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THE DEVELOPMENT OF THE SELTJARNARNES GEOTHERMAL FIELD, SW ICELAND DURING THIRTY YEARS PRODUCTION

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ABSTRACT

The Seltjarnarnes geothermal field is situated within the town Seltjarnarnes, a suburb of Reykjavík, the capital city. Before drilling the first gradient wells there were no signs of geothermal activity in the area, but the thermal gradient exceeds 300 °C/km. Subsequent drilling was successful, yielding 95-120 °C hot water in ample quantities for the needs of the town in the foreseeable future.

There are three main feedzones known in the geothermal field yielding 80-130 °C hot water and possibly the fourth one with temperature exceeding 150 °C. The field has proved to be rather complex with vertical as well as horizontal aquicludes. It was previously believed that the area was elongated along a NNE-SSW fault zone across the peninsula, but gradient wells drilled in 1995-1996 pointed to a circular main upflow zone located at the shoreline a few hundred meters to the north of the main area of exploitation.

A new well subsequently drilled into the supposed main upflow yielded almost nothing by tests made before stimulation. However it opened up tremendously by pressure stimulation by injection packer and is now the best production well in the field. Subsequently the other wells have been cooled and their production characteristics altered.

When the wells were first produced the water was found to be somewhat saline (<1‰ salinity) and the salinity increased with time and production rate causing severe corrosion problems. Almost no changes were observed in chemistry of the waters during the first 5-6 years of exploitation. Then the salinity started to rise at a slow speed during the subsequent 4-5 years to 1983 and then sharply during 1983-1986. The speed of increase then slowed off and finally almost stopped due to measures taken to reduce production from the field. The best production well has the most saline water probably due to increased circulation in the middle of the upflow zone.

There has not been any cooling of the reservoir due to seawater inflow, but the production characteristics have changed. Thus supersaturation of calcium carbonate has increased substantially, but no scaling has happened sofar.

The increase in production from the area has been close to what was forecasted in 1995 and the regional drawdow similar as forseen. The drawdown of the last well drilled in the supposed main upflow zone is much less than expected and the production larger.

1. INTRODUCTION

The town Seltjarnarnes, a suburb of the capital city Reykjavík, utilizes a geothermal field (Kristmannsdóttir, 1986) located within the city border for their municipal heating system, *hitaveita*. The geothermal field is located in the same Quaternary rock section (Fig. 1) within the Kjalarnes caldera (Fridleifsson, 1990) as the five other geothermal fields situated within the Reykjavík region (Fig. 2). The subsurface rock section is built of eight formations of basaltic lavas and hyaloclastites interbedded with thin sedimentary beds and also intrusives of increasing density by increasing depth. A typical formation consisting of acid and andesitic rocks can be traced through the entire rock section, dipping from less than 1 km depth below Seltjarnarnes to about 2 km below the Elliðaár geothermal field in SE. In the geothermal fields faults and displacement of the rock formations has been observed (Fridleifsson, 1990). All the fields appear to have a transient pressure connection, but a local heat source and different chemical properties and water recharge.

No geothermal actity was known in the Seltjarnarnes area before drilling of the first gradient wells in 1965. This area is the only geothermal field in the region where no surface acivity was known prior to development. Two gradient wells were drilled in the seventies, one on the southern shore of the peninsula and another on the northern shore. The geothermal gradient was found to be about 300 °C/km and slightly higher in the northern part of the peninsula. It was assumed that the area was elongated along a NNE-SSW fault zone across the peninsula. The main upflow zone of the field was supposed to be located towards west and probably connected with the Álftanes geothermal field to the south (Tulinius et al, 1987). Later development of the field and drilling of further gradient wells has changed this concept considerably. The production characteristics of the field were found to be more complicated than in the previously developed fields in the region, especially due to the increasing salinity of the water by production. Elaborate monitoring of the area (Kristmanns-dóttir and Ármannsson, 1996) and continous research has however resulted in a very profitable production of the field. The *hitaveita* was established in 1972 when the number of inhabitants was less than 3000. At present there are approximately 4500 inhabitants in the town.

2. DEVELOPMENT OF THE FIELD

A total of twelve wells have been drilled in the area (Table 1), including five for intended production. The two first gradient wells, were later deepened, tested and produced for a while. Neither could sustain enough production to be used as production wells for the hitaveita. The first production wells were drilled in 1970 and the *hitaveita* started regular production in 1972.

