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**CHEMICAL MODELLING PROGRAMS FOR PREDICTING  
CALCITE SCALING, APPLIED TO LOW TEMPERATURE  
GEOTHERMAL WATERS IN ICELAND**

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**ABSTRACT**

Three chemical models, the WATCH program, the VDATA program and the Ryznar index are used for the study of calcite scaling potential in low temperature geothermal wells in Iceland. Fields with known calcite scaling in some wells were chosen for the study. They are: Laugarnes field, Sudureyri field, Hrisey field, Selfoss field and Seltjarnarnes field. The study involved training in the use of chemical models to predict calcite scaling and to determine the allowable supersaturation before calcite scaling formation becomes a problem. This is done by comparing the degree of calcite supersaturation and actual scaling status in the selected wells. The saturation index,  $\log(Q/K) = 0.36 - 0.5$  was found to be the boundary between calcite scaling and no scaling. If the saturation index,  $\log(Q/K)$ , is higher than 0.5, calcite scaling problems occur, if it is lower than 0.36, no calcite scaling will occur. Between 0.36-0.5, calcite scaling may and may not occur, depending on other factors. This implies a calcite supersaturation ratio,  $Q/K$ , of 2.3-3.2 and thus geothermal waters can contain 2.3 times more  $\text{CaCO}_3$  in solution than the theoretical amount. The information from changes of chloride concentration and temperature as well as mixing calculations show that mixing of different waters is the main reason for the high degree of calcite supersaturation in the low temperature wells selected in this study. The results from the WATCH program agree with the results from the Ryznar index. Calcite scaling occurs at high calcite saturation index values and low Ryznar index values. Based on these findings more accurate predictions of calcite scaling can be made.

## TABLE OF CONTENTS

	Page
ABSTRACT .....	3
TABLE OF CONTENTS .....	4
LIST OF FIGURES .....	4
LIST OF TABLES .....	5
1. INTRODUCTION .....	6
2. CALCIUM CARBONATE SCALING IN GEOTHERMAL SYSTEMS .....	7
2.1 Solubility of calcium carbonate .....	7
2.2 Major reasons for calcium carbonate scaling .....	8
2.3 Models for predicting calcite scaling .....	9
2.3.1 The WATCH program .....	9
2.3.2 The VDATA program .....	10
2.3.3 The Ryznar index .....	10
2.4 Chemical data required .....	10
2.5 Criteria for scaling formation .....	11
2.6 Calcite scaling in Iceland .....	12
3. APPLICATION OF SCALE PREDICTION MODELS .....	14
3.1 Laugarnes .....	14
3.2 Sudureyri .....	19
3.3 Selfoss .....	22
3.4 Hrisey .....	22
3.5 Seltjarnarnes .....	29
3.6 Calculating calcite scaling tendency by using Ryznar index .....	34
4. DISCUSSION .....	36
4.1 Comparison of WATCH program, VDATA program and Ryznar index .....	36
4.2 Supersaturation criterion for calcite scaling formation .....	37
4.3 Data used for analysis .....	38
5. CONCLUSIONS .....	39
ACKNOWLEDGEMENTS .....	40
REFERENCES .....	41
APPENDIX: Typical raw chemical data used in this study .....	43

## LIST OF FIGURES

1.	Log K for calcite, aragonite and vaterite based on the aqueous models .....	7
2.	The solubility of calcite in water and sodium chloride solutions .....	8



3.	Effect of changing pH on distribution of different CO <sub>2</sub> related ions in solution . . . . .	8
4.	Determination of K <sub>c</sub> for geofluids contain. < 6000 mg/kg total dissolved solids . . . .	11
5.	The location of the Hrisey, Laugarnes, Sudureyri, Selfoss and Seltjarnarnes geothermal fields . . . . .	13
6.	The location of wells in the Laugarnes field . . . . .	14
7.	CaCO <sub>3</sub> supersaturation in the Laugarnes field . . . . .	15
8.	Chloride ions in the well water of the Laugarnes geothermal field . . . . .	18
9.	The degree of calcite supersat. and chloride content in the Laugarnes field . . . . .	19
10.	The location of wells in the Sudureyri geothermal field . . . . .	19
11.	CaCO <sub>3</sub> supersaturation in wells H-2 and H-5 at Sudureyri . . . . .	20
12.	Chloride in the Sudureyri wells H-2 and H-5 . . . . .	21
13.	The CaCO <sub>3</sub> supersaturation and the chloride content in Sudureyri wells . . . . .	21
14.	The location of wells in Selfoss geothermal field . . . . .	22
15.	CaCO <sub>3</sub> supersaturation in the Selfoss geothermal field . . . . .	24
16.	The location of wells in the Hrisey field . . . . .	25
17.	CaCO <sub>3</sub> supersaturation in the Hrisey wells (mixing of wells 10 and 11) . . . . .	26
18.	Comparison of waters in Hrisey wells 5, 10 and 11 . . . . .	28
19.	CaCO <sub>3</sub> supersaturation in the Hrisey geothermal field . . . . .	29
20.	The location of wells in the Seltjarnarnes field . . . . .	29
21.	CaCO <sub>3</sub> supersaturation in the Seltjarnarnes geothermal field . . . . .	30
22.	Comparison of deep waters and surface waters in well SN-04 . . . . .	31
23.	The temperature change in the Seltjarnarnes well SN-04 . . . . .	33
24.	Chloride in the Seltjarnarnes wells SN-04, 05 and 06 . . . . .	33
25.	CaCO <sub>3</sub> supersat. and the chloride content in the Seltjarnarnes wells . . . . .	34
26.	The Ryznar index in selected wells . . . . .	35
27.	Comparison of Ryznar index and saturation index (log Q/K) . . . . .	36
28.	CaCO <sub>3</sub> supersaturation in selected wells . . . . .	37
29.	Chloride change after start of pumping in Laugarnes wells RV-5, 21, 34 and 35 . . .	38

