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**The Effect of Volcanic Activity  
on the Groundwater System in  
the Námafjall Geothermal Area,  
NE Iceland**

Eric de Zeeuw and Gestur Gíslason

OS-88042/JHD-07

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## **ABSTRACT**

An evaluation is made on the effect of volcanic activity on the fluid chemistry of the Námafjall geothermal area and its natural output into Lake Mývatn, since volcanic activity started in the area in 1975. A special attention is given to the eruption of September 1977. Chemical data from deep drillholes and of groundwater is used for this evaluation.

The observed changes of the shallow groundwater system due to volcanic activity are:

An increase in temperature and the concentration of SiO<sub>2</sub>, CO<sub>2</sub>, Na, K and Cl.

A decrease in the concentration of Ca, Mg and SO<sub>4</sub>.

The deep geothermal system was also affected by volcanic activity and the observed changes are:

An increase in the concentration of SiO<sub>2</sub>, CO<sub>2</sub>, Na and Cl.

A decrease in the concentration of SO<sub>4</sub>.

The groundwater flows from the geothermal area in three major tongues and there is a clear relation between the flow direction of the groundwater and the flow direction of the lavas in the area, due to cooling cracks and fissures that have developed in the lavas, parallel to the flow direction. The large north-south striking faults like Stóragjá and Grjótagjá do not form a barrier to the groundwater flow.

Mixing of hot and cold groundwater is only important near the hot/cold water boundary zone, and the amount of infiltrated rain-water is small compared to the amount of hot groundwater flow.

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## 1. INTRODUCTION

The purpose of this study is to describe the impact of volcanic activity on the geothermal system and the shallow groundwater system in the Námafjall area, NE Iceland (Figure 1).

Volcanic activity started in the Krafla central volcano, 10 km north of Námafjall in December 1975. The activity is characterized by repeated uplift and subsidence of an area near Leirhnúkur in the central part of the Krafla caldera. The following model has been developed to describe the present sequence of events in the area (Björnsson, A. et al. 1979).

A continuous inflow of magma enters a magma reservoir below Leirhnúkur, and this causes an inflation of the central part of the Krafla caldera. Occasionally, magma is released from the reservoir along the fissure swarm which goes through the Krafla area in direction N10°E to N15°E, and the inflation process is interrupted by a rather sudden subsidence event. The magma is transported towards north and/or south, and in nine such events volcanic eruptions have been observed.

The Námafjall geothermal system is situated in this fissure swarm some 10 km south of Leirhnúkur and transport of magma towards Námafjall has taken place in the following volcano-tectonic events in the Krafla area:

- September 1976
- April 1977
- September 1977
- December 1979
- February 1980
- March 1980
- June 1980

The eruption of September 8th, 1977 had a great impact on the Námafjall geothermal area. Wells were destroyed and a small volcanic eruption took place through the well B-4. The well was damaged but is still in production. Due to increased heatflow surface activity increased at Bjarnarflag during and after this eruption. Geothermal steam from the field has been used for electricity production (3 MW) since 1970, and for the energy supply of a diatomite factory and space heating.

Samples of shallow groundwater has been collected by the staff of The National Energy Authority twice a year for about ten years. The geothermal drillholes have been regularly monitored from 1969.

The senior author of this report participated in the fieldwork in May 1983 and worked on the report under the supervision of Gestur Gíslason at the Geochemistry section of the National Energy Authority. This was a part of his training at the UNU geothermal training programme. Magnús Ólafsson at the Geochemistry section of the National Energy Authority prepared the manuscript for publication.

## **2. CHANGES IN THE GROUNDWATER CHEMISTRY**

### **2.1 Introduction**

This chapter describes the geochemical changes of the groundwater in the Námafjall geothermal area and its natural output, the shallow groundwater system east of Mývatn (Figure 2). The following data is used:

- Chemical analysis from wells 4 and 8 of the Námafjall field from 1973 to 1982.
- Chemical analysis from well 10 of the Námafjall field from 1976 to 1980.
- Chemical analysis from two shallow groundwater wells near the diatomite factory, the Hitaveita cold-water well (1975 to 1983) and the Kísiliðja well (1974 to 1983).
- Chemical analysis from the Grjótagjá and Stóragjá fissures, from 1973 to 1984.

The chemical analysis of the samples from Grjótagjá, Stóragjá, Hitaveita cold-water well, Kísiliðja well and wells 4, 8 and 10 are plotted against time in order to demonstrate the changes in chemistry which have occurred since the volcano-tectonic activity in the Krafla area started in 1975. In this way the changes in chemistry can be compared with the volcano-tectonic events.

The shallow groundwater system consists of the fresh water in the area with a variable hot-water component from the underlying geothermal fluid.

### **2.2 Changes in the shallow groundwater system**

In order to evaluate the chemical changes in the shallow groundwater system the chemical analysis of Grjótagjá, Stóragjá, Hitaveita cold-water well and Kísiliðja well are used.

It is obvious from Figures 3 to 6 that major chemical changes occurred in 1977 at all locations which can be related to the volcano-tectonic event of September 1977. However, there were some changes prior to the September 1977 event, some clearly related to the initial activity in the Krafla area in 1975.

The chemical changes are most obvious at Grjótagjá (Figure 3), which is located in the center of the shallow warm groundwater system. The other locations are situated closer to the edges of the system. Changes in the chemistry are less abrupt there, probably due to dispersion, cooling along the flow path and mixing with cold groundwater. The general observed changes are:

- An increase in temperature and the concentrations of SiO<sub>2</sub>, CO<sub>2</sub>, Na, K, and Cl since 1977.
- A decrease in the concentrations of Ca, Mg and SO<sub>4</sub> since 1977.
- Some fluctuation in pH.

### **2.2.1 Temperature**

At all locations a major rise in temperature occurred in 1977, related to the eruption of September 1977. The temperature increased 15°C in Grjótagjá and Stóragjá, 20°C in the Kísiliðja well and 10°C in the Hitaveita cold-water well. The change in temperature is quite abrupt at Grjótagjá, but more gradual at the other locations. Especially was the temperature rise at the Hitaveita cold-water well very slow. This is probably due to dispersion, cooling and or mixing with cold groundwater. The well is located near the cold/hot groundwater boundary in the north, where possible mixing occurs between hot and cold groundwater.

In Grjótagjá and Stóragjá a minor temperature increase occurred in 1975 (2 - 3°C) which is related to the beginning of the volcanic activity in 1975.

### **2.2.2 Silica**

All monitored locations show a considerable increase in silica concentrations following the volcanic activity in 1977. The increase is approximately 70% at Grjótagjá, 35% at Stóragjá, 100% at the Kísiliðja well and 55% at the Hitaveita cold-water well. During the period 1978 to 1984 the silica concentrations of samples from Grjótagjá show a slightly increasing trend, whereas samples from Stóragjá, the Kísiliðja well and the Hitaveita cold-water well show a slightly decreasing trend. Prior to 1977 the silica concentrations were at a relatively constant value at all locations.

### **2.2.3 Sodium and potassium**

The concentrations of sodium increased at all sample sites except the Hitaveita cold-water well, in 1977. The increase is approximately 5% at Grjótagjá and 40% at Stóragjá and the Kísiliðja well. During the period 1978 to 1984 these locations have a more or less constant concentration of sodium (90 - 100 mg/kg). There is, however, an indication that the sodium concentration is decreasing at Stóragjá.

The increase in sodium is superimposed on a general decreasing trend, which can be explained by a decreasing sodium input at Bjarnarflag. At the Hitaveita cold-water well sodium remains almost constant, indicating mixing with cold groundwater.

The changes in potassium concentrations are more or less the same as those for sodium. Potassium increased by 80% at Grjótagjá and Stóragjá and some 60% at the Kísiliðja well. At the Hitaveita cold-water well there is an peak in early 1977, otherwise the potassium concentration is at a constant value (6 - 7 mg/kg). It is striking to note how uniform the concentrations of sodium and potassium are at Grjótagjá, Stóragjá and the Kísiliðja well with sodium approximately 90 mg/kg and potassium 8 - 10 mg/kg. This might indicate that the groundwater at these locations is derived from the same groundwater system. The lower concentrations of sodium and potassium at the Hitaveita cold-water well may be due to mixing of hot water with cold groundwater. In addition the waste water from the diatomite factory may have some influence on the chemistry of the Hitaveita well.

#### 2.2.4 Calcium and magnesium

There is a sharp decrease in the concentrations of calcium and magnesium at all locations in 1977. Calcium decreases approximately 50% at Grjótagjá and Stóragjá and 70% at the Kísiliðja well. Magnesium decreases approximately 50% at Grjótagjá and Stóragjá and 60% at the Kísiliðja well. The samples from the Hitaveita cold-water well show more scatter in the concentrations of calcium and magnesium, but there is however a general decrease in 1977.

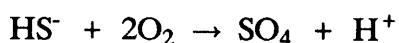
The decrease in the concentration of calcium can be explained by the decreased solubility of calcite, since all samples are supersaturated with respect to calcite. The decreased solubility is caused by the increased temperature of the water. Precipitation of calcite could then be correlated with a decrease in CO<sub>2</sub> and an increase in pH. These changes are most evident at Grjótagjá. A decrease in the concentration of calcium in Grjótagjá took place in 1975 when the volcano-tectonic activity in the Krafla area started. The decrease in magnesium is also due to the fact, that the solubility of magnesium-silicates decreases with increasing temperature which most likely controls the magnesium concentration of the water.

#### 2.2.5 Chloride

The response of chloride to the eruption of September 1977 is not as clear as for some of the other elements, but generally the concentration of chloride has increased. It should be mentioned that the chemical analysis of chloride at low concentrations levels are not as accurate as the analysis of the other elements used in this study, so it is more difficult to interpret changes in the chloride concentrations.

#### 2.2.6 Sulphate

The sulphate is of volcanic origin like CO<sub>2</sub>. The increased volcanic activity has increased the H<sub>2</sub>S of the groundwater, which has subsequently been oxidized to SO<sub>4</sub>. This chemical reaction can be demonstrated by the following reaction:



This reaction releases hydrogen to the groundwater and decreases the pH, which in turns explains the low pH value of the hot groundwater (pH = 8.4) compared to that of the cold groundwater (pH = 9.0).

The volcanic origin of sulphate explains the peaks in SO<sub>4</sub> at Grjótagjá at the end of 1975 and 1977. The peaks are clearly related to the eruptions in December 1975 and September 1977. These volcanic events also explain the increase in SO<sub>4</sub> prior to 1977 at the Kísiliðja well and the Hitaveita cold-water well.

The overall effect of the increased volcanic activity, however, caused a decrease in SO<sub>4</sub>. After 1977, SO<sub>4</sub> decreased to much lower concentrations than before 1975, and at present there is a decreasing trend in SO<sub>4</sub> at all sample sites. This observation indicates, that the total amount of SO<sub>4</sub> is limited. One possible explanation might be that the groundwater is in equilibrium with anhydrite, which would then control the

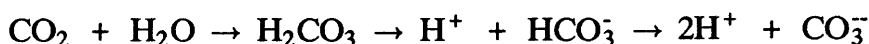


amount of SO<sub>4</sub> available to the system. This is not the case however, because all the samples are undersaturated with respect with gypsum as other geothermal waters in Iceland.

Another explanation for the lowering of the SO<sub>4</sub> concentration is a decrease of the sulphate input into the shallow groundwater system at the hydrothermal zone of Bjarnarflag.

### 2.2.7 Carbon-dioxide and pH

The increase in the concentration of CO<sub>2</sub> in the groundwater is related to the volcanic activity in December 1975 and September 1977. This is also reflected in the changes in the pH of the water. An increase in the concentration of CO<sub>2</sub> decreases the pH. This can be explained by the following carbonate reaction:



As noted before the equilibrium with calcite is also important when evaluating the changes in the concentration of CO<sub>2</sub> and the pH.

The changes in CO<sub>2</sub> are most evident at Grjótagjá. There are sharp peaks which correlate with the eruptions of December 1975 and September 1977. The changes are not as evident at Stóragjá. There are small peaks that correlate with the eruptions in 1975 and 1977 and they are superimposed on a decreasing trend. The pH is more or less constant (ca 8.4). At the Kísiliðja well the changes in CO<sub>2</sub> are comparable with the changes at Stóragjá, whereas at the Hitaveita cold-water well the only change that occurs follows the eruption in December 1975.

## 2.3 Chemical changes in the Námafjall geothermal system

Chemical analyses from well 4, 8 and 10 are used to evaluate the chemical changes in the Námafjall geothermal system. Samples were taken from these wells prior to and after the eruption in September 1977. Well 10 can be expected to behave somewhat differently from the other wells, because it is much deeper and derives fluid from deeper aquifers. The depth of well 10 is about 2000 m, whereas the depth of wells 4 and 8 is about 1200 m.

It is to be expected that there is a relation between the chemical changes in the shallow groundwater system and the changes in the deeper geothermal system of the Námafjall area. After flashing and degassing some of the geothermal water enters the shallow groundwater system as the natural outlet of the Námafjall geothermal field.

In the following discussion of the chemical changes in wells 4 (Figure 7), 8 (Figure 8) and 10 (Figure 9), the concentration of each chemical component has been calculated from analyses of water and steam samples collected on wellhead (Arnórsson, S. et al. 1982), assuming that the enthalpy of the total discharge corresponds to that of water at the initial quartz equilibrium temperature.

The chemical changes in the deep geothermal system are much more abrupt than in the shallow groundwater system. Sharp peaks due to increased concentrations of

different chemical components can be correlated with the eruption in September 1977, and especially do the gasses show large fluctuation. The general chemical changes in the deep system are comparable to the those of shallow groundwater system:

- An increase in the concentration of  $\text{SiO}_2$ ,  $\text{CO}_2$ , Na, K and Cl.
- A decrease in the concentration of  $\text{SO}_4$ .

