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CHEMICAL ASPECTS OF FLUID INJECTION INTO THE GEOTHERMAL FIELDS IN EYJAFJÖRDUR, N-ICELAND

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ABSTRACT

Geothermal fields in the Eyjafjördur area supply thermal water for space heating in the town of Akureyri, N-Iceland. In this study, the Cl-SO_4-HCO_3 and K-Na-Mg triangular diagrams, Cl/B ratio and stable isotope ratios were used to classify the geothermal water. The classification results show that each geothermal field in the Eyjafjördur area has its own character. The geothermal water is classified as "sulphate-rich water". Changes in chemical composition with time were observed in Thelamörk, and were noticed for some constituents in well HG10 at the Botn geothermal field. Geothermometers were used to evaluate the reservoir temperature, and predict possible cooling in the reservoir during production. Most of the geothermometers give temperatures in pretty good accordance with measured temperatures. Some decrease in calculated reservoir temperature with time is noticed in the Thelamörk and Botn fields.

During geothermal exploitation in the Eyjafjördur area, the water level decreased over time. Injection is a way to deal with this problem. Modelling of cooling, heating and mixing was employed to study the chemical processes that may take place during injection. According to modelling results, no mineral deposition problem is expected if return water from the heating system of Akureyri is used for injection, even if the water is supersaturated with respect to quartz and chalcedony. However, if cold groundwater were to be used for injection, considerable magnesium silicate deposition would take place.

1. INTRODUCTION

Geothermal energy in Iceland is mostly used for space heating. Most of the hot water comes from the numerous low-temperature geothermal systems, which are found outside the volcanic zone passing through the country. These low-temperature systems are all embedded in fractured basaltic rocks and most of the thermal energy in the systems is stored in the reservoir rocks. In some cases cold natural recharge may extract some of this thermal energy and stabilize the production-induced pressure draw-down during production. In most cases, however, recharge is limited.

The Eyjafjördur geothermal area supplies hot water for space heating to Akureyri, a town of 15,000 inhabitants, in North Iceland. As the water level in the geothermal fields has decreased since the beginning of geothermal utilization, action has been taken to save the resource, such as the adoption of a double-line distributing system, and the use of a heat pump. Another possibility is to inject return or cold water to counteract the pressure draw-down due to production, as well as to extract additional thermal energy from the rocks.

Fluid injection has received increased interest during the last 10 to 20 years. In the past, the main purpose of injection in geothermal fields was to get rid of the waste water for environmental reasons. At present, injection has been carried out in a few areas to maintain reservoir pressures, and to extract thermal energy stored in the hot rock. Usually the natural recharge to geothermal reservoirs is small in relation to production, and additional fluid is needed to recover more energy from the reservoir rock. Fluid injection is currently used in many geothermal fields in the world. It is anticipated that injection will soon become an integral part of the management of low-temperature (<150°C) geothermal systems in Iceland (Axelsson et al., 1995).

Injection experiments have been carried out in several low-temperature areas in Iceland, including Laugaland and Thelamörk. The results indicate that substantial cold water injection may be advantageous in some cases, whereas in others only limited injection of warm rather than cold water is feasible (Axelsson et al., 1995). In Laugaland, Eyjafjördur, reinjection started in September of this year.

Various chemical processes take place during injection, including the movement of chemical fronts in the reservoir and chemical deposition in the surface pipeline, the injection wells, or in the reservoir itself. One of the problems encountered with injection is the deterioration of injection well permeability, which has been attributed to chemical deposition from the injected water, either in the well or in the receiving aquifer. Chemical deposition from the injected fluid may block the well and/or damage formation permeability in the vicinity of the injection well. It is, however, possible to predict with reasonable confidence the conditions for such deposition of specific minerals from water of a specified composition and to assess whether hot or cold injection is preferred from the point of view of mineral deposition (Arnórsson, 1995a).

The main objectives of the present study are (1) to evaluate chemical characteristics of the Eyjafjördur geothermal fields, to distinguish and classify them by geochemical methods, and obtain information on the response of the geothermal systems upon exploitation; (2) to estimate reservoir temperatures of the fields by means of various geothermometers and indicators of cooling in the system; (3) to model the possible influence of reinjection into the geothermal system on chemical equilibrium in the reservoir.

2. GEOLOGICAL SETTING AND GEOTHERMAL ACTIVITY

2.1 Geological outline

The geology of the Eyjafjördur region is summarized by Kristmannsdóttir (1982) and Flóvenz et al. (1995). Iceland is situated on a constructive plate boundary, the North- Atlantic Ridge, which crosses the country from southwest to northeast (Figure 1). The boundary is visible as an active volcanic zone characterized by numerous volcanic systems, including fissure swarms and central volcanoes. The volcanic zone is flanked by Quaternary rocks, characterized by sequences of sub-aerial lava flows intercalated by hyaloclastites and morainic horizons corresponding to glacial conditions. Quaternary formations are flanked by Tertiary flood basalts.

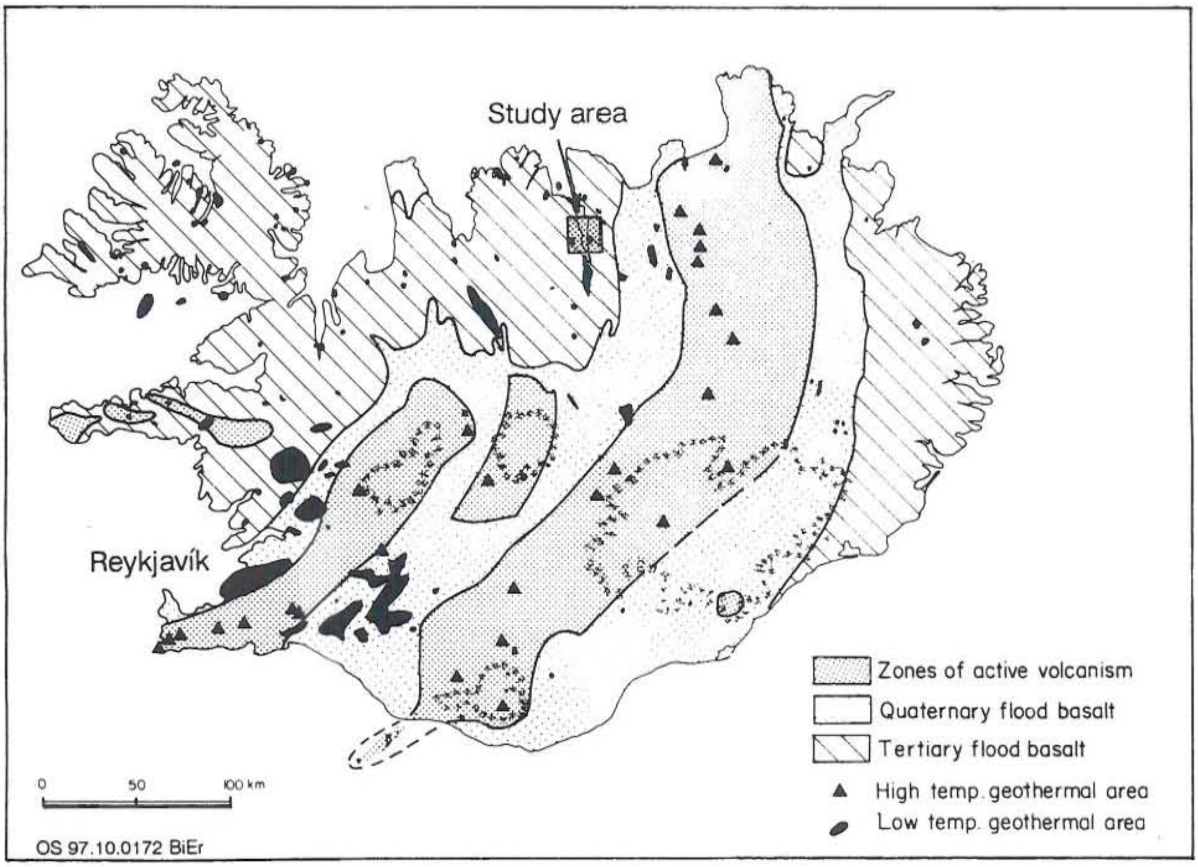

FIGURE 1: The main geological features and geothermal areas of Iceland, and the location of area studied (modified from Flóvenz et al., 1985)

The mountains of Eyjafjördur are built of Tertiary volcanic formations of age 3-10 m.y. The rocks are mainly basalt lavas with thin scoriaceous and sedimentary inter-layers. The lava pile dips about 4-7°C to the south and southeast. Thick sediment beds are found locally. At least three extinct central volcanoes are buried in the basaltic lava pile around Eyjafjördur. They are not close to the geothermal areas, so the surface rocks at Laugaland are not expected to have gone through previous high temperature alteration. On the other hand, geothermal waters could have interacted with rocks connected with the central volcanoes. A dyke swarm (6-7% dyke density) lies along the Eyjafjördur Valley. Laugaland is located within this zone. The predominant dyke direction in the area is NNE-SSW. Most of the dykes dip gently (1-7°) to the west or are near-vertical.

The crust around Akureyri is made of 6-10 m.y. old flood basalt. The nature of the aquifers is not known, but it is believed that at least the upflow is governed by tectonic features such as crossing dykes or faults. The inflow into the drillholes commonly occurs where dykes are crossed or in scoriaceous horizons near the dykes. The dykes can probably act both as impermeable barriers and as permeable channels, depending on how fractured they are. Most of the main aquifers are found to be connected with dykes and knowledge of this is used for locating drillholes. Only a few dykes in a dyke system are connected to aquifers.

The lava pile has suffered low-grade alteration which, together with precipitation of alteration minerals, has dramatically reduced the primary permeability. The lavas are zeolitized up to about 1000 m elevation. Exposures are rather scanty in the Laugaland area. In the mesolite- scolecite zone of porphyritic lavas a common mineral assemblage is mesolite, gyrolite, stilbite, heulandite, chabazite and platy calcite. In olivine tholeiite basalts gyrolite, mesolite, analcime, heulandite and calcite are abundant. In recent geological times crustal movements have created tectonic fractures, which often coincide with older dykes or faults.

2.2 Geothermal fields

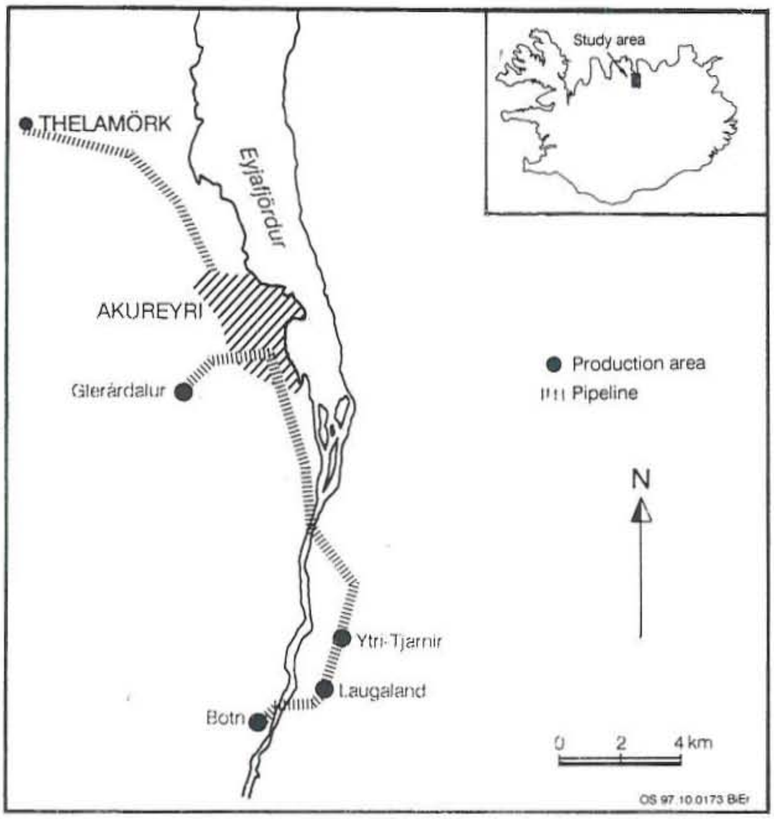

FIGURE 2: The location of geothermal fields in the Eyjafjördur area

The low-temperature geothermal systems utilized by Hitaveita Akureyrar (Akureyri Heating Utility and Water Work) are fracture-dominated convection systems surrounded by low-permeability volcanic rock. Currently, five separate geothermal fields are utilized, i.e. Laugaland, Ytri-Tjarnir, Glerárdalur, Botn and Thelamörk in the Eyjafjördur area (Figure 2). On the basis of interference test data the permeability thickness (kh) has been estimated at 1.3, 1.8 and 12 Dm (10^{-12} m^3) for the Thelamörk, Botn and Laugaland systems, respectively. The permeability thickness for the other two systems, Glerárdalur and Ytri-Tjarnir, is also in this range. Measured temperatures are up to 100°C and the maximum observed wellhead pressure is 20 bar (Flóvenz, et al., 1995). The geothermal water in the Eyjafjördur area is believed to draw its heat from a regional heat source (Kristmannsdóttir and Johnsen, 1982). The aquifer depths are different in each, but no major aquifer is found at a greater depth than 1700 m. In the Laugaland field the main aquifers are cut at 600-1500 m depth with water temperatures 92-96°C, a smaller shallow aquifer is encountered at 200-300 m depth with water temperatures of about 60°C. At Ytri-Tjarnir the main aquifers are cut at 800-1500 m and the water temperatures are 75-82°C. A shallow aquifer was also encountered in this field. In Botn the water in the main aquifer is around 85°C. A hotter aquifer, near to 100°C, is cut at about 1700 m depth (Kristmannsdóttir and Johnsen, 1982). In the Thelamörk field, well LL11 intersected a high productive feedzone at 430-450 m depth.