## LIST OF TABLES

1.	Analytical data required for thermodynamic modelling . . . . .	12
2.	Calcite scaling in Iceland . . . . .	13
3.	Overview of the wells in Laugarnes geothermal field . . . . .	14
4.	Calcite calculations for the Laugarnes geothermal field . . . . .	16
5.	Three types of well fluids and calcite scaling status in Laugarnes field . . . . .	17
6.	Calcite calculations for the Sudureyri geothermal field . . . . .	20
7.	Calcite calculations for the Selfoss geothermal field . . . . .	23
8.	Overview of the Hrisey geothermal wells . . . . .	23
9.	Mixing ratio of wells 10 and 11 according to chloride ion parameter . . . . .	26
10.	Mixing ratio of wells 10 and 11 according to temperature parameter . . . . .	26
11.	Calcite calculations and some components in Hrisey wells . . . . .	27
12.	Overview of the Seltjarnarnes geothermal wells . . . . .	30
13.	Main aquifers in wells SN-04 - SN-06 . . . . .	31
14.	Calcite calculations for the Seltjarnarnes geothermal field . . . . .	32
15.	Ryznar index and calcite scaling . . . . .	35
16.	The saturation index boundary between calcite scaling and no scaling . . . . .	37

## 1. INTRODUCTION

Scale formation is one of the major problems in geothermal operations. Deposition can take place in the reservoir as well as in the production, utilization and reinjection facilities. Depending on the chemical composition of the geothermal well fluids, different types of scales are found in various geothermal areas.

The presence of the calcium ion and bicarbonate alkalinity is common in almost every source. The relative insolubility of calcium carbonate is one of the most common causes of scaling. Calcium carbonate scaling problems have been reported in most of the countries using and developing geothermal resources, for example, in Turkey (Parlaktuna and Okandan, 1988), in the United States (Vaska et al., 1988; Lovekin, 1990 and Benoit, 1988), in New Zealand (Robson et al., 1990), in Italy (Pieri et al., 1988), in Greece (Koutsoukos, 1990, 1991), in Iceland (Arnorsson, 1988; Kristmannsdottir, 1988), and in China (Chang, 1990).

Understanding the mechanism of calcium carbonate formation and further, giving the precise prediction information is very important in order to decide upon the type of scale prevention or scale removal methods. Calcium carbonate scaling is often caused by the mixing of waters from different aquifers, but degassing of carbon dioxide because of lower pressure or flashing is the main reason for calcite scaling. From the information yielded by the scale prediction models, one can also predetermine scaling problems that may arise from fluids used in the drilling and completion operations.

Scale prediction models are also of importance in another area of geothermal operations, namely the reinjection of the heat-depleted brine or injection of foreign waters for the purpose of pressure maintenance. In such cases, the scale prediction models are extremely useful in determining the incompatibility of injected fluids with the native reservoir fluids (Vetter and Kandarpa, 1982).

Based on thermodynamic and experimental studies, various calcium carbonate scaling prediction models have been developed. In Iceland the WATCH program (Arnorsson et al., 1982), and VDATA program (Hauksson, pers. com.) have been developed. The Ryznar index (Ellis, 1989) is also used in this study.

In this report, the WATCH program, VDATA program and Ryznar index are used to analyze the calcium carbonate scaling problem in low temperature wells in Iceland. The determination of allowable calcite supersaturation without scaling is attempted. In addition, a comparison and an evaluation of the prediction models are given.



## 2. CALCIUM CARBONATE SCALING IN GEOTHERMAL SYSTEMS

### 2.1 Solubility of calcium carbonate (calcite, aragonite and vaterite)

There are three polymorphs of calcium carbonate minerals, calcite, aragonite and vaterite. Many experimental studies have been carried out to determine the solubilities of the calcium carbonate minerals in aqueous solution. Respectively, aqueous models are provided. Using these models, the equilibrium constants for calcium carbonate and its temperature dependence have been determined (e.g. Ellis, 1959, 1963; Plummer and Busenberg, 1982; Arnorsson, 1982):

$$\text{Calcite: } \log K_c = -171.9065 - 0.077993T + 2839.319/T + 71.595 \log T \quad (1)$$

$$\text{Aragonite: } \log K_a = -171.9773 - 0.077993T + 2903.293/T + 71.595 \log T \quad (2)$$

$$\text{Vaterite: } \log K_v = -172.1295 - 0.077993T + 3074.688/T + 71.595 \log T \quad (3)$$

$$\text{Calcite: } \log K_c = 10.22 - 0.0349T - 2476/T \quad (4)$$

Equations 1-3 are from Plummer et al., 1982, and Equation 4 from Arnorsson, 1982.

The equilibrium constants of calcium carbonate as a function of temperature are shown in Figure 1. The solubility of calcium carbonate decreases with increasing temperature which makes it one of the few minerals with "reverse solubility". In natural hydrothermal solutions, the solubility of the calcium carbonate is influenced by many dissolved constituents and a variety of chemical reactions in which pH, the partial pressure of carbon dioxide,  $P_{CO_2}$ , temperature and the pressure and concentrations of other dissolved salts are the main affecting factors. Adding NaCl to the solution increases the solubility of calcite (Figure 2). Fluid pH controls the distribution between carbonate and bicarbonate ions. The concentration of carbonate ions increases with increasing pH (Figure 3). Thus, an increase in pH is likely to cause calcite scaling.

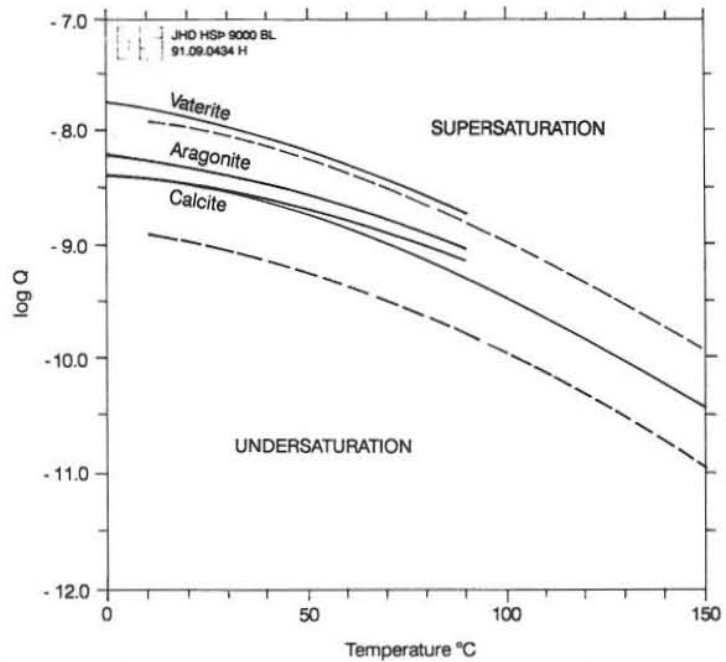


FIGURE 1:  $\log K$  for calcite, aragonite and vaterite based on the aqueous models (data from Plummer et al. 1982; Arnorsson, 1982)

