistocene about 30.000 km^2 which coincide with the neovolcanic zone.

3. Postglacial formation cover about 10% of the country.

Hot springs are very abundant in the country as a result of high heat flow. High temperature areas, with base temperature >200°C, are situated within the active zones of rifting, whereas low temperature areas, with base temperature <150°C, are situated in the Plio-Pleistocene and Tertiary volcanics.

2.2. Geological framework of the area

The Hrunamannahreppur low-temperature area is located within the South Iceland low-temperature area just east of the western active volcanic zone in Quaternary basaltic lavas and hyaloclastites. The definition of a low temperature area is that the maximum temperature does not exceed 150°C at 1000 m depth. The lavas formed during interglacials of the Quaternary epoch whereas the hyaloclastite formations formed during the glacial periods in melt-water chambers within the ice-sheet (Stefánsson and Arnórsson, 1975).

The area is characterized by northeast-southwest faults, approximately parallel to the axis of the active volcanic zone. Experience has shown that only few of the numerous faults and dykes in Iceland are permeable. It is a good assumption that the dykes or the fractures are permeable if the hot water flow to the surface is along an exposed dyke or fissure (Flovenz and Georgsson, 1982). Intensive drilling in the low-temperature geothermal area of Iceland indicate that aquifers are mostly connected with some near vertical structures such as dykes, faults or fractures. Further, it is common that hot springs are found at the intersection between two such structures where one acts as an aquifer and the other as an aquiclude.

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3. SAMPLING AND CHEMICAL ANALYSIS OF THE THERMAL FLUID

3.1. Sampling

"The credibility and usefulness of
geochemical data depend on the method
used and the care taken in the collection
of samples. For this reason it is
recommended that geochemist undertake the
fieldwork. If the sampling conditions are
not well known, the significant of the
analytical work may not be fully
appreciated. A person without chemical
knowledge may contaminate samples during
collection, or volatile constituents may
be lost from samples by faulty handling.
It is also unrealistic to expect a
geochemist to take a detailed interest in
area with which he has had no practical
association."

As clearly indicated in the above quotation from Ellis and
Mahon (1977, page 163) the credibility and usefulness of all
the data from chemical analysis, and the meaningfulness of
their interpretation depend on the sampling conditions, and
sampling methods. Bearing this in mind 9 samples of
geothermal water were collected from hot springs and hot-
water drillholes. The sampling sites were selected with the
aim to cover all the area of interest. Figure 4 shows the
sampling spots for the both new and old samples.

3.1.1. Collection of thermal waters

During the collection of water samples in the field a
complete record of the sampling conditions was recorded. For
this purpose a convenient field record card was used
(Appendix I). Description of sampling methods are give by
Olafsson (1987). To get a representative sample from the hot

spring a funnel connected to a silicone tubing was submerged into the water. The tubing was fitted to a cooling coil of stainless steel placed in a bucket of cold water. The water from the spring was flown through the tubing and the cooling coil, making sure that the far end of the coil was at a lower level than the water level in the spring so that gravity flow would be established. For one spring (Hrunalaug) a water pump was used since the water level of the spring is too low to established gravity flow.

First a water sampling bulb, which had been rinsed thoroughly, was filled with cooled water (about 20°C) and the flow was maintained through the tube for a few minutes so that the water in the bulb, which was to be analyzed for CO_2, pH, and H_2S, should not come into contact with the atmosphere. Then, untreated triplet samples were collected for SiO_2 analysis into 100 ml polyethylene bottles. Samples which are expected to have SiO_2 concentration higher than 100 ppm were diluted to have SiO_2 concentration in the range of 30 to 100 ppm and the dilution factor was marked on the bottle. Then 500 ml polyethylene bottle was filled with filtered and untreated sample and labeled as Fu. Next, 2 ml of 6N HCl were added into 1000 ml volumetric flask and the flask filled to the mark with filtered sample, and it transferred to 500 ml bottles and labelled Fa. Next 10 ml of 0.2 Zn(CH3COO) solution were added to a 500 ml volumetric flask and it filled to the mark with filtered sample, and the sample transferred to a 500 ml polyethylene bottle and labelled Fp. And finally filtered sample was collected in 100 ml polyethylene bottle for isotopes.

The samples from the hot water drillholes were collected in the same way except that the silicone tubing was connected to the sampling point of the drillholes.

3.2. Analytical procedures

The analysis of the volatile constituents such as CO_2, H2S, and pH were done within 24 hours of sampling. The analytical method which was used for samples collected by the author are summarized as follow.

Total carbonate as CO_2 was measured by titration with 0.1N HCl using a pH-meter from pH 8.2 to 3.8 pH was adjusted to 8.2 with NaOH or HCl solution.

H2S was determined by titration with 0.001 $Hg(CH_3COO)_2$ solution.

pH was measured by a pH-meter with a glass electrode.

Na, K, Ca, and Mg were measured by atomic absorption spectrophotometric methods.

Cl and SO_4 were measured by ion chromatography.

F was measured by an ion sensitive electrode.

SiO_2 was measured spectrophotometrically as yellow silicomolybdate complex or reduced to molybdenum blue complex.

Fe was measured by a spectrophotometer.

4. APPLICATION OF THE COMPUTER PROGRAMME

A computer programme by Arnórsson, et al. (1982) was used to calculate the composition and aqueous speciation of the geothermal reservoir waters including pH, redox potential and gas partial pressures. The input and the output data of the programme are shown in Appendix 2.

The programme is presented as "WATCH1" and "WATCH3". The WATCH1 programme can be used for chemical analyses of water and steam from wet-steam wells. Whereas the WATCH3 programme is used for water from boiling hot springs and drillholes or springs and drillholes were the water has not boiled. For the water from the Hrunamannahreppur area WATCH3 was used for calculations. In this case it was assumed that there had been no loss of steam from the water prior to sampling.

5. GEOCHEMISTRY OF THE WATER

5.1. Previous geochemical work on the area

Based on geochemical methods Arnórsson (1970) proposed an over all picture of the geothermal area on the eastern side of the volcanic zone in SW-Iceland. In addition, a regional investigation of low-temperature in the area has been in progress for several years. Arnórsson (1970) and Stefánsson and Arnórsson (1975) distinguished three hydrothermal systems within the area based on the Cl/B ratio in the thermal water. Figure 5 shows the three above mentioned hydrothermal systems from Stefánsson and Arnórsson (1975).

Furthermore, a rather comprehensive picture of the area has been achieved by extensive geological, geochemical, and geophysical survey since 1970. The results from these investigations strengthen the model proposed by Arnórsson (1970), and demonstrates how the characteristics of a geothermal reservoir can be revealed by inexpensive surface exploration methods.

5.2. Chemical characteristics of the geothermal water

The composition of geothermal water depend on many factors. Temperature dependent reactions between host rock and water is one of the major factors. Leaching plays a big role when the amount of a particular constituent is too small to achieve equilibrium. However, a process like mixing, boiling, and cooling have a pronounce influence on the final composition of the geothermal water.

The chemical composition of the geothermal waters from the Hrunamannahreppur area sampled by the present author is given in Table 2.

Data from the chemical laboratory at Orkustofnun has been made available for this report. Some of that data is

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incomplete and have only been analyzed for CO_2, H2S, pH and SiO_2, and some of the samples were collected with different purpose in mind. It is impossible to study the compositional changes of the water with time, since there is no well monitored spring or drillhole in the area. However, it was tried to look at some time-dependent changes, for a few of the sampling locations. These sites are, Flúðir well 4, Vadmalahver, Reykjarbol well 1, and Reykjarbol hver. Different chemical components versus time were plotted for comparison (Figure 6 to 12).

The water from those places show variation in composition with time, however the variation is not constant for all constituent. But in general sulphate (SO_4), and silica (SiO_2) decrease with time, whereas calcium (Ca), total carbonate (CO_2), pH, sodium (Na), and chloride (Cl) increase with time.

In general the water in the Hrunamannahreppur area is low in carbonate, hydrogen sulphide, fluoride, and chloride with pH in the range between 8.3-9.5. The major cation is sodium and sulphate is the dominant anion.

Stefánsson and Arnórsson (1975) described that the hydrogen sulphide content of boiling springs in the low temperature area tend to be in the range of 1 to 2 ppm and lower in cooler springs. With the exception of the Reykjabol Hver, the hydrogen sulphide content of all the springs are in the range of 1-2 ppm and no detectable hydrogen sulphide was found in the Hrunalaug sample.

In general the waters from springs and drillholes in this area posses chemical composition typical for low-temperature area in Iceland, except the sample from Reykjabol Hver. Hydrogen sulphide content of this spring indicates high temperature activity rather than low-temperature activity. It seems that the origin of the water for this particular spring might be from a hidden high temperature source.

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6. ESTIMATION OF SUBSURFACE TEMPERATURE

The estimation of subsurface temperature of the geothermal fluid is one of the major application of geochemistry in geothermal exploration. A number of geothermometers are available for this purpose and they rely on the temperature dependence of the concentration of certain constituents in the thermal water Arnórsson et al. (1983b). For a particular temperature dependent chemical equilibrium to be of use as a geothermometer it is essential for the reaction rate to be sufficiently slow. The application of chemical geothermometry to geothermal water is based on the following assumptions (Fournier, 1977):

1. Temperature dependent reactions involving rock and water fix the amount or amounts of dissolved "indicator" constituents in the water.
2. There is a adequate supply of all the reactants.
3. There is equilibrium in the reservoir or aquifer with respect to the specific indicator reaction.
4. No re-equilibrium of the "indicator" constituents occurs after the water leaves the reservoir.
5. No mixing of different waters occurs during ascend to the surface or an evaluation of the results of such a mixing is possible.

As mentioned above it is necessary for a particular constituent to be used as a geothermometer that it has come to equilibrium with a certain mineral. But the attainment of equilibrium in the reservoir will depend on a number of factors, such as the nature of the host rock, the temperature of the reservoir, the residence time of the water in the reservoir at particular temperature, kinetics of the particular reaction, and the concentration of the indicator elements in the water. However, all other factors being equal, geothermal systems situated in low chloride rocks are expected to be closest to chemical equilibrium (Arnórsson et al. 1983a).

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6.1. Solution geothermometer

The silica temperature is the temperature at equilibrium between chalcedony or quartz and the unionized silica in the thermal water. It is used to determine the minimum underground water temperature. Experience shows that temperature from chalcedony equilibrium is more reliable for low-temperature waters than quartz. In Icelandic geothermal waters equilibrium is attained between dissolved silica and quartz at temperatures higher than 180°C and with chalcedony at temperature below 180°C (Arnórsson, 1975).

The silica temperature for the thermal fluid in the Hrunamannahreppur area give a value in the range of 80-170°C for quartz and 60-140°C for chalcedony equilibrium. And the silica temperature tend to be 0-45°C higher than the measured temperature in both springs and drillholes. Furthermore, the silica geothermometers indicate high subsurface temperatures for the thermal spring and drillholes in the Flúðir and Reykjaból areas, which clearly indicates of the main upflow zones in the area. However, some warm spring waters around the major upflow zones (i.e. Hrunalaug, and Skipholt) are considered to have formed by mixing of thermal water with cold ground or surface water to a considerable extent, which complicate the interpretation of the silica temperatures.

Results from geothermometry show that some cooling takes place in the up-flow zones. The cooling is either by conduction or flashing so silica temperatures give an idea of subsurface temperature conditions below the zone of flashing and conducting cooling.

Subsurface temperature estimated from Na-K geothermometer yield values which give the same overall pictures as the silica geothermometer. Discrepancy are observed between the two geothermometers in springs with relatively low water temperatures. For most of the springs the Na-K geothermometer

tends to give a relatively higher value than the silica geothermometer.

In general, the Na-K geothermometer show greater deviation from the measured temperature in springs than dose the silica geothermometer. The Na-K geothermometer tends to give too high underground temperatures for mixed water. However, waters which have not equilibrated also show similar characteristics. So, in addition to mixing, equilibrium may not be reached at low temperatures of these springs and the water is likely to be high in potassium due to the relatively high mobility of this element in the soil (many of the warm springs appear in peat soil).

Na-K-Ca geothermometer from Fournier and Truesdell (1973) was used to calculate subsurface temperature. The estimated temperatures from all the geothermometers are listed in Table 8 for comparison. Underground temperature from Na-K-Ca geothermometer is unreliable for mixed water, since dilution will have an effect upon the Na-K-Ca geothermometer because the square root of the concentration is involved in the calculation. However, the use of different geothermometers have an advantage for comparison. In addition to this a process like mixing, mineral water equilibrium, and leaching can be evaluated with the help of different geothermometers.

In general Na-K-Ca geothermometer yield low values in the case of boiling springs, however it tends to give a little higher values than chalcedony equilibrium temperature when the silica temperature is over 100°C.

7. EVALUATION OF THE PROCESSES THAT TAKE PLACE IN THE UP-FLOW ZONES

7.1. Controlling factors for the final chemical composition of the thermal water

When a geothermal water ascends from depth to the surface the water can be cooled on the way, either by conduction, or mixing. Therefor the chemistry of the thermal water may be changed. However, those are only two of the number of factors which can affect the chemical composition of the thermal water. Figure 13 shows the change in concentration as a function of temperature under different condition.

One can see from this figure that dilution with groundwater and steam condensation lead to a decrease in the concentration of various elements, whereas boiling and heating leads to an increase in concentration. The dotted line shows the limit where precipitation occurs. When a solution that suffered from conducting cooling reach this limit the chemical concentration of the water will tend to decreases. Yet conductive heating does not show an influence on the composition. However, those processes are more complicated in natural condition, where the composition can be affected by any combination of those mentioned processes.

7.2. Chemical characteristic of mixed water

Water formed by mixing of geothermal water and cold ground or surface water possesses many chemical characteristics which serve to distinguish it from unmixed geothermal water (Arnórsson, 1985).

Unmixed geothermal water have a characteristic chemical composition which is controlled by equilibrium conditions between certain dissolved elements in the water and minerals in the rock. However, kinetics of the leaching process control the composition of cold ground or surface water.

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Thus, waters formed by mixing of these two types of water tend to have a chemical characteristic in between those two. As was mentioned in section 7.1 mixing is one of the factors that affect the chemical composition of thermal water. So, there is a possibility to change the final composition of the spring discharge caused by other factors depending on the conditions after mixing.

The chemical characteristics of mixed water which can be used as evidence for mixing were discussed by Fournier (1981) and Arnórsson (1985). Some of these can be summarized as follows:

1. Relatively high concentrations of silica in relation to discharge temperature.
2. Low pH relative to the water salinity.
3. Cool springs with large mass flow rates and relatively high estimated subsurface temperature by chemical geothermometers.
4. Variation in oxygen and hydrogen isotopes.
5. Relatively high estimated temperature by gas ratio (CO_2/H2S) geothermometers compared to gas geothermometers.
6. The tendency of calcite under saturation and low calcium/proton activity ratio compared to geothermal water.

7.3. Mixing characteristic of the geothermal waters from the area

Section 7.2 discussed the chemical characteristics of mixed waters that can be used as evidence of mixing. In this section the thermal waters from Hrunamannahreppur geothermal field are examined in order to demonstrate if they were formed by mixing or not. For this purpose some of the characteristics that were mentioned in section 7.2 were used as evidence, or in other words if the thermal waters have some of these characteristic it is assumed that mixing had occurred.

Figure 14 shows the state of calcite saturation for waters

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from Hrunamannahreppur geothermal area. As can be seen from this figure, almost all the waters are slightly undersaturated with respect to the saturation curve for equilibrated waters according to Arnórsson et al. (1983b). The mixing nature of some of the waters here shown by their affinities towards cold water, whereas some of the water approach equilibrium conditions. However, no water show supersaturation except water from Húsatoftir drillhole 6 which is more saline and has much higher concentration of calcium than other samples in the present investigation. The possible explanation for undersaturation with respect to calcite is that waters from the spring are mixed with cold ground water during ascending from the depth to the surface.

Arnórsson (1985) described that the relationships between chloride and silica, and chloride and sulphate could be used to quantified mixing. Figures 15 and 16 shows the relationships between chloride and silica, and chloride sulphate respectively. The thermal water show nearly-linear relationship in both cases. Thus the chloride and silica, and chloride and sulphate relationships of the waters in the area are taken as a strong evidence for the mixing nature of the thermal water. Furthermore Arnórsson (1985) gave an explanation for high sulphate content of the waters by assuming oxidation of sulphide to sulphate by atmospheric oxygen in the cold water, which is mixed with the hot geothermal water. Sulphate is in general high in these waters and is the dominant anion. Moreover, the state of anhydride saturation (Figure 17) shows that all the waters are highly undersaturate with respect to anhydride at depth. Therefore the assumption for high sulphate content of the waters due to mixing is more reasonable.