The geothermal fields are all small in volume. The Thelamörk and Glerárdalur systems are estimated to be of the order of only 1 km^3, whereas the Laugaland system is estimated to be a few km^3. The low permeability and small volumes lead to a great pressure draw-down and limited productivity for all the systems. The productivity of the five systems, estimated on the basis of lumped modelling, is presented in Table 1. The Laugaland reservoir is so far the most productive, because of its relatively great volume and permeability. The Botn system appears to be connected to recharge systems, much larger than the production reservoir, most probably a geothermal system at a greater depth as well as the surrounding groundwater system (Flóvenz et al., 1995). The water is very dilute and direct use is possible without problems. Nevertheless, sodium sulphite is mixed into the water to remove minor oxygen contamination which can cause corrosion problems in pipelines and radiators.

TABLE 1: Productivity of geothermal reservoirs utilized by Hitaveita Akureyrar (Flóvenz et al.,1995)

Area	**Initial pressure [1] (bar)**	**Maximum pump depth (m)**	**Productivity (l/s) [2]**	**Water temperature (°C)**
Botn	17.5	250	30	85
Laugaland	19.8	250	46	95
Ytri-Tjarnir	5.7	400 [3]	33	80
Glerárdalur	6.3	250	15	60
Thelamörk	1.9	250	17	90

1) Well-head; 2) Until the year 2005; 3) A submersible motor down-hole pump

2.3 History of geothermal utilization

Akureyri has been heated by geothermal energy since the end of the seventies. Prior to that it was partly heated by electricity but mainly with oil burners. Events leading to the establishment of the Heating Utility may be traced as far back as the year 1933, when a few enthusiastic individuals piped hot water from springs in a gorge by the river Glerá, 3.6 km to the Akureyri swimming pool. This was a quantity of 3 l/s and the temperature was 48°C. From that time to 1970 several attempts were made to explore geothermal areas close to Akureyri, but they failed. Following the jump in energy price in the oil crisis of 1973, an effort was put into further exploration. The results of resistivity soundings led to the selection of Laugaland for deep drilling. In 1975 this resulted in the discovery of a big feed zone, which initially yielded about 100 l/s of 90°C hot water artesian flow. Two years later, another big feed zone was located in the Ytri-Tjarnir geothermal field initially yielding 50 l/s of 80°C water (Flóvenz et al., 1995). In 1977, Hitaveita Akureyrar (Akureyri Heating Utility) was established. Construction of the district heating system was started in 1976 and most of the town were connected by 1979 (HVA, 1997).

Soon after pumping from the fields began, it became evident that draw-down would be much greater than had been predicted. After a few years in operation the annual average production from these fields was reduced to 75 l/s (Flóvenz et al., 1995). Later, careful surface exploration, followed by drilling, resulted in the discovery of productive feed zones in 3 different geothermal fields; Botn in 1980, Glerárdalur in 1981 and Thelamörk in 1992. These new fields, together with heat pumps, electric boilers and energy saving efforts have ensured sufficient geothermal energy in Akureyri.

The geothermal water is used for house heating, bathing and for industrial purposes. Water quality is very good, suitable for direct use. The figures from Hitaveita Akureyrar in 1996 show that (1) the water temperature is 60-95°C; (2) the water level in the geothermal fields is at 180-280 m depth in winter; (3) the amount of water pumped from boreholes is 4,000,000 m^3. The energy used for house heating constitutes approximately 230 GWh, of which homes take 2,150,000 m^3, and all others 1,400,000 m^3.

3. CHEMISTRY OF THE GEOTHERMAL FLUIDS

3.1 Fluid classification

3.1.1 Cl-SO_4-HCO_3 triangular diagram

The Cl-SO_4-HCO_3 triangular diagram (Giggenbach, 1988) is based on the relative concentrations of the three major anions (Cl^-, SO_4^{2-}, CO_3^{2-}). The position of data points in this diagram is obtained by first obtaining the sums of the concentrations C_i (in mg/kg) of all three constituents and then working out the percentage concentrations for each constituent. This diagram aids in (1) classification of water, (2) the weeding of unsuitable waters for application of geo-indicators, (3) providing an initial indication of mixing relationships or geographic groupings. The relative distribution of Cl^-, HCO_3^- and SO_4^{2-} in the Eyjafjördur geothermal waters is shown in Figure 3. The results for samples collected in 1981 are plotted in Figure 3A, but samples collected 1992-1997 in Figure 3B.

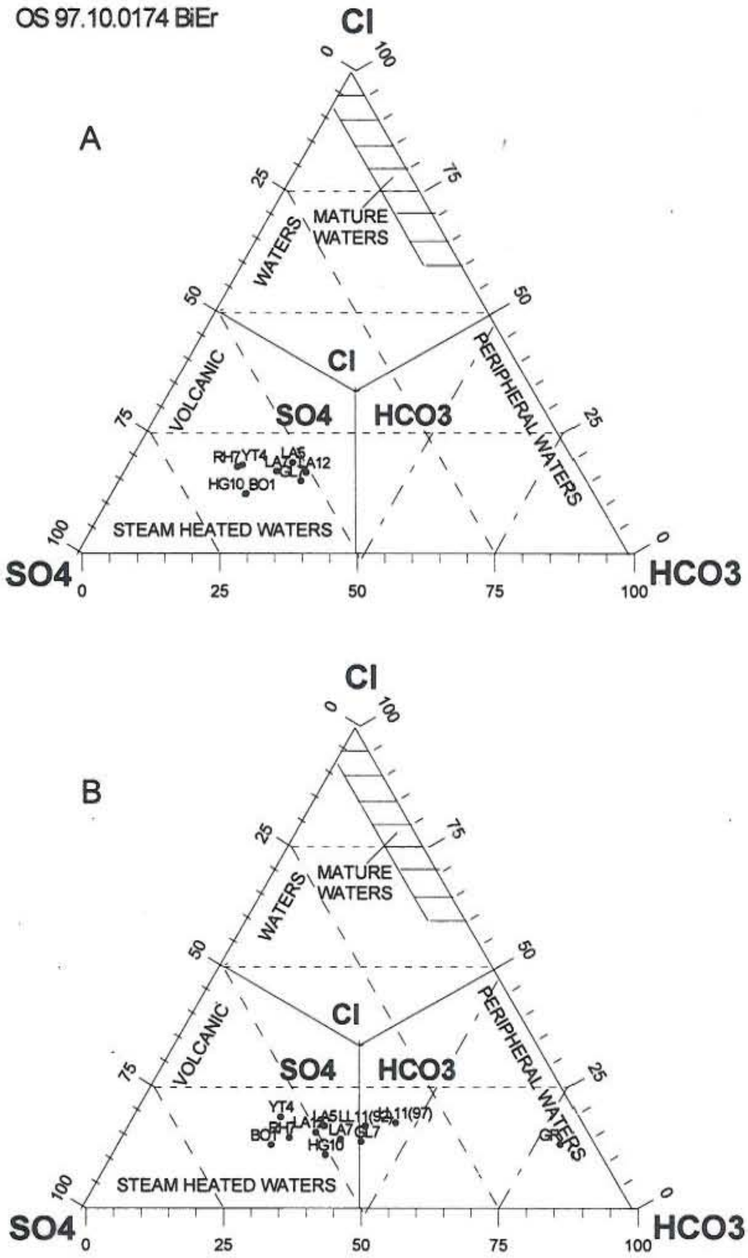

FIGURE 3: Cl-SO_4-HCO_3 diagrams for the Eyjafjördur water; a) Samples collected in 1981, b) Samples collected 1992-1997

In Figure 3A, all the samples plot in the sulphate corner. In Icelandic geothermal water, the sulphate could be derived in varying proportions from; 1) magmatic sulphur from the active volcanic zone; 2) sulphur leached from bedrock; 3) seawater sulphate spray carried in meteoric water; 4) sulphate from seawater contamination of the groundwater sources or leaching of trapped marine formations (Gunnlaugsson, 1977).

It is clear from the high pH of the Eyjafjördur geothermal water that it is not steam heated water with sulphate originating from magmatic sources. Neither is it reasonable to conclude that water with such a low Cl concentration is contaminated by sea water. The sulphate probably originates from leaching of the bed rock, and the relatively high concentration of sulphate is due to the very low Cl content of the basaltic rock in Iceland. Probably this water could be classified as "mature sulphate-rich water".

In Figure 3B, we see that most sample points move a little to the right with time. The groundwater (GR) plots close to the carbonate corner, so this could be an indication of mixing with groundwater. Nevertheless, this change is probably not significant because of the very dilute character of the water and cannot be confirmed without some other indications of groundwater inflow.

3.1.2 Cl/B ratio

The Cl/B ratio is a convenient tool to distinguish between aquifer systems as neither Cl nor B participates in any important mineral/solute equilibria. Boiling and cooling of the geothermal water should, thus, not change the relative concentrations of the elements (Kristmannsdóttir and Johnsen, 1982). The distribution of B and Cl in Icelandic water is determined by their essentially incompatible behaviour and supply from four sources. These sources are (1) the atmosphere, i.e., seawater spray and aerosols incorporated in the precipitation, (2) the soil and rock with which the water interacts, (3) seawater that has percolated into the bedrock, and (4) magma intrusions. Most geothermal waters contain B and Cl within 0.05-1 and 10-100 ppm, respectively. These rather low values are attributed to the low content of B and Cl, which are 0.1-6.6 and 75-750 ppm respectively, in the basaltic rock. Boron and Cl concentrations generally increase with water temperature. The Cl/B ratio in seawater is 4350 and a little lower in surface water and groundwater in Iceland. In Icelandic basalt this ratio is much lower, or in the range 25-50. The Cl/B ratio in geothermal water decreases with increased temperature and approaches that of the rock. The reason is that with higher water temperature, the leaching of Cl and B from the rock becomes faster, and because of the low Cl content in Icelandic basalt, the B enrichment is greater (Arnórsson and Andrésdóttir, 1995). So, a study of this ratio can yield valuable information on the origin of the water.

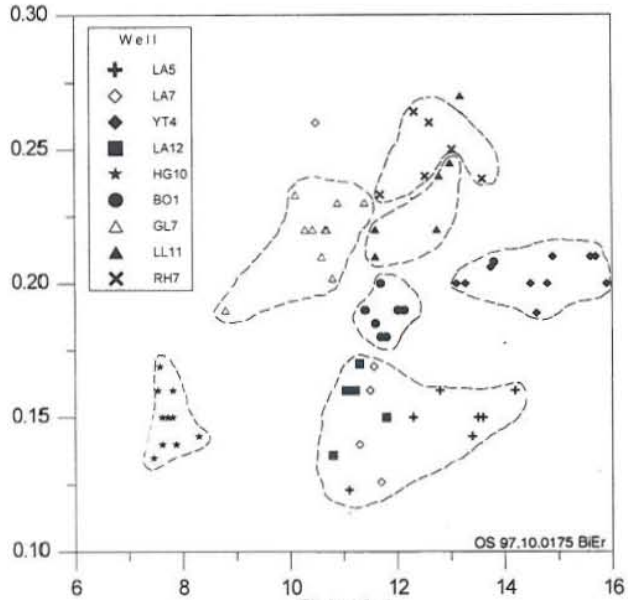

FIGURE 4: B-Cl graph for Eyjafjördur water

Figure 4 shows how samples from each well in the Eyjafjördur area can be classified on the basis of their B and Cl content. Even water from the same geothermal field plots in different groups on this graph, as can be seen for wells HG10 and BO1 in the Botn geothermal field. In the Eyjafjördur area, the concentration of B and Cl in the geothermal water is in the range 0.1-0.3 ppm and 7-16 ppm, respectively. The Cl/B ratio in most waters is stable with time. The Cl/B ratios of all the geothermal waters are in the range 40-100 (Figure 5). The source of Cl and B is the rock with which the water interacts, and the Cl/B ratio in the Eyjafjördur area seems not to reflect the difference in water temperature in the wells. The Cl/B ratio of the water in Laugaland, is relatively high. The Cl/B ratio of LA12, LA7 and YT4 values is in the range 65-80, and LA5 in the range 80-100. The Cl/B ratio of HG10, RH7, GL7, and LL11 water is in the range 43-58. The ratio for BO1, which is located near HG10, is in the range 58-67. This shows that the waters of BO1 and HG10 come from different systems. There is probably a barrier, such as an impermeable dyke,