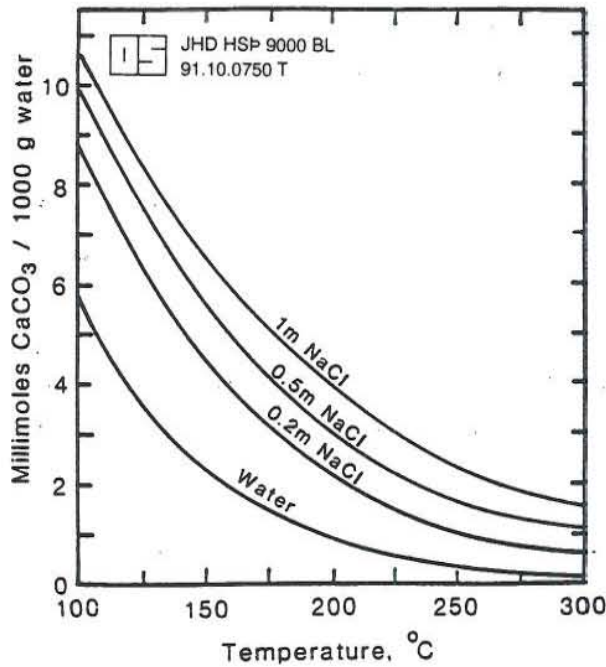


FIGURE 2: The solubility of calcite in water and sodium chloride solutions at a carbon dioxide pressure of 12.2 bars (Ellis, 1963)

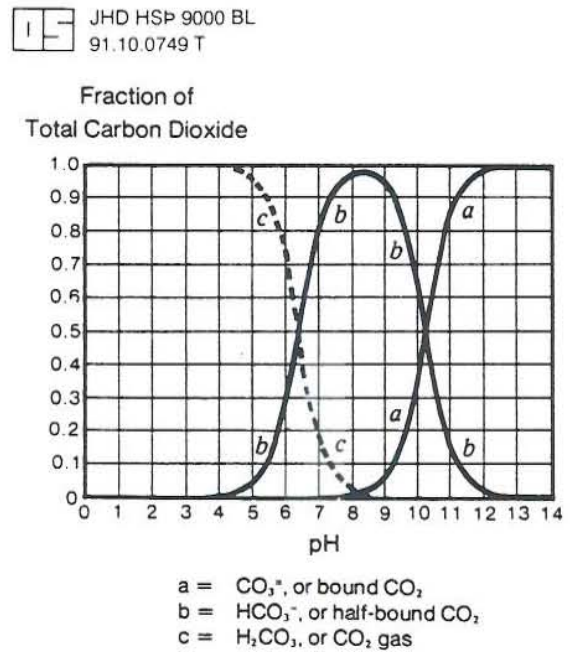


FIGURE 3: Effect of changing pH on distribution of different CO<sub>2</sub> rel. ions in solution (Nalco Chem. Co., 1979)

## 2.2 Major reasons for calcium carbonate scaling

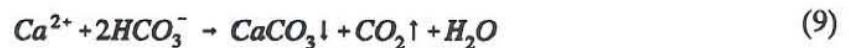
The precipitation of calcium carbonate mainly occurs as a result of CO<sub>2</sub> evolution from the liquid phase, with a consequent increase in the pH.



This shifts the equilibrium between bicarbonates and carbonates towards the latter and the solubility product of CaCO<sub>3</sub> is exceeded (Michels, 1981).



The precipitation of calcium carbonate is also caused by the heating of water. When the temperature of the water increases, the bicarbonate breaks down to carbonate and combines with calcium by the following reaction (Vaska, 1989):



The mixing of different water is another reason leading to supersaturation of calcium carbonate. This will be discussed in a later section. In addition, physical factors also affect the location of



calcium carbonate scaling. Scale is more easily formed on geometric irregularities such as orifices, bends, etc.

## 2.3 Models for predicting calcite scaling

### 2.3.1 The WATCH program

The computer program WATCH (Arnorsson et al., 1982) is a useful tool for calculating the chemical composition of geothermal waters. This includes the pH, aqueous speciation, partial pressures of gases, redox potentials, and activity products. The program is briefly described below.

Input to the program is a component analysis of the geothermal water at the surface, including the temperature at which the pH was measured, and a reference temperature at which the composition is to be calculated. The concentrations of all the 69 species considered in the program are expressed in terms of the component concentrations by mass balance equations, and the chemical equilibria between the species are expressed as mass action equations. The two sets of equations are solved simultaneously by an iterative procedure. This procedure is carried out a few times during each run of the program. An initial estimate of the ionic strength of the water is obtained using only the concentrations of the major cations. This value of the ionic strength is used to compute activity coefficients, at the temperature of the pH measurement, using the extended Debye-Huckel formula. The chemical equilibria and mass balance equations are now solved simultaneously at this temperature to yield a distribution of species. From the new distribution of species, a proper ionic strength is computed. This ionic strength is used to recompute the activity coefficients and species concentrations, still at the temperature of the pH measurement. The concentrations of the anions of the weak acids and their complexes are now added up, weighted by the number of protons that each can accept:

$$\begin{aligned} XOH = & (HCO_3^-) + (CaHCO^+) + (MgHCO^+) + (H_3SiO_4^-) + (NaH_3SiO_4) + (HS^-) \\ & + 2 \cdot ((CO_3^{2-}) + (CaCO_3) + (MgCO_3) + (H_2SiO_4^{2-}) + (S^{2-})) + (OH^-) - (H^+) - (NH_4^+) \end{aligned} \quad (10)$$

This quantity, which is a measure of total alkalinity, is assumed to be constant, independent of temperature. This property is used to compute the pH at the reference temperature. The pH-calculation, the calculation of the activity coefficients, the mass balance iteration, and the ionic strength calculation are all repeated, in turn, a couple of times. The equilibrium gas pressures are then computed from the final equilibrium species concentrations.