7.4. Isotopic chemistry

Oxygen and hydrogen isotopic composition of a thermal water can be used to evaluate mixing and to identify the origin of the water (Arnórsson, 1976). However, isotopic data for the

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samples from previous years is not available and only four of the present samples have been analyzed for oxygen and hydrogen isotopes.

Figure 18 shows a plot of δD versus δO-18, for samples from Reykjarbol hver, Husatoftir well 6, Flúðir well 4 and Flúðir well 6. The concentration of these four points at one place is a clear indication of that the origin of all the water is same. Specially the two points the sampling spot from Flúðir well 4 and well 6 are almost overlap.

A good relation between chloride concentration and δO-18 is considered to reflect mixing (Arnónsson 1985). A plot of chloride concentration versus δO-18 for the above mentioned sampling point shows a good linear relation (Figure 19).

7.5. Mixing model

Since water in many hot springs in the area found to be a mixture of deep hot geothermal water and shallow cold water the use of mixing models is necessary. There is also a possibility of partial or complete chemical equilibrium after mixing. If chemical equilibrium is established after mixing, the chemical geothermometers indicate the temperature at the final equilibrium or the temperature of mixed water.

The mixing models which are used here to estimate the temperature of the deep hot geothermal water is based on the silica content and the measured temperature of the spring (used to calculate the enthalpy of the water). Figure 20 and 21 shows dissolved silica-enthalpy graph in order to determine the temperature of hot-water component with respect to quartz and chalcedony solubilities. It is assumed that no further solution or deposition of silica has occurred before or after mixing.

The measured temperature and the silica content of a river from the area is taken as the composition of the cold-water

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component. And it is assumed that no loss of heat, nor steam formation occurs after mixing and that no steam loss occurred before mixing.

The temperature of the deep geothermal hot water component is found to be 211°C and 166°C with quartz and chalcedony solubilities respectively. These temperature, specially with solubility of quartz, are higher than those of estimated by geothermometer and encountered by drilling, but it was mentioned previously that low temperature geothermal water is expected to be in equilibrium with chalcedony but not quartz. In other words, the mixing model based on the chalcedony solubility is more reliable for this geothermal system. Figure 22 shows the downhole measured temperature fore Reykjaból well 1, which is the hottest drillhole in the area. This indicates most likely that the deep hot water is relatively concentrated in SiO_2 and the shallow water (from the river) is very diluted.

Further investigation of the mixing models show that all springs from the area can be grouped into two groups based on their extent of mixing. As clearly observed from the model some of the springs lie near to the cold water component, which is shown by their high concentration of the cold ground water. Others with high composition of hot deep geothermal water lie near the up-flow of hot geothermal water. Although most of the springs in the upflow zones have high concentration of the hot water, there are some springs with high concentration of the cold surface water (eg. Hrunalaug from Flúðir and Skipholt from Reykjaból).

In general the mixing is more dominated as we go further away the upflow zones.

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8. A TENTATIVE MODEL OF THE GEOTHERMAL SYSTEM

"A preliminary model should be laid out based on the geochemical data and their interpretation. The model effectively summarizes the geochemical results used to site wells and should, of course, be incorporated with the results of other surveys into one model." Arnórsson 1979.

The results from geochemistry together with the results of other investigations and previous work in the area is used to get a tentative model of the geothermal system.

Figure 23 shows the silica temperature isolines for the Hrunamannahreppur area. As can be seen from this figure the two relatively high temperature isoline are located near Flúðir and Reykjaból. Experience shows that such anomalies indicate the major upflow zones. The electrical resistivity at 500 m depth (Figure 24) is used to compare the result from electrical resistivity survey with the geochemical results. In Figure 25 the result from the geochemical investigation is drawn together with the true resistivity at 500 depth. This figure makes it possible it to compared the results of the two exploration method easily.

As is clearly seen from Figure 25 the highest silica temperature isolines coincide with low resistivity (<20 Ωm) in the bedrock. The agreement between the two investigation strengthen the results of the geochemical methods. Further it can be observed that most of the natural out-put of the springs is near the boundary to the high resistivity (which coincides with Cl/B boundary of hydrothermal systems by Stefánsson and Arnórnsson 1975). A possible explanation was give by Stefánsson and Arnórnsson (1975), that on the boundaries there are some kind of impermeable walls which bring the thermal water to the surface. This hypothesis is particularly agreed with by the results from present investigation.

Further investigation of the resistivity results show SW-NE structural trend dominated the geology. These SW-NE geological structures are in agreement with the overall resistivity data in the area. However, the work of Björnsson and Einarsson (1974) proposed an E-W transform faults.

To summarized the above results, the thermal waters that are possibly transported by the help of E-W transform faults to the surface as hot springs with the help of some kind of impermeable walls which are more likely parallel to the NE-SW geological structure. Figure 23 shows this hypothetical model.

It also evident, that most of the waters in the area are a mixture of hot geothermal fluid and cold ground water.

9. CONCLUSION

1. In general the waters both in the thermal springs and drillholes from the Hrunamannahreppur geothermal area show homogeneity in the chemical composition of all the major chemical constituent and have a chemical characteristic typical of low-temperature areas in Iceland. Sulphide and chloride are the dominant anions and sodium is the dominant cation of the water. The waters have pH in the range of 8.3-9.5.

2. The chemical geothermometers which have been used to estimate the subsurface temperature of the geothermal water give an overall picture of the area. However, because of the mixed nature of the water, discrepancy between different geothermometers are observed.

3. The two major upflow zones in the area are found to be at Flúðir and Reykjaból. The deep geothermal water underlying these areas is believed to have silica concentration about 275 ppm with temperature in the range of 150-170°C.

4. The waters in the area are under saturated with respect to calcite, and highly undersaturated with respect to anhydride at depth. Furthermore a linear relationships between chloride and silica, and chloride and sulphate is observed. In general most of the waters in the area are mixtures of cold ground or surface water and hot geothermal water.

5. The silica-ethalpy mixing modal shows that the hot water component of the mixed geothermal water have temperature in the range of 160°C.

6. The results from the geochemical investigation is in agreement with the results of other investigation (geophysics, and geology).

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10. RECOMMENDATION

The following recommendations based of the present work are considered valuable for further investigation on the area.

1. In order to get a representative sample from the drillholes, a sampling valves should be installed on the drillholes.

2. Additional elements such as, lithium, rubidium, boron, and aluminum should be analyzed. This could improve interpretation of water mineral equilibrium study.

3. The Hrunamannahreppur geothermal area is a typical low-temperature area so drilling for high temperature fluid is not promising within this geothermal field.

4. To get relatively good and productive drillholes the future drilling sites should be located within the high temperature anomalies indicated by the silica isolines.

ACKNOWLEDGMENTS

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APPENDIX 1

Summary of sampling and data gathered (Ólafsson, M. ,1987)

A field-record card.



A lab-record card for chemical analyses.

COLLECTION OF HOT WATER

The necessary apparatus

Funnel, rubber hoses and connectors
Cooling device
Water sampling bulbs
Polyethylene bottles for samples (100ml and 500 ml)
Pump
Filtering apparatus
Thermometer
Pipettes
Distilled water
500 ml volumetric flask
Hydrochloric acid (6N HCl)
Field record card and a permanent marker

SÖFNUN Á HEITU VATNI
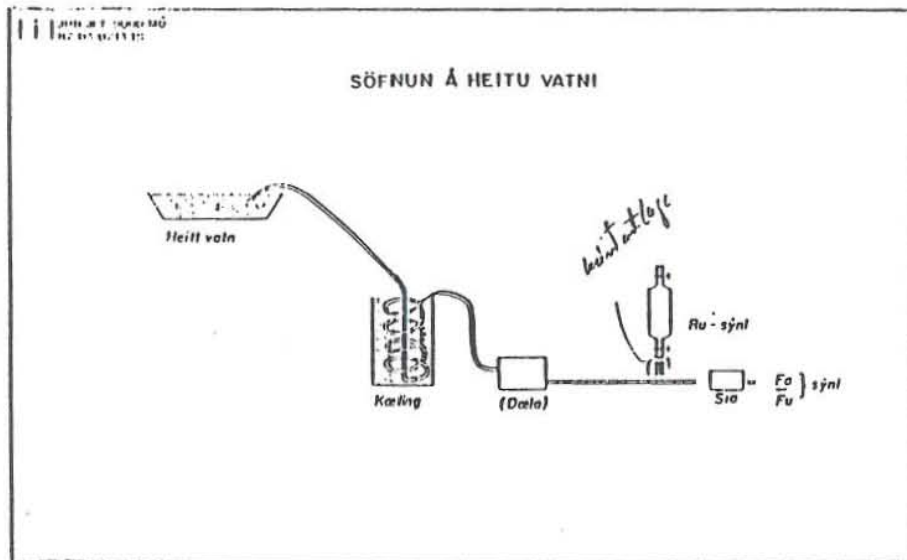
SAMPLES AND DATA GATHERED

The following abbreviations are employed to describe various treatments of the samples. The sample containers are labeled accordingly:

    Ru: raw material, untreated
    Rb: raw but base added (note amount of base)
    Rd: raw but diluted (note dilution)

    Fu: filtered, untreated
    Fp: filtered and precipitated (note amount of
        $Zn(CH_3COO)_2$)
    Fa: filtered and acidified (note amount of HCl)

Notice: Before sampling, always rinse the sample containers three times with the fluid to be sampled.

Water: One sampling bulb, cooled to approx. 20°C
                One 500 ml sample untreated in polyethylene
                bottle
                Two 499 ml samples + 1 ml 6N HCl in each
                One 490 ml sample + 10 ml $Zn(CH_3COO)_2$

APPENDIX 2

Samples of the input and output data of the programme "WATCH3"

DATA FOR THE "WATCH3" PROGRAM

Computer term	Format
SAMPLE	28A1
TEXT	80A1
DISCHA,TEMPME,PHM,PHTEMP,RES,TRES	10F8.0
ESI,ENA,EK,ECA,EMG,ECO2,ESO4	10F8.0
EH2S,ECL,EF,XUPPL,EAL,EB,EFE,ENH3	10F8.0
CHEMO1	22A1
CHEMO2	22A1
CHEMO3	22A1
TRUN,TINPUT,SSTEMP,AKF,AKFS,EHPOT,TEHPOT	10F8.0
NB,BOTEMP(1), ...,BOTEMP(10) NB frequency of BOTEMP	I2,10F7.0
NC,COTEMP(1), ...,COTEMP(10) NC frequency of COTEMP	I2,10F7.0
NAQ (within the range of 0-11)	I4
DEPTH(1),DHTEMP(1),AQUIFE(1) NAQ number of lines	10F8.0
. . .	.
DEPTH(NAQ), DHTEMP(NAQ),AQUIFE(NAQ)	10F8.0

Example of Input Data Sheet

```
0,8706180055
VADMALAHVER - GARUR/HVAMMUR.
0,98.5,9.29,23.8,0,0
145.4,81.43,2.74,1.52,0,47.1,55.02
1.1,23.43,0,0,0,0,0,0


2,0,999,1,1,0,0
0,0
0,0
```

UNU Geothermal Training Programme   FLUDIR

```
=================================================================================
8706180055                    VADHALAHVER - GARUR/HVAMMUR.

PROGRAM WATCH2.

WATER SAMPLE (PPM)          STEAM SAMPLE
```

	WATER SAMPLE (PPM)		STEAM SAMPLE				
PH/DEG.C	9.29/23.8	GAS (VOL.%)		REFERENCE TEMP.	DEGREES C	.0 (CHA)	
SIO2	145.40	CO2					
NA	81.43	H2S		SAMPLING PRESSURE	BARS ABS.		
K	2.74	H2		DISCHARGE ENTHALPY	MJOUL/KG		
CA	1.52	O2		DISCHARGE	KG/SEC.	.0	
MG	.000	CH4					
CO2	47.10	N2		MEASURED TEMPERATURE DEGREES C		98.5	
SO4	55.02			RESISTIVITY/TEMP.	OHMM/DEG.C	.0/	.0
H2S	1.10			EH/TEMP.	MV/DEG.C	.000/	.0
CL	23.43						
F	.00	LITERS GAS PER KG					
DISS.SOLIDS	.00	CONDENSATE/DEG.C		MEASURED DOWNHOLE TEMP.	FLUID INFLOW		
AL	.0000			DEGREES C/METERS	DEPTH (METERS)		
B	.0000						
FE	.0000	CONDENSATE (PPM)		.0	.0	.0	
NH3	.0000	PH/DEG.C		.0	.0	.0	
		CO2		.0	.0	.0	
		H2S		.0	.0	.0	
		NA		.0	.0	.0	
				.0	.0	.0	
				.0	.0	.0	
				.0	.0	.0	
		CONDENSATE WITH NAOH (PPM)		.0	.0	.0	
		CO2		.0	.0	.0	
		H2S		.0	.0	.0	

```
IONIC STRENGTH =  .00428    IONIC BALANCE :  CATIONS (MOL.EQ.) .00365723
                                            ANIONS  (MOL.EQ.) .00348828
                                            DIFFERENCE  (%)    4.73
```

DEEP WATER (PPM)				DEEP STEAM (PPM)		GAS PRESSURES (BARS ABS.)	
SIO2	145.41	CO2	47.10	CO2	.00	CO2	.225E-02
NA	81.43	H2S	1.10	H2S	.00	H2S	.288E-04
K	2.74	H2	.00	H2	.00	H2	.000E+00
CA	1.52	O2	.00	O2	.00	O2	.000E+00
MG	.000	CH4	.00	CH4	.00	CH4	.000E+00
SO4	55.02	N2	.00	N2	.00	N2	.000E+00
CL	23.43	NH3	.00	NH3	.00	NH3	.000E+00
F	.00					H2O	.185E+01
DISS.S.	.00					TOTAL	.185E+01
AL	.0000						
B	.0000			H2O (%)	.00		
FE	.0000			BOILING PORTION	.00		

SAMPLE = 8706180055

===

ACTIVITY COEFFICIENTS IN DEEP WATER

H+	.925	KSO4-	.919	FE++	.718	FECL+	.917
OH-	.916	F-	.916	FE+++	.495	AL+++	.495
H3SIO4-	.917	CL-	.915	FEOH+	.919	ALOH++	.715
H2SIO4--	.715	NA+	.917	FE(OH)3-	.919	AL(OH)2+	.919
H2PO3-	.915	K+	.915	FR(OH)4--	.713	AL(OH)4-	.318
HCO3-	.917	CA++	.718	FEOH++	.713	ALSO4+	.918
CO3--	.711	MG++	.727	FE(OH)2+	.919	AL(SO4)2-	.918
HS-	.916	CAHCO3+	.920	FR(OH)4-	.919	ALF++	.715
S--	.713	MGHCO3+	.917	FESO4+	.919	ALF2+	.919
HSO4-	.918	CAOH+	.920	FECL++	.713	ALF4-	.918
SO4--	.708	MGOH+	.921	FECL2+	.919	ALF5--	.711
NASO4-	.919	NH4+	.915	FECL4-	.917	ALF6---	.464

CHEMICAL COMPONENTS IN DEEP WATER (PPM AND LOG MOLE)

H+ (ACT.)	.00	-8.175	MG++	.00	.000	FE(OH)3	.00	.000
OH-	2.76	-3.789	NACL	.03	-6.224	FE(OH)4-	.00	.000
H4SIO4	189.05	-2.706	KCL	.00	-8.362	FECL+	.00	.000
H3SIO4-	41.44	-3.361	NASO4-	.89	-5.124	FECL2	.00	.000
H2SIO4--	.09	-6.019	KSO4-	.10	-6.152	FECL++	.00	.000
NAH3SIO4	1.94	-4.785	CASO4	.48	-5.450	FECL2+	.00	.000
H3BO3	.00	.000	MGSO4	.00	.000	FECL3	.00	.000
H2BO3-	.00	.000	CACO3	.32	-5.497	FECL4-	.00	.000
H2CO3	1.21	-4.712	MGCO3	.00	.000	FESO4	.00	.000
HCO3-	62.36	-2.986	CAHCO3+	.27	-5.579	FESO4+	.00	.000
CO3--	.79	-4.879	MGHCO3+	.00	.000	AL+++	.00	.000
H2S	.03	-6.131	CAOH+	.01	-6.805	ALOH++	.00	.000
HS-	1.04	-4.501	MGOH+	.00	.000	AL(OH)2+	.00	.000
S--	.00	-12.116	NH4OH	.00	.000	AL(OH)3	.00	.000
H2SO4	.00	-18.239	NH4+	.00	.000	AL(OH)4-	.00	.000
HSO4-	.00	-8.296	FE++	.00	.000	ALSO4+	.00	.000
SO4--	53.89	-3.251	FR+++	.00	.000	AL(SO4)2-	.00	.000
HF	.00	.000	FEOH+	.00	.000	ALF++	.00	.000
F-	.00	.000	FE(OH)2	.00	.000	ALF2+	.00	.000
CL-	23.41	-3.180	FE(OH)3-	.00	.000	ALF3	.00	.000
NA+	80.87	-2.454	FE(OH)4--	.00	.000	ALF4-	.00	.000
K+	2.71	-4.159	FE(OH)++	.00	.000	ALF5--	.00	.000
CA++	1.14	-4.547	FE(OH)2+	.00	.000	ALF6---	.00	.000