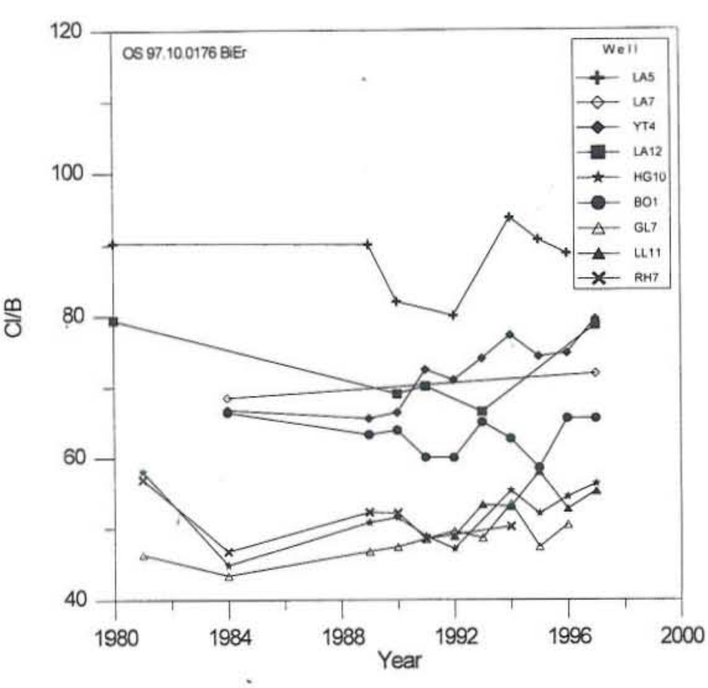

FIGURE 5: Changes in the Cl/B ratio with time in Eyjafjördur water

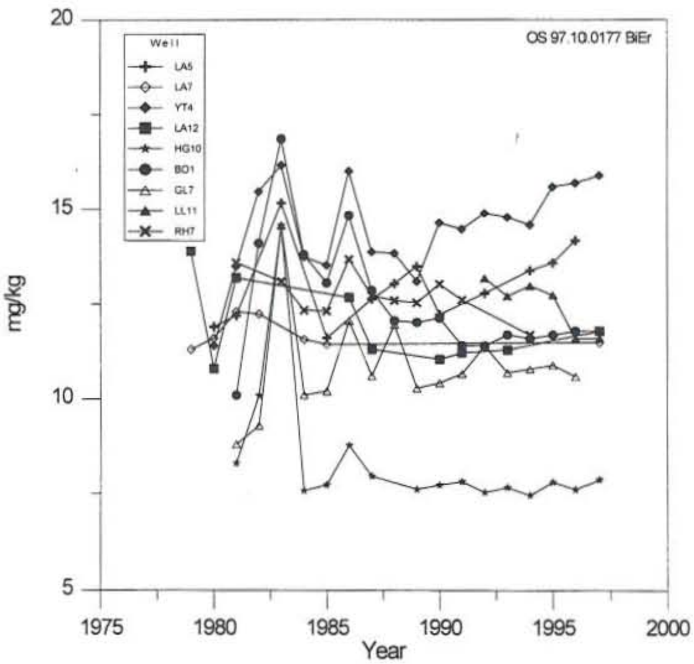

FIGURE 6: Changes in the Cl concentration with time in Eyjafjördur water

between them. The fluctuation of the Cl/B ratio and the concentration of Cl (Figure 6) may be caused by different mixing proportions of water from different aquifers due to changes in the production flowrate, except in LL11. The Cl/B ratio of LL11 water increases and the concentration of Cl decreases with time. This is probably caused by recharge of groundwater, which has low Cl and B concentrations, and a relatively high Cl/B ratio.

3.1.3 Stable isotopes

Craig et al. (1956) first discussed the possibility of using combined δD and δ^{18}O measurements on thermal water to determine whether such water is of meteoric origin and whether it has undergone any isotopic changes during its underground passage. The deuterium concentration of the precipitation in Iceland varies significantly from one place to another. This suggests the possibility of using deuterium as a natural tracer to locate recharge areas for groundwater systems and to study their flow patterns. When a sample of groundwater is discharged from either a cold or a hot spring whose deuterium value is similar to the mean value of the local precipitation, this indicates a local origin for the groundwater (Árnason, 1976). The use of deuterium as a natural tracer in groundwater studies is based on the assumption that groundwater is derived from precipitation and that the deuterium content of the water does not change underground. Furthermore, the method assumes that the deuterium value of the precipitation has not changed significantly during the time the water has remained underground. Árnason (1976) concluded that the δD-δ^{18}O relationship obtained for hot and cold water in Iceland supports the contention that the groundwater is almost entirely of meteoric origin, and suggested that the stable isotope ratios of precipitation have not changed greatly during the last 8000 years, so that deuterium values for groundwater younger than 8000 years should be comparable to the values of the deuterium map of Iceland he presented. However, the results of deuterium measurements suggest that most groundwater in Iceland is younger than 8000 years. Comparison of the deuterium content of a deep ice core with the δ^{18}O content of a more recent ice core, indicates that precipitation deposited between 10,000 and 60,000 years ago was -50 ‰ to -100‰ lower than today. When "ice-age water" is present in the geothermal water, deuterium cannot be used as a tracer to locate the recharge areas to the geothermal areas and in this way draw conclusions about regional groundwater flow (Arnórsson, 1995b).

The δD and δ^{18}O values for the geothermal water and groundwater in Eyjafjördur fall close to the world meteoric line (Figure 7). The δD and δ^{18}O values for the geothermal water are lower than those for the local groundwater. Compared to the deuterium map of Iceland (Árnason, 1976), δD values in Eyjafjördur geothermal waters, ranging from -91.2‰ to -103.8 ‰ in samples studied, are close to values of precipitation in Central Iceland. So, the origin of the geothermal water could be meteoric water from Central Iceland. Kristmannsdóttir (1982) concluded that the geothermal water appears to have its origin in the northwestern part of Vatnajökull and the mountains north of Vatnajökull. Studies of stable isotopes, carried out by Árnason (1976), indicated that in the Eyjafjördur area the lowest δD value is -

107‰,with the δD value varying from -92‰ to -107‰ within the area, either due to mixing of deep water with more local groundwater or to different origins or age of the water. Kristmannsdóttir and Johnsen (1982) indicated that water in at least one of the reservoirs is believed to be older than ten thousands years. So mixing of this water, which has a low δD value, with younger water is probably the reason for the variation in δD values for different geothermal water in Eyjafjördur. The deuterium measurements seem to indicate that the thermal water in Eyjafjördur is derived from a deep groundwater flow that originates in central Iceland but flows to the north along the valley and possibly further north under the ocean bed (Árnason, 1976). The low $\delta^{18}O$ value is caused by an exchange between geothermal water and reservoir basaltic rock whose $\delta^{18}O$ is low.

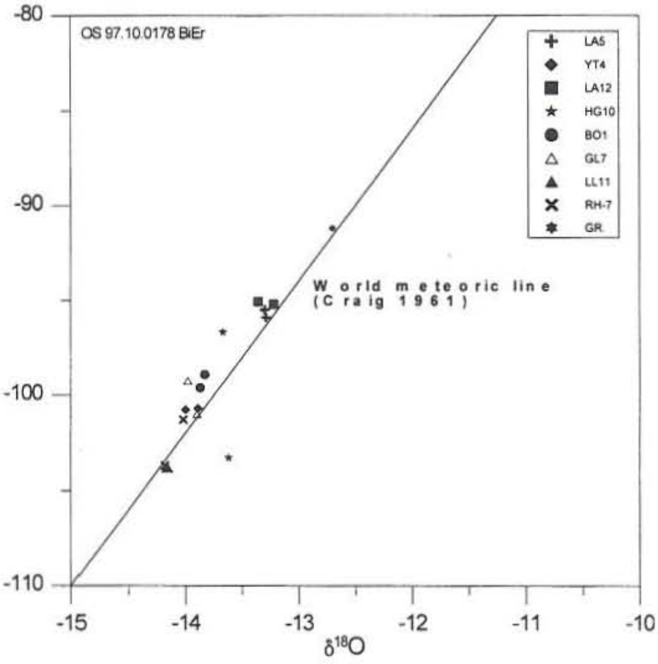

FIGURE 7: δD vs. $\delta^{18}O$ for Eyjafjördur waters

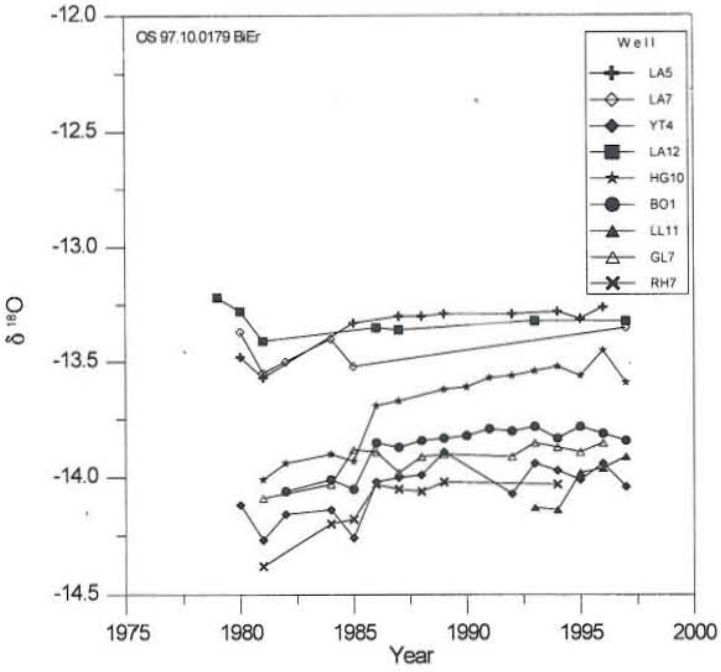

FIGURE 8: Changes in $\delta^{18}O$ with time in Eyjafjördur water

In Figure 8, a weak tendency of the $\delta^{18}O$ values is noted for geothermal water to increase with the time Kristmannsdóttir and Johnsen (1982) indicated that $\delta^{18}O$ decreases with the increment of the depth of drillholes, and there appear to be two separate reservoirs feeding the geothermal areas in the northern Eyjafjördur region. So, changes in $\delta^{18}O$ were probably caused by changes in the amounts of geothermal water from different aquifers, the $\delta^{18}O$ of whose waters vary during exploitation. The increase in $\delta^{18}O$ ratio in LL11 water, is probably caused by the recharge of some shallow groundwater, whose $\delta^{18}O$ value is relatively high. This is also inferred by the decrease of silica concentration and the increase of Cl/B ratio in the same water.

3.2 Geothermometry

3.2.1 Na-K-Mg triangular diagram

This plot is employed to determine whether the fluid has equilibrated with hydrothermal minerals as well as to predict equilibration temperatures. Giggenbach (1988) suggested that a triangular diagram with

Na/1000, K/100, and √Mg at the apices could be used to classify waters according to their state of equilibrium at given temperatures. He adopted the Na/K and slightly modified K/Mg geothermometer equations given by Giggenbach et al. (1983). The full equilibrium curve is for reservoir water composition corrected for loss of steam owing to decompressional boiling. Uncorrected boiled water will plot slightly above the full equilibrium line. This overcomes some of the disadvantages of the direct use of Na-K and Na-K-Ca geothermometers where, mixing with an immature water or incomplete equilibrium interferes with their use, but the magnesium concentration (low in equilibrated geothermal waters) can help in weeding out unsuitable samples. The use of the triangular diagram is based on the temperature dependence of the three reactions:

$$albite + Na^{+} = K\text{-}feldspar + K^{+}$$

$$0.8\,muscovite + 0.2\,clinochlore + 5.4\,silica + 2Na^{+} = 2\,albite + 0.8\,K\text{-}feldspar + 1.6\,water + Mg^{2+}$$

$$0.8\,muscovite + 0.2\,clinochlore + 5.4\,silica + 2K^{+} = 2\,albite + 2.8\,K\text{-}feldspar + 1.6\,water + Mg^{2+}$$

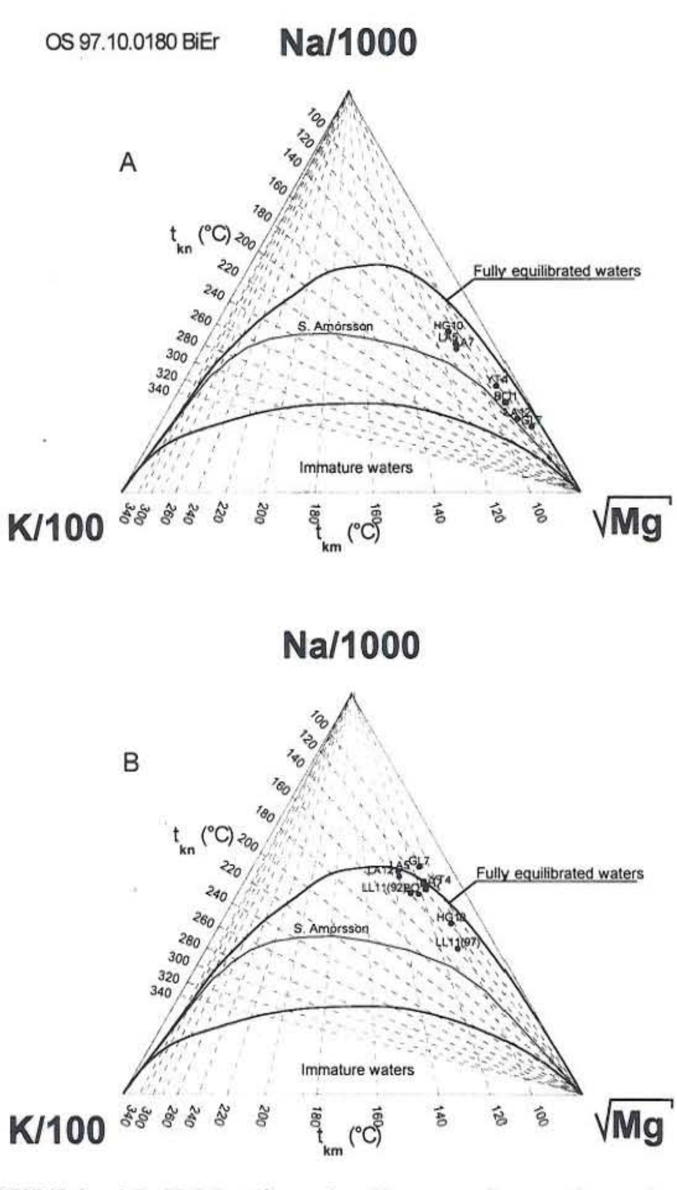

FIGURE 9: Na-K-Mg triangular diagrams for geothermal well waters in the Eyjafjördur area; a) Samples from 1981; b) Samples from 1991-1997

They involve minerals of the full equilibrium assembly after isochemical re-crystallization of an average crustal rock under conditions of geothermal interest. Na, K, and Mg concentrations of water in equilibrium with this assemblage are accessible for rigorous evaluation.