The output from the program lists the component and species concentrations at the reference temperature, as well as the activity coefficients. Finally, the ion activity products, log Q, and solubility products, log K, of selected minerals are computed and printed. From these, it is straightforward to compute the corresponding saturation indices, log Q/K.

The WATCH program can also be used to compute the resulting species concentrations, activity coefficients, and activity and solubility products when the original water is allowed to cool conductively or by adiabatic boiling from the reference temperature to some lower temperature. This is particularly useful in the study of scaling.

In this report, the WATCH program is used to analyze chemical equilibria between calcite and solution in geothermal systems as well as the potential for calcite scaling in the process.



### 2.3.2 The VDATA program

The computer program VDATA (Hauksson) has been developed in Iceland for interpretation of geothermal field data such as well flow measurements, well logs and chemical analysis of well fluids. Results of chemical analysis of water, steam and gas fractions are entered and the ion balance and mass balance calculated. For analysis of the chemical data, it is possible to calculate the chemical composition at different separation pressures and temperature. The subsurface chemical equilibrium temperatures are calculated (quartz, calcedony, Na/K, H<sub>2</sub>/H<sub>2</sub>S and CO<sub>2</sub>). Also the chemical speciation and saturation of scaling chemicals (e.g. calcite, anhydrite, amorphous silica, magnesium silicate and iron sulphide) are calculated using a thermodynamic database (e.g. WATCH). Addition of various streams of scaling chemicals and calculation of chemical speciation of mixtures are possible for predicting supersaturation. For these calculations the total alkalinity, as defined above for the WATCH program, is considered an additive property and the pH of the mixture is calculated from the sum of alkalinity. Also the effect of chemical treatment, such as acidification, on saturation of scaling chemicals can be assessed.

In this report the VDATA program was used to assess the effect of mixing two fluids of different known compositions and comparing it to analysis from a well where calcite scaling has occurred.

### 2.3.3 The Ryznar index

Based on the studies of reported conditions of scaling and corrosion in a variety of municipal systems, the Ryznar index was developed to predict the likelihood of scale forming or corrosion occurring (Nalco Chemical Company, 1979):

$$\text{Ryznar index} = 2pH_s - pH_a \quad (11)$$

where,

$pH_s$  - is the pH above which calcium carbonate will precipitate.

$pH_a$  - is the measured pH of the fluid.

Thus,

$$pH_s = pCa + pALK + Kc \quad (12)$$

where,

$pCa$  =  $-\log [Ca]$ ,

$[Ca]$  - is the molar concentration of calcium,

$pALK$  =  $-\log [ALK]$ ,

$[ALK]$  - is the total alkalinity of calcium,

$Kc$  - is a function of temperature and the total diss. solid, available from Figure 4.

The calculated Ryznar index can then be used to predict the scaling tendency (see Chapter 2.5).

## 2.4 Chemical data required

Good chemical data is very important for any calculations. It depends on the analytical methods used as well as the care taken in the collection and analysis of samples. Geothermal samples must be collected in such a way, that the concentration of the elements does not change until the analysis is carried out. Sampling and analytical methods for geothermal fluids and gases were

described in detail by Olafsson (1988), Arnorsson and Gunnlaugsson (1975).

Ionic charge balance and mass balance can be used to evaluate the quality of chemical data. The water is electroneutral, so the total amount of cation charges should be equal to the total amount of anion charges. Calculation of ionic balance and mass balance are included in the WATCH and VDATA programs. Samples with more than 10% difference in ionic balance are not usable.

In addition, the equilibrium of carbon dioxide is also sometimes used for evaluation of the data. In aqueous solutions, dissolved carbon dioxide exists in three forms:  $\text{CO}_3^{2-}$ ,  $\text{HCO}_3^-$  and  $\text{H}_2\text{CO}_3$ . The fraction of each species depends on the pH. From pH as well as the analyzed content of  $\text{CO}_3^{2-}$ ,  $\text{HCO}_3^-$  or  $\text{H}_2\text{CO}_3$  and the total dissolved carbon dioxide, the other species can be calculated. The chemical data needed for the WATCH and VDATA programs are listed in Table 1.

## 2.5 Criteria for scaling formation

The Ryznar index gives a qualitative estimate of the calcium carbonate scaling tendencies of waters (Ellis, 1989). In using this index, a water is considered to be corrosive when the value of the Ryznar index is higher than 7.0 and to be scale-forming when the value is lower than 7.0.

The criteria for scaling formation is (Ellis, 1989):

<u>Ryznar index</u>	<u>Scaling tendency</u>
<4.0	extreme
4.0 to 5.0	heavy
5.0 to 6.0	moderate
6.0 to 7.0	light
>7.0	none

The WATCH program can be used to study chemical equilibria between minerals and solutions in geothermal systems. It yields activity products of various minerals ( $\log Q$ ) which can be compared to the solubility products ( $\log K$ ). If the activity products are higher than the solubility product, then potential for scaling in the process exists.