### **2.3.1 Silica in wells 4 and 8**

For both wells the  $\text{SiO}_2$  concentrations decreases during the period recorded. The  $\text{SiO}_2$  concentration in well 4 has decreased from 560 to 420 mg/kg and in well 8 it has decreased from 510 to 420 mg/kg. This can be explained by increased flashing in the reservoir caused by pressure drop due to exploitation of the system. The increased flashing of the reservoir leads to cooling and the precipitation of silica (Arnórsson, S., 1977). The decrease in  $\text{SiO}_2$  concentration after 1978 can also be explained by the intrusion of cold groundwater along faults and fissures, which were active during that periode. A peak in the concentration of silica is superimposed on the decreasing trend in 1977, probably due to the increased solubility of silica at higher temperatures, following the volcano-tectonic activity in September 1977.

### **2.3.2 Sodium and potassium in wells 4 and 8**

The concentrations of sodium and potassium show a decreasing trend for the recorded period. This is probably caused by the same factors that affect the  $\text{SiO}_2$  concentrations. The Na/K ratio increased, indicating that reequilibrium of the cooled water with NaKCa-silicates takes place. It is likely that equilibrium exists between Na, K and Ca on one hand and H and some silicates on the other. Mixing with cold water can not explain the decrease in Na and K, because there is no correlation between the changes in the concentration of  $\text{SiO}_2$  on one hand and Na and K on the other.

In relation to the eruption of September 1977, both wells show a sharp increase in the concentration of sodium. In well 8 there is also a sharp increase in the concentration of potassium. The peaks in sodium and potassium might be explained by a shift in the equilibrium between sodium and potassium with the silicates due to the increased temperature of the reservoir in 1977.

### **2.3.3 Calcium and magnesium in wells 4 and 8**

The concentrations of calcium and magnesium are much lower in the deep geothermal system than in the shallow groundwater system due to the low solubility of carbonates at high temperatures. The concentration of calcium and magnesium are generally less than 4 and 0.1 mg/kg for wells 4 and 8 respectively.

Since 1977 the concentration of calcium seems to have increased from about 1 to 3 mg/kg. This has led to a stronger supersaturation with respect to calcite. It is possible that the increase in calcium is caused by the increased solubility of calcite during periods of increased gas concentrations ( $\text{CO}_2$  and  $\text{H}_2\text{S}$ ), which are reflected in lower pH of the fluid.

During flashing and degassing CO<sub>2</sub> and H<sub>2</sub>S are transferred into the steamphase, causing an increase in pH and CO<sub>3</sub><sup>-</sup> activity of the fluid. The increase in CO<sub>3</sub><sup>-</sup> is sufficient to cause supersaturation with respect to calcite, when the rate of precipitation is not sufficient to restore equilibrium (Arnórsson, S. et al. 1978).

### 2.3.4 Chloride in wells 4 and 8

The changes in the concentration of chloride seem to be more scattered than those for silica, sodium and potassium. This could be due to inaccurate analysis of chloride which makes all interpretation of the changes in chloride concentrations very difficult. The overall effect of the volcanic activity is though a general increase in chloride, which indicates increased leaching of chloride from the country rock, or an intrusion of Cl-rich gases from the magma into the geothermal system.

### 2.3.5 Gasses and sulphate in wells 4 and 8

Peakes in the gas concentrations can be related to the volcanic activity of the area, indicating the volcanic origin of gasses like CO<sub>2</sub>, H<sub>2</sub> and H<sub>2</sub>. A sharp increase in the gas concentrations is associated with the eruption of September 1977. Peaks in gas concentrations can also be correlated with the volcanic events of November 1978 and May 1979, although no magma flow from the Krafla central volcano towards the south has been reported (Tryggvason, E. 1980).

To get a better insight into the changes in the SO<sub>4</sub> and H<sub>2</sub>S concentrations it is of importance to consider the H<sub>2</sub>S/H<sub>2</sub> ratios of the fluid. The average concentrations of H<sub>2</sub>S and H<sub>2</sub> and their ratios prior to and after the eruption of September 1977 are reported in Table 1.

Table 1. Concentrations of H<sub>2</sub>S and H<sub>2</sub> and their ratio from wells 4 and 8 (mg/kg).

	Well 4			Well 8		
	H <sub>2</sub>	H <sub>2</sub> S	H <sub>2</sub> S/H <sub>2</sub>	H <sub>2</sub>	H <sub>2</sub> S	H <sub>2</sub> S/H <sub>2</sub>
before 1977	4.4	160	36.4	4.7	171	36.4
peak 1977	83	724	8.7	43	489	11.4
after 1977	9.6	220	22.9	24.5	334	13.6

Before the eruption of September 1977 the H<sub>2</sub>S/H<sub>2</sub> ratio of the samples from wells 4 and 8 are equal. The eruption added relatively much more H<sub>2</sub> than H<sub>2</sub>S to the geothermal system. This caused a decrease in the H<sub>2</sub>S/H<sub>2</sub> ratio. The ratio has remained much lower after the eruption than it was before.

The following equilibrium exists between H<sub>2</sub>S and H<sub>2</sub>:



This equilibrium can be shifted because of degassing of magma (Ármansson, H. et al. 1982). During the eruption of September 1977 this equilibrium was shifted to the left, which may explain the decrease in the concentration of  $\text{SO}_4$  after 1977.

The concentration of sulphate prior to 1977 are scattered and uncertain, which is assumed to be mainly due to different analytical methods. However, it can be concluded that in general has the concentration of  $\text{SO}_4$  decreased since 1977. Superimposed on this decreasing trend are peaks which may be correlated with volcanic activity October - November 1978 and May 1979.

### **2.3.6 Silica and chloride in well 10**

In contrast to wells 4 and 8 there was a sharp decrease in the concentration of silica and chloride which can be correlated with the eruption in September 1977. The samples taken just prior to the eruption show high silica concentrations then the silica content decreases drastically and increases again in 1979.

The concentration of chloride decreases at the end of 1977 but increases slightly again in 1979. Similar changes were observed for wells 4 and 8 and a plausible explanation is an invasion of cold groundwater into the geothermal system after the eruption in 1977.

The chemical changes in well 10 can clearly be related to a cold water intrusion. There is a clear correlation between the chemical changes of silica and chloride, and also sodium, potassium, hydrogen and hydrogen sulphide and the mixing with cold groundwater. Furthermore it is known that the enthalpy of the well decreased in 1977. The temperature decreased from 260 - 220°C, which agrees more or less with the temperatures obtained by the quartz-thermometer (280 - 220°C) and the Na-K thermometer (260 - 200°C).

Based on the current data it can be concluded that an invasion of cold water into the geothermal system took place after the eruption in September 1977. The opening of many fissures which took place during this eruption favoured the downward transportation of cold water, just as it favoured the upward movement of the hot geothermal fluid. This caused increased hydrothermal activity at Bjarnarflag.

### **2.3.7 Sulphate in well 10**

The changes of the fluid chemistry from well 10 with respect to sulphate is exactly opposite to that of the shallow wells 4 and 8. The concentration of sulphate increased in well 10 whereas it decreased in wells 4 and 8 during the volcanic activity in the area. A better insight into these changes can be obtained by comparing the  $\text{H}_2\text{S}/\text{H}_2$  ratios, as shown in Table 2.

*Table 2. Concentrations of H<sub>2</sub>S and H<sub>2</sub> and their ratio from well 10 (mg/kg).*

	H <sub>2</sub>	H <sub>2</sub> S	H <sub>2</sub> S/H <sub>2</sub>
before 1977	12.6	285	22.6
peak 1977	26.1	430	16.5
after 1977	7.7	222	28.8

Prior to the eruption the H<sub>2</sub>S/H<sub>2</sub> ratio of well 10 was much lower than those of wells 4 and 8. This indicates that the geothermal fluid becomes more and more degassed during upward transportation. Because of the eruption the H<sub>2</sub>S/H<sub>2</sub> ratio of wells 4 and 8 decreased whereas the ratio in well 10 increased. From this it may be concluded that increased flashing and degassing after the eruption in 1977 has led to a depletion in H<sub>2</sub> in the deepest part of the geothermal system. An other possible explanation is that the cold water invasion has caused these changes in the fluid chemistry.

The decrease in H<sub>2</sub>S/H<sub>2</sub> ratio in wells 4 and 8 resulted in lower concentration of sulphate in those wells whereas the opposite happened in well 10.

## 2.4 Conclusions

It is clearly reflected by the present data that there is a connection between the deep geothermal system at Námafjall and the shallow groundwater system. Hot geothermal fluid flashes from the Námafjall geothermal field upwards through open fissures, causing the hydrothermal activities (hot springs, mudpools and fumeroles) at Bjarnarflag. Hot flashed water then enters the shallow groundwater system.

The eruption of September 1977 caused major changes in the chemistry of the groundwater and in the hydrology of the groundwater system. In the deep geothermal system an decrease in the concentration of silica, sodium, potassium, chloride, carbon-dioxide, hydrogen-sulphide, hydrogen, calcium and magnesium took place and an increase in the concentration of sulphate and the H<sub>2</sub>S/H<sub>2</sub> ratio. Many new fissures opened and old once were reactivated in September 1977. Along many fissures the hydrothermal activities at Bjarnarflag increased as well as the natural discharge from the shallow groundwater system. This caused an increase in temperature and in the concentration of silica, sodium, potassium, chloride and carbon-dioxide of the shallow groundwater system and a decrease in the concentration of sulphate.

The opening of fissures in September 1977 caused intrusion of cold water into the geothermal system. This cold water invasion led to the lowering of the concentrations of chloride, silica, sodium, potassium, hydrogen-sulphide and hydrogen in the deepest part of the geothermal system (well 10). A cold water invasion was also observed in the shallower wells 4 and 8.

The deepest part of the geothermal system was depleted in hydrogen due to increased flashing and degassing. This resulted in higher H<sub>2</sub>S/H<sub>2</sub> ratios and in higher concentrations of sulphate. The shallower part of the deep geothermal system

became enriched in hydrogen which then in turn caused lower concentrations of sulphate.

Most of the chemical changes of the geothermal fluid can be explained by shifting of the mineral/solute equilibria caused by increased temperature or flashing and by the increased fluid exchange between the different groundwater systems through opened fissures. The changes in gas concentrations ( $\text{CO}_2$ ,  $\text{H}_2\text{S}$  and  $\text{H}_2$ ) are of direct magmatic origin and were caused by the degassing of magma.

### **3. THE HYDROLOGY OF THE SHALLOW GROUNDWATER SYSTEM**

#### **3.1 Description of the aquifers**

In the area studied east of Mývatn, different basaltic lava flows are exposed as indicated on the geological map on Figure 10. They are all of postglacial age (Thorarinsson, S. 1979). The lava flows are bound in the north by glacial moraines and in the east by older lava flows and by pleistocene hyaloclastites of the Námafjall ridge. A detailed description of the volcanic history of the Mývatn area has been given by S. Thorarinsson 1979.

The postglacial lava flows act as very good aquifers, because of the numerous open fissures and large active faults with a NNE/SSW strike like Grjótagjá and Stóragjá. The faults are related to a large north-south fissure swarm. That the lavas are derived from north-south fissures near the Námafjall ridge and they have flowed in western to southwestern direction into lake Mývatn. Only the Young Laxá lava has flown in northwestern directions. From this it can be concluded that fissures which have developed in the lava flows during cooling have preferential E-W to SW-NE directions. It can also be expected that the lava layers have a general dip towards the southwest.

Figure 11 shows a map of observational points associated with the present study. Furthermore, Table 3 lists measured temperature at all locations and some remarks on some of the places.

The stratigraphic section west of Námafjall is only known from borehole profiles of some shallow boreholes east of Reykjahlid (Figure 12). The wells are all 40 to 45 m deep and only the well at location 42 reaches the bottom of the lava flows. There at a depth of 24 m moraines were present and at a depth of 38 m pleistocene hyaloclastites. The well does not contain any water, so the moraines and the hyaloclastites are less permeable than the lavas. Going from location 42 to the south the thickness of the postglacial lava flows increases rapidly to at least 50 m. It can also be seen on figure 10 that the lava layers are dipping southwest.

The postglacial lava flows consist of an alternation of lava and scoria layers. From the bore profiles it can be concluded that the uppermost layer consist mainly of lava layers to a depth of 20 to 25 m. These layers are underlain by a sequence of scoria layers, interbedded with lavas.

It can be expected that the fissured lavas to a depth of 25 m act as very good aquifers. Groundwater will flow preferentially from north to south through the north-south faults and from east to west according to the direction of the lava flows. The scoria layers act probably more as homogeneous aquifer.

#### **3.2 The direction of the groundwaterflow**

During a fieldwork in May 1983 measurements were made of groundwater temperature in hot springs near Lake Mývatn and in shallow boreholes and in the fissures Grjótagjá and Stóragjá. With a compilation of this data a isothermure-map

Table 3. Description on observational locations.

Location	Temperature (°C)	Remarks
1	36.0	Stóragjá, sample 83-1006
2	37.0	Egilshola, sample 83-1026
3	46.6	Kísiliója well, sample 83-1009
4	34.2	Hitaveita well, sample 83-1007
5	53.0	Grjótagjá, sample 83-1005
6	47.0	
7	7.0	
8	-	Vapour, temp. >20°C
9	5.5	
10	5.6	
11	6.0	Sample 83-1018
12	5.5	
13	6.8	
14	7.2	
15	7.0	
16	14.0	Sample 83-1017
17	16.8	
18	27.0	
19	26.5	Sample 83-1016
20	25.5	
21	-	
22	23.0	
23	22.4	
24	21.5	
25	15.0	
26	17.0	
27	19.8	
28	18.0	
29	22.0	
30	21.0	
31	20.0	
32	21.0	
33	24.0	
34	24.7	
35	26.5	
36	27.5	
37	26.0	
38	27.0	
39	29.0	Helgavogur
40	32.5	Sample 83-1015
41	31.5	
42	-	Shallow dry well
43	-	Injection of waste water from diatomite factory
44	-	Shallow well
45	22.0	Measured in 1981



has been drawn (Figure 13).