IONIC STRENGTH = .00416   IONIC BALANCE :   CATIONS (MOL.EQ.) .00364643
                                            ANIONS (MOL.EQ.) .00347212
                                            DIFFERENCE (%)   4.90

CHEMICAL GEOTHERMOMETERS DEGREES C   1000/T DEGREES KELVIN = 2.56

QUARTZ   140.7
CHALCEDONY 117.8
NAK   104.1

OXIDATION POTENTIAL (VOLTS) :   EH H2S= -.475   EH CH4= 99.999   EH H2= 99.999   EH NH3= 99.999

LOG SOLUBILITY PRODUCTS OF MINERALS IN DEEP WATER

	TEOR.	CALC.		TEOR.	CALC.		TEOR.	CALC.
ADULARIA	-16.579	99.999	ALBITE LOW	-15.898	99.999	ANALCIME	-12.765	99.999
ANHYDRITE	-5.866	-8.031	CALCITE	-9.757	-9.718	CHALCEDONY	-2.706	-2.706
MG-CHLORITE	-79.970	99.999	FLUORITE	-10.526	99.999	GOETHITE	-3.995	99.999
LAUMONTITE	-26.420	99.999	MICROCLINE	-17.835	99.999	MAGNETITE	-28.337	99.999
CA-MONTMOR.	-81.702	99.999	K-MONTMOR.	-39.536	99.999	MG-MONTMOR.	-82.930	99.999
NA-MONTMOR.	-39.603	99.999	MUSCOVITE	-20.205	99.999	PREHNITE	-35.282	99.999
PYRRHOTITE	-90.899	99.999	PYRITE	-134.167	99.999	QUARTZ	-2.938	-2.705
WAIRAKITE	-24.317	99.999	WOLLASTONITE	10.302	8.954	ZOISITE	-35.558	99.999
EPIDOTE	-42.174	99.999	MARCASITE	-111.783	99.999			

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Table 1. The role of geochemistry in geothermal exploration, development and utilization (Arnórsson 1979 modified)

Phase in development	Individual tasks
Surface exploration	1. Evaluate origin of water and direction of regional underground water flow. 2. Estimate underground temperatures. 3. Evaluate regional cold groundwater composition. 4. Evaluate mixing with cold water in upflow zones. 5. Map the extent of geothermal systems. 6. Evaluate local direction of hot water flow. 7. Characterize, as far as possible, reservoir water chemistry with respect to the intended utilization. 8. Define, as far as water chemistry goes, potential environmental influence of utilization. 9. Delineate a preliminary model of the geothermal system (together with the results of other investigations).
Exploratory drilling	1. Assess reservoir water composition with reference to the intended utilization. 2. Attempt to establish a quantitative understanding of the reservoir water composition through the study of mineral/solute equilibria. 3. Estimate water temperatures at the point of well inflow. 4. Evaluate, if boiling and phase separation in the reservoir affects the well discharge chemistry. 5. Reevaluate direction of underground water flow. 6. Define potential scaling and corrosion problems. 7. Propose a model for the geothermal system. 8. Revise potential evironmental impact of the intended utilizaton.
Investigation drilling and testing	1. Improve the results listed under items 1-5 in the exploration drilling stage. 2. Establish changes (if any) in total well discharge composition that accompany long term well testing. 3. Participate in scaling and corrosion tests which may include fluid transmission, fluid disposal and heat exchange. 4. Participate in working out methods for disposal of waste fluids. 5. Provide chemical data on fluid compositions relevant for construction design. 6. Revise and refine reservoir model.
Production drilling and production	1. Continue with research listed under items 2-6 in the investigation drilling and testing stage. 2. Monitor the chemical composition of well discharges.

Table 2.Chemical analysis of geothermal waters (ppm)

Location	Temp. C	pH/ C	SiO2	Na	K	Ca	Mg	CO2	SO4	H2S	Cl	F	Total Diss.	Fe	Mn	δO-18	δD
Vadmalahver	98	9.29/24	145	81	2.7	4.1	-	47.1	55	1.1	23	1.4	389.5	.0	-		
Hrunalaug	38	9.32/24	54	38	.8	4.1	.1	28	29	.1	13	.6	182.7	.0	-		
Reykjabol well 1	93	9.45/24	252	109	6	1.5	-	54	65	5.3	31	.6	583.7	.0	-		
Reykjabol hver	100	9.65/24	277	118	6.8	1.3		40.8	70	3.6	33.4	1.97	638.8	.0		-9.70	-77.0
Reykjadalur we.1	83	9.28/24	127	75	2.4	2	.009	48	48.2	1.6	24	1.24	315.6	.0		-9.79	
Mifell well 2	62	9.47/24	82	59	1	2.7	-	33.1	43	.4	21.5	1	253.3	.3			
Husatoftir we.6	74.2	9.79/24	71	144	2.7	12	.001	9	65	0	168	2.5	506.7	.0		-10.69	-75.3
Flúðir well 4	100	9.22/24	150	77	2.6	1.2	.005	45	52	1.9	21	1.34	364.4	.0		-9.92	-72.6
Flúðir well 6	100	9.25/24	131	75	2.3	1.5	.008	46	49	1.4	20.4	1.33	348.2	.0		-9.84	-72.6

Chemical geothermometers °C

Samples	Quartz	Chalcedony	Na/K	Na-K-Ca
Fluðir hola 4	144	121	104	137
Flúðir hola 6	135	116	97	131
Husatoftir hola 6	89	63	69	75
Reykjdalur hola 1	133	100	101	131
Reykjarbol hver	170	149˙	147	169
Reykjarbol hola 1	171	145	142	164
Midfell hola 2	106	81	63	62
Vadmalhver	141	118	104	136
Hlid	78	53	132	66
Kotlaugar	169	148	129	162
Skiphol	89	62	145	95
Kopsvatn	103	79	212	59
Kiskjuskard	98	73	144	100
Midfell	95	70	79	64
Midfell hola 1	119	95	59	53
Birtingr holt hola 1	108	83	66	65
Hellisholt hola 1	135	112	91	79
Reykjabkki I	137	113	97	131
Reykjabiki II	134	110	84	84
Laugar hver	169	147	133	159
Hrunalaug	90	65	73	44
Basahverir	143	121	89	95