Applying this diagram to the Eyjafjördur area, the samples analysed in 1981 (Figure 9A) indicate that all samples represent partially equilibrated water, and in Figure 9B we see that with time the composition of most samples moves close to the curve of fully equilibrated water as suggested by Giggenbach (1988). Probably the real cause of this is an improvement in the method of determination of Mg at the Orkustofnun chemical laboratory which was made after 1990. Therefore, points in Figure 9B probably represent more reliable analyses. It is remarkable that the Eyjafjördur water plots close to the equilibrium curve suggested by Giggenbach (1988), but well above the curve suggested by Arnórsson (1991). Both curves are empirical, the latter being based on water-rock interaction with Icelandic basalts, but the former on equilibration with more sodium-rich, andesitic or basaltic andesitic rocks. It has been noticed before that Giggenbach´s (1988) curve is more suitable for some Icelandic low-temperature water (Idris, 1994).

Because samples from Eyjafjördur water plot as partially to fully equilibrated water, the K-Na and K-Mg geothermometers are considered reliable for these waters. However, the results for these geothermometers seem very unreasonable compared to results for other geothermometers used, or for measured temperatures of the water. For most samples t_{kn} and t_{km} are in the range 100-140°C, which is considerably higher than for other results. The temperature range is 100-120°C for GL7, YT4, RH7 and HG10; 120-140°C for LA5, LA12 , LL11(92)and BO1. Comparing the points for LL11 (97) and LL11(92), the water in LL11 (97) is moving far away from the equilibrium curve with time. This is probably evidence of mixing with some Mg-rich groundwater. Subsurface temperatures of 120-140°C and 100-120°C from the Na-K and K-Mg geothermometers, are indicated for the sample from LL11 (97) respectively. This is difficult to explain. The K-Na equilibrium reaction is very slow, so it could theoretically represent an old equilibrium in the reservoir which probably has cooled down. On the contrary, the K-Mg equilibrium reaction is much faster and often tells us more about the sampling temperature than the reservoir temperature. The K-Mg temperature would be expected to be much lower if the K-Na temperature were an indication of an old temperature.

3.2.2 Silica geothermometry

The silica geothermometers used to predict subsurface temperature of reservoirs, are based on experimentally determined solubilities of chalcedony and quartz. In Iceland, rocks are young, but equilibrium with chalcedony seems to be attained at temperatures up to 180°C, and equilibrium with quartz at higher temperatures. The formation of quartz or chalcedony is considered to be determined by the rate of dissolution of the silica from the primary constituents of the rock, and the kinetics of precipitation. Since 1960, several formulae for the estimation of deep temperatures, based on the concentrations of silica in thermal water, have been presented. These formulae give more or less the same temperature results, the difference is that the quartz geothermometer yields higher temperatures than the chalcedony geothermometer for the same concentration of silica due to their different equilibration solubilities.

Application of the silica geothermometer often assumes that analysed aqueous silica concentrations are equal to the activity of H_4SiO_4, which is temperature dependent. The geothermal waters in the Eyjafjördur area have a high pH (above 9.5). For such water, allowing analysed silica to represent H_4SiO_4 is unsatisfactory, as dissolved silica is an important proton donor at a high pH. At this high pH, a significant fraction of the dissolved silica ionizes, generating protons. In this case, the computer program WATCH (Arnórsson et al., 1982; Bjarnason, 1994) was used to calculate the reservoir temperature. In WATCH, the effect of pH on the silica formed was accounted for. The calculated results are listed in the Table 2.

The chalcedony geothermometer temperatures are lower than the measured temperatures for most water, but similar for GL7, LL11, and RH7. According to Gíslason et al. (1997), chalcedony is a very fine-grained mineral, which is probably not a separate mineral but a mixture of quartz and moganite, and with time it will probably all change to quartz. This is a possible explanation for the lower temperatures estimated for the other wells by the chalcedony geothermometer. The decreasing chalcedony temperature of LL11 geothermal water shows that cooling is taking place during exploitation in Thelamörk. The chalcedony temperature of HG10 decreased from 69°C in 1981 to 61°C in 1997, and that of BO1 from 85°C to 76°C during the same time interval. This may be caused by some minor cold groundwater inflow. The measured reservoir temperatures of these wells are 79°C and 91°C, respectively. In BO1 it has been stable through its production history, but a slight lowering of temperature is seen in HG10. Chalcedony temperature, as well as the measured one, is stable in other wells through the production history.

TABLE 2: The Eyjafjördur waters, measured reservoir temperatures (T_m) and calculated temperature by chalcedony geothermometers (T_{ch}) in °C

	LA5		**LA7**		**YT4**		**LA12**		**HG10**		**BO1**		**GL7**		**LL11**		**RH7**	
Date	T_m	T_{ch}	T_m	T_{ch}	T_m	T_{ch}	T_m	T_{ch}	T_m	T_{ch}	T_m	T_{ch}	T_m	T_{ch}	T_m	T_{ch}	T_m	T_{ch}
1997			93.2	81	80.5	71	94.4	82	78.9	61	90.7	76			89.8	93		
1996	93.2	82			81.1	70			79.2	60	91.7	77	60.5	58	89.7	93		
1995	93.6	84			80.2	71				61	91.0	78	60.1	62	90.1	95		
1994	93.3	83			80.5	71			79.3	59	92.1	74	59.3	59	90.4	97		
1993					81.2	75	94.4	89	80.1	62	92.2	78	60.3	64	91.5	98		
1992	91.2	85			80.2	74			80.0	62	89.2	75	59.0	61	85.8	107		
1991					80.5	71	95.5	82	81.2	59	91.0	76	60.0	58			77.4	74
1990	94	81			80.8	71	95.7	81	81.0	61	92.4	77	60.5	62			77.2	77
1989	92.6	81			79.3	71			81.6	63	90.6	75	59.9	59			76.5	76
1988	94	92			80.4	79					92.6	85	60.1	74			77.2	85
1987	95	88			80.2	75	92.7	85	81.7	67	91.4	81	60.7	64			76.5	82
1986					80.5	77	92.5	87	82.0	69	91.0	83	60.8	67			76.2	84
1985	93.5	83	94.9	84	80.5	71			83.0	65	91.3	80	60.6	61			76.6	77
1984			90.6	74	79.0	72			80.7	59	88.5	76	59.0	62			71.5	75
1983		87				78				78		86	59.0	73				84
1982			92.0	88	79.1	82			83.1	72	83.1	90	58.9	73				
1981	89.5	84	95.0	85	78.4	73	90.4	78	82.7	69	89.2	85	54.7	58			75.4	76
1980		83	94.0	87		73	96.0	95										
1979			93.0	88				76										
1977				81														
1976	90.5	81																
1975	89.5	88																

3.2.3 Cation geothermometers

Na-K geothermometry is based on ion exchange reactions whose equilibrium constants are temperature dependent. Where reservoir temperatures are changing in response to production, the Na/K geothermometer generally appears to take longer than the silica geothermometer to attain a new water-rock chemical equilibrium. Therefore, there is a tendency to use the Na/K ratio to estimate the possibility of higher temperatures in deeper parts of a system where waters reside for a relatively long time, and other geothermometers to estimate lower temperatures which occur in shallower reservoirs where waters reside for a relatively short time (Fournier, 1991).

The Na-K-Ca geothermometer (Fournier and Truesdell, 1973) takes account of reactions involving the exchange of Na^+, K^+, and Ca^{2+} with mineral solid solutions. It gives realistic temperature estimates for many fields of relatively low temperature (<150°C) for which the Na-K geothermometer gives unreasonably high values (Arnórsson, 1991). This minimizes but does not eliminate effects of disregarding the activity coefficients of solids. The geothermometer is entirely empirical and assumes one type of base exchange reaction at temperatures below about 100°C but another one at higher temperatures. For equilibrated waters, which have cooled by conduction in upflow zones, estimation of underground temperatures by the Na-K-Ca geothermometer is probably more conservative than estimation by the Na-K geothermometer, as the ratio $\sqrt{Ca}/Na$ appears to respond faster to cooling than the Na-K ratio (Arnórsson, 1983).The following formulae were applied to calculate reservoir temperature in the Eyjafjördur area:

Na/K (Arnórsson et al.,1983)

$$t(°C) = 933/(0.993 + \log Na/K) - 273.15 \tag{1}$$

Na/K (Tonani, 1980)

$$t(°C) = 833/(0.780 + \log Na/K) - 273.15 \tag{2}$$

Na/K (Fournier, 1979)

$$t(°C) = 1217/(1.483 + \log Na/K) - 273.15 \tag{3}$$

Na/K/Ca (Fournier and Truesdell, 1973)

$$t(°C) = \frac{1647}{(\log Na/K + \beta \log(\sqrt{Ca}/Na) + 2.06) + 2.47} - 273.15 \tag{4}$$

1) Calculate $[\log(Ca^{1/2}/Na)+2.06]$; if it is positive, calculate the temperature, t, using $\beta=4/3$;
2) If $t < 100°C$, use this temperature;
3) If $t > 100°C$ or $[\log(Ca^{1/2}/Na)+2.06]$ is negative, then use $\beta=1/3$ to calculate the temperature.

Results are shown in Table 3. The function given by Tonani (1980) gives values which are quite close to measured temperatures, and compare well with the results obtained with the function of Arnórsson et al. (1983) below 100°C. The function of Fournier (1979) yields considerably higher temperatures for all Na/K ratios (Arnórsson 1991). The temperature given by the Na-K-Ca geothermometer confirms that the Na-K-Ca geothermometer is inferior to the Na-K geothermometer in the basaltic terrain in Iceland at all temperatures(Arnórsson et al.,1983).

TABLE 3: Reservoir temperatures (°C) for Eyjafjördur waters calculated by cation geothermometers

Well	**LA5**	**LA7**	**YT4**	**LA12**	**HG10**	**BO1**	**GL7**	**LL11**	**RH7**
Dates	1975-1996	1979-1997	1980-1997	1979-1997	1981-1997	1981-1997	1981-1996	1992-1997	1981-1991
$T_{measured}$	89.5-95.0	90.6-95.0	78.4-81.2	92.5-96.0	78.9-83.0	83.1-92.4	54.7-60.8	85.8-91.5	71.5-77.4
$T_{mean\ (1)}$	82	91	65	83	69	79	55	83	72
$T_{mean\ (2)}$	93	102	74	93	79	90	63	93	81
$T_{mean\ (3)}$	118	125	101	118	106	115	92	118	108
$T_{mena\ (4)}$	66	70	53	65	51	57	50	77	56

4. GEOCHEMICAL MODELLING OF THE INJECTION WATER

4.1 Geochemical modelling of fluids

The quality of geothermal water in the Eyjafjördur area is very good. Total dissolved salt concentration is low. In direct utilization, no problem has resulted from mineral deposition. But during injection, the system temperature and the composition will be changed by the injected fluid. In Iceland, system composition is not so much fixed by rock composition as by the rate of leaching of the various constituents from fresh rock and the composition of inflowing water. The water chemistry is determined by the system composition and the external variables acting on the system (Arnórsson et al., 1983). So, changes in system temperature and composition during injection may cause some problems. One of the problems encountered with injection is the deterioration of injection well permeability which has been attributed to chemical deposition from the injected water, either in the well or the receiving aquifer. If chemical deposition caused by injection occurs, it may block the well and/or damage formation permeability in the vicinity of the injection well.

Computer models simulating the destruction and formation of minerals and the evolution of the equilibrium in geothermal systems, as a function of a wide variety of variables, have recently been developed and are becoming more and more complex and realistic. Computer models of geothermal chemical processes can be used to solve engineering problems related to controlling scale formation, reinjection of fluids or disposal of sulfide-rich gases, for example (Reed, 1991). So it is possible to predict with reasonable confidence the conditions for such deposition for specific minerals from water of specified composition and to assess whether hot or cold injection is preferred from the point of view of mineral deposition (Arnórsson, 1995 a). When data on the chemical composition of produced and injected fluids is available as well as the percentage of produced fluids coming from the injection wells, estimates of the deposition rate of various chemicals can be made (Bödvarsson and Stefánsson, 1989).

Two geochemical computer programs, SOLVEQ and CHILLER (Reed, 1982; Reed and Spycher, 1989; Spycher and Reed, 1990 and 1992) were employed to model the geochemical processes of the injection, mainly the deposition of silica and calcite. SOLVEQ is a program for computing aqueous-minerals-gas equilibria. It is also quite helpful for preparing CHILLER calculations. CHILLER is a reaction path program for simulating water-rock interaction at a given temperature and pressure, calculating aqueous phase cooling and heating, computing mixing of fluids at different temperatures and modelling boiling and condensation processes.

Three modelling approaches were used. 1) Modelling the potential cooling of the geothermal water in the reservoir by the injection fluid. 2) Modelling potential heating of the injection water by the reservoir. 3) Modelling mixing to simulate the effect of injection water mixing with geothermal water in the reservoir. The chemical processes that take place during injection are very complicated. From geochemical modelling we can get information which can help us understand or predict geochemical processes taking place in the reservoir during injection.