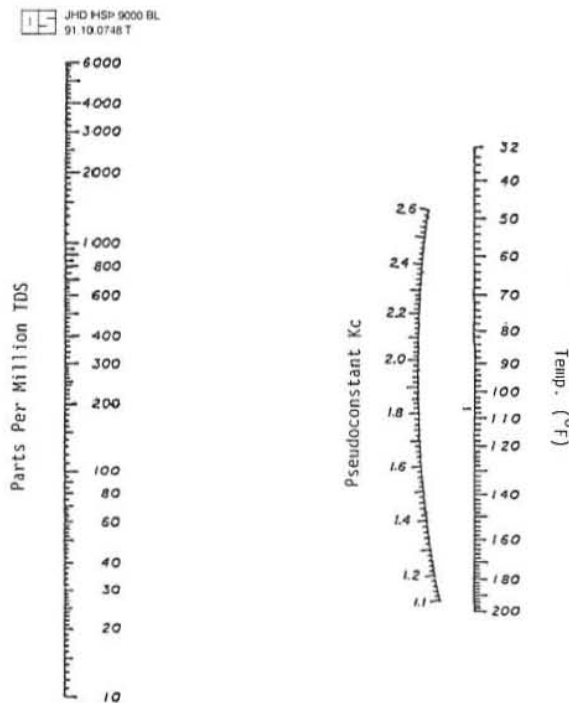


FIGURE 4: Determination of  $K_c$  for geofluids contain. < 6000 mg/kg total dissolved solids (TDS)



TABLE 1: Analytical data required for thermodynamic modelling

WATER SAMPLE	TWO PHASE SAMPLE (STEAM AND WATER) (The same data is needed for liquid phase as for water sample, the following data is also needed)
Sampling pressure (bar)	Liter gas/kg condensate
Source temperature (°C)	Temperature of gas sampling (°C)
Enthalpy of fluid (MJ/kg)	CO <sub>2</sub> vol %
pH/°C liquid phase	H <sub>2</sub> S vol %
SiO <sub>2</sub> liquid phase (mg/kg)	H <sub>2</sub> vol %
Na liquid phase "	O <sub>2</sub> vol %
Ca liquid phase "	CN <sub>4</sub> vol %
Mg liquid phase "	N <sub>2</sub> vol %
CO <sub>2</sub> liquid phase "	
SO <sub>4</sub> liquid phase "	CO <sub>2</sub> condensate (mg/kg)
H <sub>2</sub> S liquid phase "	H <sub>2</sub> S " "
Cl liquid phase "	Na " "
F liquid phase "	
Al liquid phase "	CO <sub>2</sub> steam phase collected in alkaline solution (mg/kg)
Fe liquid phase "	H <sub>2</sub> S " " "
B liquid phase "	
NH <sub>3</sub> liquid phase "	

If the activity product for calcium carbonate is lower than the solubility product for calcite, that is, the saturation index,  $\log Q/K < 0$  or  $Q/K < 1$ , then the solution is undersaturated and no calcite scaling is predicted. If the saturation index,  $\log Q/K > 0$  or  $Q/K > 1$ , then the solution is supersaturated and the potential for calcite scaling exists. But there is no criterion to provide what extent of supersaturation will lead to calcite precipitation. If the degree of calcite supersaturation is high or the solution undersaturated and far from equilibrium, it is easy to judge whether precipitation will occur (Figure 1). But if the activity product for calcite is close to the solubility curve, it is difficult to judge whether calcite precipitation will occur.

The main purpose of this study is to determine an allowable degree of supersaturation, based on real cases in low temperature geothermal wells.

## 2.6 Calcite scaling in Iceland

Calcite scaling has been found in Iceland in several geothermal fields (Table 2). This report focuses on the low temperature geothermal fields where a calcite scaling problem has been noticed. Figure 5 shows the location of these geothermal fields.



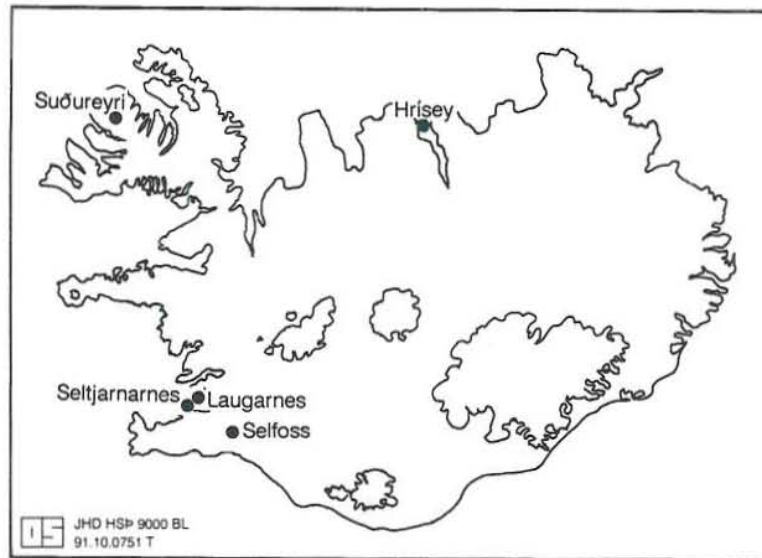


FIGURE 5: The location of the Hrisey, Laugarnes, Sudureyri, Selfoss and Seltjarnarnes geothermal fields

TABLE 2: Calcite scaling in Iceland

High and medium temperature geothermal fields	Low temperature geothermal fields
Krafla borhole (well KJ-9) Svartsengi Kroggolfsstadir Leira Klausturholar Hveragerdi	Hrisey (well HR-05) Laugarnes (wells RV-34 and 21) Sudureyri (wells H-2 and 5) Selfoss (well ÞK-11)

### 3. APPLICATION OF SCALE PREDICTION MODELS

#### 3.1 Laugarnes

The Laugarnes geothermal field is located inside the city of Reykjavik (population: 134,513 with suburbs). The exploitation of hot ground water in this area was begun in 1928-1930. Now, there are 12 wells in use (Table 3). The location of these wells is shown in Figure 6. Water from this field is used in the Reykjavik Municipal Heating Service district heating system. The 130°C water pumped from the wells is cooled to 80°C before entering the system by mixing with return water of 40°C. From 1982, a calcite scaling problem was found in wells RV-21 and RV-34 in succession. In order to study the changes that occurred during that period, available chemical analyses (see Appendix) were entered into the WATCH program and the results were used to compute the saturation index. The results are listed in Table 4 and shown in Figure 7.