Due to the setting and residental status of the area little or no geophysical surveying could be done in order to locate promising well sites. Cost of drilling was very high so drilling a number of exploration wells was not a feasible choice. The location of the first production wells, SN-3 and SN-4 (Table 1) was based mainly on the results from the two gradient wells. Both were successful and yielded up to 15 and 35 l/s of 105 and 118 °C (maximum temperatures) hot water respectively. The casings in both wells were shallow. Several aquifers are encountered in both wells and the temperature of the produced water changed with different pumping rates.

Subsequent drilling was also based mainly on results from earlier wells. Well SN-5 was drilled in 1981 and yielded up to 30 l/s of 95-105 °C hot water, but the total production did not increase noticable. In 1985 well SN-6 was drilled to the depth of 2701 m and cased to 414 m, which was believed to be deep enough to exclude the most saline part of the reservoir. Before the location of the last production well several, exploration wells were drilled (Sæmundsson et al., 1993, 1994), which showed that the geothermal area was not connected to the Álftanes geothermal field (Fig. 2) and strongly indicated that the main upflow zone was located at the extreme north of the peninsula and even north of it.

A new well was drilled subsequently in the supposed main upflow, but no loss of circulation was observed during drilling and it yielded almost nothing in tests made after the drilling and before stimulation (Kristmannsdóttir, 1995). However it opened up tremendously by pressure stimulation by injection packer (Tulinius et al., 1996) and is now the best production well in the field and the one which is used as a base load. The reason for this is believed to be partly the drilling technique producing very finegrained cuttings clogging up the aquifers and partly due to the permeability distribution in the field.

3. RESERVOIR CHARACTERISTICS

Three main feed zones are known in the geothermal field yielding 80-130 °C hot water. The uppermost is 60-75 °C and extends to 400-600 m depth, deepening towards south. A 80-100 °C hot reservoir extends down to 1500 m depth and below that a reservoir with 120-140 °C hot water is encountered. There are indications of still another reservoir at depth, believed to be 150 °C hot or more.

The production water turned out to be much more saline than that of the other geothermal fields in the region. When the wells were first produced the water was found to be somewhat saline (<1‰ salinity and chloride concentration less than 550 mg/l) and the salinity increased with time and increased production (Kristmannsdóttir and Ármannsson, 1996). There is no dissolved oxygen in the water and the water was not considered to be corrosive for steel pipes and radiators. As it turned out steel radiators were quickly considerably corroded in the system rending it impossible to use the water directly. Later investigations showed that in most houses air was leaking into the cirquit, but a very small oxygen content will cause rapid corrosion at such high water salinity. In 1984 the use of heat exchangers was made mandatory according to the building codes of the town, which solved most of the corrosion problems.

The uppermost reservoir is the most saline and the most effected by inflow of seawater, with probably up to 3000 mg/l of chloride. The produced water is a mixture of aquifers from at least two different reservoirs so a pure sample from the upper resevoir has not been obtained. However the deepest producing reservoir has been sampled in both wells SN-4 and SN-6 and appears to contain about 900 mg/l of chloride without any change from 1984 until present. Well SN-5, which is located outside the main upflow zone, has the least saline production water. The chloride concentration of the production water at present (Table 2) varies from 1000 to 1900 mg/l depending on wells and production rate (Kristmannsdóttir et al., 1998). Well SN-12, which produces from the middle and upper part of the deepest production zones has production water of the highest salinity of all the wells in spite of the production casing reaching down to almost 800 m depth. This ambiguity has been explained by more rapid circulation and inflow of seawater near the main upflow zone of the geothermal field. However, no deep water samples have been obtained from that well. Sampling of deep water from the bottom of well SN-6 (Kristmannsdóttir et al., 1994) has revealed water of much lower salinity, about 260 mg/l of chloride, and calculated silica temperature exceeding 150 °C. This may indicate still another reservoir at greater depth.

The water is as most Icelandic geothermal waters, in equilibrium with the silica mineral chalcedony (Arnórsson et al., 1983) as well as several aluminium-, alkali-, iron- and magnesiumsilcates. The water is supersaturated with respect to calcium carbonate (calcite), which is probably due to the mixture of aquifers of different temperature and salinity. Icelandic geothermal water is normally found to be in eqilibrium with calcite at reservoir temperatures. The concentration of heavy metals is low. The stable isotope composition (δD and $\delta^{18}O$) is similar to precipitation in the mountains some tens of km to the north and northeast.

Due to the saline character of the water and lower pH than is common for Icelandic geothermal water it is found to be relieving for skin diseases as psoriasis. The possible balneological potential of the geothermal field is beeing surveyed at present.