In modelling, it is important to take account of related factors, for example the kinetics of the deposition of silica and the threshold saturation index of deposition of calcite. So, it is important to remember that they only take place for sure in the model; some of them may also occur in the natural systems (Reed, 1991). In CHILLER, there is an important parameter SUPNAM designed to suppress certain minerals and species, because their thermodynamic data are questionable or because their formation is kinetically retarded on the time scale of the reactions in the system. It provides the possibility for making the modelling results quite close to the actual situation. Meanwhile, incorporating related research results into the modelling is useful for getting the correct information about the chemical processes occurring during injection, for example, the data on both the breakthrough time and the return fraction for a certain injection/production doublet. The path volume is especially of interest when chemical deposition in the reservoir is suspected.

According to Arnórsson et al. (1983) pressure variations in the range 1-200 bars occurring in the geothermal systems are not expected to greatly modify the equilibrium conditions. So, 200 bars was chosen as the pressure value, to avoid boiling, to set in during the modelling run. The chemical analysis results used in the modelling are shown in Table 4.

TABLE 4: The chemical composition of different water samples (mg/kg) used for geochemical modelling

Site	**Return-water from upper area 97-0119**	**Return-water from lower area 97-0118**	**Groundwater in Thelamörk 94-9187**	**LA-05 in Laugaland 96-0062**	**LL-11 in Thelamörk 95-0321**
T(°C)	25.0	26.5	0.5	93.2	90.1
pH/T(°C)	9.83/20.5	9.83/20.5	7.55/21.4	9.79/21.7	9.89/16.6
CO_2	22.0	21.2	13.06	21.0	24.24
H_2S	0.0	0.0	0.0	0.09	0.17
B	0.17	0.16	0.01	0.16	0.22
SiO_2	94.4	88.6	16.9	97.6	122.1
TDS	248.0	233.0	57.0	245.0	229.0
Na	53.1	53	3.77	54.2	55.5
K	1.0	0.96	0.56	1.17	1.21
Mg	0.0	0.0	1.83	0.001	0.009
Ca	2.82	3.15	4.78	2.77	1.9
F	0.49	0.44	0.04	0.42	0.75
Cl	12.7	13.5	3.0	14.2	12.75
SO_4	35.7	39.7	1.63	40.1	24.28
Al	0.101	0.117	0.011	0.166	0.079
Mn	0.0	0.0	0.0018	0.0	0.0
Fe	0.0056	0.0144	0.0158	0.006	0.027

4.2 Modelling the cooling of geothermal water

During injection, the geothermal water temperature and composition will be changed due to the different temperature and composition of injected water, especially in the vicinity of the injection well. Cooling of geothermal water will cause changes in its pH as a result of temperature dependence of the dissociation of weak acids and bases, and the solubility of the minerals due to the change in the solubility dissolution constant with temperature. This will affect the conditions for mineral deposition. In the modelling of cooling, the geothermal waters from Laugaland and Thelamörk were simulated.

4.2.1 Geothermal water from Laugaland

In Laugaland, injection started in September of this year. The return water from Akureyri, about 25°C, is reinjected into the geothermal reservoir. The injection probably causes cooling of the geothermal water, especially in the vicinity of the injection well. From the chemical analysis results (Table 4) we find that the chemical composition of the return water is quite close to that of the geothermal water. Thus, modelling cooling will be very useful to understand the chemical processes during injection in cases where the injection water has almost the same composition as the geothermal water.

The modelling results are shown in Figure 10. First, the saturation indices for the different minerals were calculated by SOLVEQ. It shows that saturation indices for quartz, chalcedony, amorphous silica and microcline increase with decreasing water temperature. On the other hand, the saturation index of calcite decreases with cooling. During cooling, water is supersaturated with respect to calcite and quartz, but undersaturated with respect to amorphous silica; the water is undersaturated at the beginning but then supersaturated with respect to microcline and chalcedony with decreasing temperature. If only the saturation index results are considered, there should be some quartz, chalcedony, microcline and calcite deposited.

The results of earlier studies show that kinetics is an important factor in the deposition processes of silica. Silica scaling is a complex process, and the precipitation rate depends in part on the following factors, temperature, pH of the fluid, concentration of silica and the concentration of coexisting solutes (Stefánsson 1997). It is well known that quartz does not precipitate easily from supersaturated solutions due to its slow deposition rate and the troublesome silica scaling associated with geothermal utilization is only experienced if the water becomes supersaturated with amorphous silica. It appears that considerable amorphous silica super-saturation is required for some water before amorphous silica precipitation sets in at an appreciable rate, at least if the water does not come into contact with the atmosphere (Arnórsson, 1995a). Rimstidt and Barnes (1980) suggest that the rates of dissolution and precipitation of quartz and amorphous silica change are logarithmic functions of absolute temperature, with a moderately fast rate at very high temperatures and an extremely slow rate at low temperatures. As the temperature and concentration of silica are both low in the present case, it will take a long time for silica minerals to attain equilibrium. The saturation index results show that saturation index of amorphous silica is less than zero. So, quartz, chalcedony, α-cristobalite, β-cristobalite and microcline were suppressed in the CHILLER programme due to kinetic considerations before modelling started. This was done in all cases for which the saturation index of amorphous silica was less than zero. Otherwise, there will be some quartz precipitated from the solution during cooling, and this cannot reflect the actual situation. In the modelling, the temperature was decreased from 95 to 30°C in 5°C steps.

The cooling modelling results (Figure 10) show that (1) the pH value increases, (2) the fugacity of CO_2 decreases, (3) there are no changes in the activities of SiO_2 and Ca^{2+}, which relate to the minerals deposited in the model, (4) the activity of CO_3^{2-} increases with decreased temperature. In the model results, the main precipitate is calcite, but the mass is insignificant, only 0.0032 g at 90°C and 0.0024 g at 30°C in 1 kg water. When the saturation index of one mineral is greater than zero, the program will calculate mineral deposition until the saturation index is equal to zero. The result of the modelling shows the biggest saturation index of calcite to be 0.32, which is very low, and produced precipitate mass decreases with decreased temperature. In the Oguni geothermal field (Todaka et al., 1995), an anhydrite saturation index of -0.3 seems to correspond to a threshold for calcite scaling. The saturation index of anhydrite in this water is -3.55 at 25°C and -2.62 at 95°C, respectively, far lower than -0.3. If this criterion were applied, calcite deposition would not take place during cooling. This result is in line with the practical condition in which there is no mineral deposition problem in connection with the utilization of this geothermal water for space heating. So, according to the modelling results, there is no scaling problem during the cooling of geothermal water.

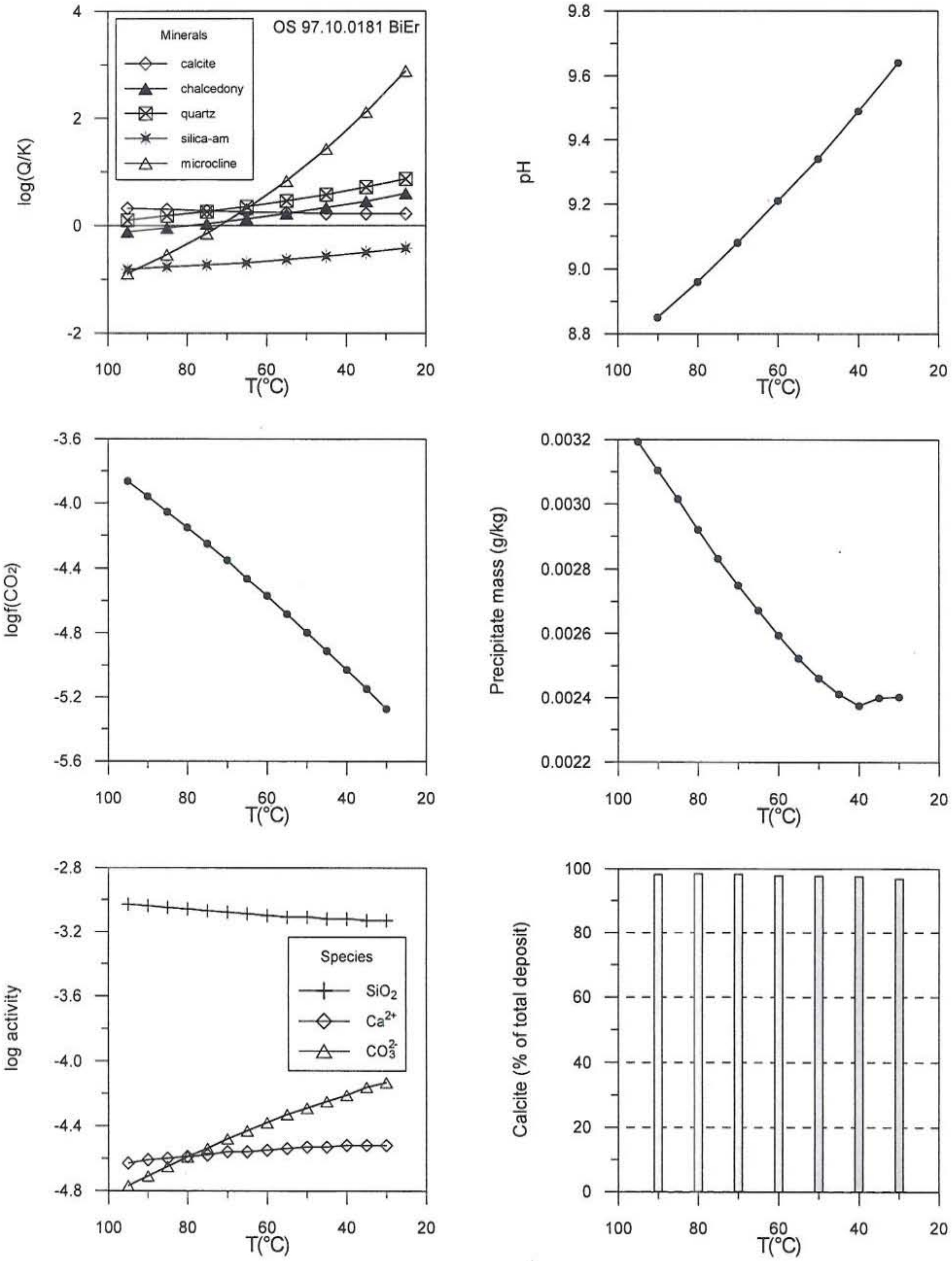

FIGURE 10: Chemical changes during cooling due to reinjection of LA5 Laugaland geothermal water

4.2.2 Geothermal water from Thelamörk

The exploitation of geothermal water has caused the water level in the Thelamörk geothermal system to decrease. Injection is one way to deal with this problem. In this part, models were used to simulate the chemical effects of the cooling of the geothermal water due to the injection of low temperature water.

The modelling results are shown in Figure 11. The saturation indices of minerals, calculated by SOLVEQ, show that the water is supersaturated with respect to quartz, chalcedony and calcite, but undersaturated with respect to amorphous silica during cooling from 90°C to 30°C in 5°C steps. The water is undersaturated with respect to microcline when the temperature is higher than 70°C, but becomes supersaturated with decreasing temperature.

During cooling, the pH increases from 8.89 to 9.66, and the fugacity of CO_2 decreases from $10^{-3.9}$ to $10^{-5.2}$ with decreased water temperature. The saturation indices for quartz and chalcedony are higher than zero, but there is no silica precipitate produced in the water due to their slow reaction rate. The small amounts of precipitate produced by the model, 0.002 g at 90°C and 0.0011 g at 30°C from 1 kg water, are only theoretical. If the minerals are not in equilibrium, the program will cause the water to attain equilibrium by dissolution or deposition of the minerals. At the same time, the main precipitate produced by the modelling is calcite. Its saturation index is only 0.25 at 90°C, and the activities of CO_3^{2-} and Ca^{2+} decrease with decreasing temperature. The saturation index of anhydrite is -3.05 at 90°C, which is far lower than the threshold for deposition of calcite observed for the Oguni field, Japan (Todaka at el., 1995). The activities of SiO_2 change insignificantly with temperature. According to the modelling results, there is no mineral deposition taking place during cooling of geothermal water. In other words, cooling does not affect the deposition of minerals.

4.3 Modelling the heating of return water and groundwater

When water is injected into the reservoir, it will be heated by the reservoir rocks. There will be some chemical changes in the water due to heating. The effect of heating on the injected water´s chemical properties was simulated by modelling as described below.

4.3.1 The return water from Akureyri

In Laugaland, the return water from the Akureyri Heating Services will be reinjected. There is no significant difference in the chemical composition of the return water and the geothermal water. Modelling of heating shows what may take place during heating of the injected water by the reservoir.

First the return water from the lower area of Akureyri was simulated. The results are shown in Figure 12. The saturation index results show that (1) the water became supersaturated with respect to quartz and calcite upon heating, (2) the water is almost saturated with respect to quartz when the temperature is 90°C, (3) the water becomes undersaturated with respect to microcline and chalcedony when it is heated to 65°C and 73°C, respectively, (4) it is undersaturated with respect to amorphous silica. Heating causes a decrease in pH, from 9.66 at 30°C to 8.85 at 90°C. There are no changes in the activities of SiO_2 and Ca^{2+}. The fugacity of CO_2 increases and the activity of CO_3^{2-} decreases with increasing temperature. The constituents of the precipitate produced by the model are mainly calcite, and there is an insignificant change of the mass of deposit with the change in temperature. The saturation index for calcite is only 0.33 at 80°C and 0.35 at 90°C, so deposition could only take place if the water attained equilibrium. Due to undersaturation with respect to chalcedony, this water may dissolve a small amount of silica minerals from the rock when the water is heated by the reservoir, because silica dissolution upon heating is faster than its deposition upon cooling in the actual system.

