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EXPLOITATION-INDUCED INFILTRATION OF SEAWATER INTO THE SELTJARNARNES GEOTHERMAL FIELD, ICELAND

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ABSTRACT

The Seltjarnarnes geothermal field, on the outskirts of Reykjavík, the capital city of Iceland, has been exploited during the last fifteen years for heating of the small town Seltjarnarnes. Chemical monitoring of the geothermal water has been effective during this time. For the first ten years slow but distinct changes in the water chemistry were registered. During the last five years the changes have accelerated. The most prominent change is an increase in salinity. Serious corrosion problems have arisen in the heating system, and they have increased along with the salinity of the water. The main reason for the increase in salinity of the geothermal water is believed to be inflow of cold seawater at shallow levels. Cooling of the geothermal water is anticipated.

INTRODUCTION

The Seltjarnarnes geothermal field is located within the town Seltjarnarnes, which is one of the suburbs of the capital city of Iceland, Reykjavík. There are several geothermal fields within and just outside of the city of Reykjavík (Fig. 1). Subsurface rocks of the area are Quaternary basalt lavas and hyaloclastites of an age about 1.8-2.8 M.y. (Tómasson et.al, 1977). Those fields are typical low-temperature geothermal fields with subsurface temperatures below 150°C at 1 km depth. The heat source of those fields is the regional geothermal gradient and no local heat source is involved as in the high-temperature geothermal fields. The water is of meteoric origin and has been traced by stable isotope ratios to precipitation in the highlands several tens of kilometers to the northeast (see Árnason 1976). Impermeable barriers separate the different geothermal fields in Reykjavík (Thorsteinsson and Eliasson, 1970).

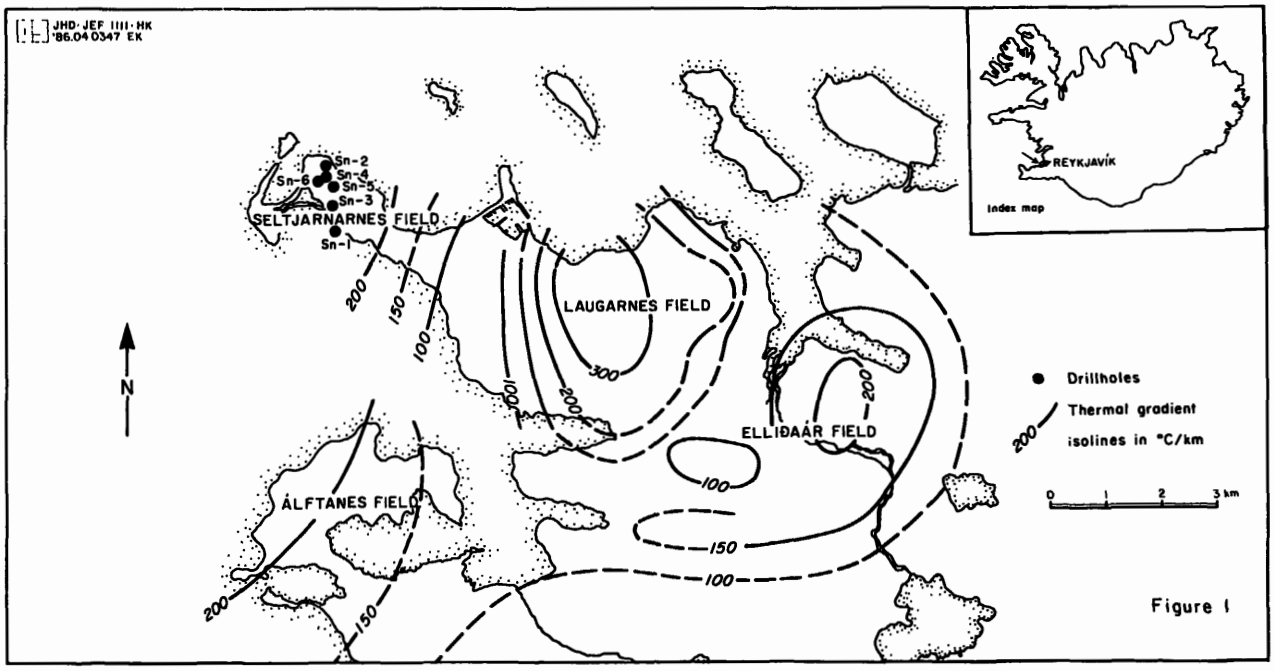

Figure 1. Low-temperature geothermal fields in Reykjavík, and thermal gradient map of the Reykjavík area based on shallow drillholes (Tómasson et. al 1977). The location of geothermal wells in the Seltjarnarnes field is shown on the map.