The development of the field has proved it to be rather complex with vertical as well as horizontal aquicludes. It was previously believed that the area was elongated along a NNE-SSW fault zone across the peninsula. The gradient wells drilled in 1995-1996 indicated that the main upflow of the field was almost circular and located at the shoreline a few hundred meters to the north from the main area of exploitation. Well SN-12 which was drilled into this area is the best production well drilled in the field. However, since it was drilled well SN-4 has both cooled and its production declined. All the wells are connected and the total production has not increased by the drilling of well SN-12. The difference is that the needed amount of water can be pumped from that well only for the most part of the year or with addition from one of the others instead of before two or three wells had to be produced simultaneously at all times. This change is also partly due to the choice of pumps, but mainly due to the exellent production characteristics of well SN-12.

The present production of the field can be greatly increased without putting any strain on the field and be maintained for decades without the drawdown getting to a dangerous level.
As indicated by recent reinjection tests into Icelandic low temperature geothermal fields (Axelsson et al., 1995, 2000) the production of the field could be still optimized by reinjection into the field.

4. PRODUCTION HISTORY

Estimated total production from 1966 to 1998 is shown in Figure 3 and the regional drawdown, from 1972, measured in well SN-2 in Figure 4. The production is estimated from the amount sold after 1990, but before that on flow measurments at each well. After 1990 the well measurements show much lower flowrate than the average amount sold by the hitaveita and are therefore considered to be wrong. It is also very likely based on waterlevel behavior in the area and on amount sold so that the estimated production before 1990 is somewhat too low. In Figure 5 calculated drawdown in well SN-2 is shown (Vatnaskil, 1994) according to given premises of 2 % yearly increase in production rate from 1993 and the use of wells SN-4, SN-5 and SN-6. As compared to Figure 4 the regional drawdown is at present very near to the one forecasted in

Figure 5, but the increase in production has been close to the 2% used in the simulation.

As mentioned earlier the production from the field started in the late sixties from wells SN-1 and SN-2. Well SN-3 was drilled in 1970 and well SN-4 in 1972, after which the hitaveita was founded. The production increased after that from about 5 l/s to over 30 l/s. The average production was at about 30 l/s until 1981 when well SN-5 was drilled and put in production. After 1981 the production increased steadely until 1988, where it reached its maximum at over 56 l/s on average. Well SN-6 was drilled in 1985 and put in production in 1986. During all this time the regional water level went steadily down. In 1989 the billing system for the hot water was changed from maximum flow restriction method to metering system. As a consequence the production decreased considerably in 1989 and 1990 and the regional water level went up. Since 1990 the production has increased steadily again at about 2% per year but the waterlevel rose for about 3 years, then it leveled of. The production has not yet reached the level before the billing system changed even though it seems like it on Figure 3, but as mentioned earlier the production before 1990 is probably estimated to be too low. The town has reached its ultimate size and cannot expand further but there could be some new industrial or balneological uses for the hot water in the future.

Well SN-12 is found to be much more productive than the forecast given from the tests after the injection packer stimulation and the drawdown for a given production is much less than the first tests indicated.

Almost no changes were observed in chemistry of the waters during the first 5-6 years of exploitation. Then the salinity started to rise at a slow speed (Fig. 6) during the subsequent 4-5 years to 1983 and then sharply during 1983-1986. The speed of increase then slowed off and finally almost stopped due to measures taken to reduce production from the field Kristmannsdóttir et al., 1995). Those changes were observed in all the wells, but they behaved very differently depending on the relative production from each feedzone. Well SN-5 produced the least saline water, but salinity always increased slowly by longtime pumping from the well and the temperature of the water decreased. After longtime rest of the well it yielded hotter and less saline water and for a while (weeks) the temperature increased and salinity went down. After rest of well SN-6 the water was also much less saline, but only for a few hours, indicating that the deepest feedzone has the highest pressure at stillstand. In well SN-4 there has been changes in yield and relative pressure of the different aquifers due to the drilling and production of well SN-12. This has changed the behavior of the well as well as the composition of the well fluid. When the well has not been used for some time the fluid is more saline at first, indicating downflow of the upper aquifers when the well is not producing. Therefore the numbers plotted for comparison in Figure 6 are from samples taken after a continous pumping for some days at least. Well SN-6 has also shown some changes after the drilling of well SN-12, but far less than well SN-4. No clear changes have been noticed in well SN-5 after drilling of well SN-12. Production in the other wells has been much less after the drilling of SN-12, which also affects the behaviour of the wells.