On the map it can be seen that the groundwater temperature decreases in western and southern directions. From the chemistry of the shallow groundwater it can be concluded that mixing of the hot groundwater with cold groundwater or infiltration by rain and snowmelt water is only important near the hot/cold water boundary zones. This means that the decrease in temperature is caused by conductive cooling of the groundwater. Assuming conductive cooling of the groundwater along its flowpath one can draw groundwater flowlines more or less perpendicular to the isotherm lines.

From Figure 13 it becomes clear, that hot groundwater is flowing from Bjarnarflag, where hot water from the geothermal system can enter the shallow groundwater system through active open faults, in southwestern directions. West of Grjótagjá the hot groundwater flows in western to southwestern directions into Lake Mývatn. The groundwater seems to move in three main tongues. The northern most through Kísiliðja and Stóragjá and ending just north of Helgavogur, the middle tongue from Grjótagjá towards the west and ending between Vogar and Kálfatjörn, the southern tongue going first south through Grjótagjá and ending south of Langivogur. The groundwaterflow is concentrated in these three tongues. This results in a higher velocity and higher temperatures of the groundwater flow because of less cooling at higher velocities.

Comparing this picture with the geology there seems to be a good fit. South of Helgavogur and west of Stóragjá, Pleistocene hyaloclastites are exposed (Figure 14). These hyaloclastites seem to be impermeable, because there are no springs at the lake shore where the hyaloclastites are exposed. It was mentioned earlier that the well at location 42, which was drilled into the hyaloclastites, was dry. The presence of hyaloclastic rocks forms a barrier for the groundwater, and its flow is deflected around the hyaloclastites. This is the case for the northern groundwater tongue at Helgavogur and for the middle tongue at Kálfatjörn.

The northern tongue could be divided into two tongues. Some of the groundwater flows from Stóragjá towards the northwest, where some springs can be found at the lake (location 45). However most of the groundwater is deflected from Stóragjá towards the southwest according to fluorescence dye experiments of 1981 (Thoroddson, Th. and G. Sigbjarnarson, 1983)

Generally there seems to be a clear relation between the direction of the groundwaterflow and the direction of the lava flows. This explains the presence of the southernmost groundwater tongue south of Langivogur where the groundwater is forced to flow in a westerly directions according to the direction of the lava flow. Cold groundwater flows to the northwest according to the direction of this lava flow. This also explains the fact that the hot/cold water boundary zone did not move far into the Young Laxá lava.

### 3.3 Chemical processes in the shallow groundwater system

In order to determine whether or not mixing occurs within the shallow groundwater system, some samples were taken in May 1983 (for location see Table 3 and Figure 11). Mixing of two different watertypes should give a linear relation between Na and Cl, and K and Cl (Figure 15). On Figure 15, two different straight lines can be drawn. The line with the steeper slope corresponds with the samples taken from Grjótagjá and from the hot/cold water boundary zone in the south (locations 5, 12, 16, 18). The straight line with the more gentle slope corresponds to the samples taken in the north (locations 40, 1, 2, 3, 4). Only the Kísiliðja well (location 3) seems to have an intermediate position with respect to Na.

From this it can be concluded that mixing between hot and cold groundwater takes place and that there are two different mixing systems. One in the north and another one in the south.

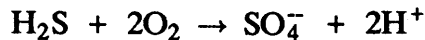
In order to get a better idea of the chemical changes in the groundwater along its flowpath two chemical profiles were drawn: Profile AB in the north, where groundwater is flowing to the west, and profile CE in the south, where groundwater is flowing towards southwest. The profiles are shown on figures 16 and 17 (for location see Figure 11).

#### 3.3.1 The mixing system in the north

Changes in groundwater chemistry along the flow-direction from the Kísiliðja well to the west (profile A-B) are quite small (Figure 16). The concentrations of Na, CO<sub>2</sub> and SiO<sub>2</sub> decrease, the rest remains more or less constant. If mixing with cold groundwater takes place, the amount of mixing is very small. This agrees with the fact that the cold groundwater flows from the north, where less pervious glacial moraines are exposed. From the samples available it is not clear whether mixing with cold groundwater from the north takes place or the changes in chemistry are caused by infiltration of rain or snowmelt water or by the cooling of the hot groundwater.

There are large differences in the chemistry of the warm water in the Hitaveita well and the Kísiliðja well. The much lower concentrations of Na, K and Cl at the Hitaveita well were already explained by possible mixing with cold groundwater. It was also mentioned earlier that the waste water of the diatomite factory has some influence on the chemistry of the Hitaveita well. The waste water is injected north east of the Hitaveita well just on the other side of the old storage ponds of the factory. From the differences in chemistry between the Kísiliðja well and the Hitaveita well it can be concluded that the waste water of the diatomite factory influences the chemical composition of the Hitaveita well. The increase of the CO<sub>2</sub>, SO<sub>4</sub>, Ca and Mg concentrations to much higher values than the normal cold groundwater concentrations indicates that mixing with pure cold groundwater can not be the case. The pH value at the Hitaveita well is also much lower than the pH of cold groundwater.

The very high SO<sub>4</sub> concentrations combined with the low pH values at Hitaveita can be explained by oxidation of H<sub>2</sub>S:



The extra H<sub>2</sub>S should than be added by the waste water of the diatomite factory.

### 3.3.2 The mixing system in the south

From profile CE (Figure 17) it can be concluded that major chemical changes occur only near the hot/cold water boundary zone. The chemical differences between spring 18 and Grjótagjá are very small compared with the differences between springs 18, 16 and 12. The mixing of hot and cold groundwater is therefore restricted to the hot/cold water boundary zone. There a sharp decrease in concentrations and in temperatures takes place (except for Mg). The pH increases at the boundary zone. This is caused by mixing of the hot groundwater with much more dilute cold groundwater (Ólafsson, J. 1979). Infiltration of rain or snowmelt water is small compared to the amount of admixed hot groundwater flow.

By comparing the samples from Grjótagjá and spring 18 something can be said about the mineral/solute equilibria which determine the groundwater composition. The decrease in SiO<sub>2</sub> concentration indicates that precipitation of silica takes place. Along the groundwater flowpath cooling increases the degree of supersaturation with respect to silica. The increasing supersaturation causes precipitation of silica.

Further there is a remarkable increase in Mg along the groundwater flowpath from 3-7.5 mg/kg although cold groundwater only contains 2-4 mg/kg of Mg. The increase in Mg can be explained by the presence of ionexchange reactions, where the exchange takes place between Mg on one hand and Na, H, K and Ca on the other hand.

### 3.4 The location of the temperature fronts

The location of the hot/cold water boundary zone in the north can be correlated with the exposure of glacial morains in the area.

In the south regular temperature measurements have been done at some springs near the hot/cold water boundary zone. A profile is drawn along these springs (profile CD on Figure 11) and the changes in the temperature front recorded (see Figure 18):

It is clear from Figure 18 that the temperature of the springs has increased since the eruption of September 1977 and the temperature front also shifted towards the south. Since 1979, however, the temperature front has been moving back again.

The shifting of the temperature front to the south indicates an increased flow of the hot groundwater. The increase in the temperature of the springs indicates an increase in the temperature of the hot groundwater. The maximum shift of the temperature front took place in 1979, two years after the eruption of September 1977.

The temperature front is moving back again, but the temperature of the springs have not much decreased yet. This indicates that although the amount of hot groundwaterflow to the south has decreased, the temperature of the hot groundwater has not decreased much yet.

In 1981 a vertical profile of groundwater temperature, velocity and resistivity was measured at Grjótagjá (location 8, Figure 11). The results are shown on Figure 19. From the profile it becomes clear how the mixing of the hot and cold groundwater takes place. In the uppermost part to a depth of 1 meter hot groundwater is flowing in the opposite direction. There is a sharp boundary between the two water types as can be derived from the temperature and resistivity profiles.

From this it can be concluded that cold groundwater is intruding into the hot groundwater like a salt water intrusion. The heavier cold water pushes the lighter hot water away. So, returning to the temperature profile CD (see Figure 18), the springs with intermediate temperatures derive their water probably from a mixing zone, where hot groundwater is moving on top of the cold groundwater in the opposite direction.

### 3.5 Conclusions

At Bjarnarflag flashed hot groundwater enters the shallow groundwater system through active open faults and fissures. The aquifers of that system consist of lavas and scoria layers. From Bjarnarflag the groundwater flows in southwestern directions and reaches Lake Mývatn in three main tongues. There seems to be a relation between the direction of the lava flows and the direction of the groundwaterflow. This is probably caused by the fact that fissures, which developed during the cooling of the lava, are mostly parallel to the direction of the lava flow. It might also be caused by the general dip of the lava and scoria layers towards the southwest. The large N-S faults like Stóragjá and Grjótagjá do not form a barrier to the groundwater flow.

From the chemistry it becomes clear that mixing of hot and cold groundwater is only important near the hot/cold water boundary zone. The amount of infiltrated rain and snowmelt water is small compared to the amount of hot groundwater flow. There appear to be two different mixing zones, one in the north and one in the south.

Disequilibrium exists along the flowpath of the hot groundwater with respect to some mineral/solute equilibria, because of the cooling of the water. This leads to precipitation of silica and probably also to some ion exchange reactions of Mg with Na, K, H and Ca.

At the mixing zone in the south the temperature front of the hot groundwater moved towards the south after the eruption of sept. 1977. Since 1979 the temperature front is moving back again. This indicates that the temperature and the amount of hot groundwater increased because of the eruption of sept. 1977. Now the amount of hot groundwater decreases again, although the temperature has decreased only slightly since 1977. The decrease of the amount of hot groundwater flow to the south indicates that the uplift of the north side of Lake Mývatn had no permanent influence on the groundwater flow pattern.

In the mixing zone hot groundwater is flowing on top of the cold groundwater in the opposite direction. Springs in this zone derive a mixture of hot and cold groundwater. This agrees with the conclusion derived from the chemistry of the water, that mixing takes only place near the hot/cold groundwater boundary zone.

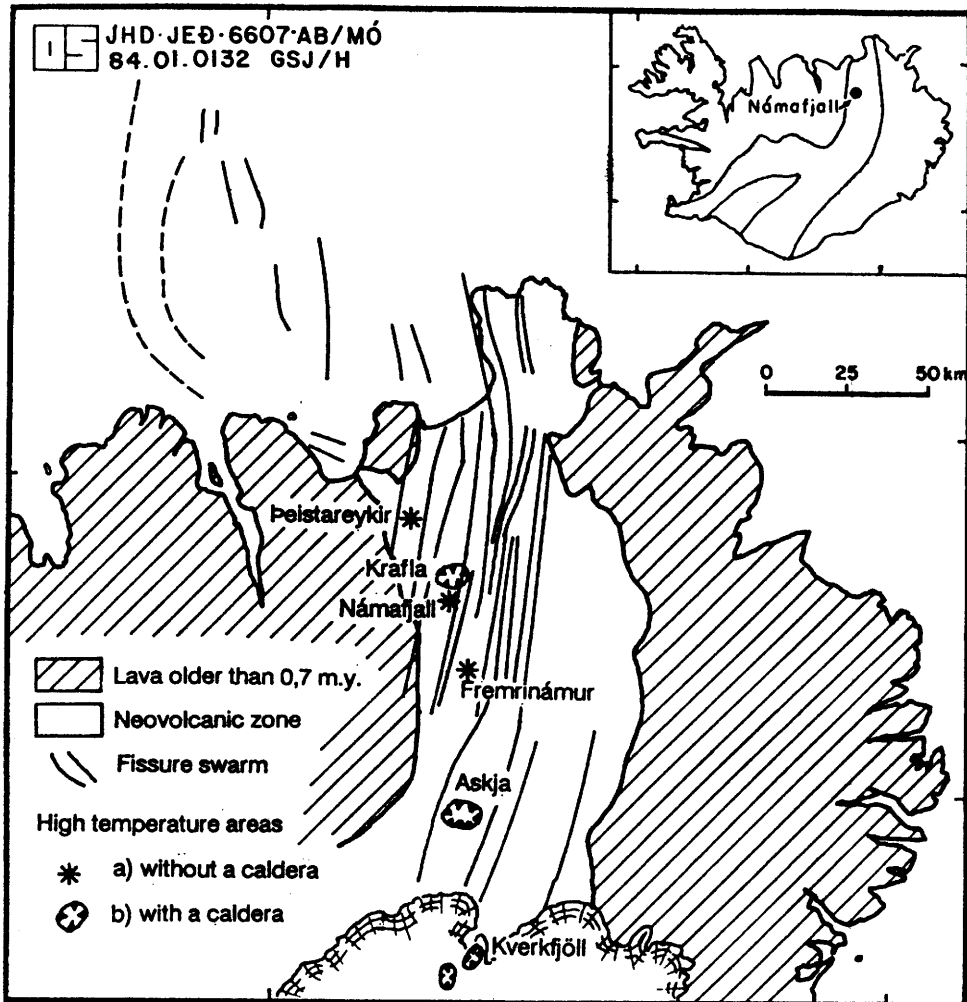
## ACKNOWLEDGEMENTS

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*Figure 1 The spreading zone of North Iceland and associated high-temperature areas.*