The municipal heating system of the town was founded in 1972, soon after the drilling of the first two deep drillholes (Sn-3 and Sn-4). It supplies the town with hot water for space heating and domestic use. At present four production wells are in use (Table 1) and two shallow ones are used as observation wells. Production casing is only•100-170 m in all but Sn-6 where it extends to 420 m depth.

Table 1 Drillholes in the Seltjarnarnes geothermal field

Drillholes	Year drilled	Depth in m	Max yield l/s	Water temp. °C
Sn-1	1967	1282		
Sn-2	1965	855		
Sn-3	1970	1715	15	101-103
Sn-4	1972	2025	35	111-116
Sn-5	1981	2207	30	90-100
Sn-6	1985	2701	30	115-117

Chemical monitoring of the geothermal water has been carried out since about 1970, and since 1981 it has been intensified due to much accelerated changes in the water chemistry. The town of Seltjarnarnes is located on a peninsula, almost surrounded by the sea. The hot water from the first production wells had a chloride concentration of about 550 mg/l, which is close to the maximum permissible for drinking water. The salinity was expected to increase with time, but the local authorities nonetheless decided to pipe the raw water directly to users.

In this geothermal field the wells appear to be fed by three different reservoirs. In the uppermost one, extending down to nearly 600 m in the southern part of the field and to 300 or 400 m in the north, the water is 60-70°C. In the northern part of the field, an 80-100°C reservoir exists at 400-1500 m depth, but in the southern part it is not pronounced. The aquifers found at these depths in the north yield less than those in the lower part of the field. The deepest reservoir yields 130°C water and extends from about 1500 to at least 2700 m. No temperature change has been observed at the lower levels of the field during the last 15 years. Figure 2 displays a temperature log of drillhole Sn-4 in 1984. A log from 1973 does not differ significantly. The bottom temperature of Sn-3, drilled in 1970, was exactly the same as the bottom temperature of Sn-4 in 1973 and 1984. No distinctive changes have occurred in the temperature of the production water. The regional drawdown of the field has been a little more than 30 m during the period of exploitation.

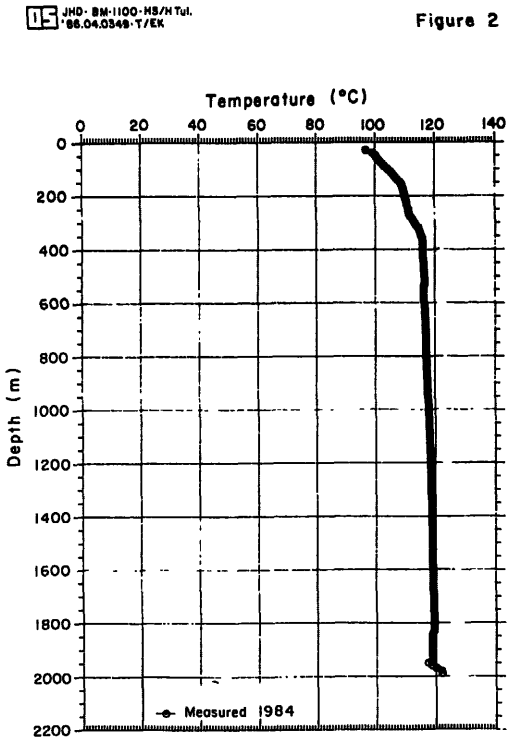

Figure 2. Temperature log from Sn-4, the main production well, in 1984.