Figure 1. Location of Hrunamannahreppur low-temperature field in relation to the active volcanic zone and southern lowlands low-temperature field (modified from Stefánsson, V. and Arnórsson, S., 1975)
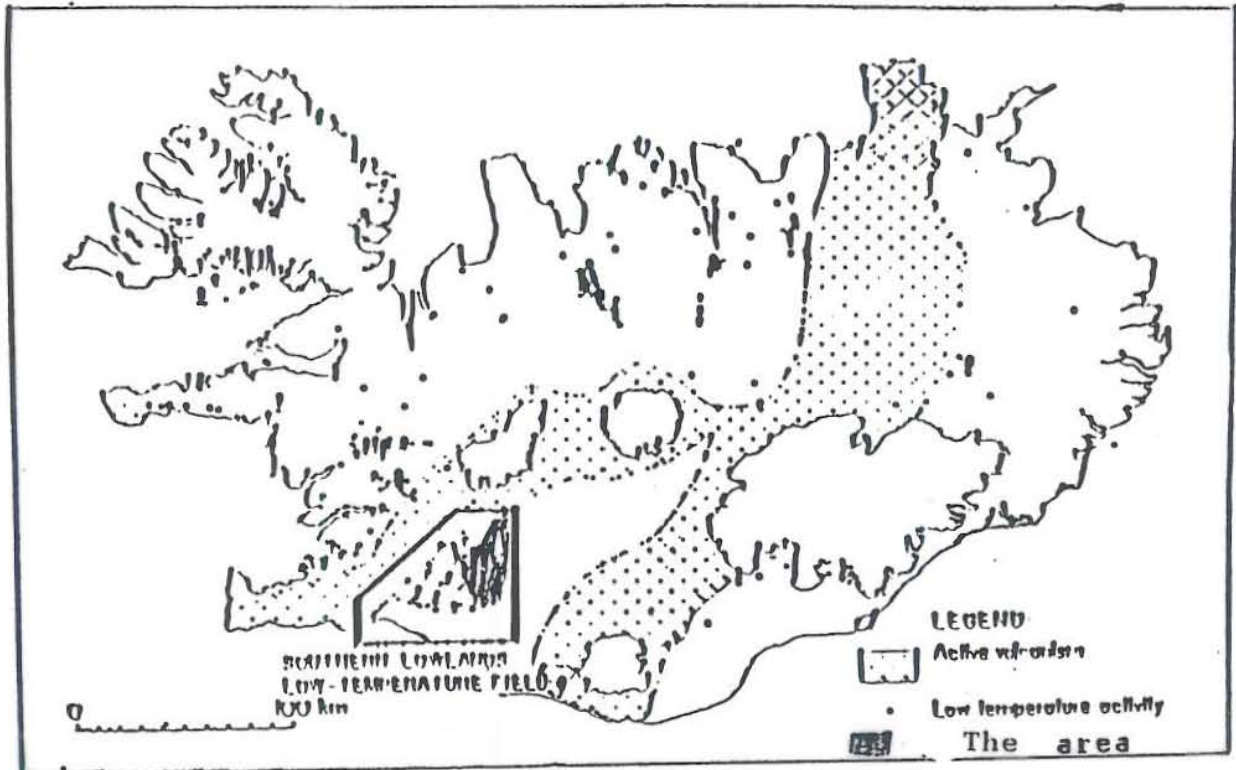
Figure 2. Location of drillholes and thermal springs around Flúðir farming village
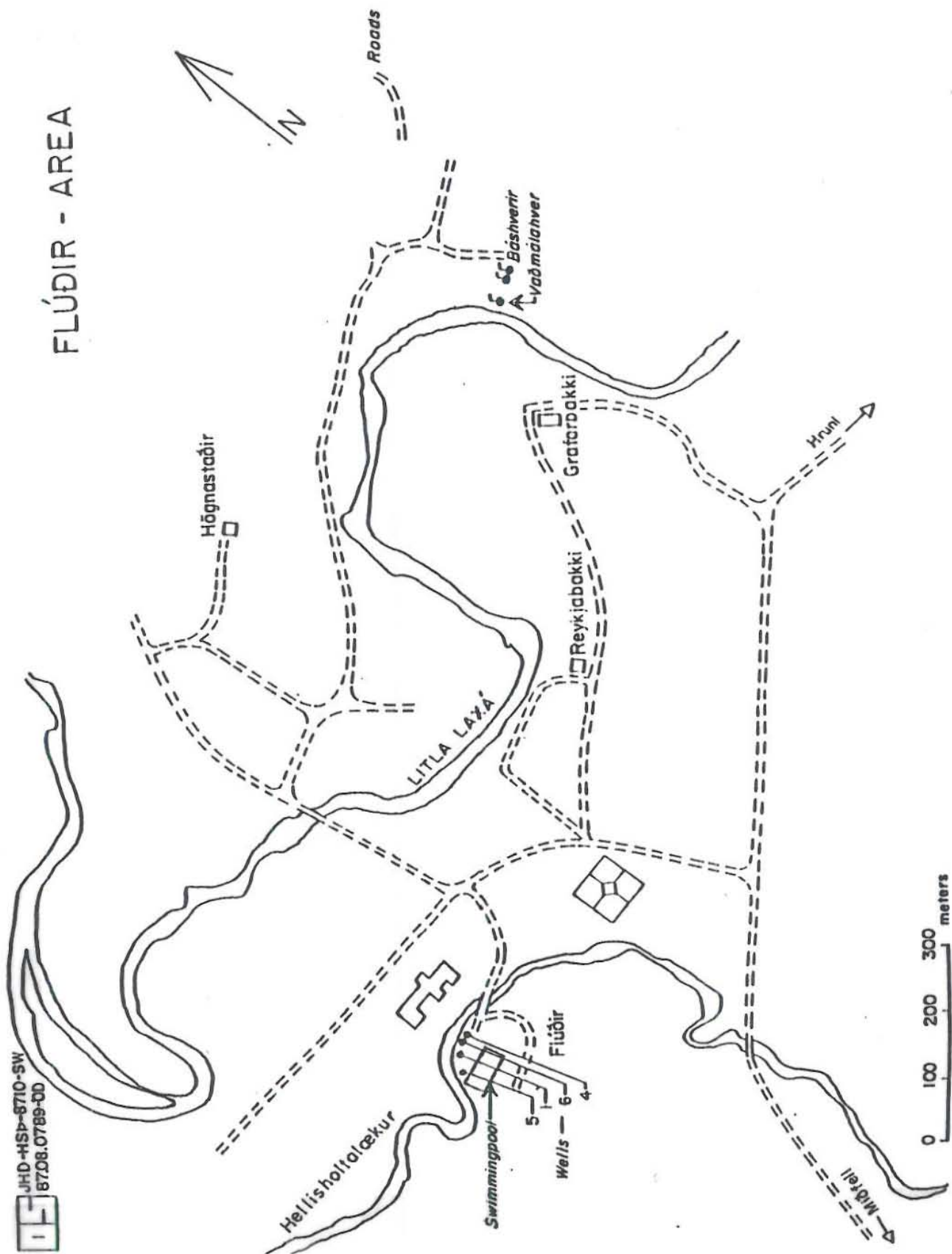
Figure 3. Geological map of Iceland (from Sæmundsson, 1979)
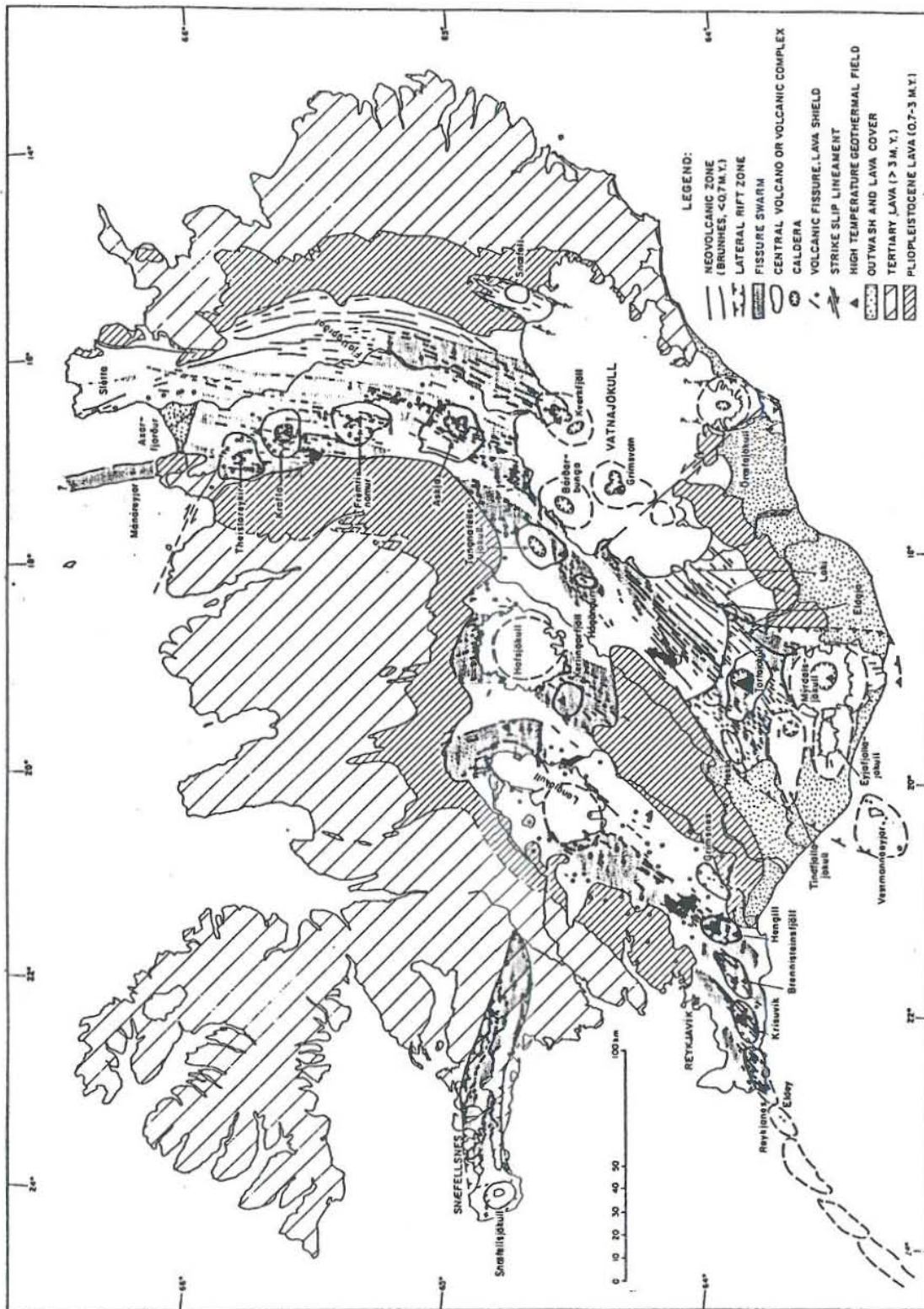
Figure 4. Location of the sampling spots in Hrunamannahreppur geothermal field
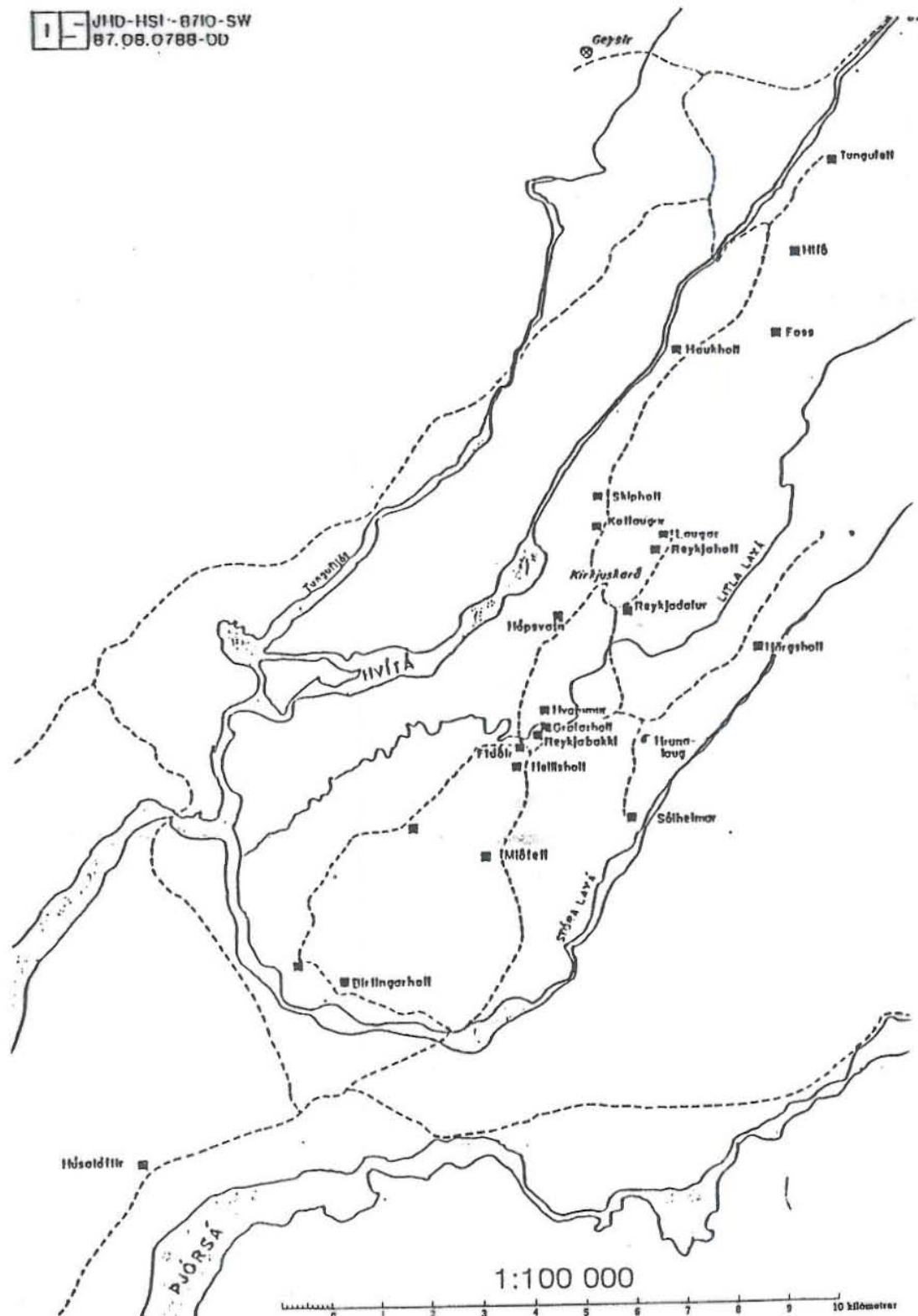
Figure 5. Hydrothermal systems in southern lowlands as deduced from the Cl/B content of the thermal water (Stefánsson, and Arnórsson, 1975)
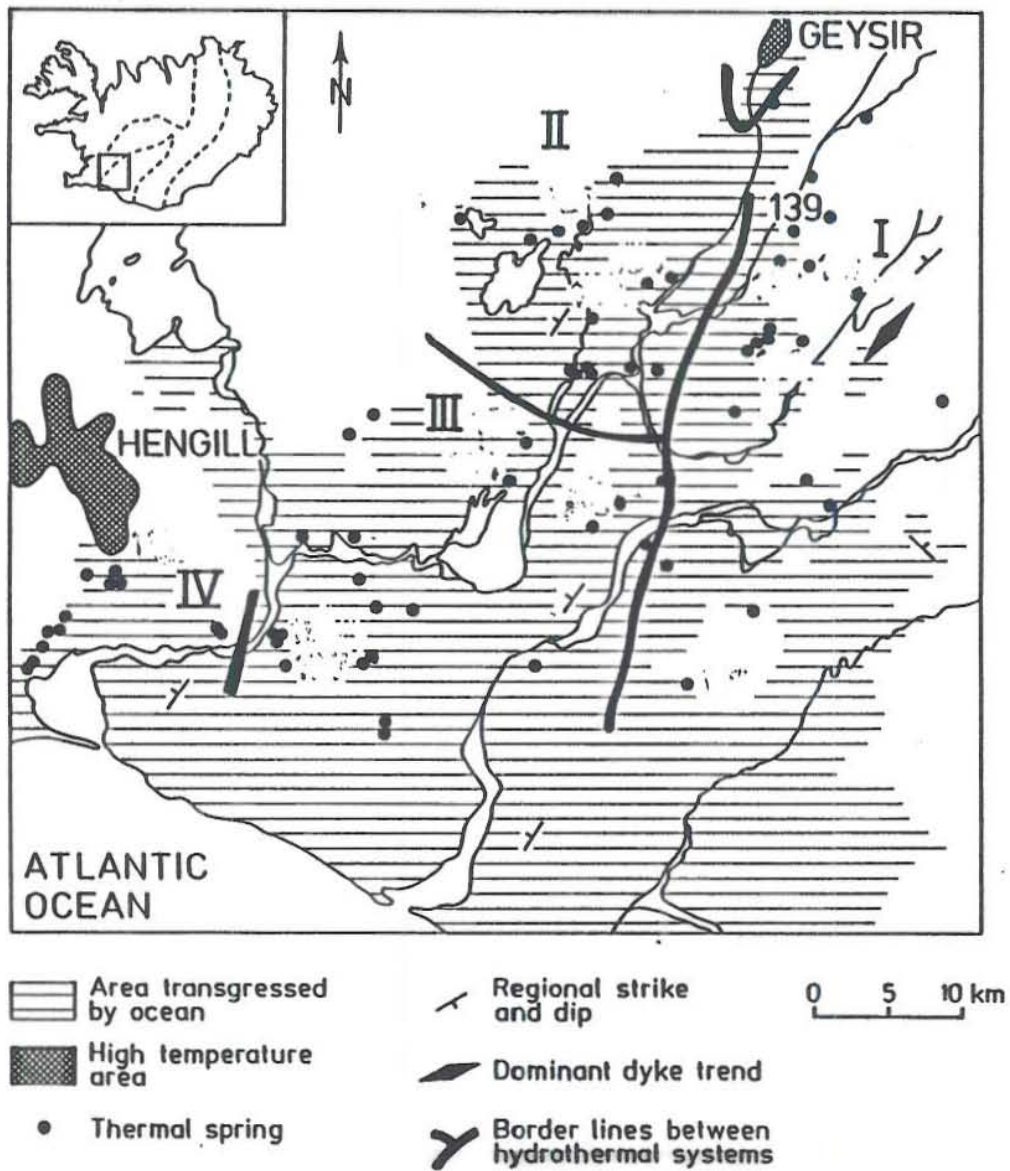
Figure 6. SiO$_2$ versus time, Reykjarból Hver, Reykjarból well 1, Flúðir well 4, Vaðmálahver
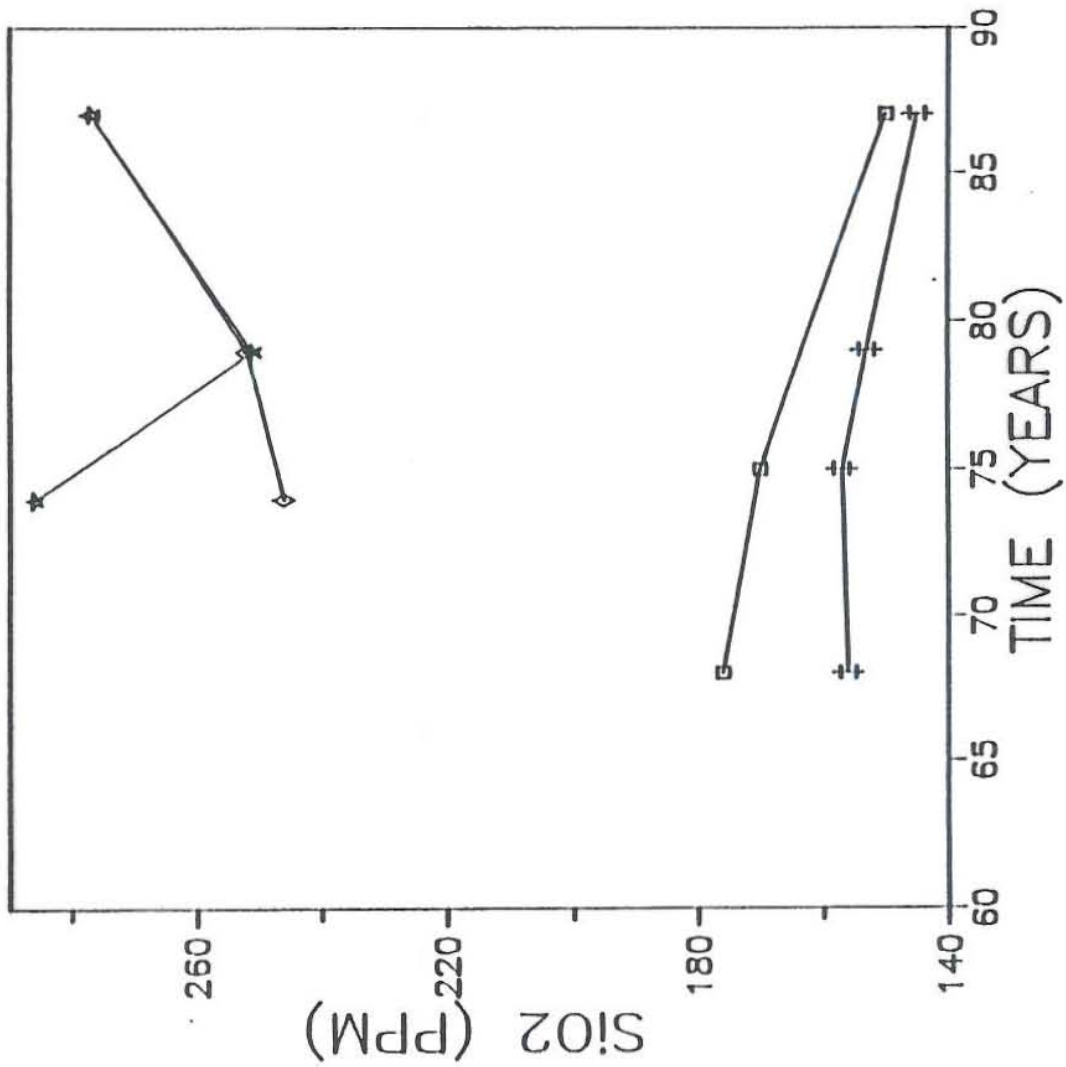
Figure 7. CO_2 versus time, Reykjarból Hver, Reykjarból well 1, Flúðir well 4, Vaðmálahver
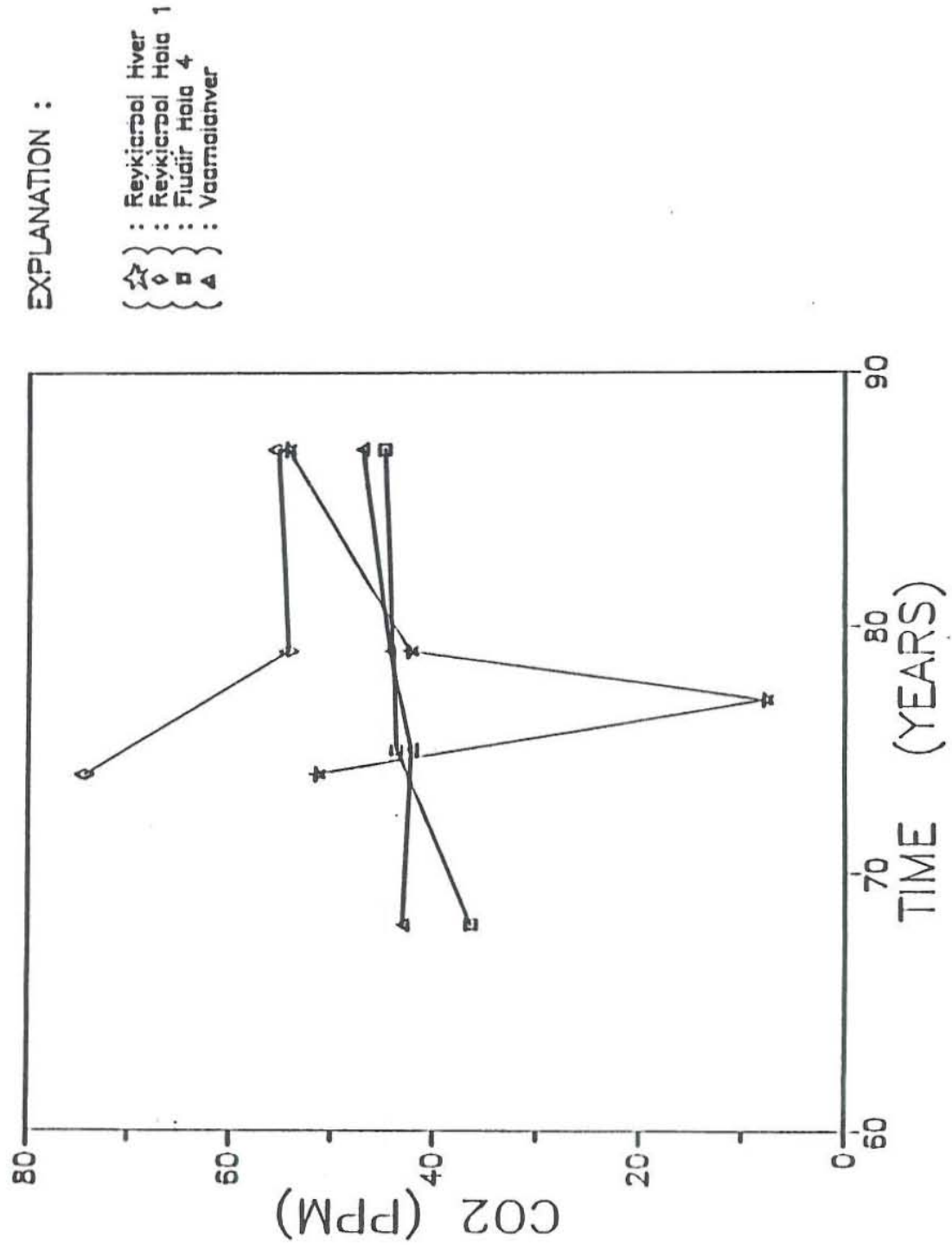
Figure 8. SO$_4$ versus time, Reykjarból Hver, Reykjarból well 1, Flúðir well 4, Vaðmálahver
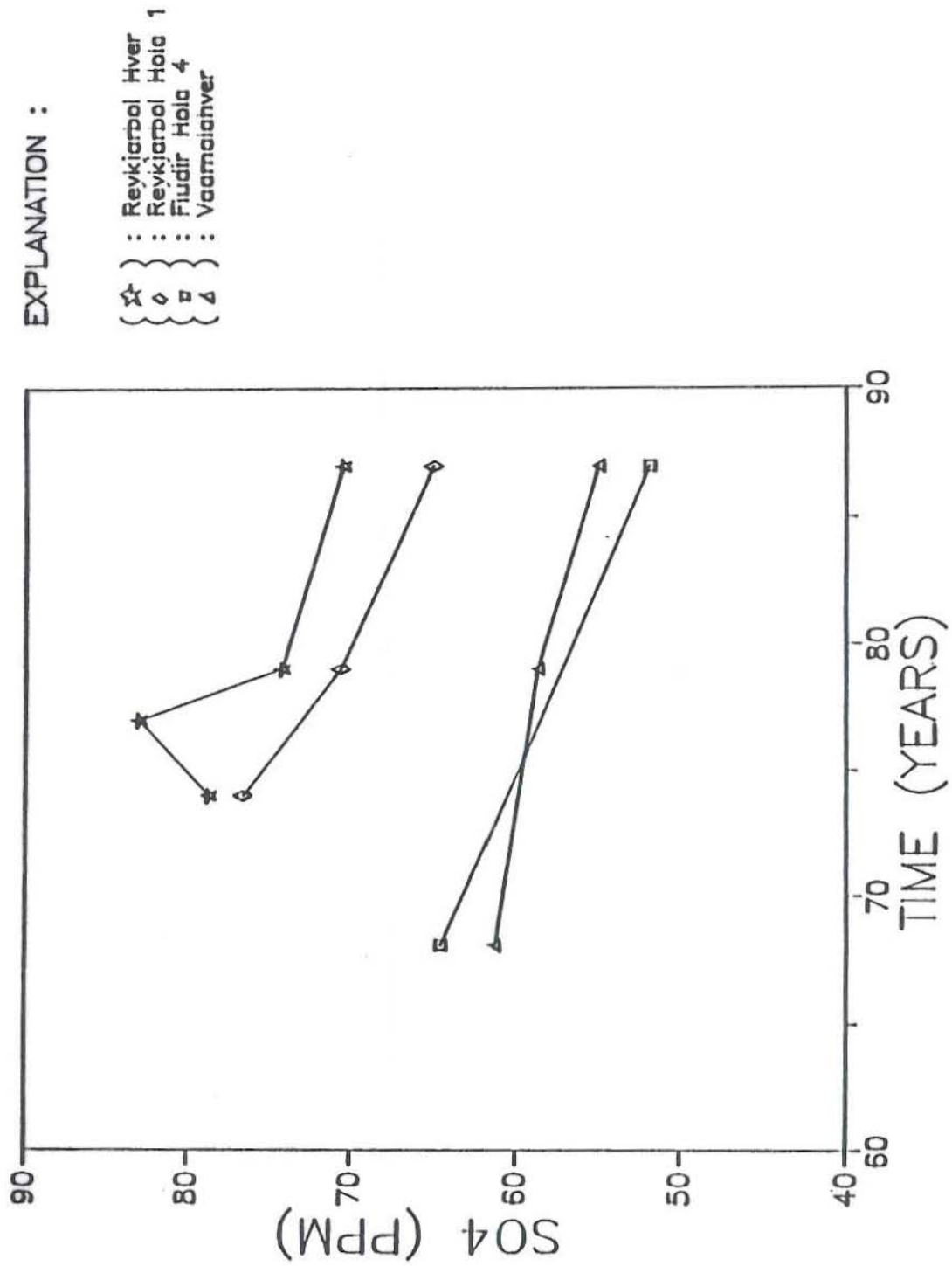
Figure 9. Cl versus time, Reykjarból Hver, Reykjarból well 1, Flúðir well 4, Vaðmálahver
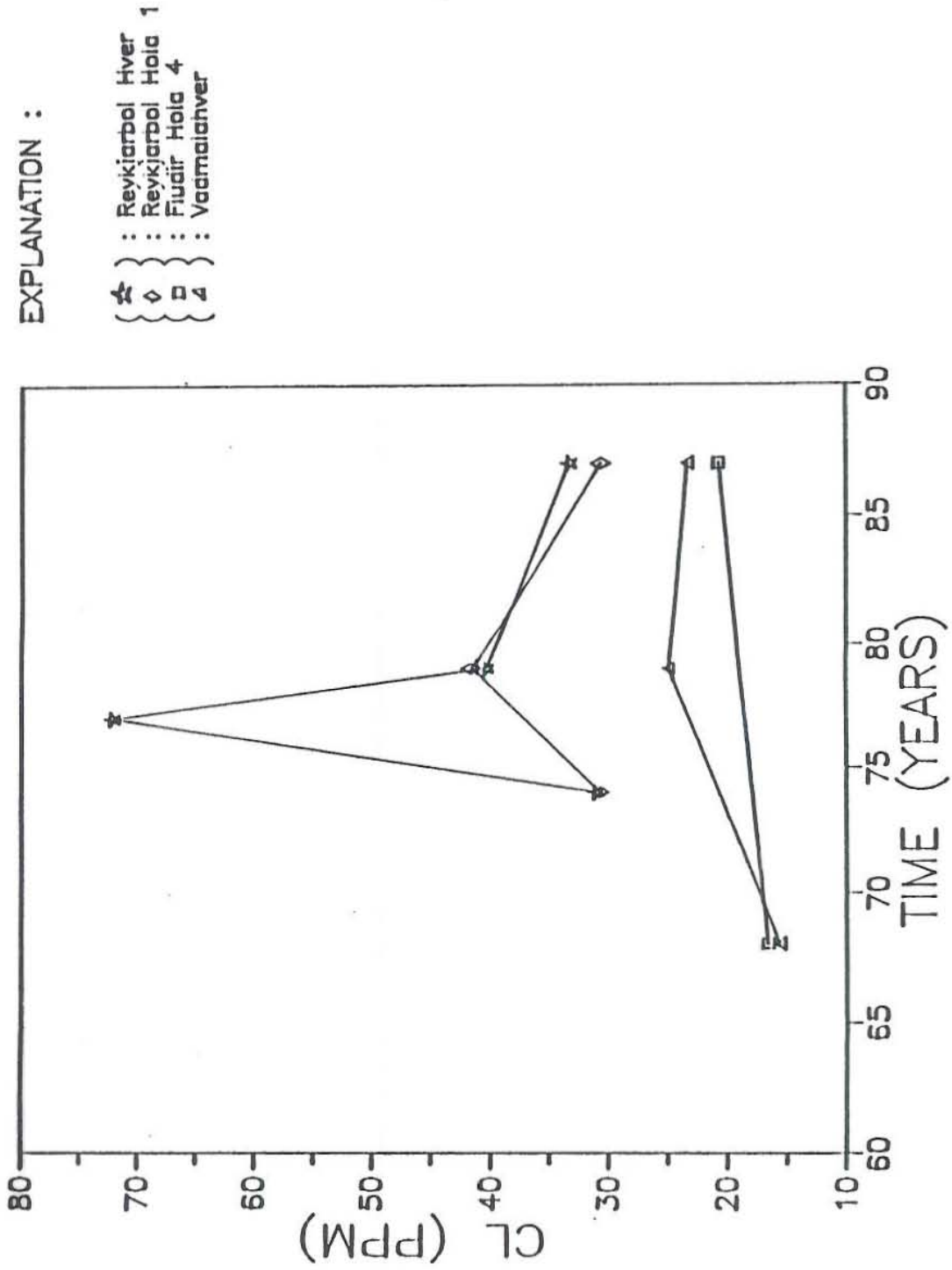
Figure 10. Ca versus time, Reykjarból Hver, Reykjarból well 1, Flúðir well 4, Vaðmálahver
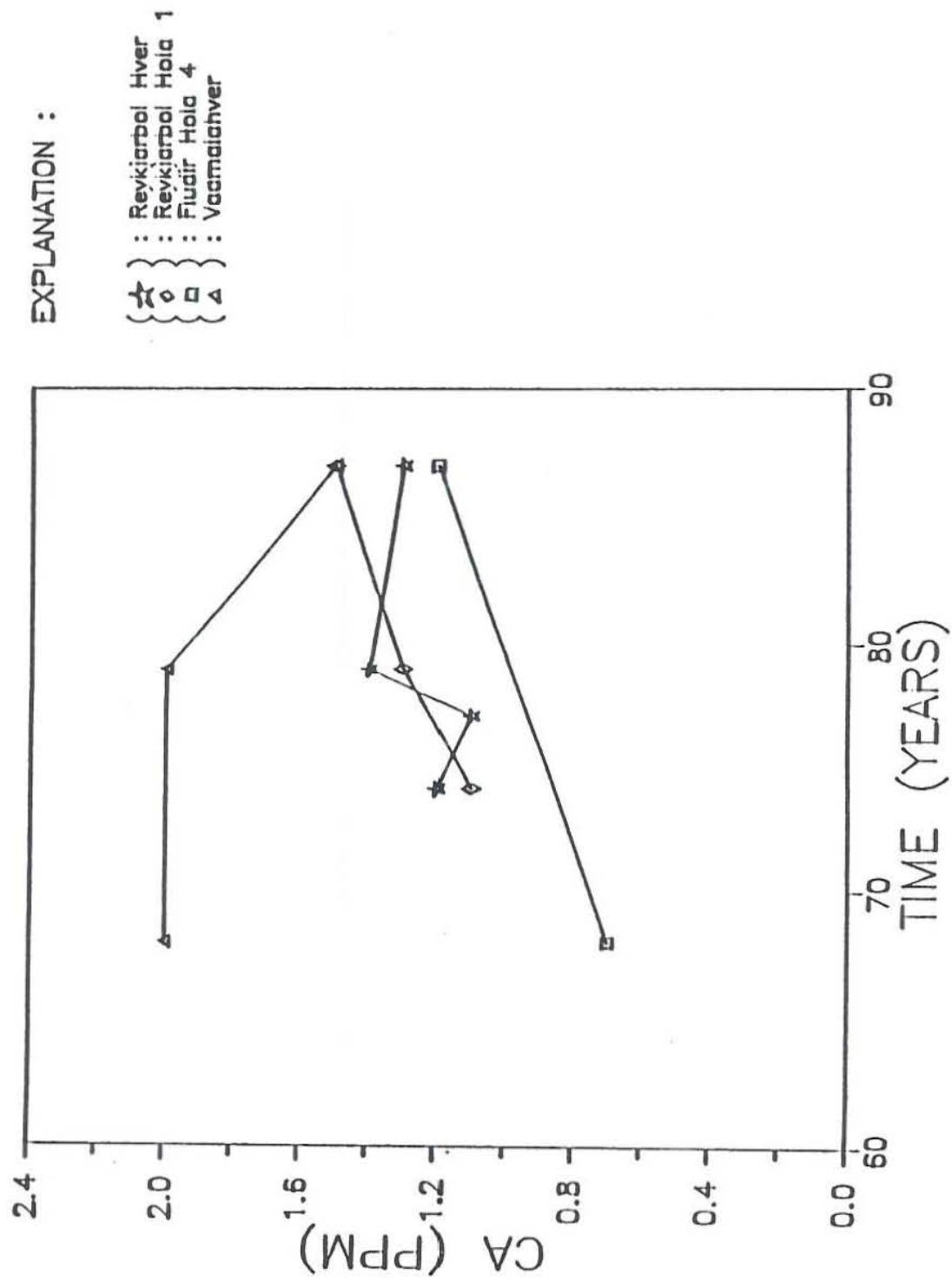
Figure 11. Na versus time, Reykjarból Hver, Reykjarból well