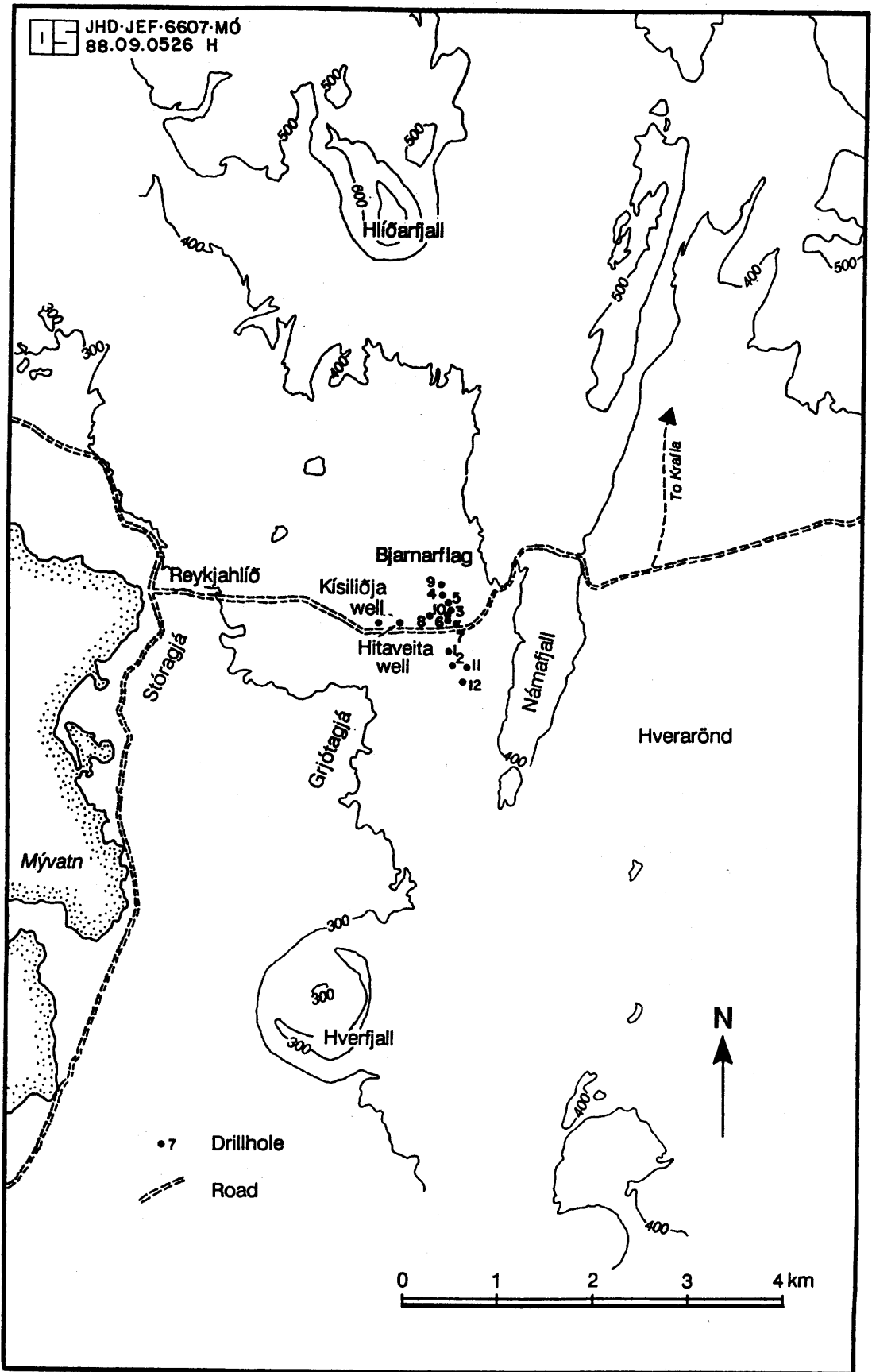


Figure 2 The Námajfall high-temperature area.  
The spreading zone of North Iceland and associated high-temperature area.

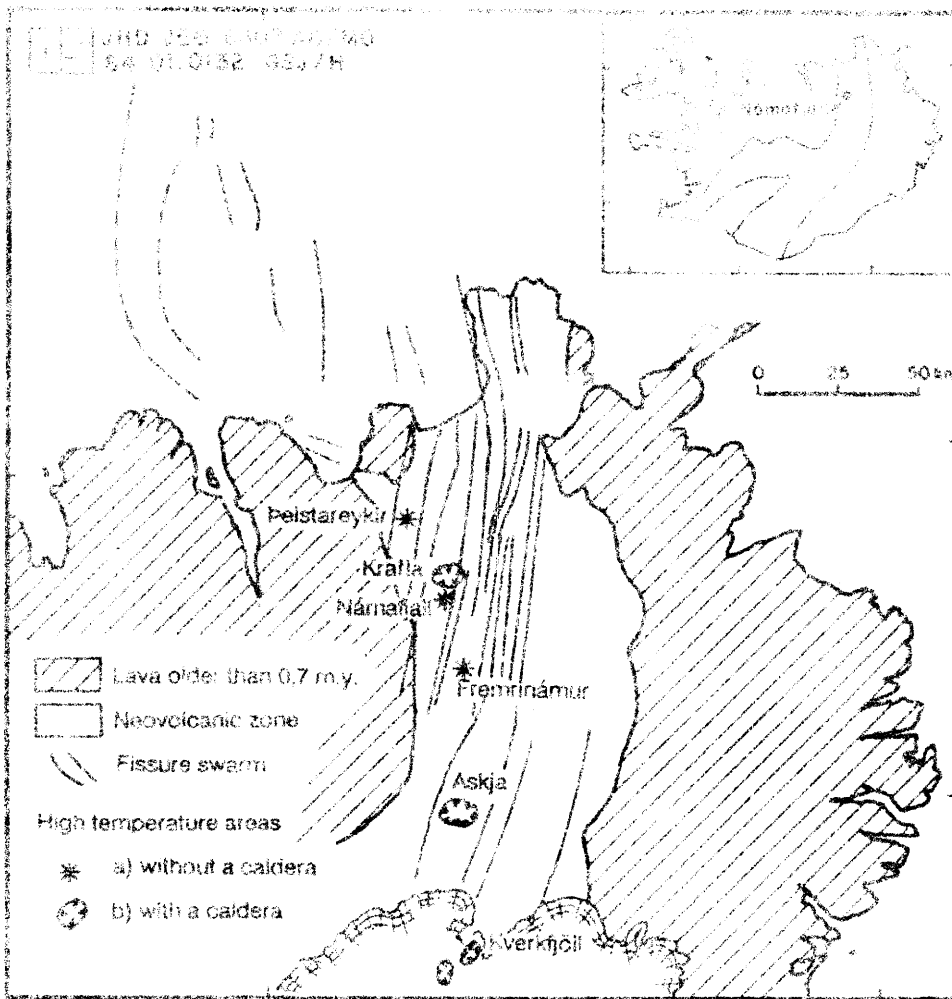


Figure 2 The Námafjall high-temperature area.



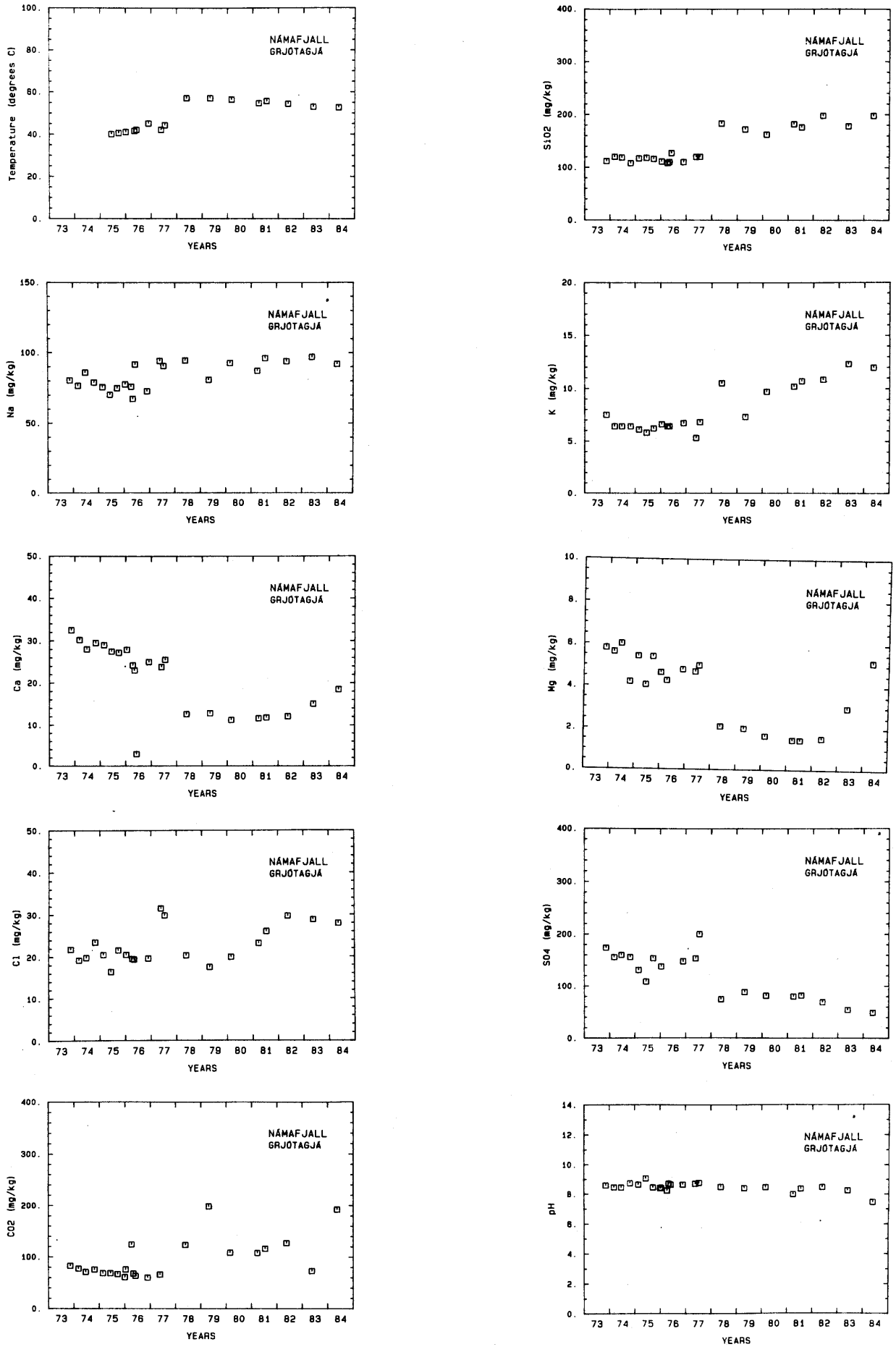


Figure 3 Chemical changes of water at Grjótagjá.

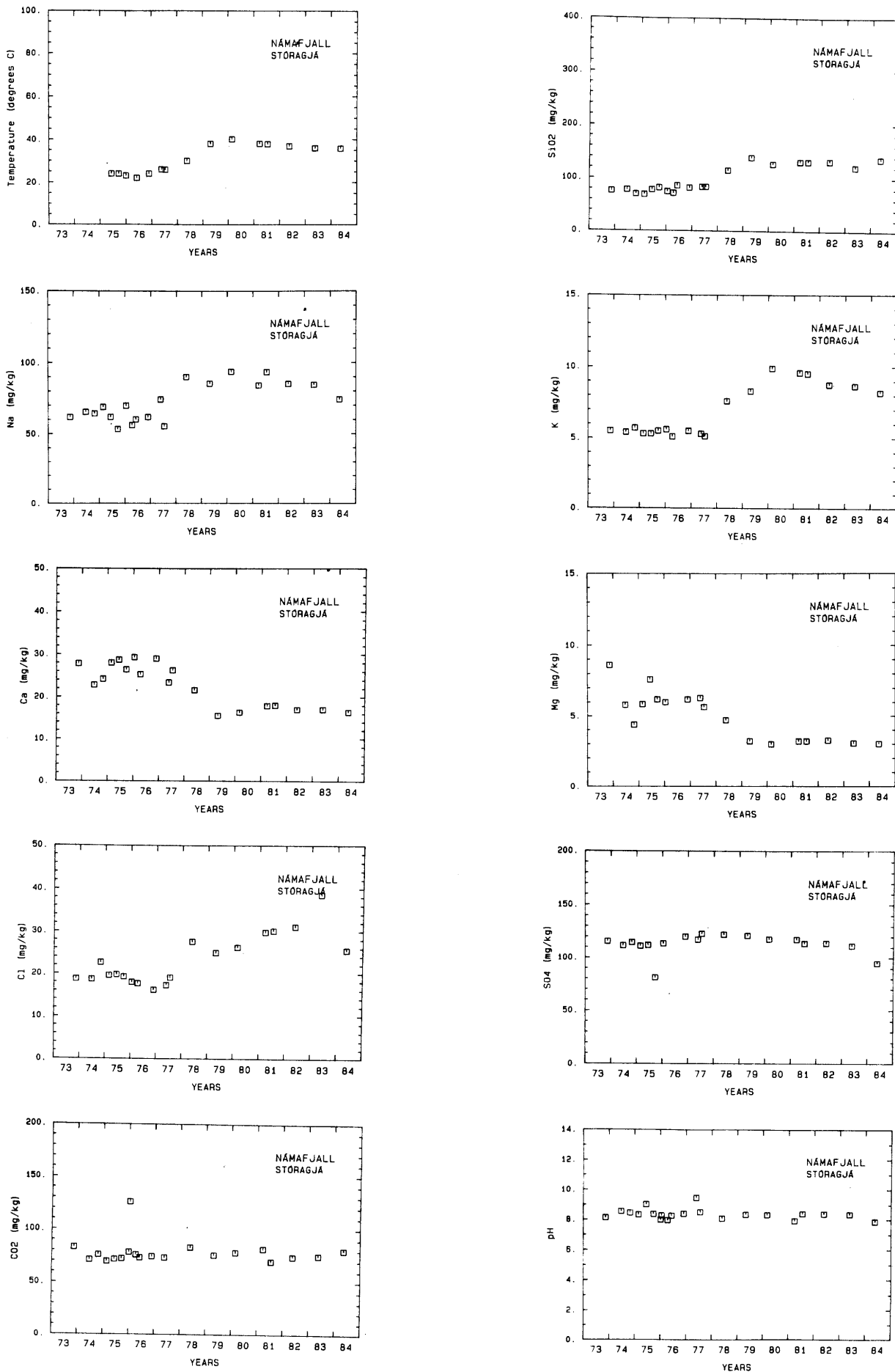


Figure 4 Chemical changes of water at Stóragjá.