No significant changes have been noted in the stable isotope composition in spite of the increased salinity of the water and supposed inflow of seawater.

As in the examples above individual wells have changed during development and production of the field. The main general change of the field has been increased inflow of saline water into the field, mainly into the uppermost reservoir. Sofar no general cooling of the field has been observed.

Even though there has not been any cooling of the reservoir due to seawater inflow there have been changes in production characteristics. In general substantial supersaturation of calcite is observed (Fig. 7) even though no scaling has happened sofar.

5. CONCLUSION

The development and production of the Seltjarnarnes field through about thirty years has proved it to be a rather complex geothermal field with vertical as well as horizontal aquicludes. The main upflow of the field appears to be almost circular and located at the northern shoreline of the peninsula. The last and sofar best production well SN-12 was drilled into this area, yielding more saline and somewhat cooler water than the hottest water obtained in some of the other wells. The drawdown in well SN-12 by production however is lower than expected and its recovery is faster than in the other wells. This is considered to be due to the higher permeability in this part of the field. The total production of 50 l/s on average is not expexted to increase the regional drawdown considerably during the next years and the production can be increased considerably without putting any strain on the field. There has not been any cooling of the reservoir in spite of seawater inflow, but substantial supersaturation of calcium carbonate is observed although no scaling has happened sofar.

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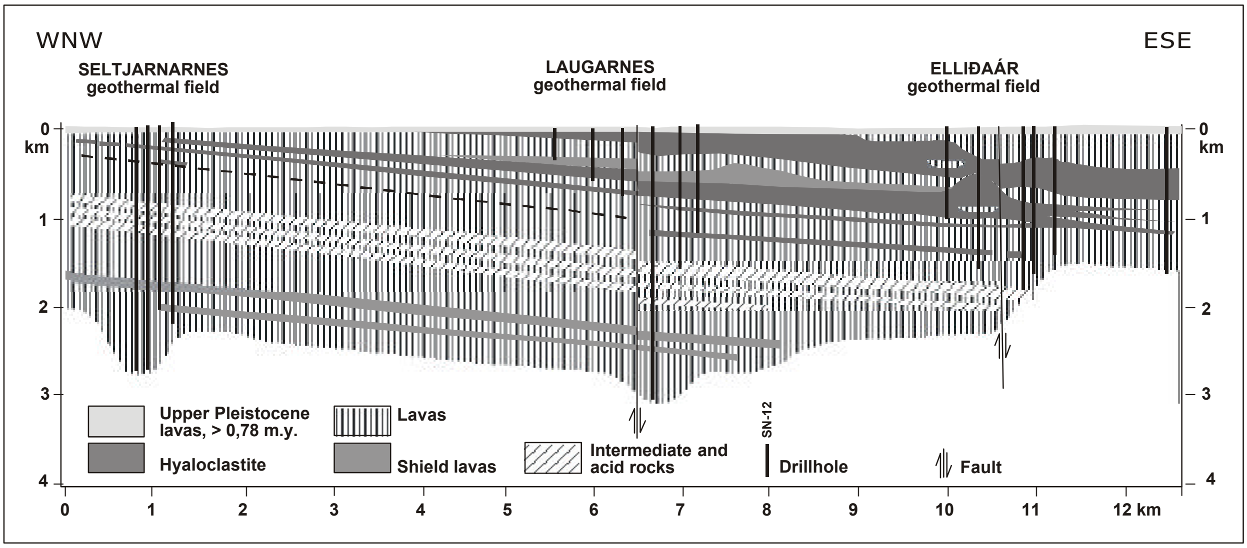

Figure 1. A cross section through the capital area from the Seltjarnarnes field in in west to the Laugarnes and Elliðaár fields in east and south east. Friðleifsson, 1990.