CHEMICAL COMPOSITION OF THE GEOTHERMAL WATER

In the first shallow drillholes the chloride concentration in the 70-80°C hot geothermal water was 400-500 mg/kg, increasing with depth to about 700 mg/kg at the deepest levels (1280 m). In the production wells the chloride concentration was 500-550 mg/kg at the beginning (see Table 2). The pH was about 8.4 at 20°C. The geothermal water had a low but detectable concentration of hydrogen sulfide. It is close to equilibrium with respect to chalcedony and saturated with respect to calcite. The sulfate to chloride (SO_4/Cl) and calcium to chloride (Ca/Cl) ratios are considerably higher than in seawater whereas the sodium to chloride (Na/Cl) and potassium to chloride (K/Cl) ratios are lower than for seawater. This is in agreement with water-rock reactions of saline water and basalt at moderate temperatures (see Mottl and Seyfried, 1980, and Kristmannsdóttir, 1984). The initial salinity was considered (Tómasson et al.) to be due to leaching of salt from sediments and hyaloclastites in the reservoir rocks. The stable isotope ratios $\delta^{18}O$ and δD, are about -10.4 o/oo and -74.5 o/oo, respectively, and indicate an origin in the inland mountains 90-100 km to the northeast of the Seltjarnarnes geothermal field.

In 1972 the geothermal water was barely acceptable as drinking water, and corrosion problems were feared because of the high salinity. There was also concern that scaling problems might appear with the rise in pH on deaeration. Table 2

Table 2 Chemical composition of selected geothermal water samples from Seltjarnarnes

			mg/kg										
Drillhole	Year	pH/°C	SiO2	Na	K	Ca	Mg	CO2	SO4	H2S	Cl	F	Total diss.
Sn-1	1969	9.15/	86	305	5.9	61	0.50	14	147	0.0	432	0.95	1055
Sn-3	1970	8.50/	130	290	9.8	156	0.20	18	179	0.0	518	1.00	1320
Sn-3	1985	8.42/22	122	541	17.7	361	0.15	16	258	0.0	1336	0.58	3004
Sn-4	1972	8.30/	106	325	6.7	116	0.10	19	204	0.0	542	1.00	1366
Sn-4	1985	8.48/22	106	524	12.9	391	0.15	9	273	0.06	1325	0.72	3017
Sn-6	1985	8.30/22	118	548	15.0	476	0.23	9	298	0.00	1545	0.63	3455

shows the composition of water from Sn-6, the most recent production well, but this well has probably not reached chemical equilibrium yet, as the salinity is still declining with time, and the water temperature is increasing.

CHANGES IN WATER CHEMISTRY BY PRODUCTION

At the outset, the geothermal water was barely fit for direct heating and domestic use. As the Seltjarnarnes field is literally surrounded by seawater, the possibility of cold seawater intruding into the field, because of declining water pressure during exploitation, was anticipated. The use of heat-exchangers was therefore recommended and the water chemistry has been monitored regularly during the period of exploitation.

Figure 3 displays the change with time of the concentration of total dissolved solids in the geothermal water, and figure 4 the change in the chloride concentration. Both exhibit the same trend of a slow increase in concentration until about 1980, after which time the concentration rises rapidly. The sharp drops and rises in the curves from 1983 to 1985 are due to stops and starts of pumping from the wells. In all the wells the chloride (and total) concentration drops after a rest.

Figure 3

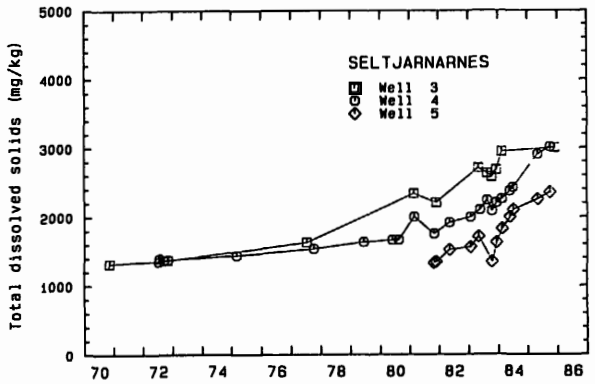

Figure 3. Total dissolved solids vs. time in geothermal water from the Seltjarnarnes field.