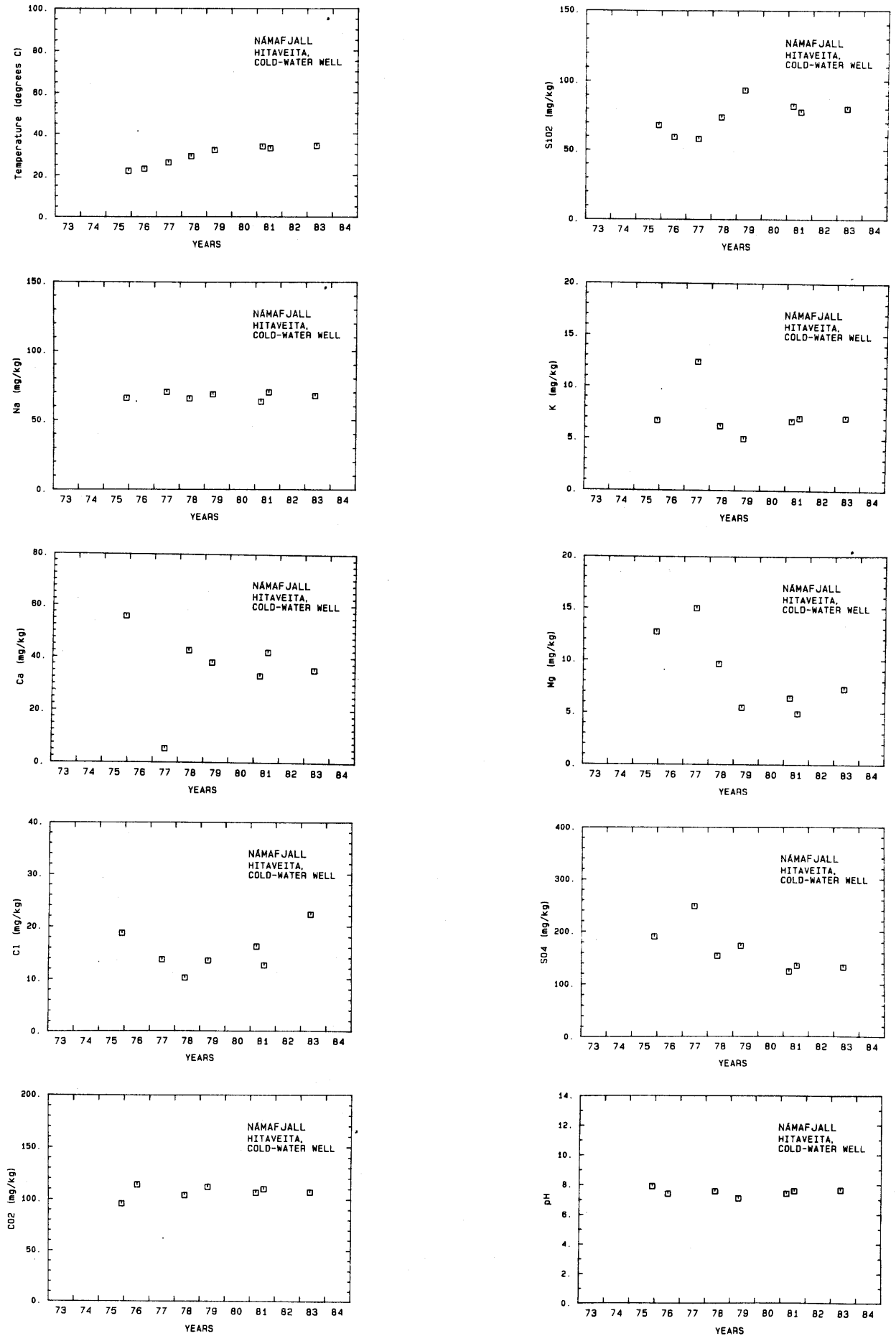


Figure 5 Chemical changes of water from the Hitaveita cold water well.

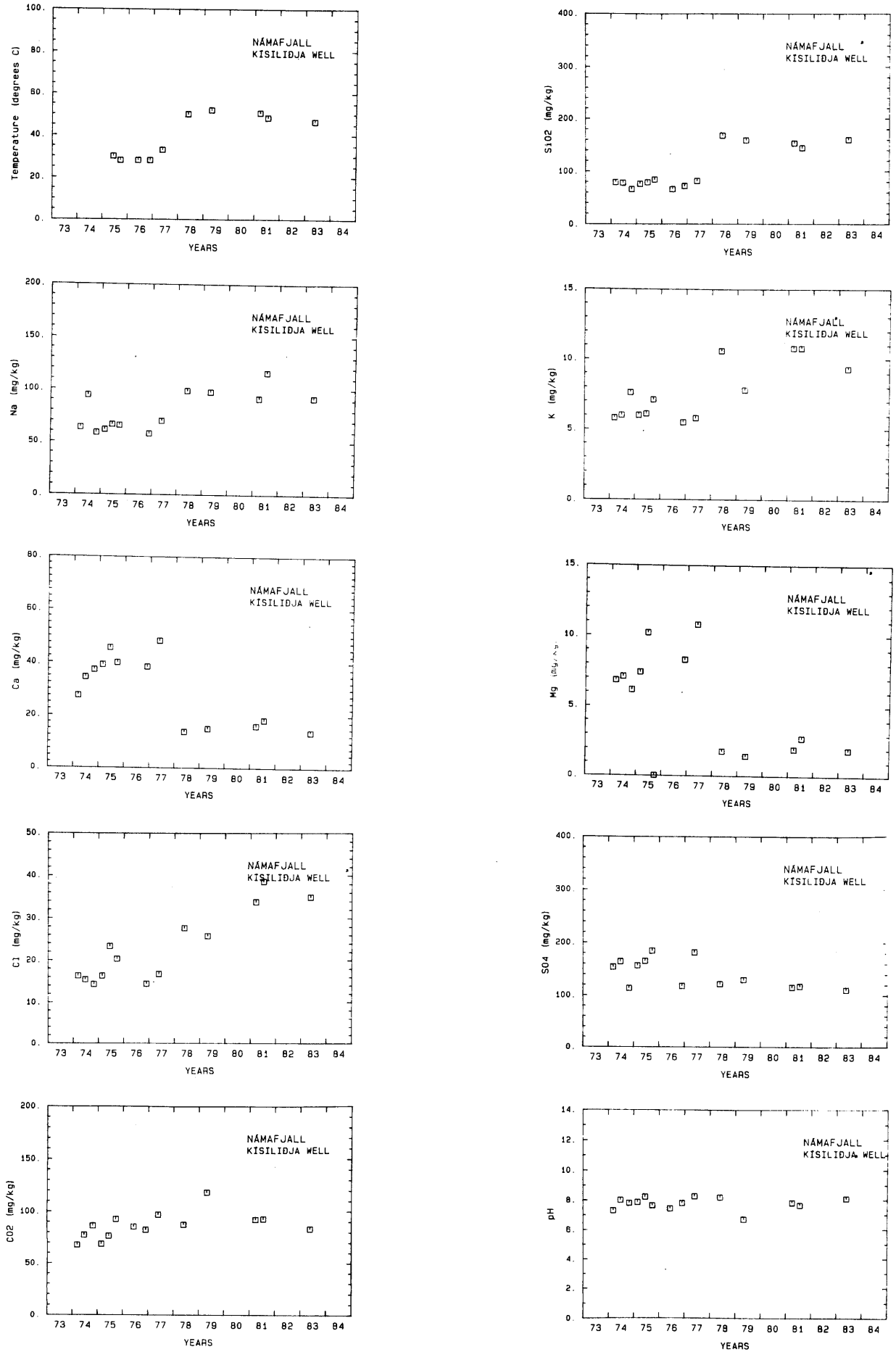


Figure 6 Chemical changes of water from the Kísiliðja well.

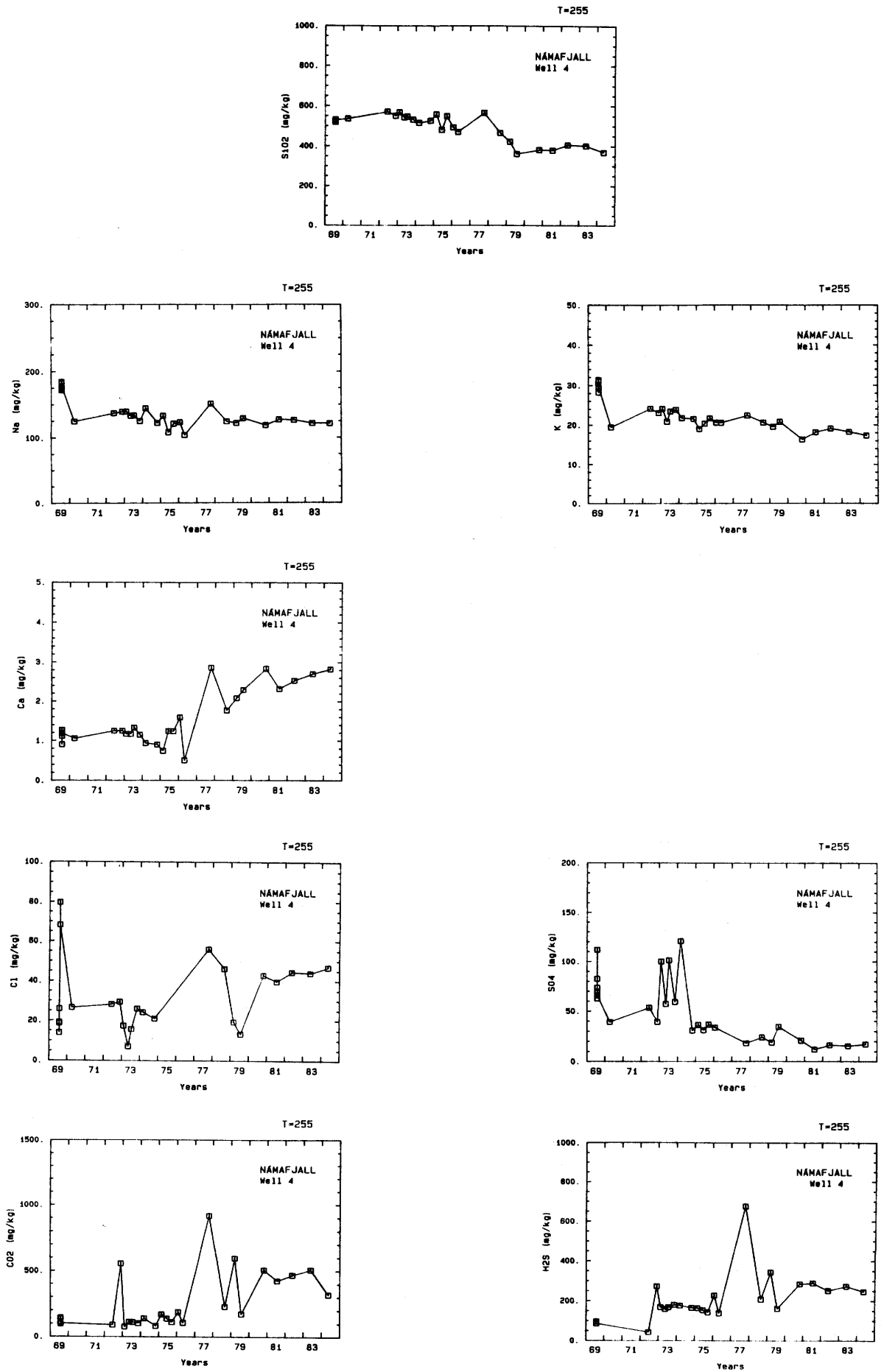


Figure 7 Chemical changes of fluid from well 4.

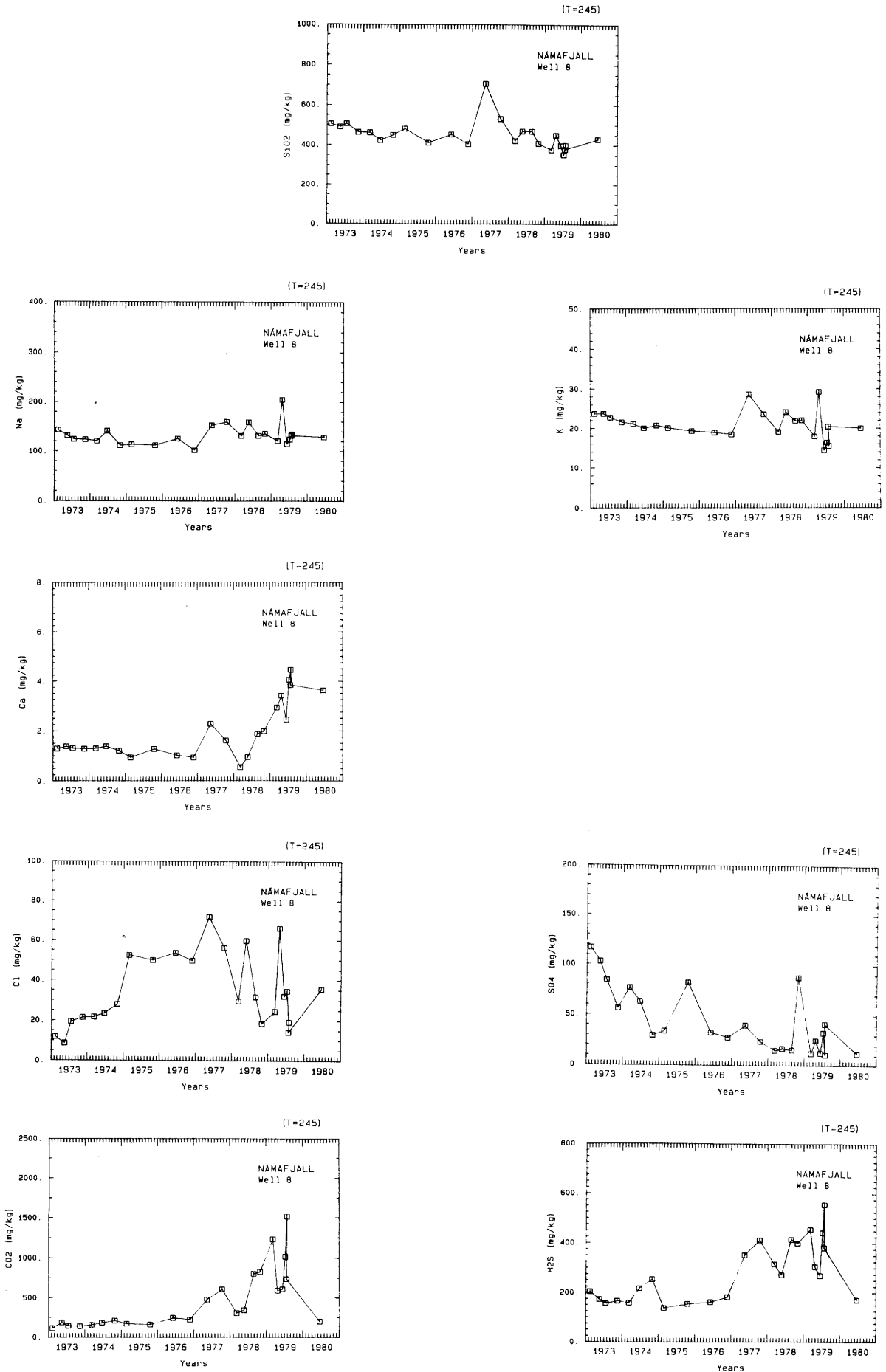


Figure 8 Chemical changes of fluid from well 8.