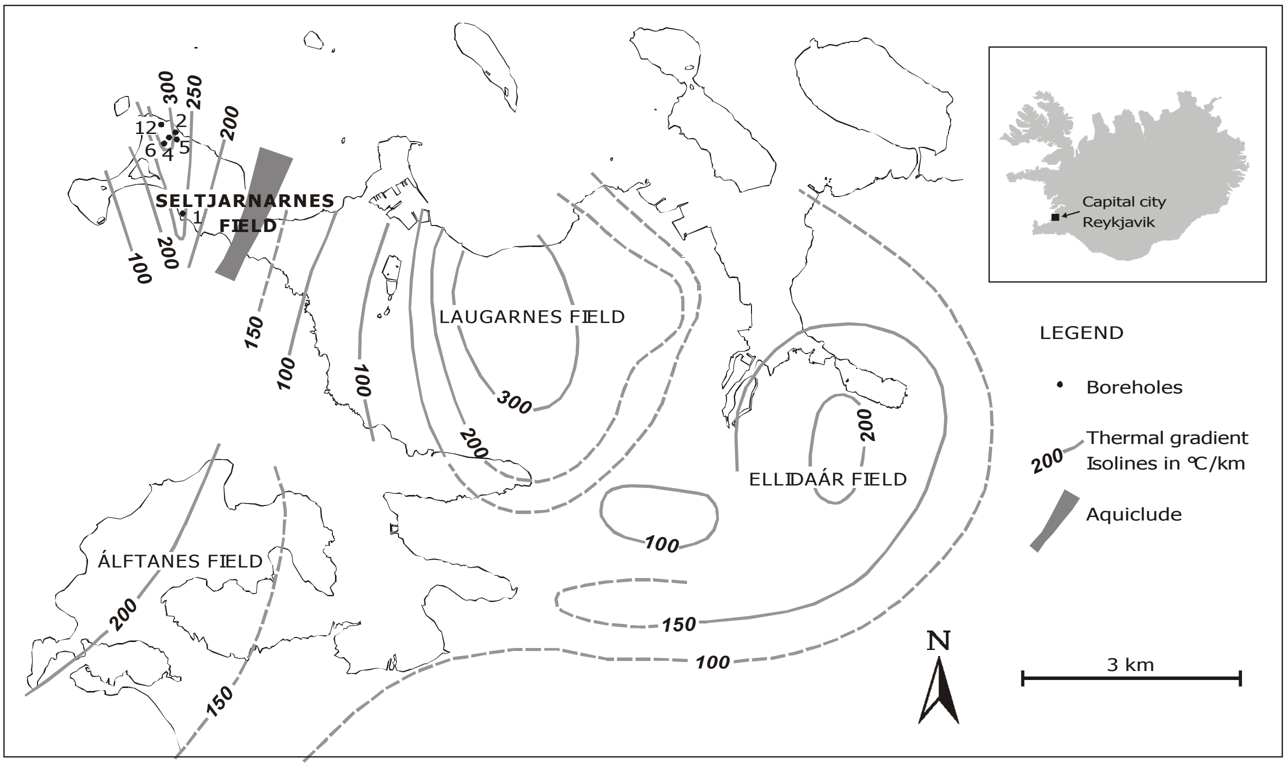

Figure 2. Thermal gradient in the area of the capital city, Reykjavík. Location of four geothermal fields within the area is shown as well as location of the production wells in the Seltjarnarnes geothermal field. Two other geothermal fields, not shown on the figure, are located a few kilometers further towards east and north.

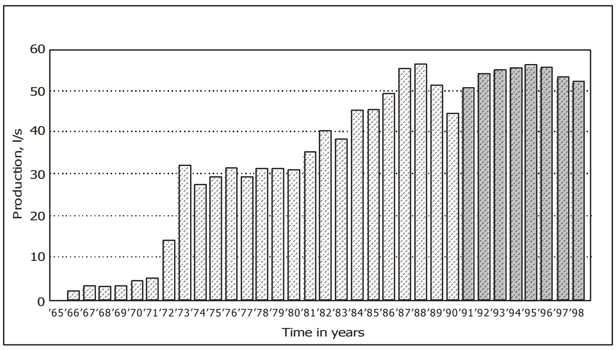

Figure 3. Yearly production from the Seltjarnarnes geothermal field from 1966 to 1998.

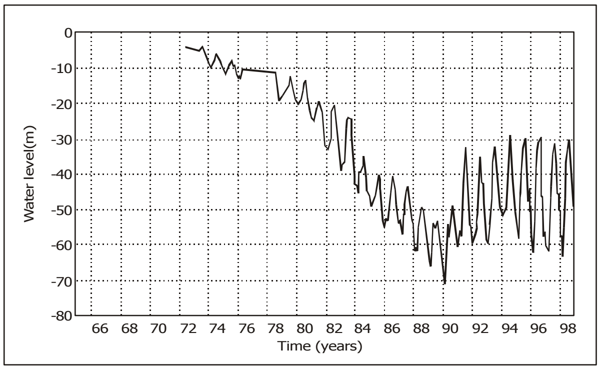

Figure 4. Regional drawdown (observation well SN-2) in the Seltjarnarnes geothermal field from 1968 to 1998.