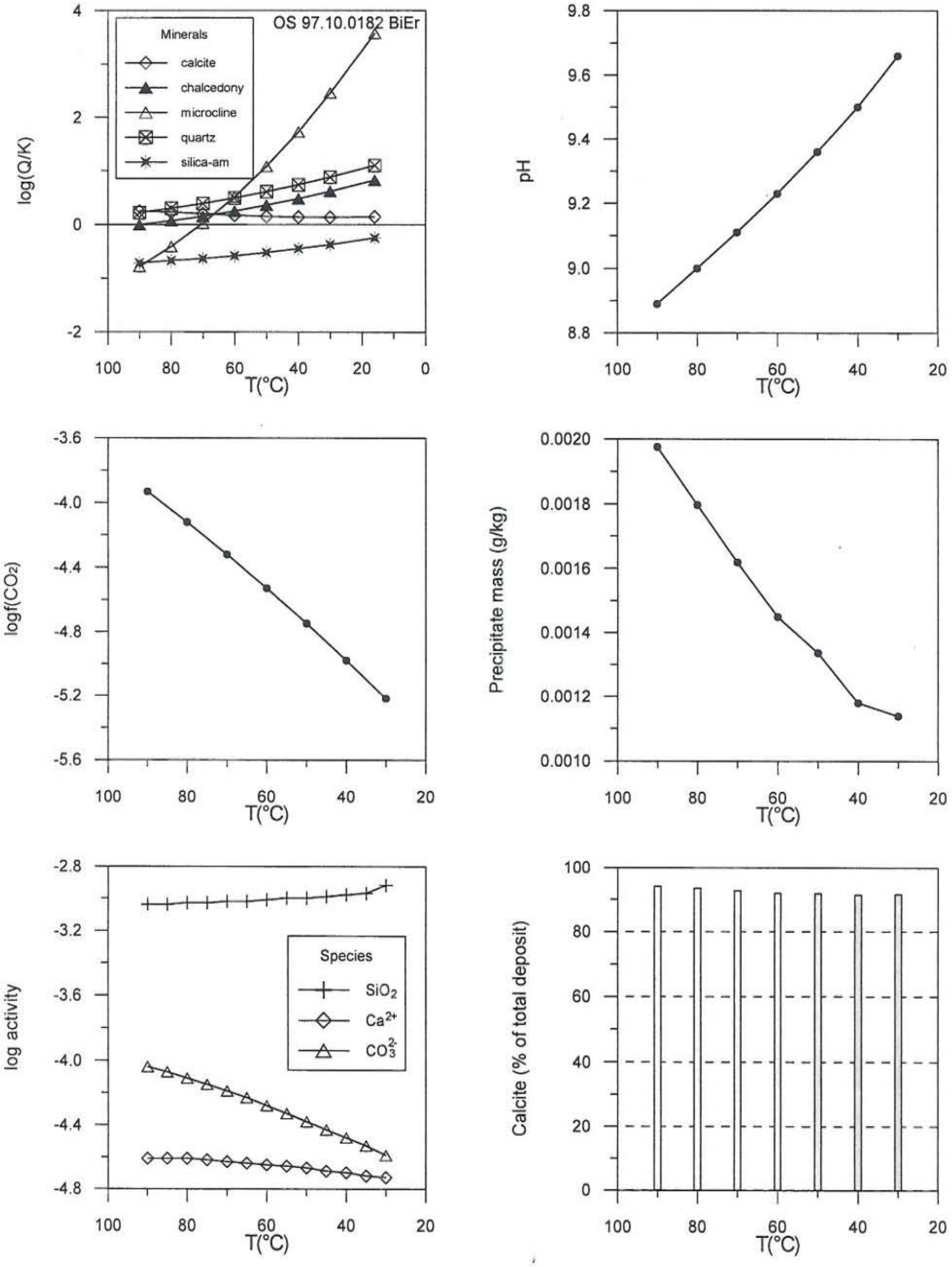

FIGURE 11: Chemical changes during cooling of LL11 Thelamörk geothermal water

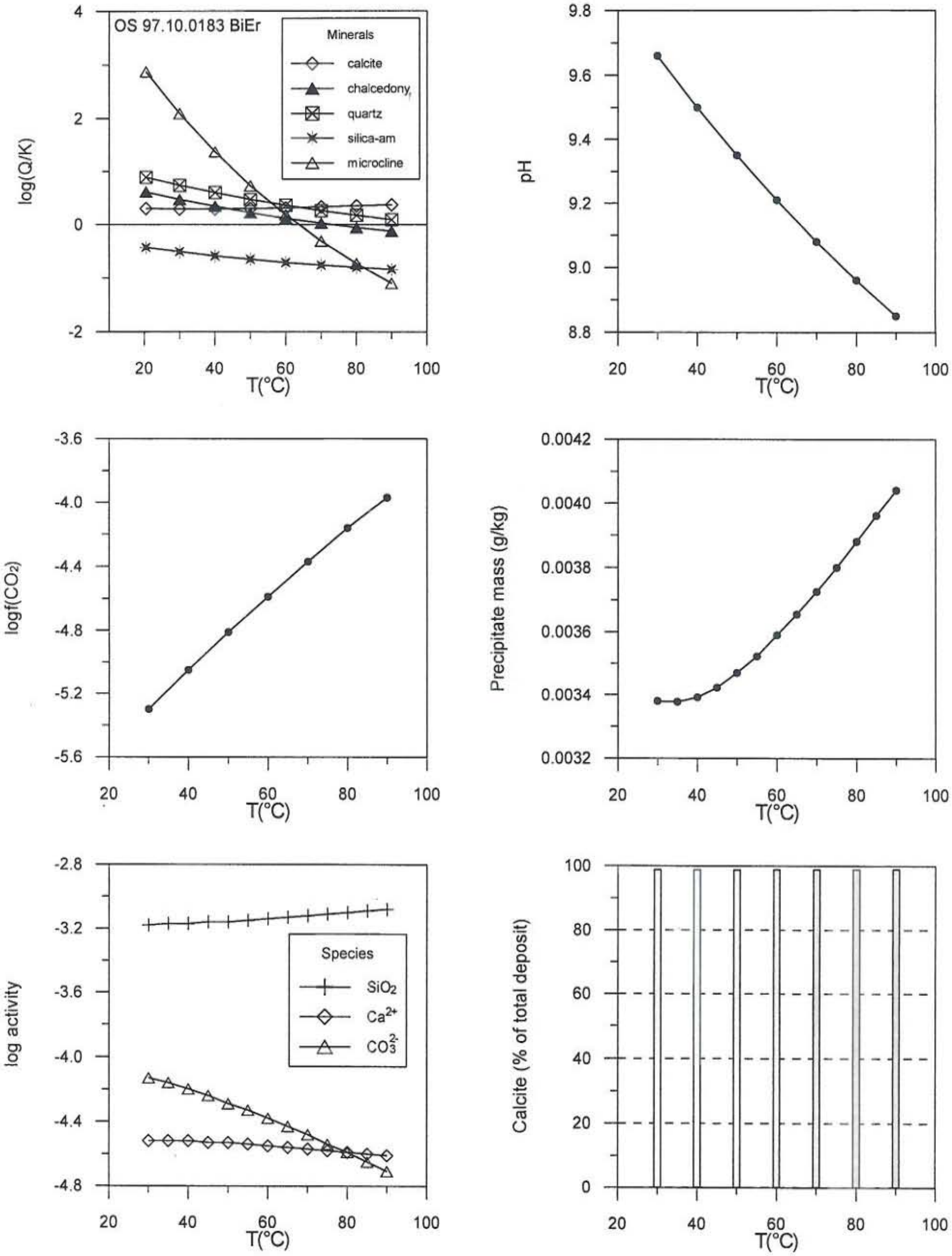

FIGURE 12: Chemical changes during heating of return water from the lower area of Akureyri

The modelling results for return water from the upper area of Akureyri are shown in Figure 13. It shows almost the same results as for the heating of return water from the lower area.

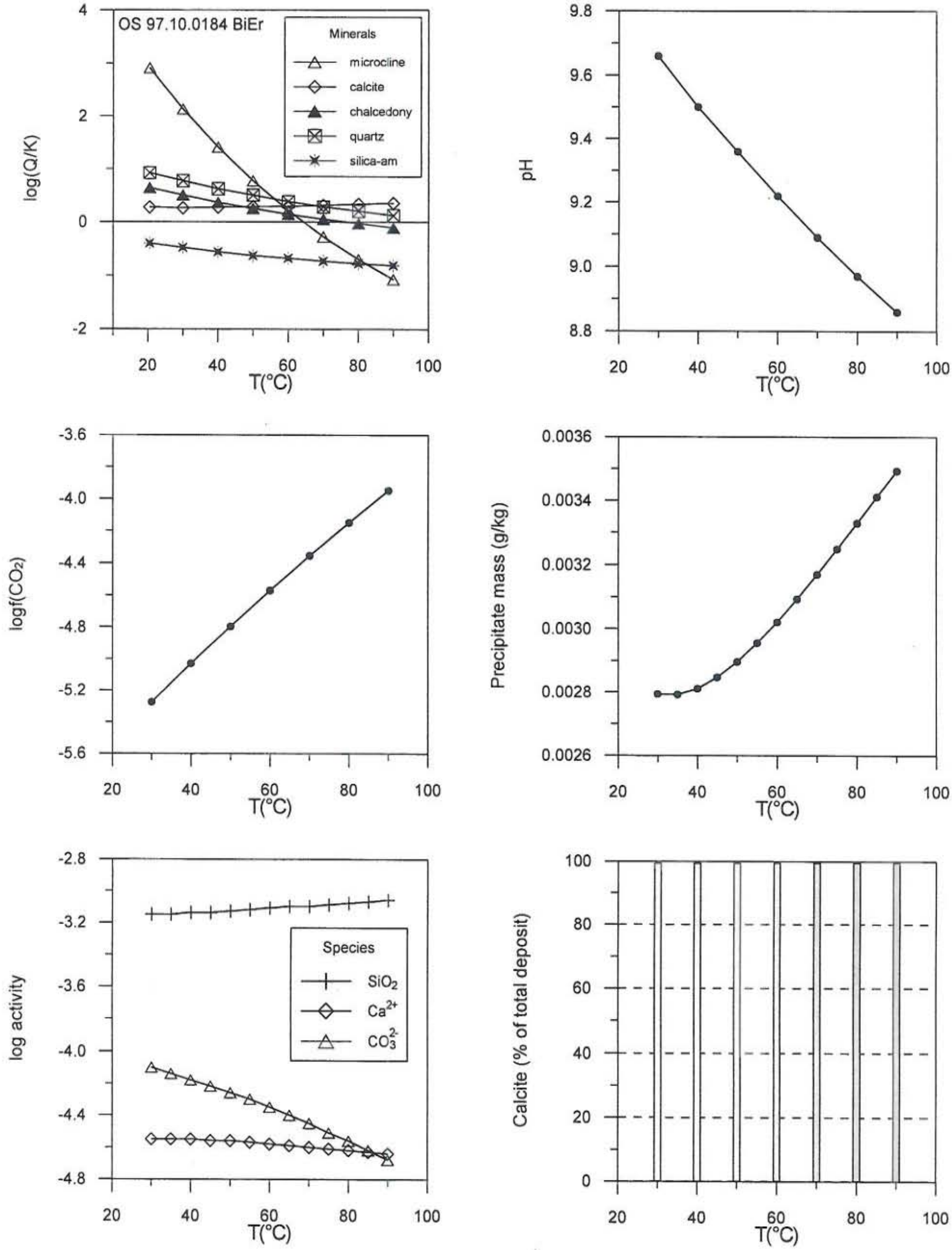

FIGURE 13: Chemical changes during heating of return water from the upper area of Akureyri

Comparing the heating results for return water to the cooling results for LA5 water, the changes in pH, fugacity of CO_2, saturation indices of minerals, activities of species and the mass of the mineral precipitate show that the heating of return water is almost an inverse process of the cooling of LA5 water. So, there is no dissolution of the rock taking place when the injected return water is heated by the reservoir rock. In many geothermal fields, the short-term injectivity has been found to increase with time. This increased injectivity has been explained to be caused by thermal contraction of the reservoir rocks (Stefánsson and Steingrímsson, 1980; Benson et al., 1987). This may be the case in the Laugaland field, if an increase in injectivity is observed at the beginning of injection.

4.3.2 The groundwater in Thelamörk

In Thelamörk, only a small amount of injection water can be obtained from the local heating system. It is not economic to pipe the return water from Akureyri because of the high cost of the pipeline. So, it is necessary to test the possibility of using groundwater as injection water. In the following part, the change in the chemistry of local groundwater upon being heated by the reservoir rock was simulated. The results are shown in Figure 14.

The saturation indices were calculated by SOLVEQ. The results show that the water (1) is undersaturated with respect to calcite and amorphous silica during heating, (2) the water is supersaturated with respect to clinochlore at all temperatures, (3) the water is supersaturated with respect to chalcedony and quartz at the beginning and becomes undersaturated with increasing temperature, (4) the saturation index for talc increases quickly, and saturation is reached at about 73°C.