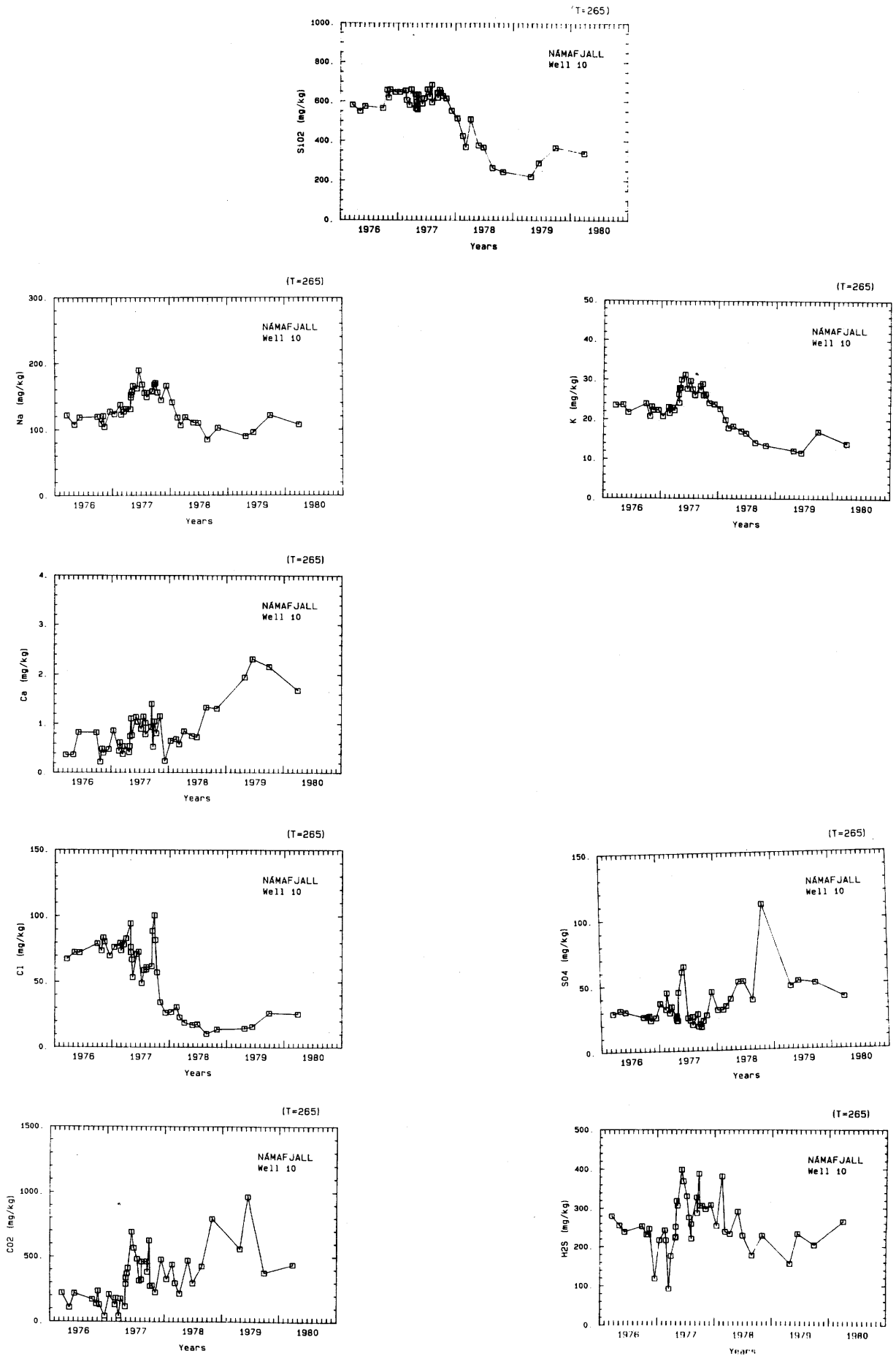


Figure 9 Chemical changes of fluid from well 10.

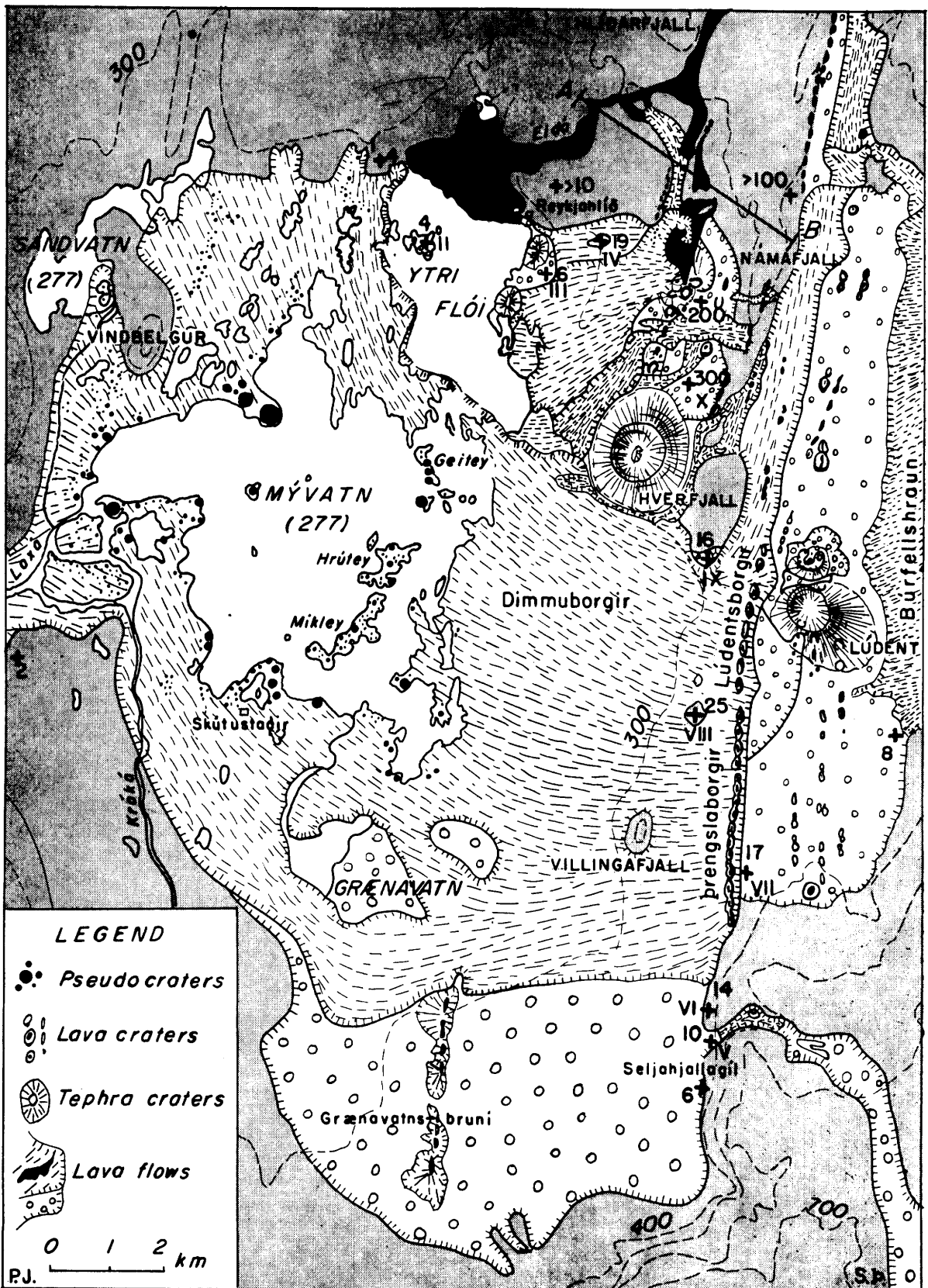


Figure 10 A geological map of the Mývatn area (from Thorarinsson, S. 1979).



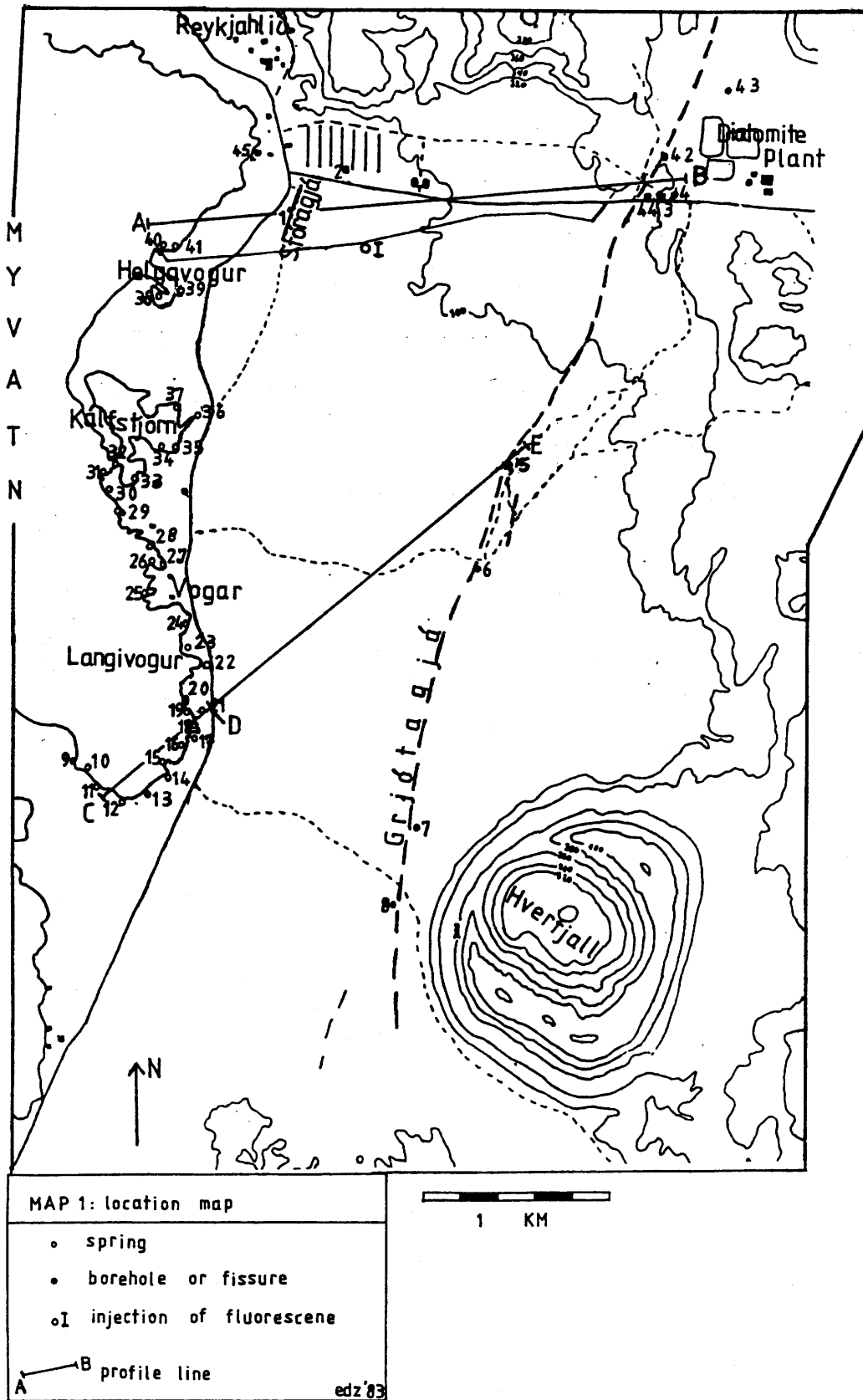


Figure 11 A map of observational locations in 1983 and the location of profiles A-B and C-D-E.