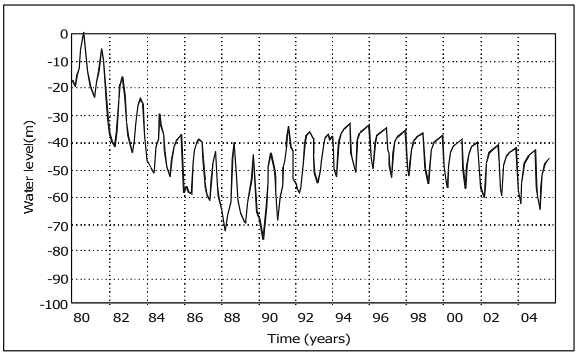

Figure 5. Calculated regional drawdown (observation well SN-2) by given premises in 1994 (Vatnaskil, 1994).

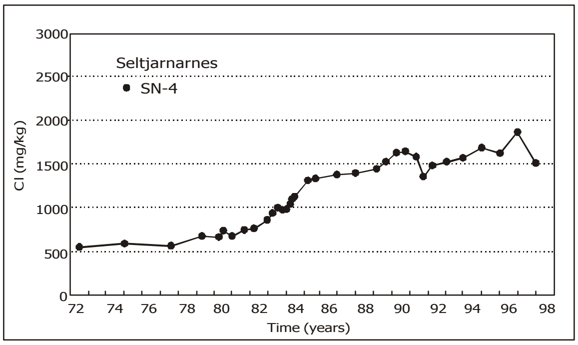

Figure 6. Changes in chloride concentration of the production water of well SN-4 from start of production in 1972.

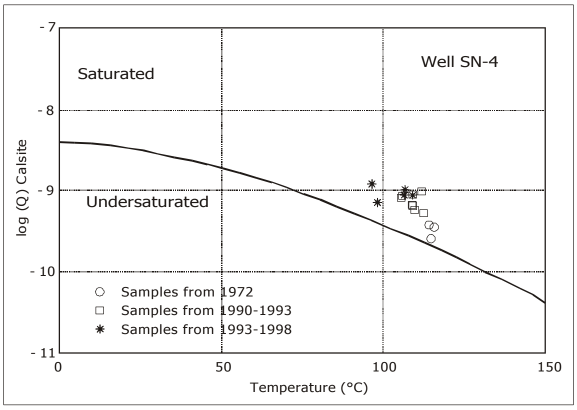

Figure 7. Changes in calcite saturation in production water from well SN-4 from start of production in 1972.

Table 1. Wells drilled into the geothermal field

Well no.	Drilling compl. in year	Depth in m	Depth of casing	Type of well
SN-01	1967	1282	18.5	Monitor.
SN-02	1965	856	81.5	Monitor.
SN-03	1970	1715	99	Monitor*
SN-04	1972	2025	172	Product.
SN-05	1981	2207	168	Product.
SN-06	1985	2701	414	Product.
SN-07	1993	154	#	Explor.
SN-08	1993	153	#	Explor.
SN-09	1994	132	#	Explor.
SN-10	1994	132	#	Explor.
SN-11	1994	145	#	Explor.
SN-12	1994	2714	791	Product.

* Previous production well # No production casing

Table 2. Concentration (in mg/l) of production water from the wells in Seltjarnarnes geothermal field in recent samples.

	Well SN-4	Well SN-5	Well SN-6	Well SN-12
Date	97-11-10	97-11-10	98-03-25	97-11-10
Temp. °C	97	92	119	108
pH/°C	8.2/22	8.5/22	8.3/24	8.3/22
Conduct. µS/cm	5270	3440	5420	5420
TDS	3100	1750	3870	3800
Tot. carb. as CO_2	14.8	17.1	6.3	14.1
H_2S	0.08	0.25	0.21	0.18
B	0.25	0.21	0.25	0.17
SiO_2	102	116	123	105
Na	668	428	636	601
K	13.2	9.5	15.0	12.1
Mg	1.09	0.11	0.475	0.27
Ca	472	245	528	491
F	0.55	0.89	0.71	0.68
Cl	1774	961	1675	1683
SO_4	205	181	310	221
Al	0.009	0.034	0.025	0.022
Fe	0.010	0.005	0.013	0.064
Mn	0.012	0.003	0.010	0.011
δD %	-73.1	-74.5	-72.9	-73.7
δ^{18}O%	-10.27	-10.52	-10.38	-10.53