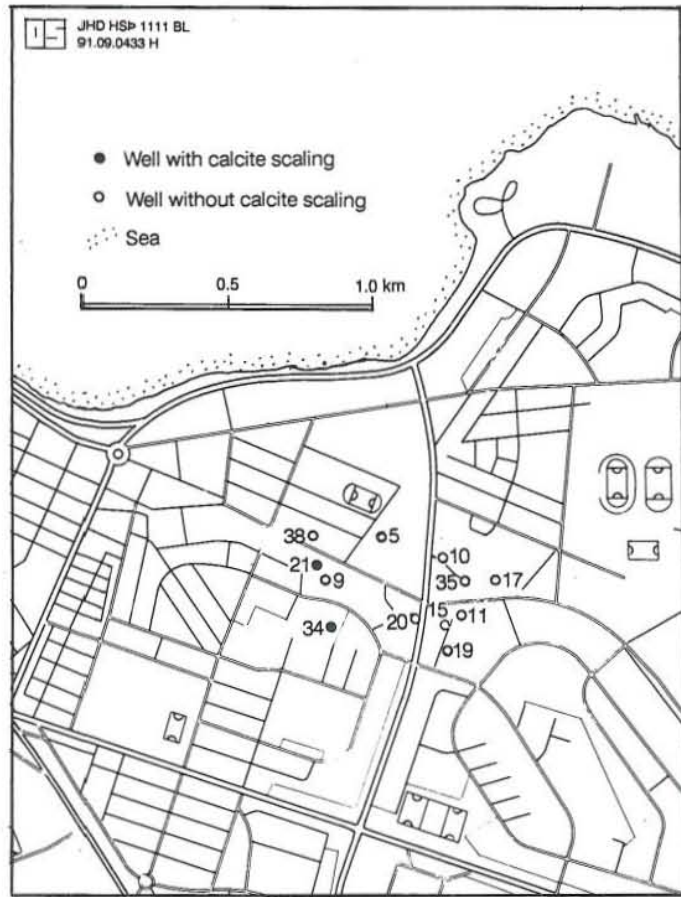


FIGURE 6: The location of wells in the Laugarnes field

TABLE 3: Overview of the wells in Laugarnes geothermal field

Well no.	RV-5	RV-9	RV-10	RV-11	RV-15	RV-17	RV-19	RV-20	RV-21	RV-34	RV-35	RV-38
T (°C)	130	128.1	131.2	126.9	124	126.1	128	126	127	121	124.8	127.5
Depth of well (m)	741	862	1306	928	1014	634	1239	764	978	3085	2857	1488
Depth of casing (m)	68	90	92	112	112	93	79	87	112	1091	765	325

The degree of the calcite supersaturation in well RV-34 is higher than in the other wells. The calcite saturation index in well RV-21 cannot be calculated because of a lack of complete data after the calcite scaling was found. The content of chloride in well RV-21 is available and its increase is very important for analyzing the transition over to calcite scaling in this field.

The initial content of chloride in Laugarnes field was 20-30 mg/kg, and the temperature was 120-130°C. But in 1985 an analysis of chloride in the wells showed that the reservoir fluid could be divided into three types, shown in Table 5.