1, Flúðir well 4, Vaðmálahver
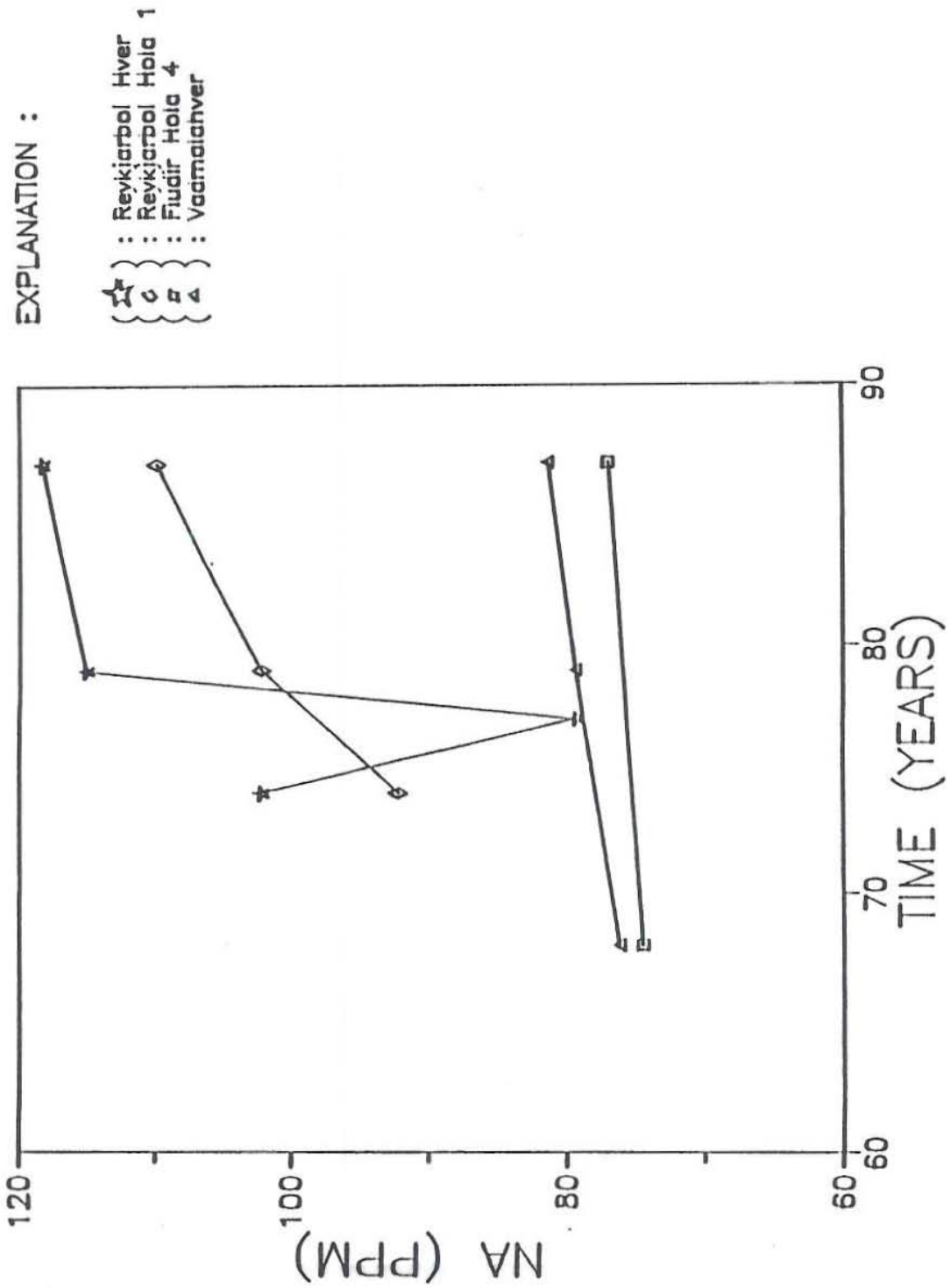
Figure 12. pH versus time, Reykjarból Hver, Reykjarból well 1, Flúðir well 4, Vaðmálahver
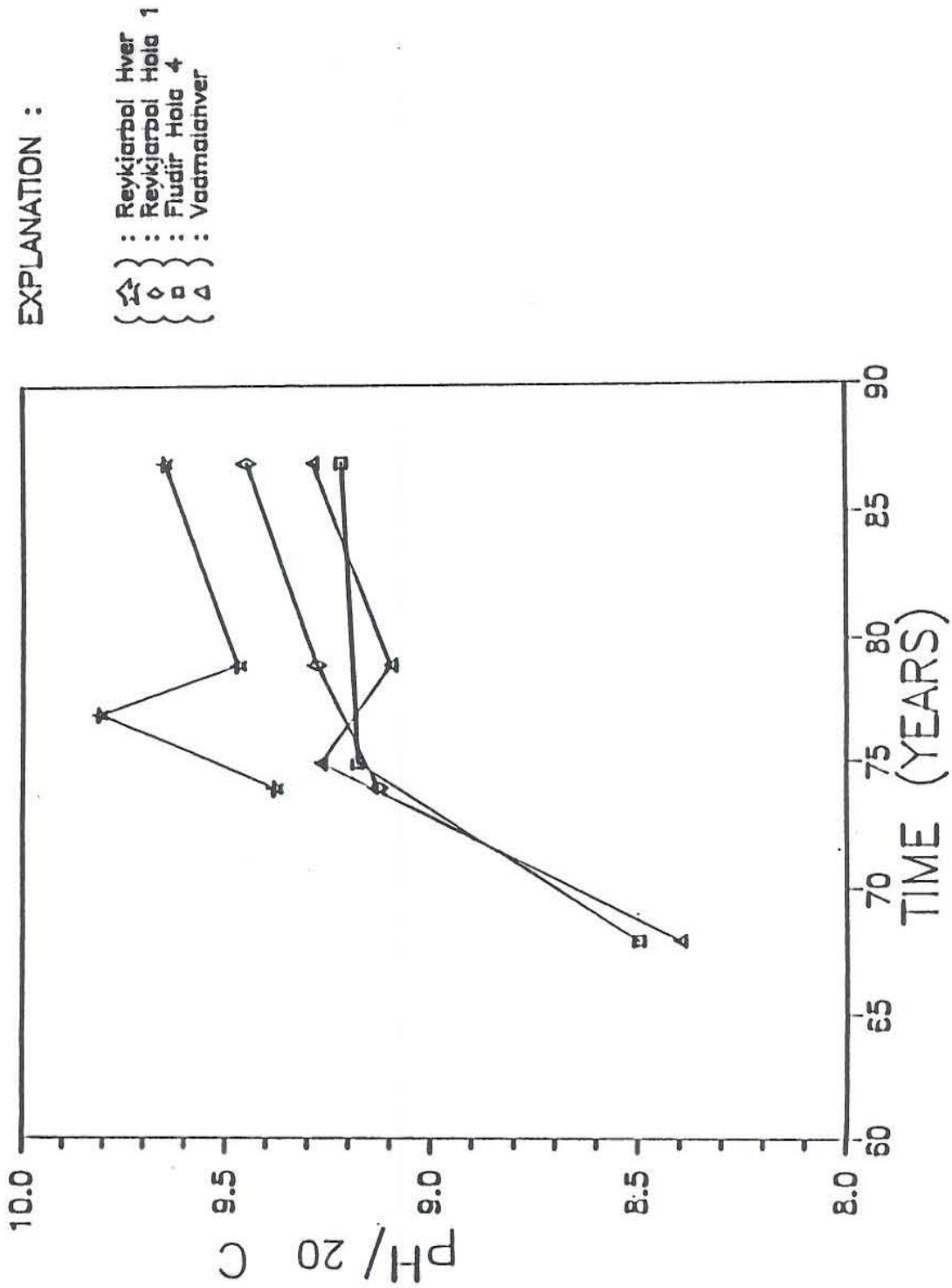
Figure 13. Generalized diagram showing the dependence of concentration on temperature under different condition (Lumb J. T., 1981)
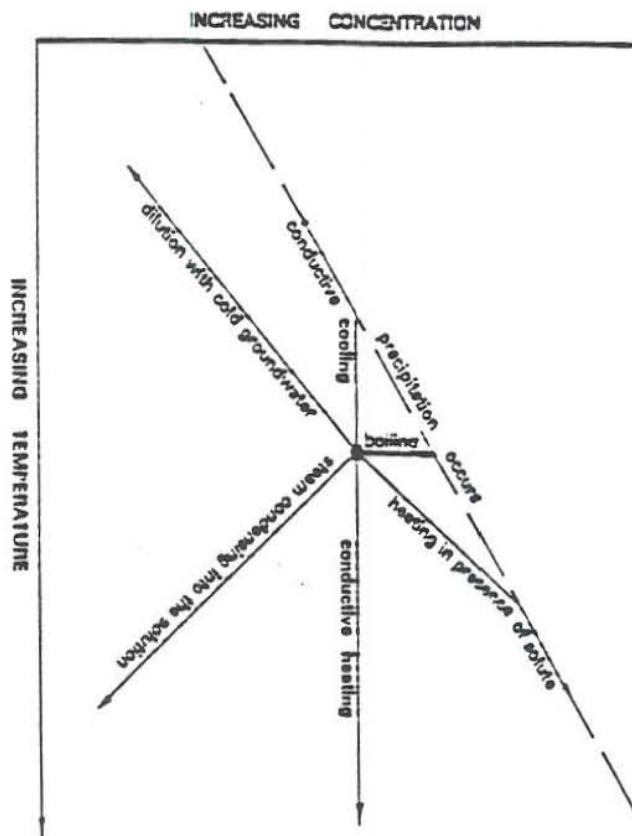
Figure 14. The state of calcite saturation at discharge
temperature of the thermal waters
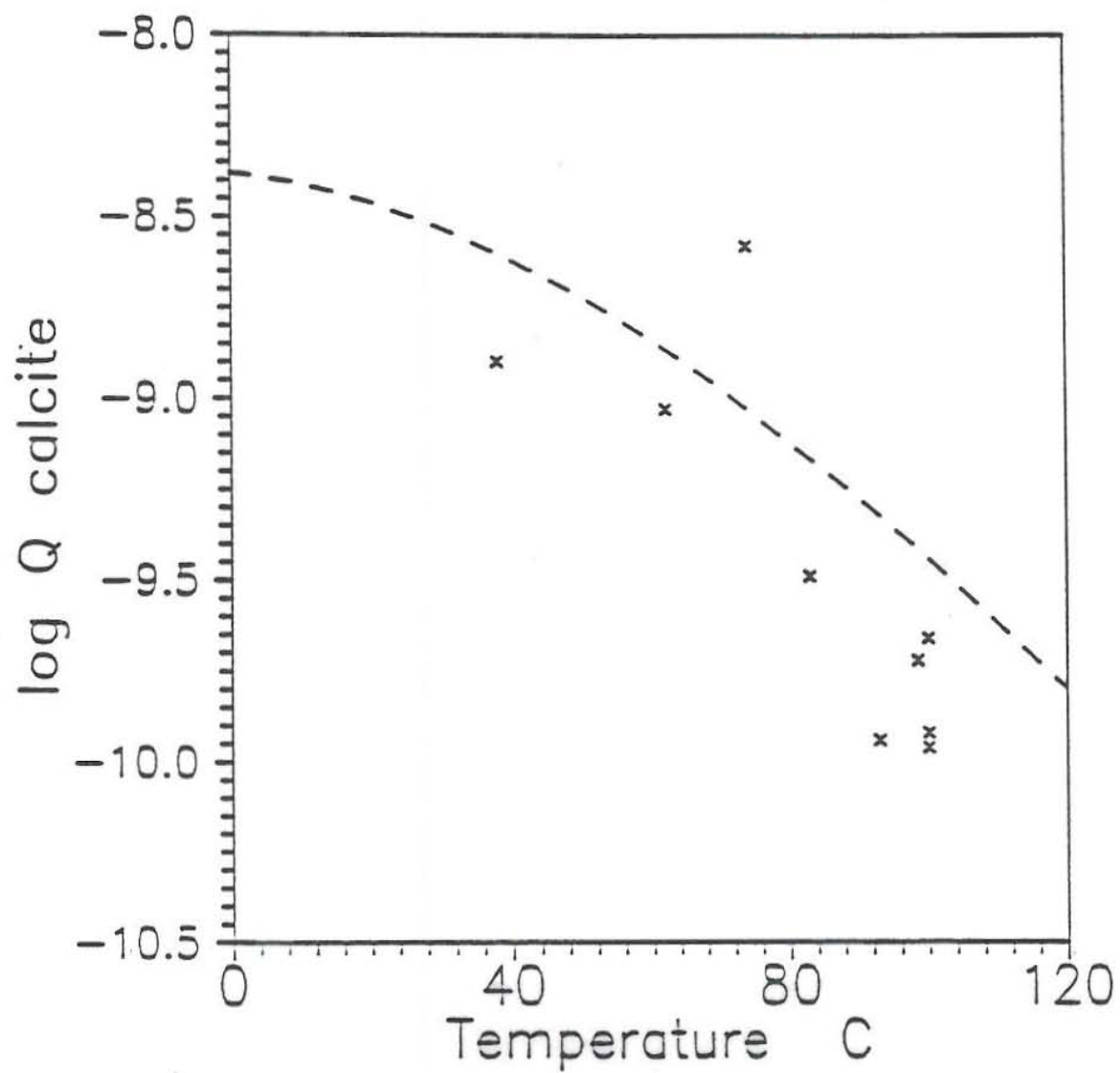
Figure 15. Chloride versus silica in cold and thermal waters from the Hrunamannahreppur area
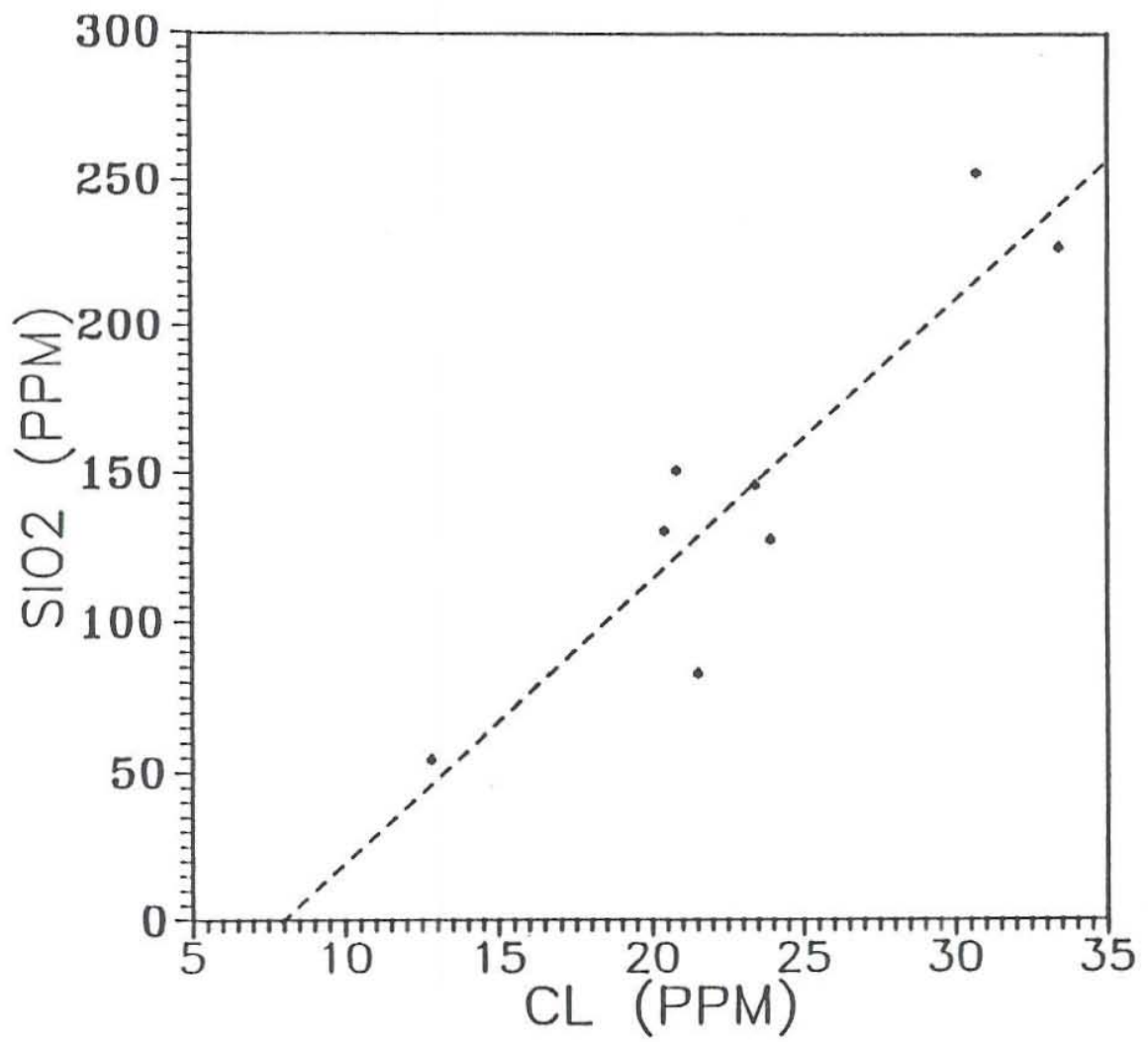
Figure 16. Chloride versus sulphate in cold and thermal waters from Hrunamannahreppur area
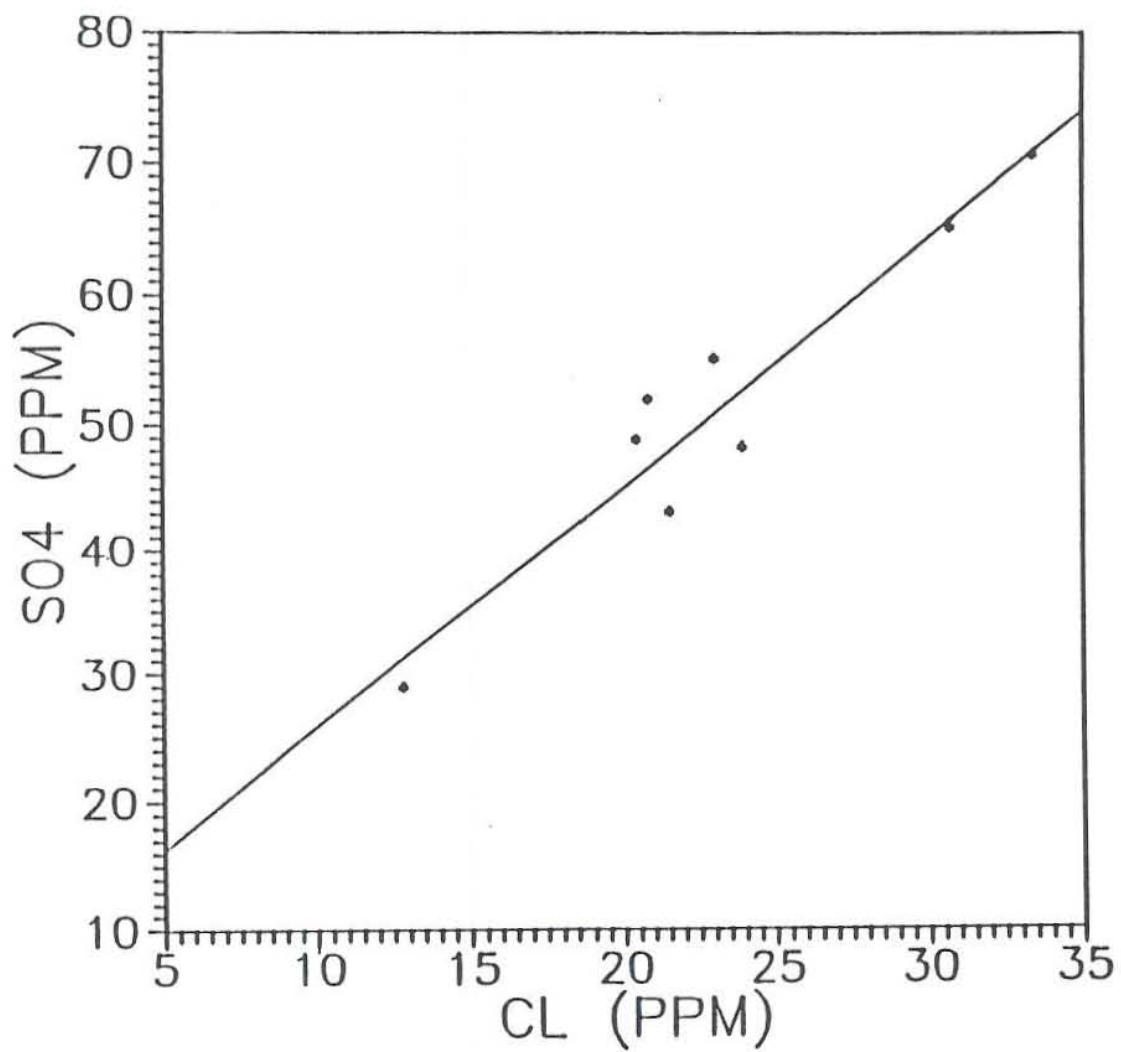
Figure 17. The state of anhydride saturation in water
discharged from thermal springs. Chalcedony equilibrium
temperature was selected for reference
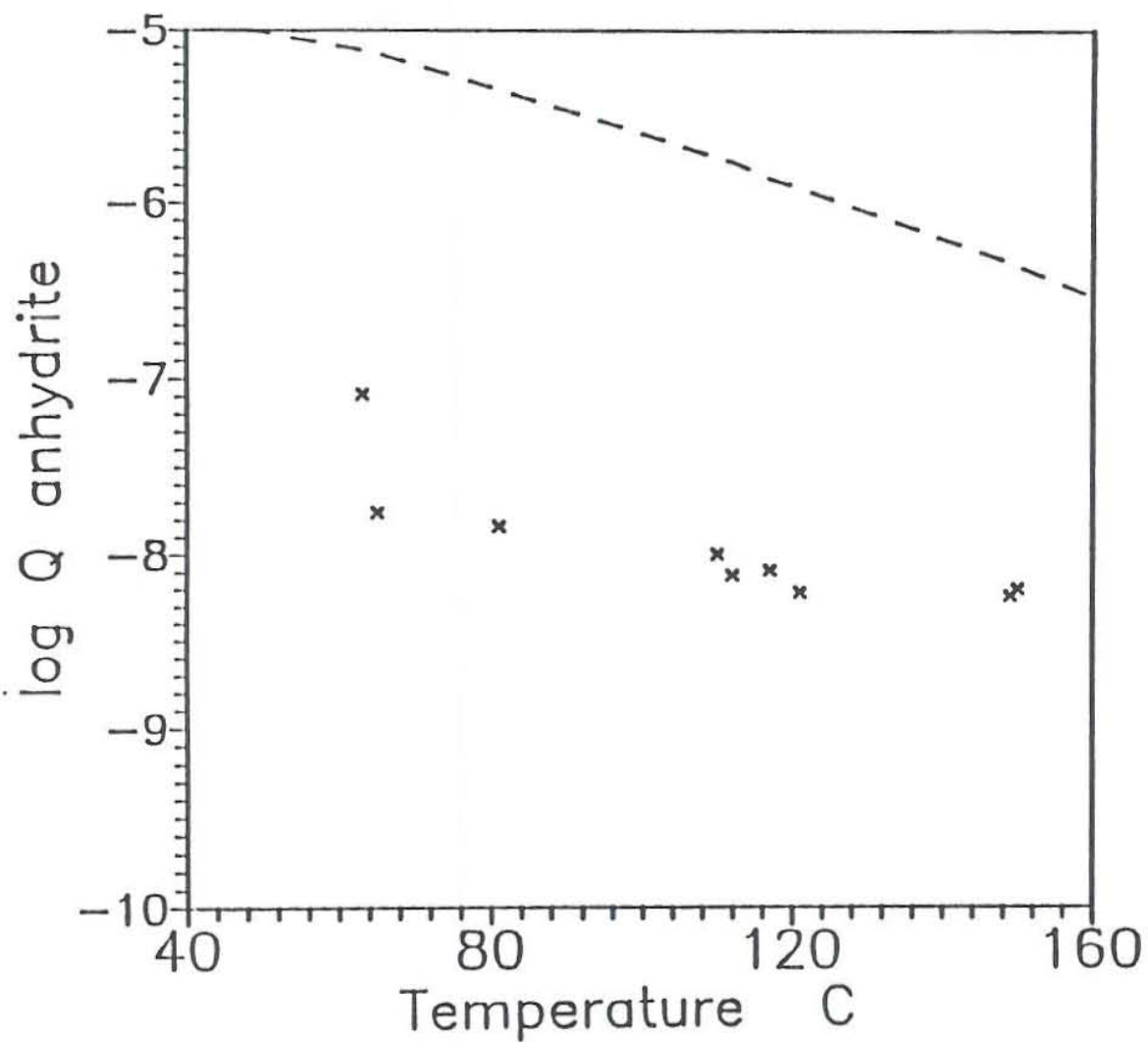
**Figure 18. Plot of δD versus δO-18 for Reykjarból hver,
Húsatóftir well 6, Flúðir well 4 and well 6**
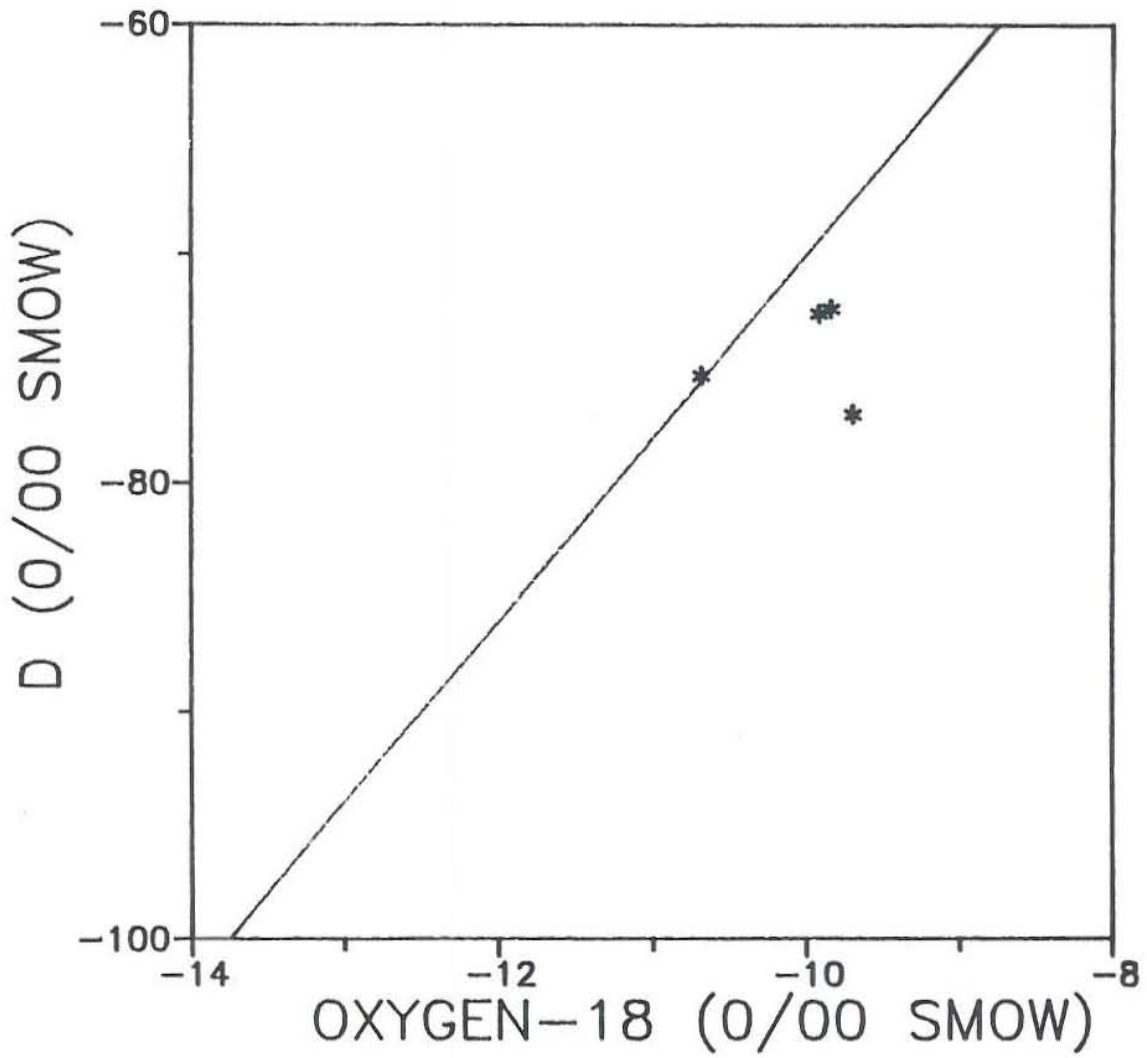
Figure 19. Plot of chloride versus δO-18 in water from Reykjarból hver, Húsatóftir well 6, Flúðir well 4 and well 6
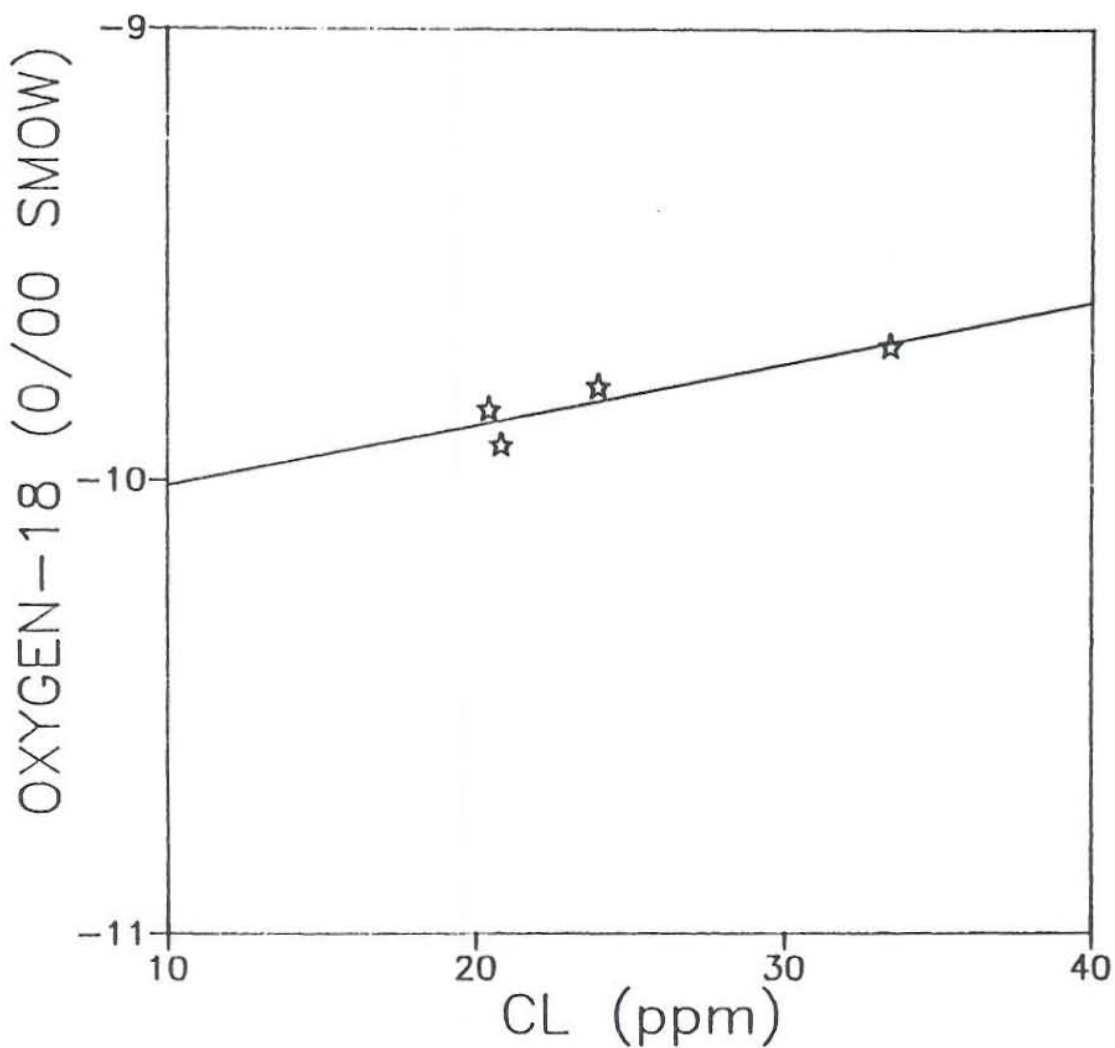
Figure 20. Silica-enthalpy mixing model with quartz
solubility
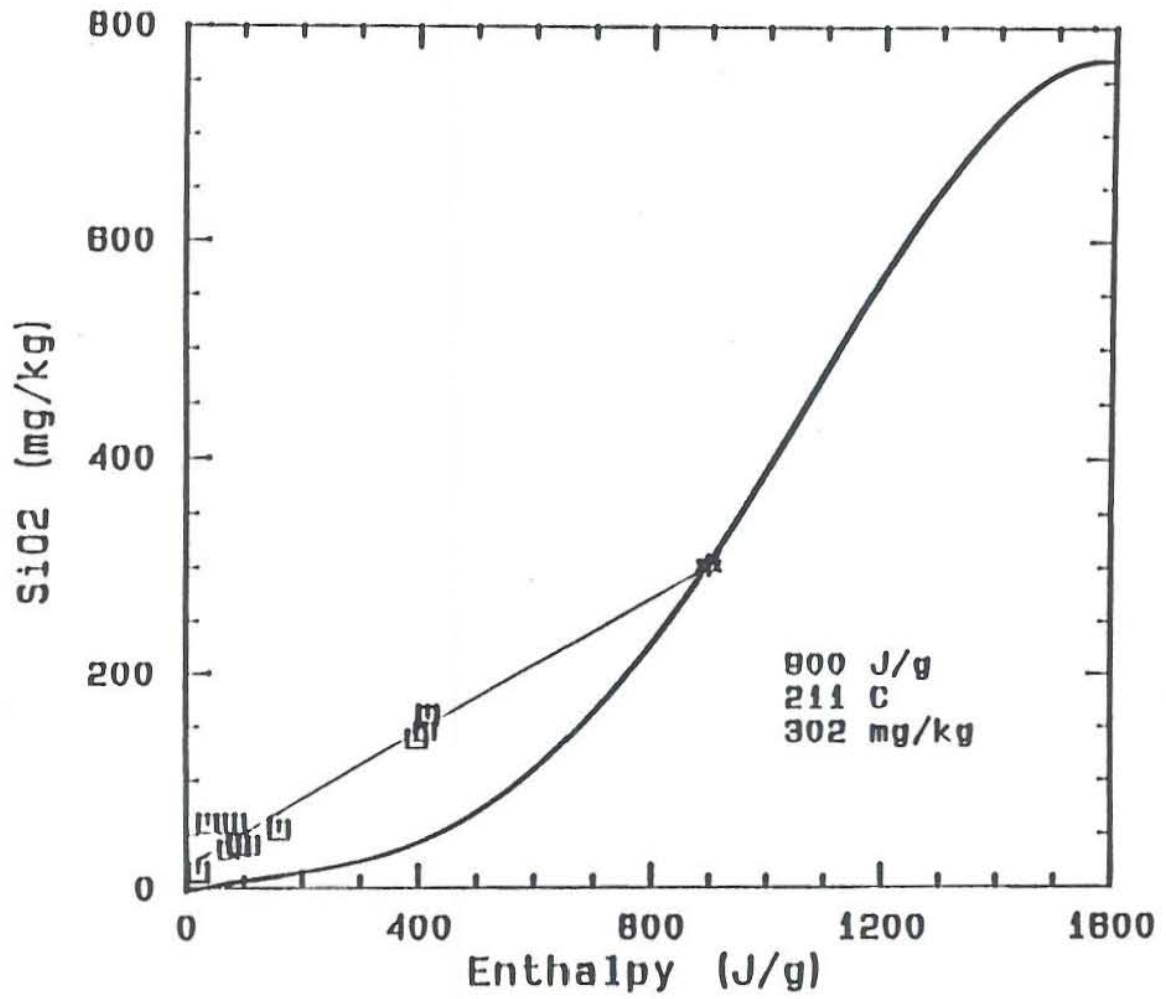
Figure 21. Silica-enthalpy mixing model with chalcedony
solubility