Figure 4

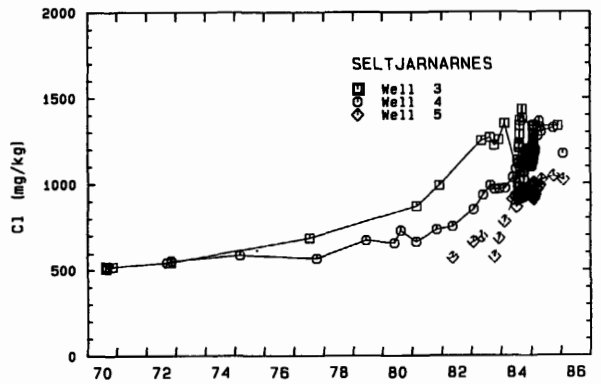

Figure 4. Chloride concentration vs. time in geothermal water from the Seltjarnarnes field.

Figure 5

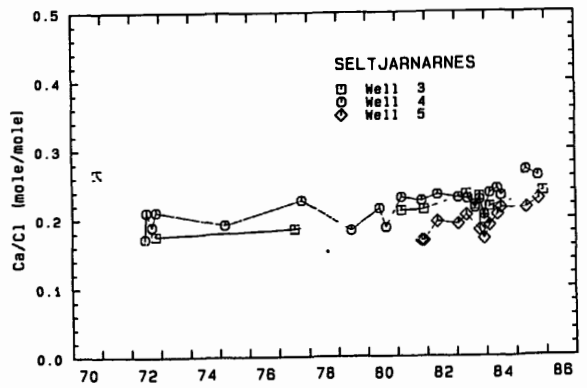

Figure 5. Changes in the Ca/Cl ratio vs. time in geothermal water from Seltjarnarnes.

Figure 5 shows the Ca/Cl ratio vs. time and figure 6 the Na/Cl ratio. The increase of the Ca/Cl ratio and the decrease of the Na/Cl ratio with time are in agreement with the changes in chloride and total concentration, Ca increases and Na decreases when saline water reacts with basalt at moderate temperatures. Those cation exchange processes may happen in a few days time. No progressive changes in the Na/K ratio (figure 7) are observed, at least not until 1984. The silica concentration (figure 8) shows rather irregular changes during the same time. Over the last three years there appears to have been a slight decrease in the silica concentration in Sn-4 and a trend towards lower chalcedony temperatures (see Fournier, 1981). The equilibration with respect to chalcedony may take weeks, or even months, and is thus much slower than the cation exchange processes.

The water has now become totally unfit for consumption, and corrosion in the heating system has increased in step with the rise in salinity.

Figure 6

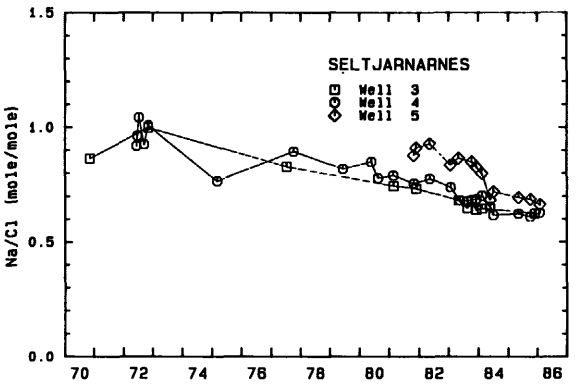

Figure 6. Changes in the Na/Cl ratio vs. time in geothermal water from Seltjarnarnes.

Figure 7

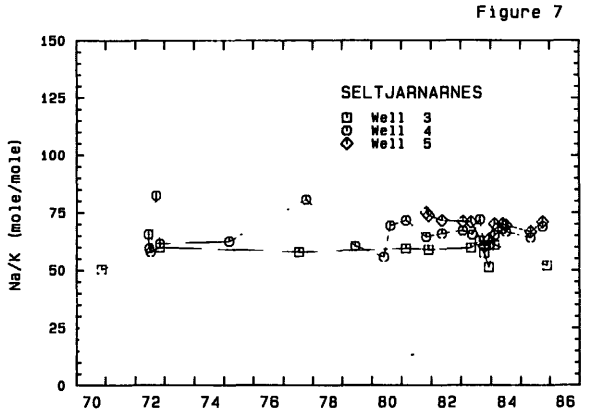

Figure 7. Changes in the Na/K ratio vs. time in geothermal water from Seltjarnarnes.