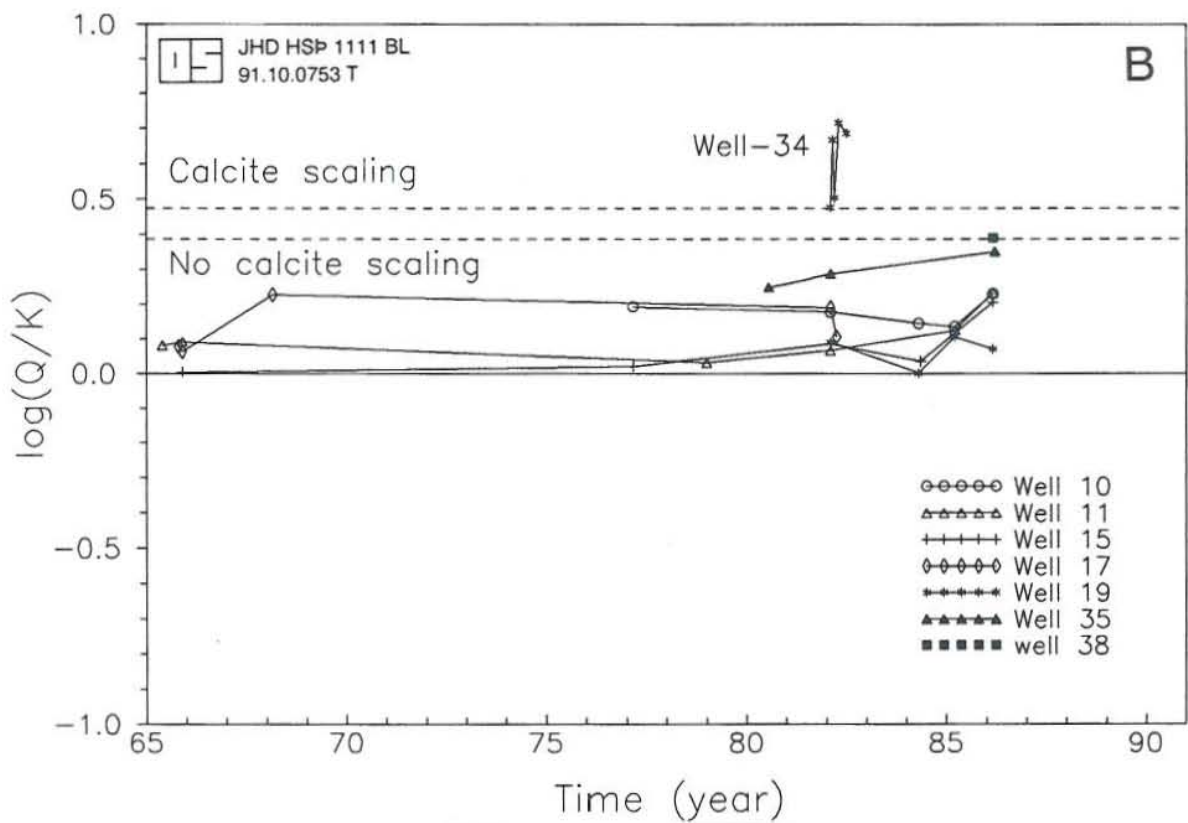
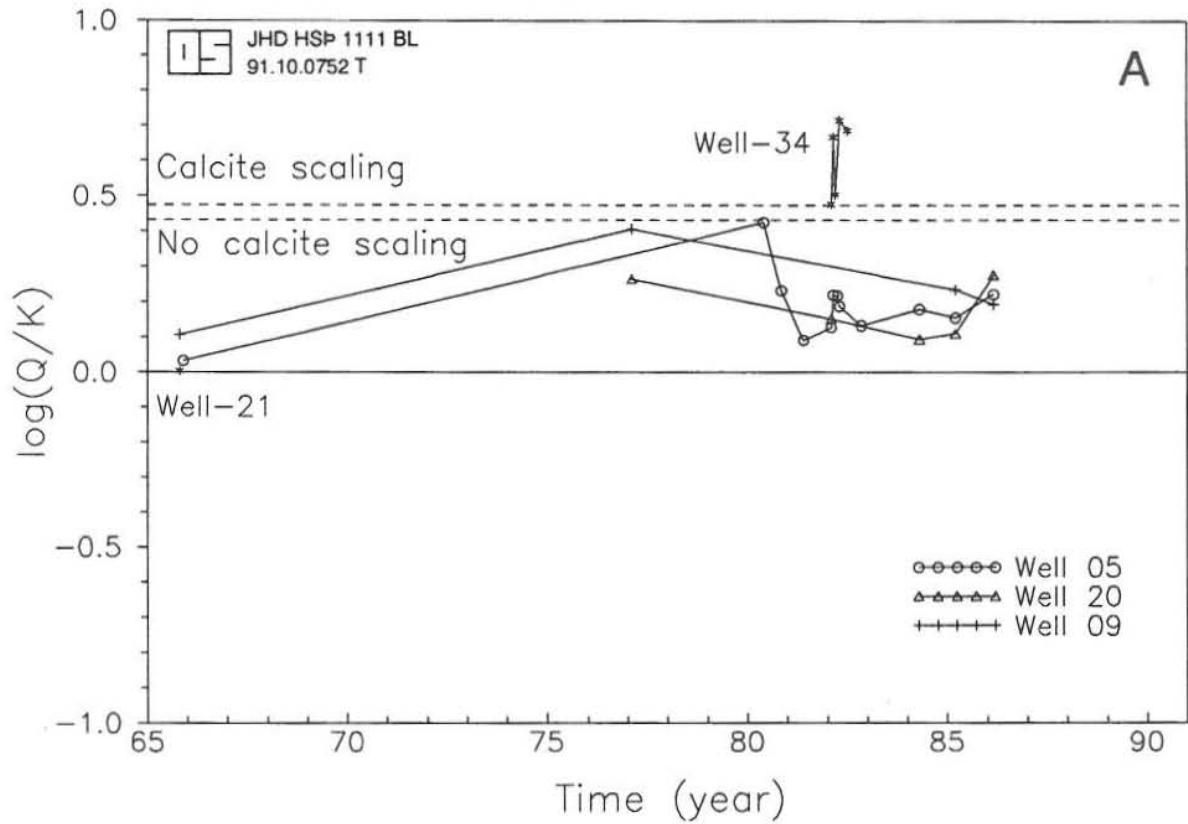


FIGURE 7:  $\text{CaCO}_3$  supersaturation in the Laugarnes field  
a) wells RV-5, 9, 20, 21 and 34, b) wells RV-10, 11, 15, 17, 19, 34, 35 and 38



TABLE 4: Calcite calculations for the Laugarnes geothermal field

Well no.	Sample no.	Ionic bal. (%)	log Q	log K	log (Q/K) (S.I.)	Cl (mg/kg)	Note
34	820112	-2.27	-9.302	-9.78	0.478	156.7	
"	820212	-1.65	-9.127	-9.795	0.668	168.6	
"	820303	2.69	-9.291	-9.795	0.504	171.9	
"	820330	-3.87	-9.097	-9.795	0.716	183.7	
"	820531	-3.72	-9.108	-9.795	0.687	197.3	
"	821111	-1.25	-9.754	-9.912	0.158	47.3	(**)
21	650927	-9.5	-9.988	-9.992	0.004	26.2	
"	770126	-83.27	-11.06	-10.031	-1.029	58.6	(*)
"	830323					50.7	
"	850328					118.3	
"	851228					134	
9	650927	-4.05	-9.844	-9.952	0.108	29.8	
"	770127	-6.69	-9.826	-10.233	0.407	61.1	
"	850305	-8.75	-9.706	-9.941	0.235	73.4	
"	860210	-7.19	-9.76	-9.954	0.194	67.3	
20	680500	7.74	-10.443	-10.031	-0.412	27.1	(**)
"	770127	-4.46	-9.946	-10.212	0.266	30	
"	820119	-8.89	-9.819	-9.972	0.153	28.8	
"	840404	-13.29	-9.807	-9.902	0.095	31.6	
"	850305	-4.52	-9.803	-9.914	0.111	29.8	
"	860211	1.35	-9.633	-9.910	0.277	36	
5	590315	5.24	-9.793	-9.992	0.199	34.8	(***)
"	630306	32.23	-10.261	-9.992	-0.269	30	(*)
"	651202	-3.15	-9.959	-9.992	0.033	28.2	
"	770126	-59.35	-10.141	-10.253	0.112	42.2	(*)
"	800110	18.67	-10.134	-9.952	-0.182	38.4	(*)
"	800528	-1.01	-9.828	-10.253	0.425	43.4	
"	801118	-3.04	-9.661	-9.894	0.233	43.3	
"	810511	-0.52	-9.845	-9.937	0.092	42.3	
"	820114	-1.83	-9.708	-9.837	0.129	42.8	
"	820212	-0.37	-9.752	-9.972	0.22	43.9	
"	820303	0.37	-9.754	-9.972	0.218	44.4	
"	820330	-4.26	-9.783	-9.972	0.189	46.4	
"	821111	2.87	-9.85	-9.984	0.134	40.3	
"	840404	-4.43	-9.79	-9.97	0.18	48	
"	850305	-3.94	-9.832	-9.988	0.156	42.9	
"	860210	2.03	-9.774	-9.996	0.222	46	
10	770126	-1.56	-10.039	-10.233	0.194	37.4	
"	770915	-20.62	-9.658	-10.011	0.353	34.5	(*)
"	820113	-2.33	-9.833	-10.011	0.178	38.3	
"	840404	-0.07	-9.854	-9.999	0.145	44.1	
"	850303	3.3	-9.877	-10.013	0.136	42.1	
"	860210	10.06	-9.784	-10.015	0.231	50.3	
11	650513	-5.01	-9.87	-9.952	0.082	25.8	
"	651202	-8.86	-9.86	-9.952	0.092	27.9	
"	770127	-68.75	-9.848	-9.992	0.144	30.8	(*)
"	79	6.69	-9.94	-9.972	0.032	36.4	
"	820114	0.74	-9.885	-9.952	0.067	29.4	
"	850315	2.97	-9.79	-9.915	0.125	37.5	
"	860220	15.68	-9.667	-9.931	0.264	46.4	
15	650525	-21.04	-9.688	-9.875	0.187	27.2	(*)