704 J/g
168 C
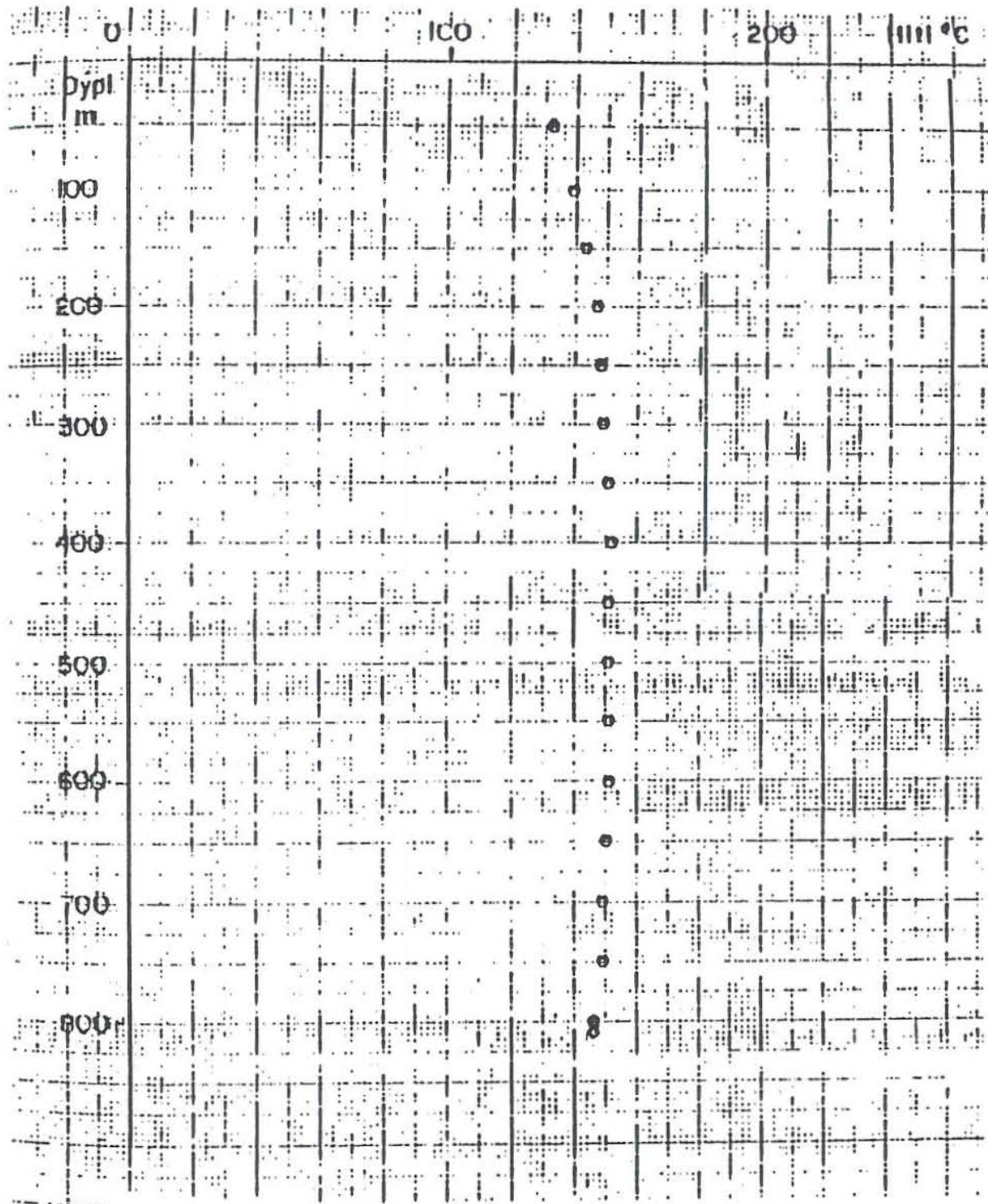240 mg/kg
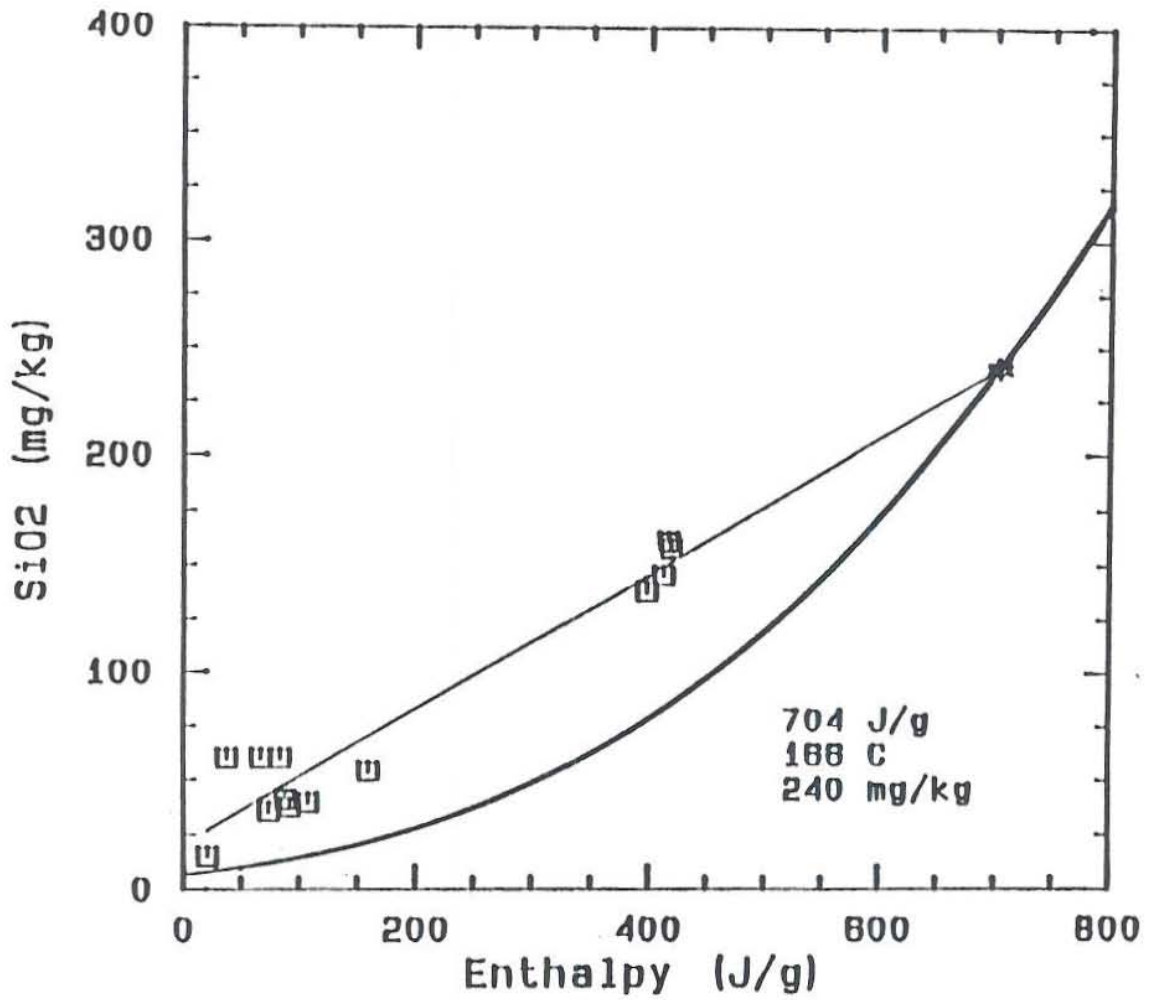
Figure 22. Downhole measured temperature of Reykjarbol well 1