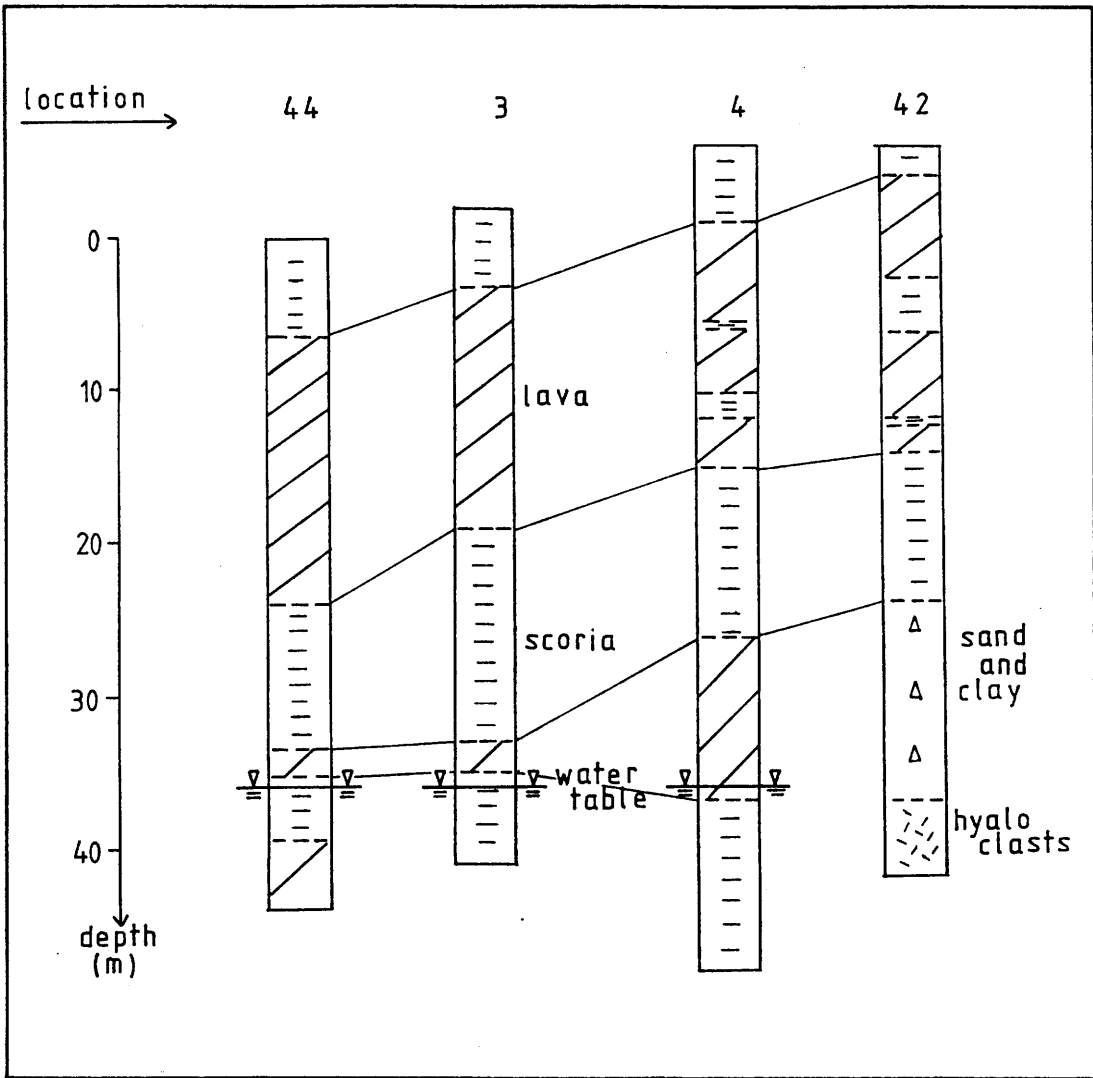


Figure 12 Borehole profiles of four shallow wells.

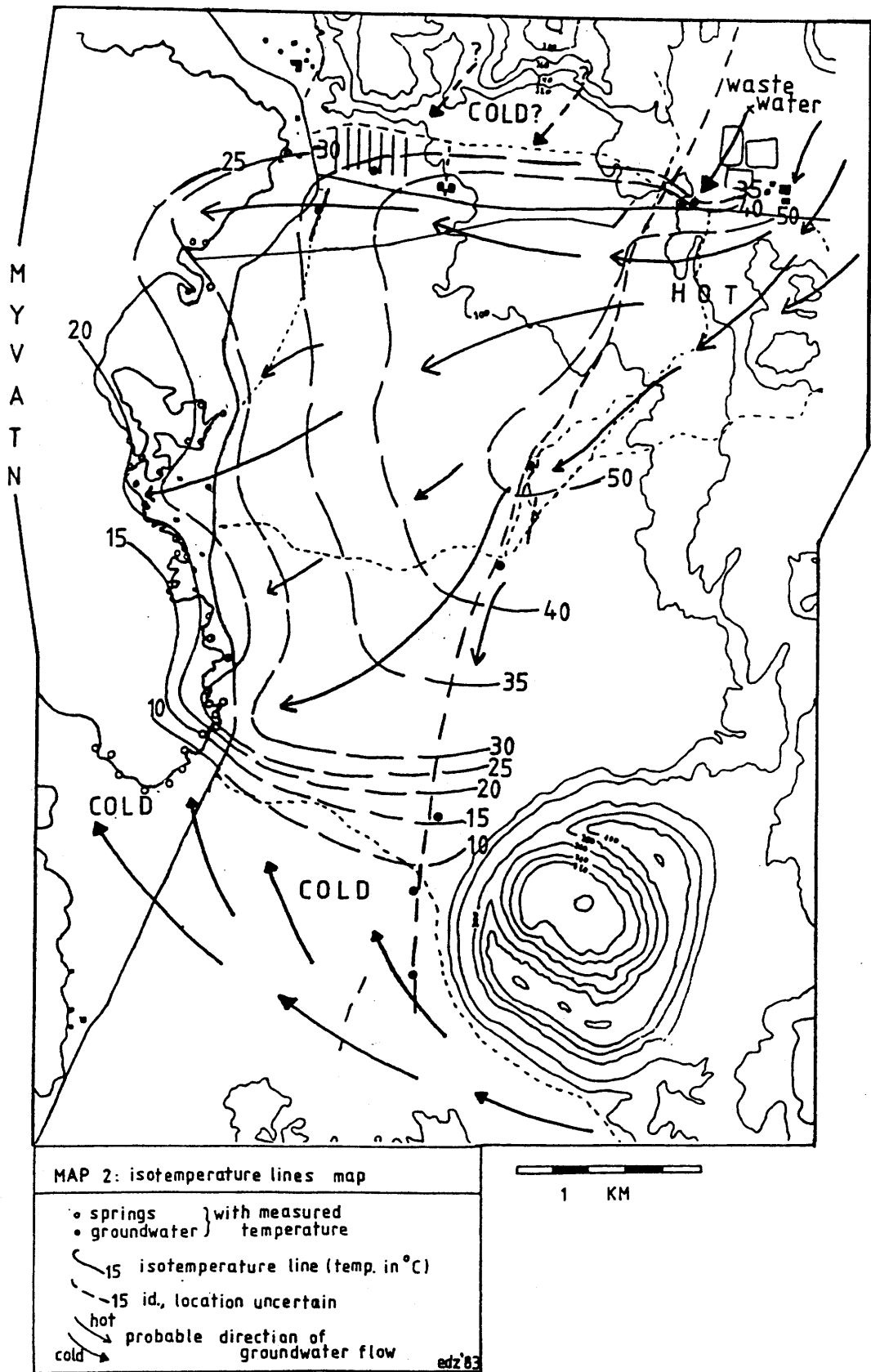


Figure 13 A isotherm map and possible direction of groundwater flow.

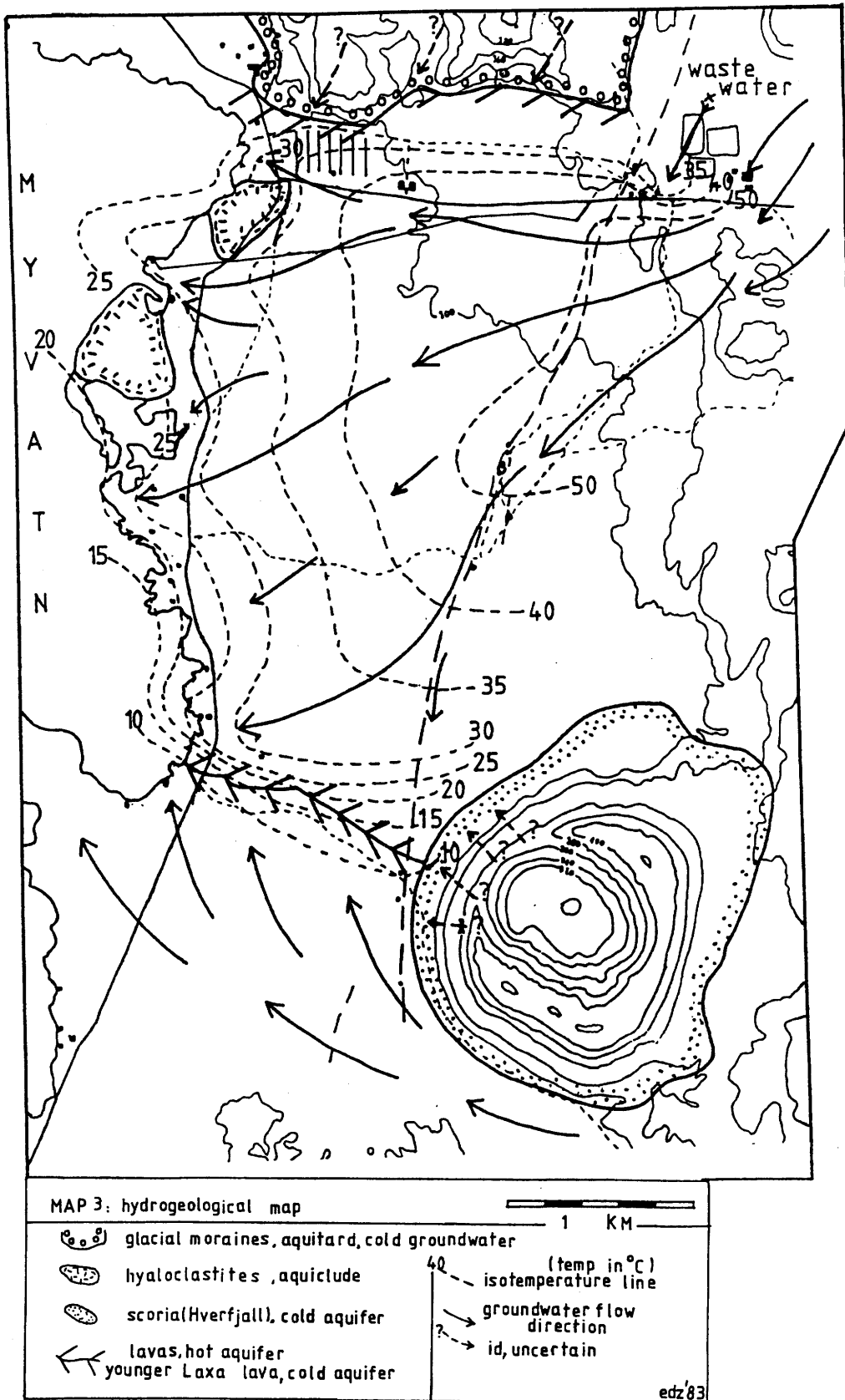
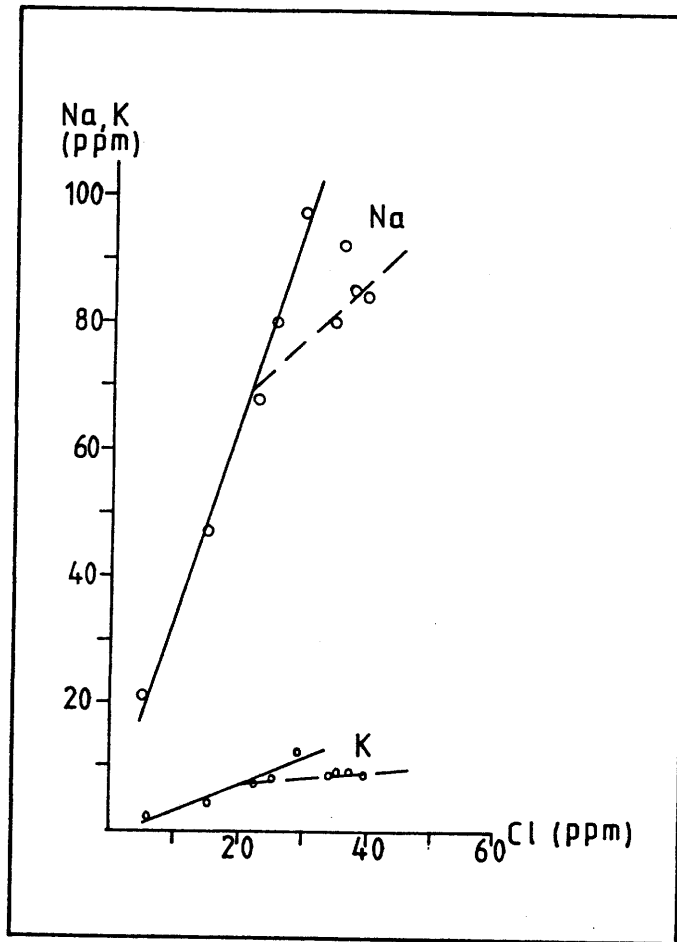


Figure 14 A hydrogeological map.