There are no significant changes in pH, CO_2 fugacity, and SiO_2 activity, but the activities of Mg^{2+} and Al^{3+} decrease during the heating of groundwater. The mass of the precipitate increases significantly when the temperature of the water is higher than 50°C. When the temperature is lower than 50°C, the precipitate produced by the modelling is mainly clinochlore, but the mass is still insignificant, only 0.0001 g in 1 kg of water. At higher temperatures, the precipitate consists mainly of talc. At the same time, its mass increases significantly. There are 0.0065 g of precipitate produced from 1 kg of solution. So, according to the modelling results, there will be some talc precipitate produced from the water when it is heated by the reservoir. Compared to the return water, at least there is a tendency for talc deposition when the groundwater is heated, the water becoming undersaturated with quartz and chalcedony during the last heating steps.

4.4 Modelling the effect of mixing

During injection, the thermal groundwater will mix with the injected water. This will cause changes in temperature and the chemical properties of the water. In particular, mixing may cause mineral deposition. Thus, injectivity will be affected by a scaling problem, especially scaling of silica, which will take place in the injection well or its vicinity. In this part, chemical changes during mixing of geothermal and injected water simulated. The injected water was added to the geothermal water in different ratios, from 0 to 1.4 in increments of 0.1. A small portion of injection water was used to simulate conditions where injection water mixes with a large amount of geothermal water upon inflow, and a large portion of injection water was employed to simulate chemical processes in the vicinity of the injection well.

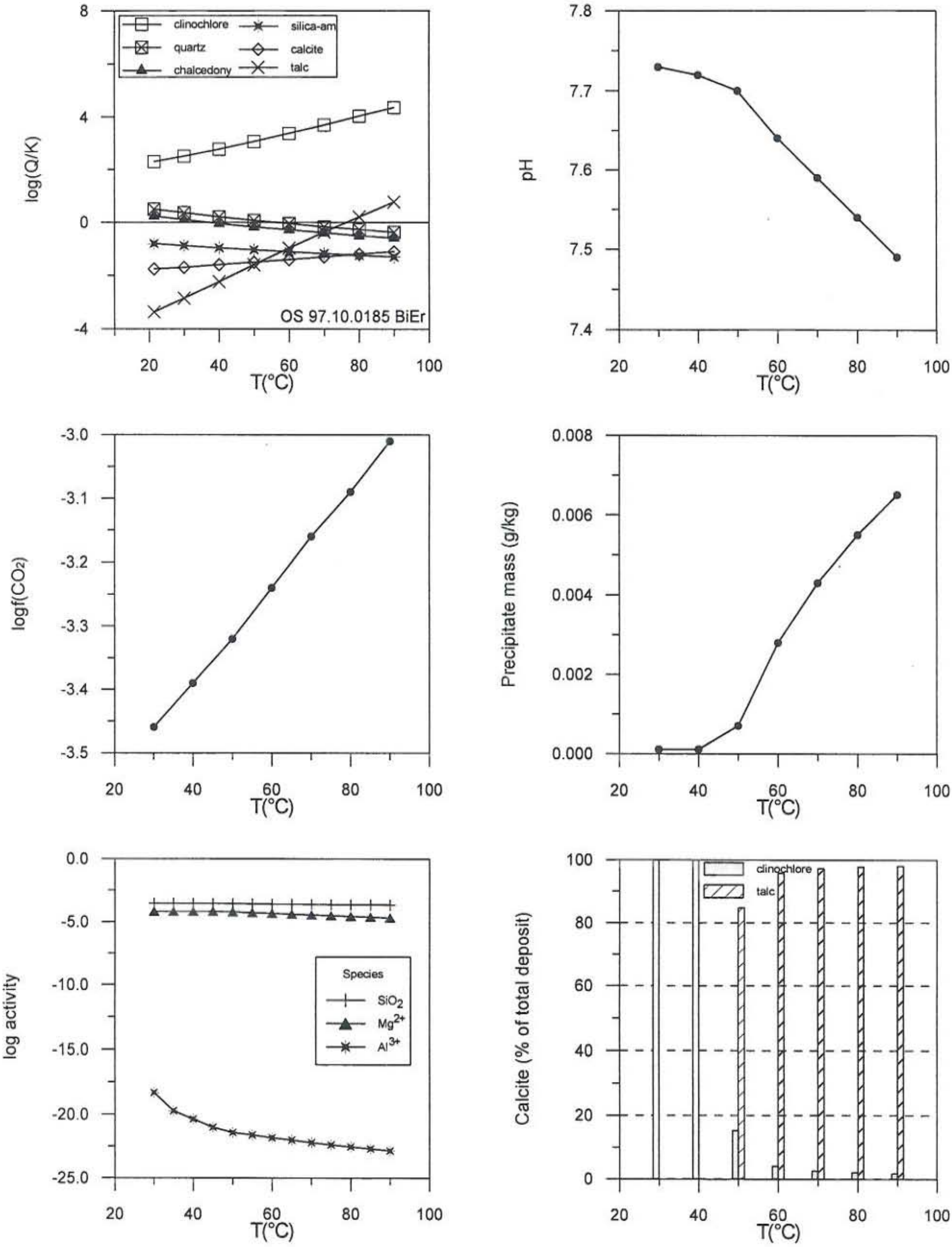

FIGURE 14: Chemical changes during heating of injected groundwater at Thelamörk

4.4.1 Mixing of thermal groundwater and injected water in Laugaland

In Laugaland, the return water from the Akureyri Heating Services will be injected into the reservoir. First, geothermal water mixing with return water from the lower Akureyri area was modelled (Figure 15).

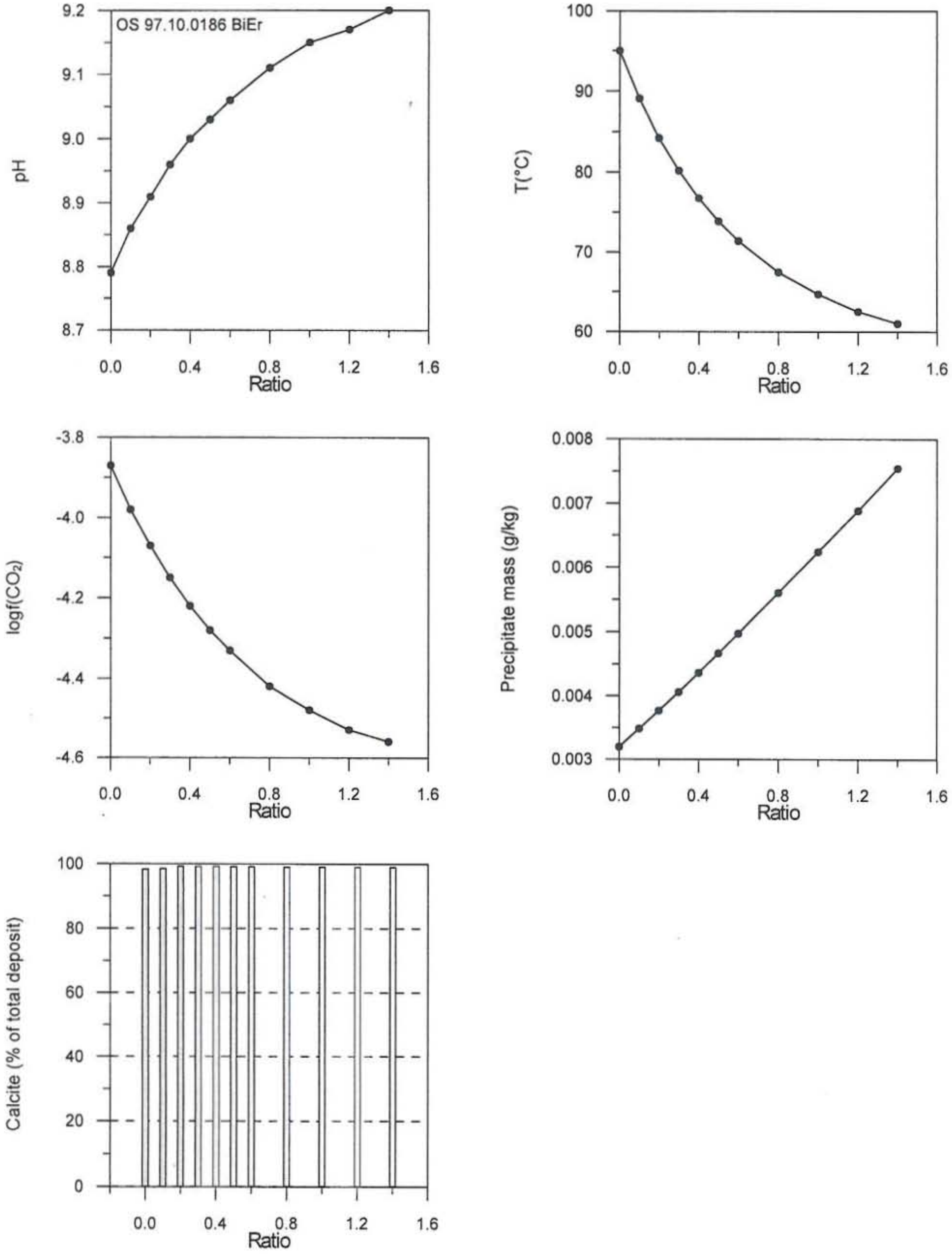

FIGURE 15: Results of mixing of LA5 water and return water from the lower area of Akureyri

During mixing of injected water and geothermal water, there is a small increase tendency in the pH, from 8.8 to 9.2. The low temperature of the injection water results in a decrease in temperature. The precipitate produced by the model is 0.0075 g from 1 kg water, when 1.4 part by weight of injection water is added to 1 part by weight of geothermal water. This value is greater than that of the precipitate produced when return water from the lower area of Akureyri was heated and the geothermal water was cooled to the same temperature, 60°C, the values being 0.0036 g and 0.0026 g from 1 kg water, respectively. This means that mixing of these two waters has a tendency to produce more precipitate in the system. The fugacity of CO_2 also decreases, and this will cause the equilibrium conditions to shift towards the deposition of calcite. But the mass of precipitate produced is still insignificant. Furthermore, the precipitate is calcite, all or at least some of which was produced to reach theoretical equilibrium. The mixing of the water from the upper area of the Akureyri Heating Services gave almost the same results (Figure 16). So, even though some chemical changes in water take place during mixing of injected water and geothermal water, they will not cause a scaling problem, if the return water from Akureyri is used for injection. This is in line with the result of an earlier injection experiment, i.e. that problems like scaling in the injection well would be minimal if return water from the district heating service was injected (Axelsson et al., 1993).

The effect of mixing geothermal water with groundwater was simulated (Figure 17). As no groundwater analysis results from Laugaland were available, the groundwater collected from Thelamörk was used in the modelling. The results show that (1) there is no significant change in the pH, (2) the fugacity of CO_2 decreases, (3) the temperature decreases faster than if the return water is used for injection during mixing, (4) there is more precipitate produced by the model when groundwater and geothermal water are mixed than when return water and geothermal water are mixed, or 0.0144 g and 0.007 g, respectively, from 1 kg water. The most important result is that the precipitate is mainly silicate, when more than 0.3 parts by weight of groundwater are added to 1 part by weight of geothermal water. The silicate is mainly a Mg-Al silicate, tremolite, due to the high concentration of magnesium in the groundwater. It has been observed that the mixing of silica rich geothermal water and magnesium rich cold water has led to precipitation of magnesium silicates that are apparently largely amorphous (Kristmannsdóttir et al., 1989). Such mixed waters are highly undersaturated with respect to amorphous silica (Arnórsson, 1995a). Hence, magnesium silicate deposition problem may be experienced during the injection of groundwater into geothermal water.

The results of the injection experiment, which was carried out in Laugaland in 1991, showed that the tracer breakthrough occurred after about 10 days. This is believed to indicate that the injected water diffused into a very large volume and that the injection well and the production well are not directly connected. The water in the geothermal system rose almost instantaneously, and no change in the production temperature of well LA-5 was observed during the experiment. The experiment also showed that the water from other production wells in the Laugaland field is expected to cool down even more slowly. It is predicted that the production temperature of the well will decline very slowly. In the earlier experiment, 10 l/s of 15°C water were injected into well LA8 and 40 l/s produced from well LA5 (Axelsson et al., 1993). A temperature of 15°C or higher can be expected for the return water when it is injected into the injection well. In this case, there is no thermal breakthrough problem.

Hence, no scaling or thermal breakthrough problems are to be expected during injection when return water is used for the injection. Also, injection is a viable means of increasing the production potential of the Laugaland geothermal system.

4.4.2 Mixing of thermal groundwater and injected water in Thelamörk

In Thelamörk, the amount of return water from the local heating system is only a few l/s. If injection is to be carried out, groundwater must be used, if it causes no problems. The chemical processes that may take place during the mixing of geothermal water and groundwater were simulated.