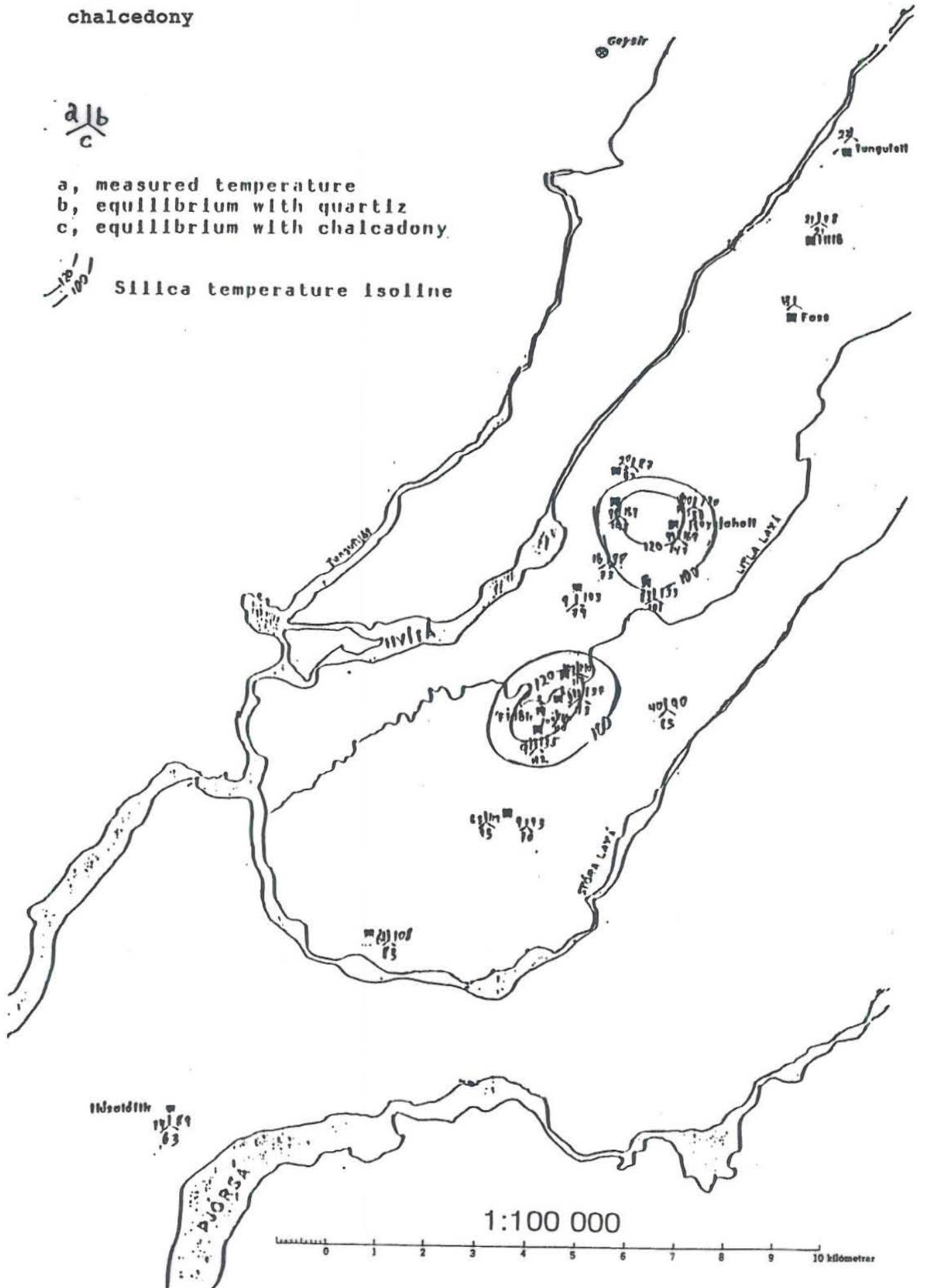Figure 23. Silica temperature isolines equilibrium with
chalcedony