*Figure 15 Na-Cl and K-Cl relationship within the shallow groundwater system.*

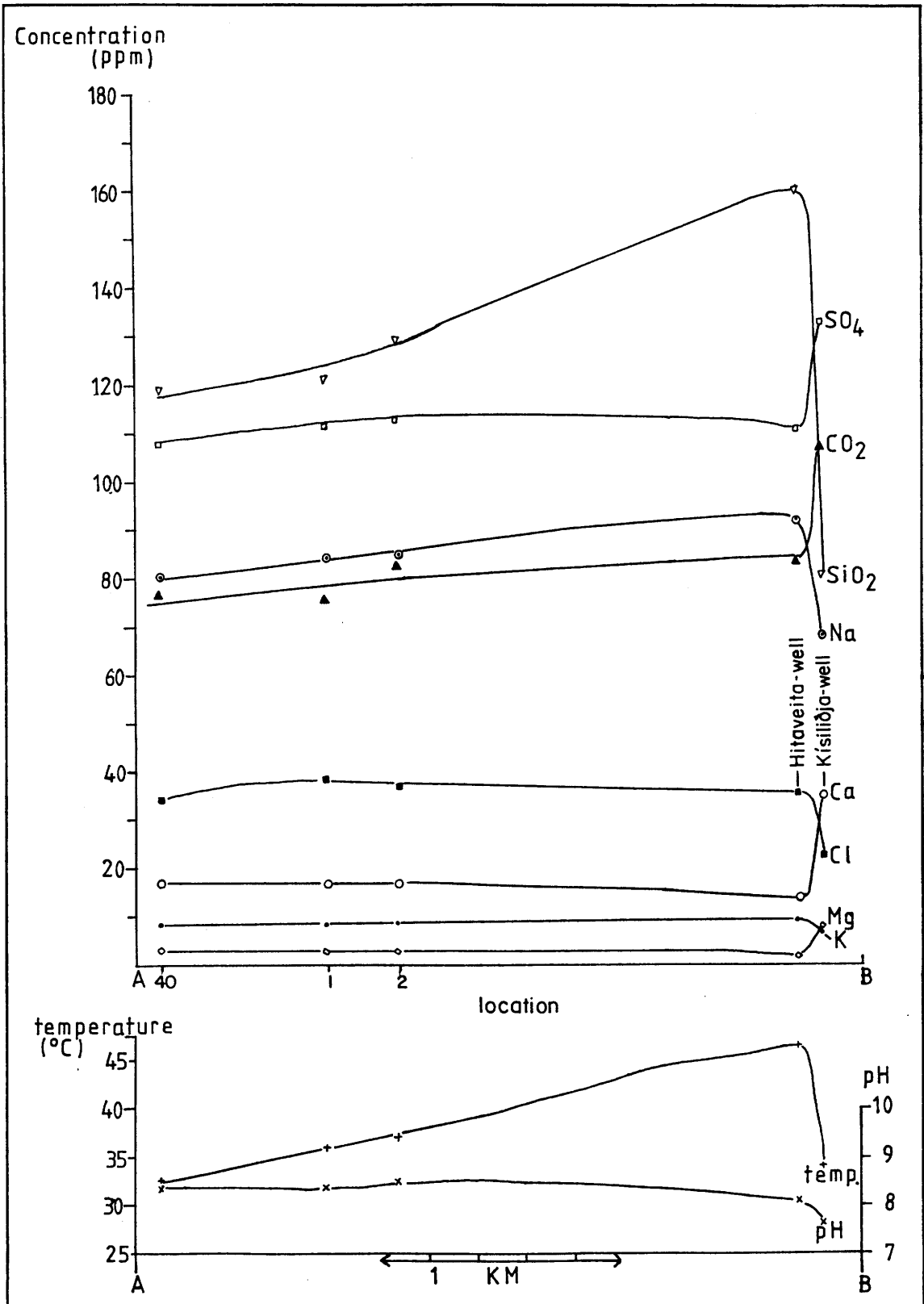


Figure 16 Chemical profile A-B (see Figure 11 for location).

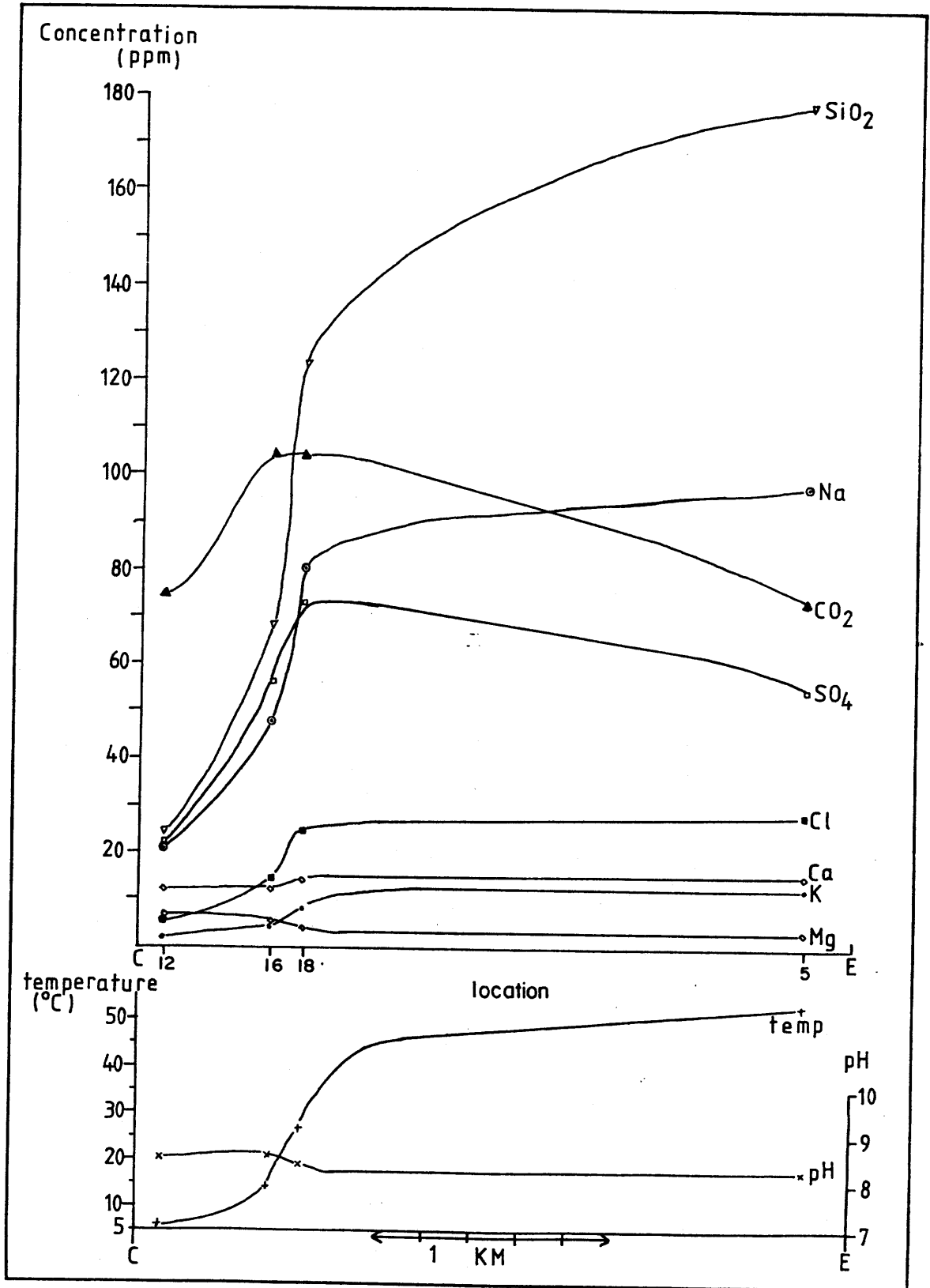


Figure 17 Chemical profile C-E (see Figure 11 for location).

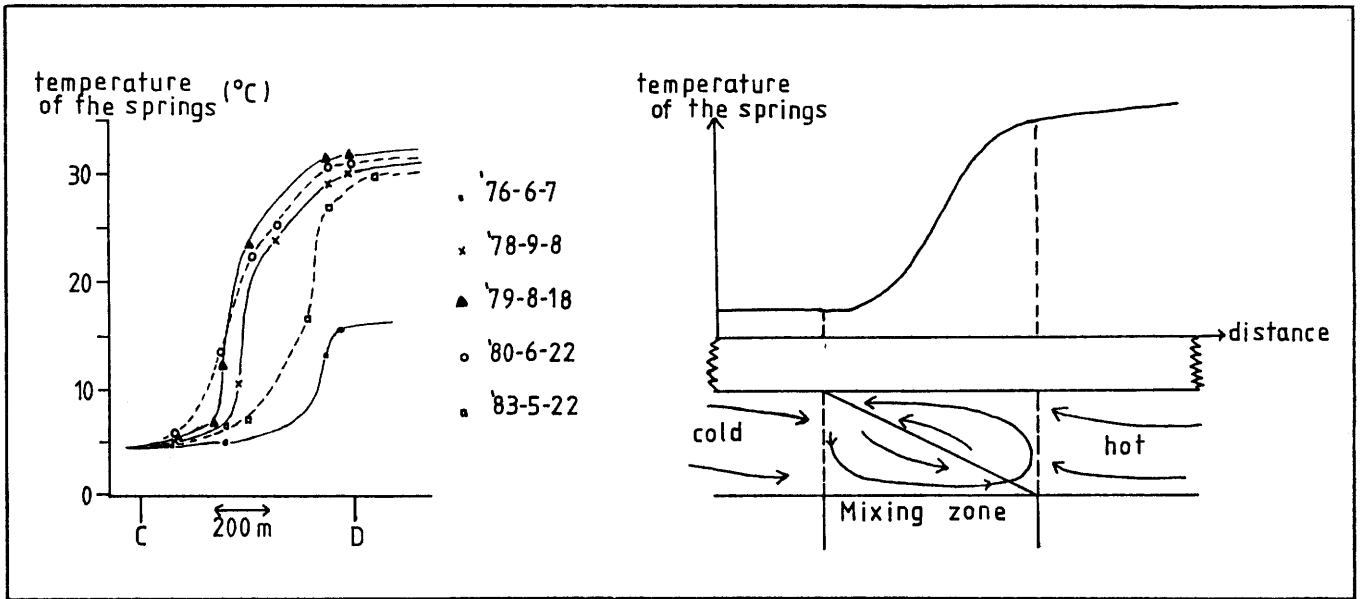


Figure 18 Temperature profile C-D (see Figure 11 for location) at five different dates and plausible explanation of mixing.



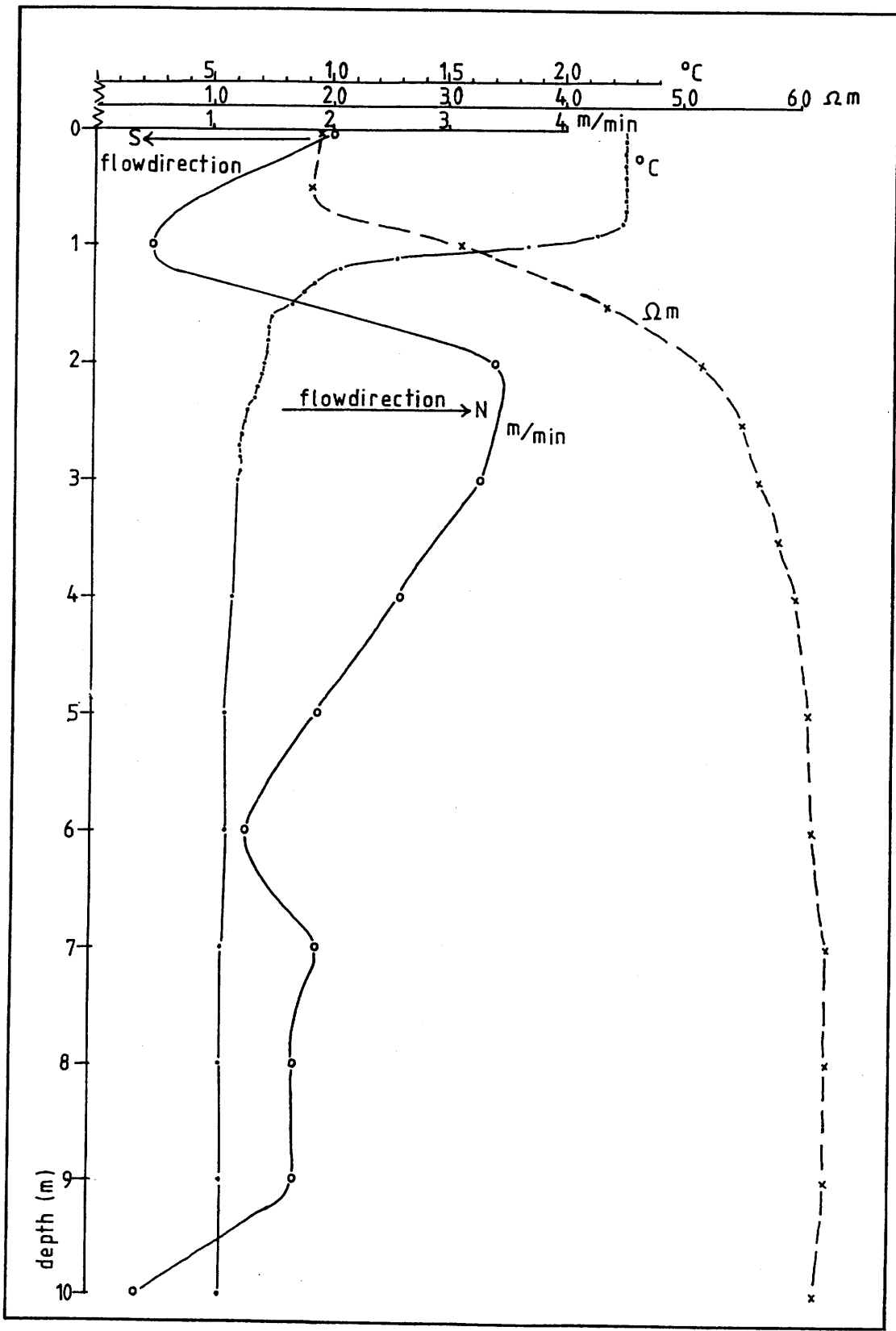


Figure 19 Vertical profile of groundwater flow, temperature and resistivity at Grjótagjá (location 8 on Figure 11).