Figure 8

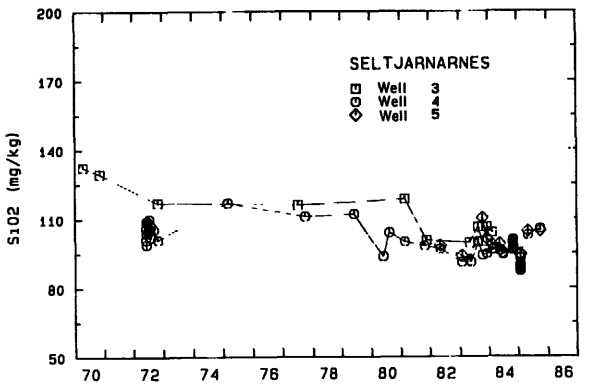

Figure 8. The concentration of silica by time in geothermal water from Seltjarnarnes.

Deep water from the two shallow observation wells Sn-1 and Sn-2 was resampled in 1984 after a time lapse of eighteen years (figure 8). No changes in salinity were seen in Sn-1, which is far from the production area. A major increase in salinity had occurred in Sn-2, which is within the production area, and a sharp gradient from upper to lower levels is seen.

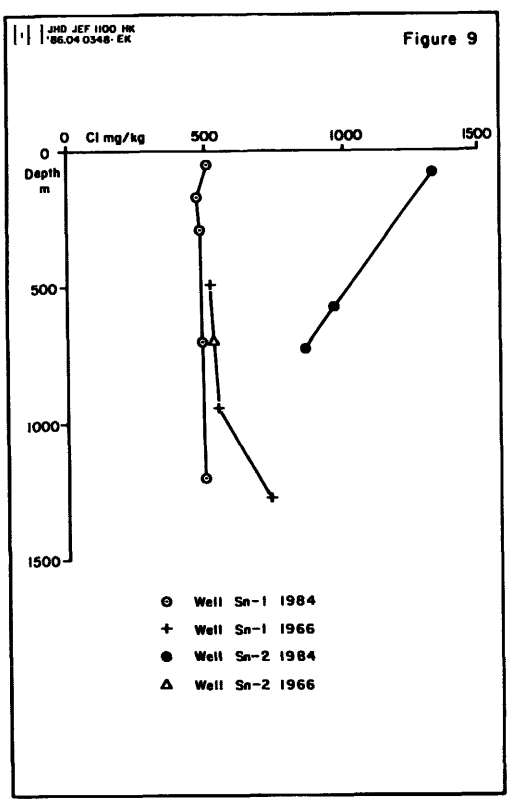

Figure 9. Chloride concentration vs. depth in deepwater samples from Sn-1 and Sn-2, taken in 1966 and 1984.

Samples have been collected from different depths in the main production well Sn-4. To prevent spouting of hot water from the well, it had to be quenched by cold water and this prevented sampling from the upper aquifers. The chloride concentration was about 900 mg/kg in all the lower aquifers (at 700 m, 1830 m, and 1940 m). A sample of pumped water from the well, taken a few days earlier contained 1100 mg/kg, and a free discharge from the well a few hours later had the same concentration. The upper aquifers at 200 m and 360 m must thus be a lot more saline than the deeper ones, but no direct measurement of the salinity of their water exists. Sampling of deep water from the other wells in the field has unfortunately not been carried out.

CONCLUSION

Seawater has been intruding into the Seltjarnarnes geothermal field during fifteen years of exploitation. The Ca/Cl and Na/Cl ratios of the water indicate that it has reacted with basalts at a moderate temperature on entering the system. Equilibrium with chalcedony appears not to have been reached in all cases, however. The minor changes in the Na/K ratio and irregular changes in the silica concentration suggest no major change in reservoir temperature during the period 1972-1984. There is an indication of a slight decline in reservoir temperature since 1984, and imminent cooling of production water is feared. The effects of seawater infiltration do not extend far outside the production area since geothermal water from well Sn-1 has not changed since 1966. Results from downhole samples from Sn-2 show that the inflow of seawater is from the surface or very shallow depths. Before production started, the deeper aquifers were considerably more saline than the shallow ones. The infiltration of seawater extends into the entire geothermal field, but the most severe effects are found in the upper aquifers.

Deep production casing and blocking of the shallow wells may thus delay or even stop the intrusion of seawater into the geothermal field.

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