Figure 24. True resistivity at 500 m depth

Resistivity at 500m depth

Figure 24. True resistivity at 500 m depth

Legend:
- ☒ < 20 Ωm
- ⬚ 20 – 40 Ωm
- ☐ 40 – 80 Ωm
- ▦ > 80 Ωm

1:100 000

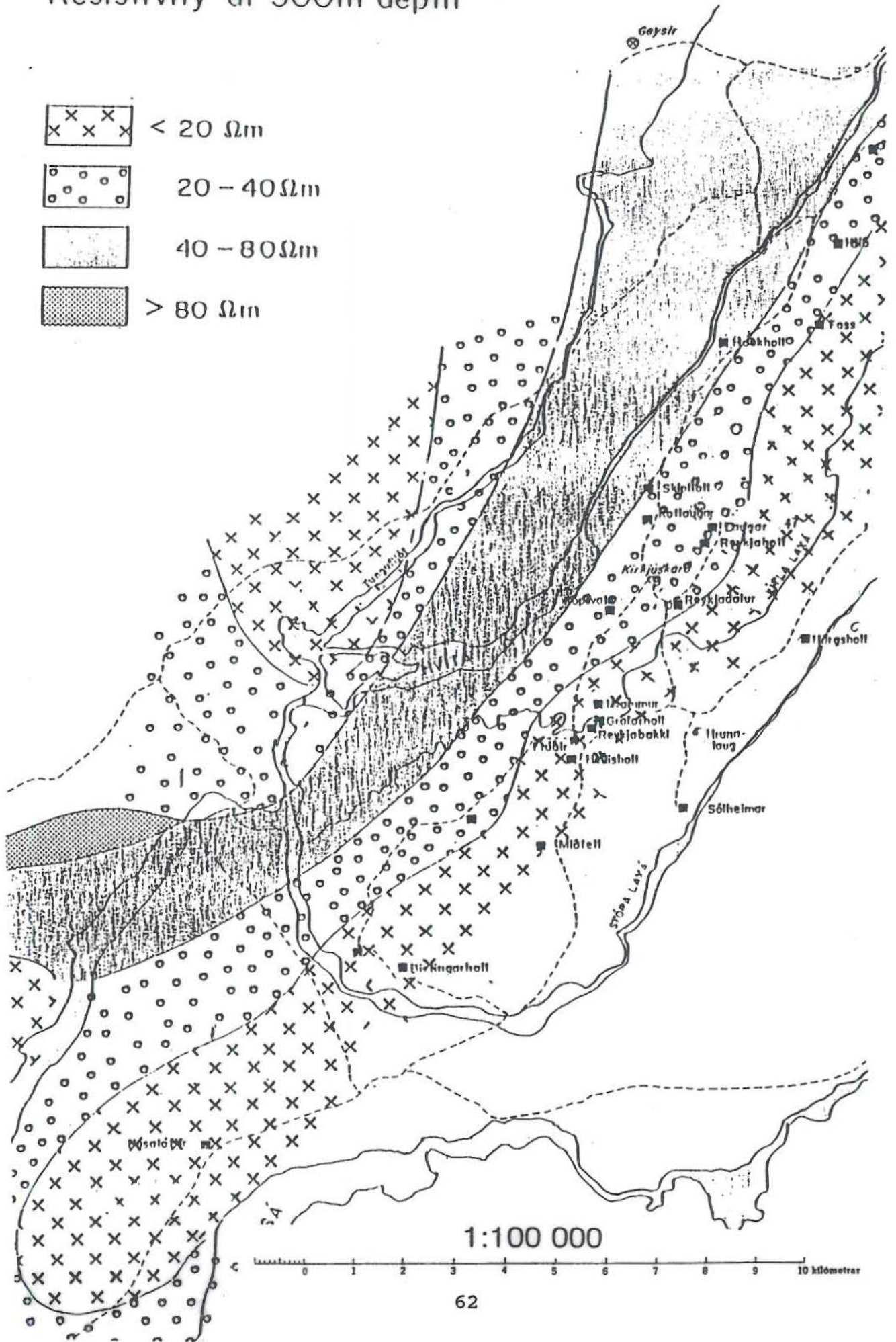0 1 2 3 4 5 6 7 8 9 10 kílómetrar

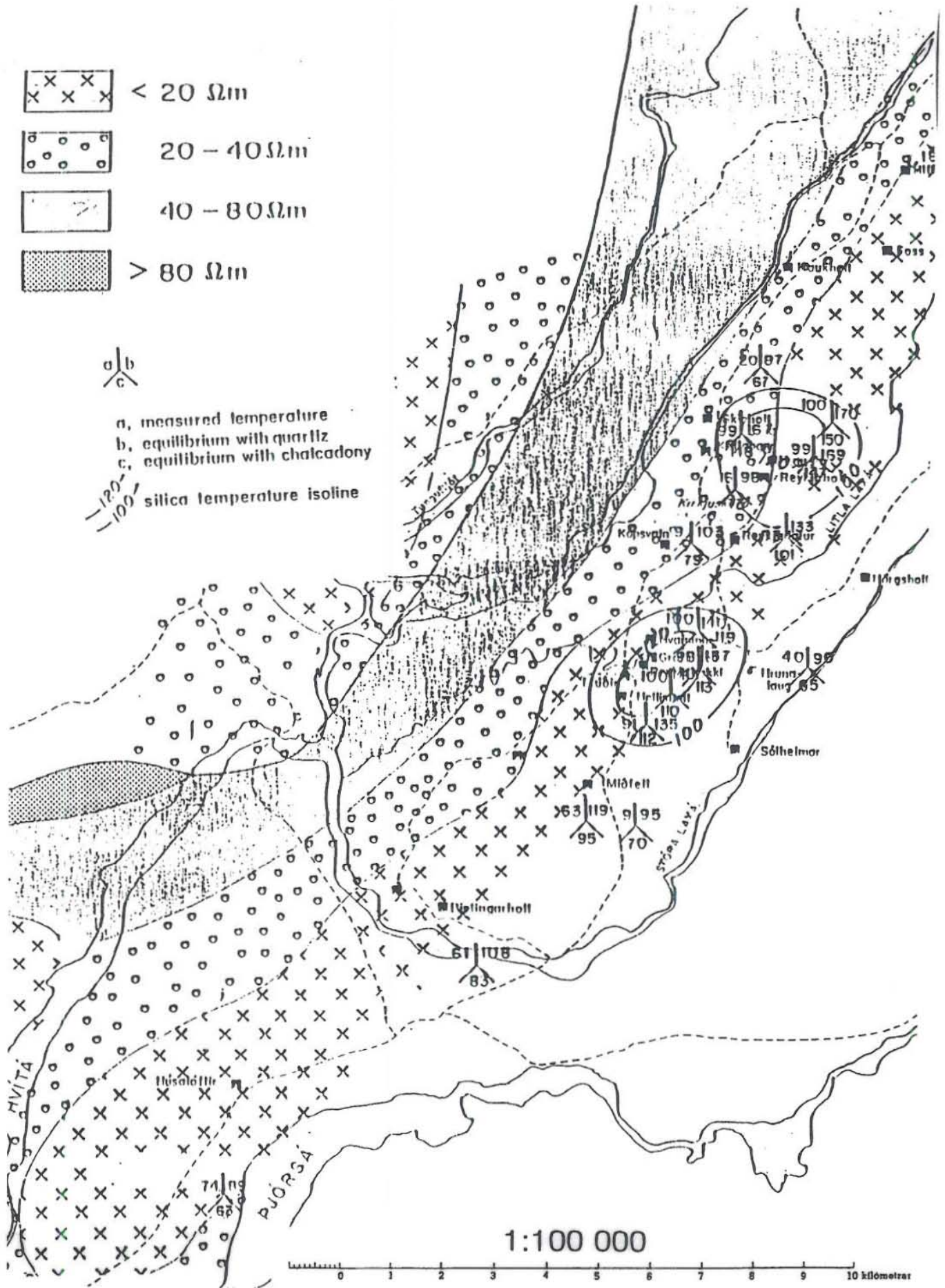Figure 25. The silica temperature isolines and the true resistivity at 500 m depth

Figure 26. Hypothetical model of the geothermal system in the area