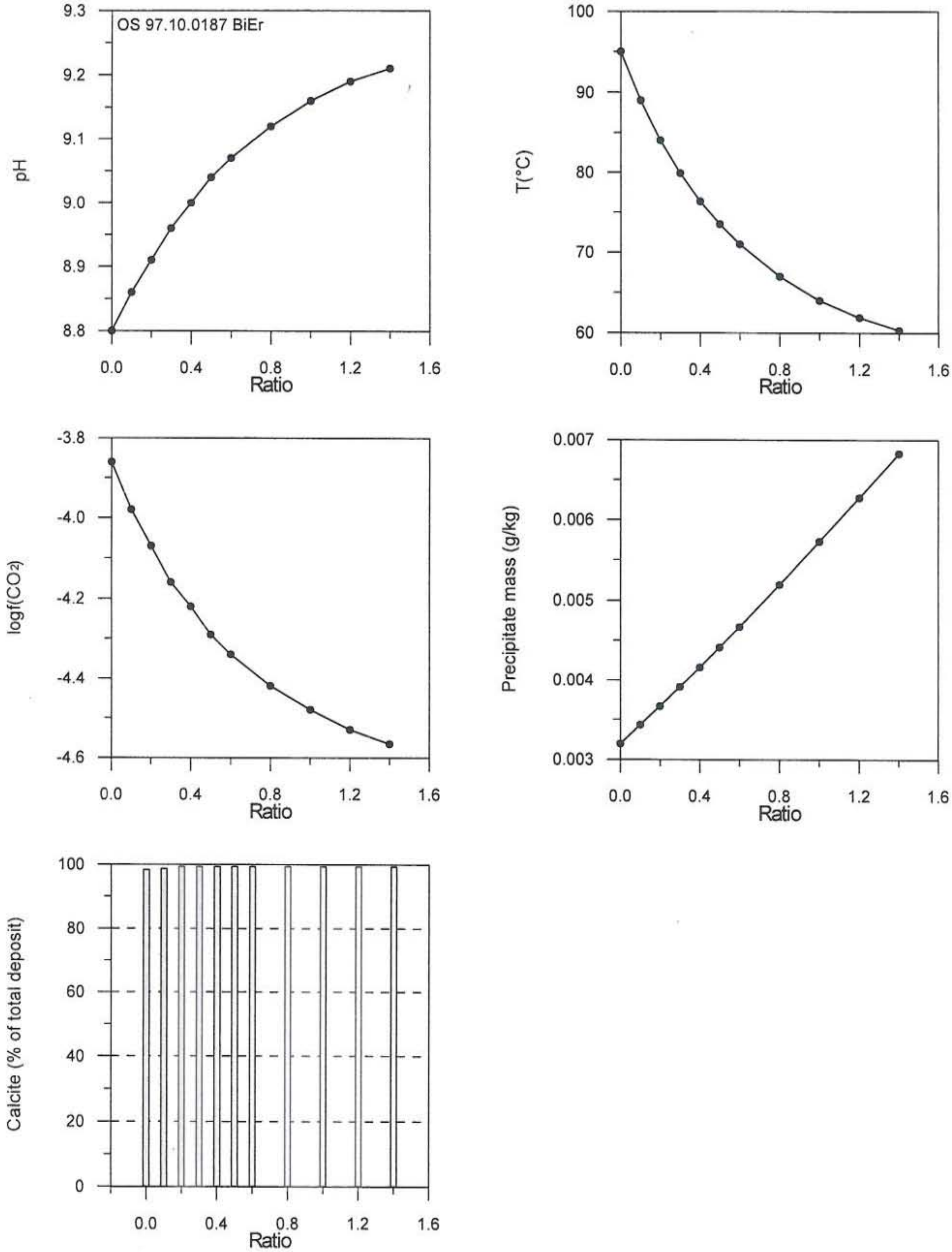

FIGURE 16: Results of mixing of LA5 water and return water from the upper area of Akureyri

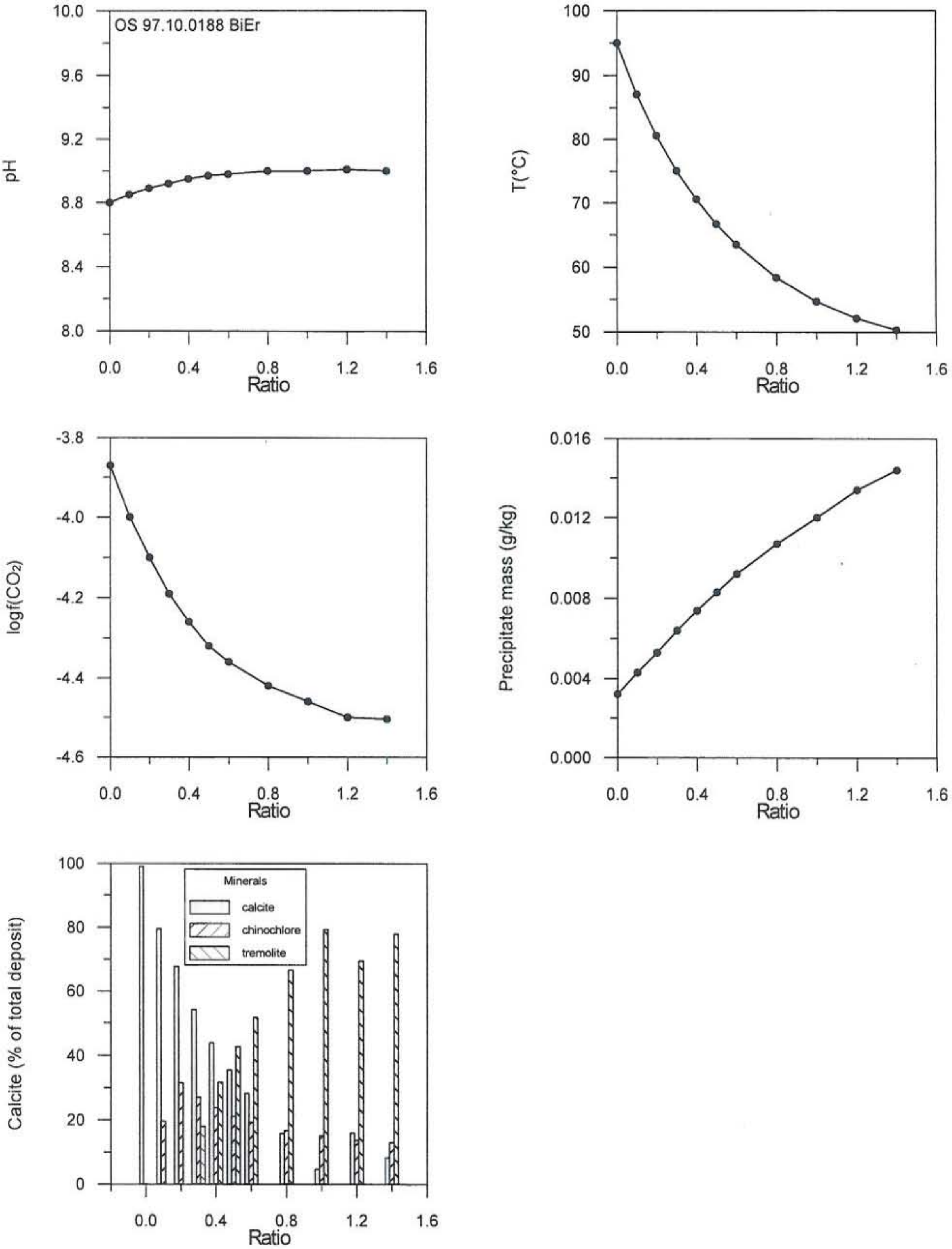

FIGURE 17: Results of mixing LA5 water and groundwater

The modelling results are shown in Figure 18. No significant change of pH is observed during mixing. The fugacity of CO_2 and the temperature of the mixed water decrease with an increased proportion of the groundwater. The precipitate produced is 0.0164 g from 1 kg water at the end of modelling. The constituents of the precipitate are magnesium silicate minerals, if more than 0.3 parts by weight of

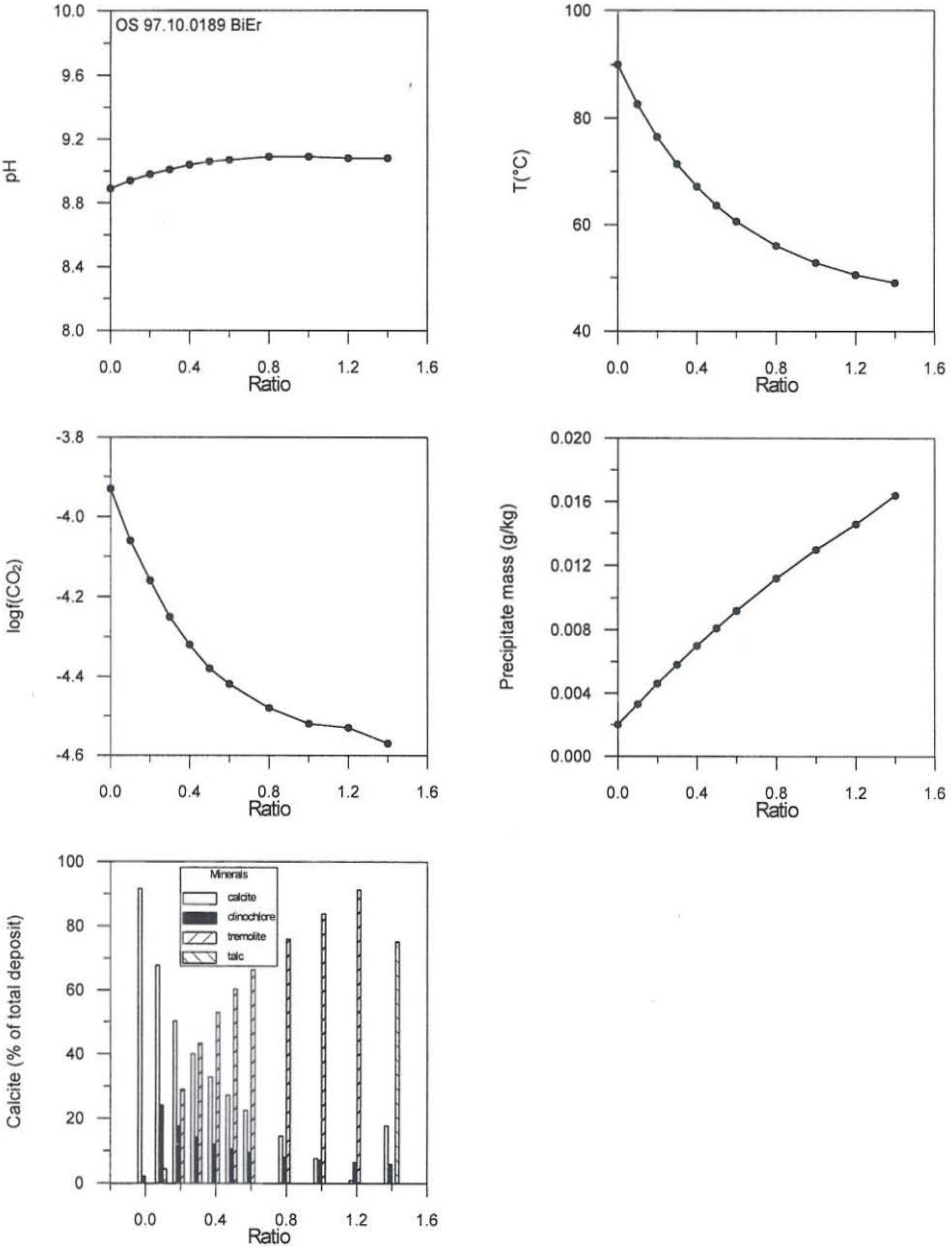

FIGURE 18: Results of mixing LL11 water and groundwater

groundwater were added to 1 part by weight of geothermal water. So, the modelling results show that the mixing of geothermal water and the injected cold water will cause the Mg-Al silicate tremolite and the Mg-silicate, talc, to deposit due to the high concentration of magnesium in the groundwater, especially in the vicinity of the injection well where a large proportion of injected water mixes with the geothermal water. The silica may precipitate from the solution with aluminium and magnesium to form largely amorphous compounds (Kristmannsdóttir, 1989; Kristmannsdóttir et al., 1989; Yokoyama et al., 1989). Such precipitation occurs even if the water is undersaturated with respect to amorphous silica (Arnórsson, 1995a). So, the groundwater cannot be used as an injection water due to potential deposition of Mg or Mg-Al silicates.

Almost no change in the chemical composition of the water is simulated upon cooling. The heating modelling results of the return water from Akureyri suggest that no problem results from using the return water from the local heating system as injection water. The injection experiment, which was carried out in Thelamörk in 1992, showed that tracer return was fast. Injection and tracer studies show that production well LL11 and the possible injection wells LL6 and LL8 are directly connected, most probably through the reservoir fracture (Flóvenz, et al., 1994). So there is a problem with heat recovery. Even using return water as injection water, the injection rate must be restricted to a limited value for efficient heat recovery, unless alternative injection wells to LL6 and LL8 are used.

5. CONCLUSIONS

1. Each geothermal field in the Eyjafjördur area has its own character, as for example shown by the Cl/B ratio. It is classified as a sulphate-rich water. Changes with time in chemical composition were observed in Thelamörk, and were noticed in some elements in well HG10 in the Botn geothermal field.

2. Most geothermometers give temperatures in pretty good accordance with measured temperature. Nevertheless, cation geothermometers suggested by Giggenbach (1988) and Fournier (1979) give considerably higher temperatures and the chalcedony geothermometer gives lower temperatures than those measured in some wells. Some decrease in calculated reservoir temperature with time is noticed at the Thelamörk and Botn fields.

3. Modelling results show that no mineral deposition is expected during cooling, even if the water is supersaturated with respect to quartz and chalcedony.

4. No mineral deposition takes place during calculated heating of return water from Akureyri, but there is a tendency for magnesium silicate deposition to take place during the heating of groundwater.

5. No scaling problem was found by modelling the mixing of return water and geothermal water in Laugaland. The modelling results show that dissolution of rock is not to be expected when the injected water is heated in the reservoir. Possible increase in injectivity at the beginning, can only be caused by contraction of the rock.

6. The modelling results show that using groundwater for injection in Laugaland and Thelamörk will probably cause magnesium silicate deposition.

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