Well no.	Sample no.	Ionic bal. (%)	log Q	log K	log (Q/K) (S.I.)	Cl (mg/kg)	Note
"	651202	-0.94	-9.87	-9.875	0.005	25	
"	770127	-3.55	-9.854	-9.875	0.021	21.5	
"	820114	-0.68	-9.789	-9.875	0.086	24.8	
"	840404	-5.99	-9.833	-9.869	0.036	24.1	
"	860211	-14.82	-9.668	-9.875	0.207	24.4	
17	650927	-3.14	-9.874	-9.952	0.078	30.3	
"	651202	-6.63	-9.888	-9.952	0.064	30.7	
"	680128	-6.94	-9.803	-10.031	0.228	37	
"	770914	-14.45	-9.561	-9.952	0.391	25.5	
"	820113	-9	-9.899	-10.091	0.192	29	
"	820330	2.42	-9.77	-9.877	0.107	26.1	
"	860225	-17.87	-9.563	-9.915	0.352	28.9	(*)
19	820114	-2.42	-9.861	-9.952	0.091	27.1	
"	840404	2.51	-9.948	-9.95	0.002	26.3	
"	850305	-6.1	-9.848	-9.954	0.106	24.4	
"	860211	-10.19	-9.876	-9.947	0.071	28.3	
35	800528	-2.79	-9.55	-9.799	0.249	41.7	
"	801119	7.55	-9.597	-9.799	0.202	21.2	
"	820113	-0.64	-9.654	-9.933	0.288	51.9	
"	860225	10.56	-9.539	-9.89	0.351	54.6	
38	850305	20.96	-9.743	-9.945	0.202	64.4	(*)
"	860210	-6.69	-9.553	-9.943	0.390	78.9	

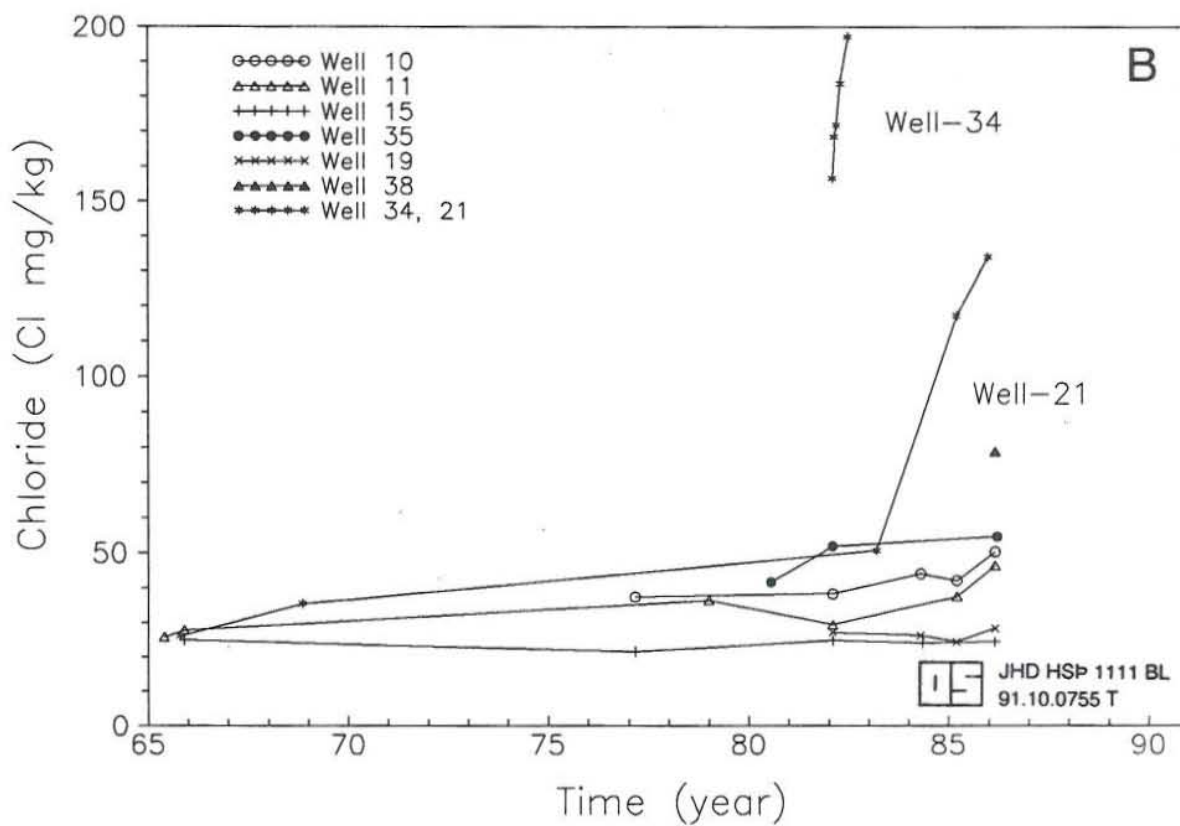
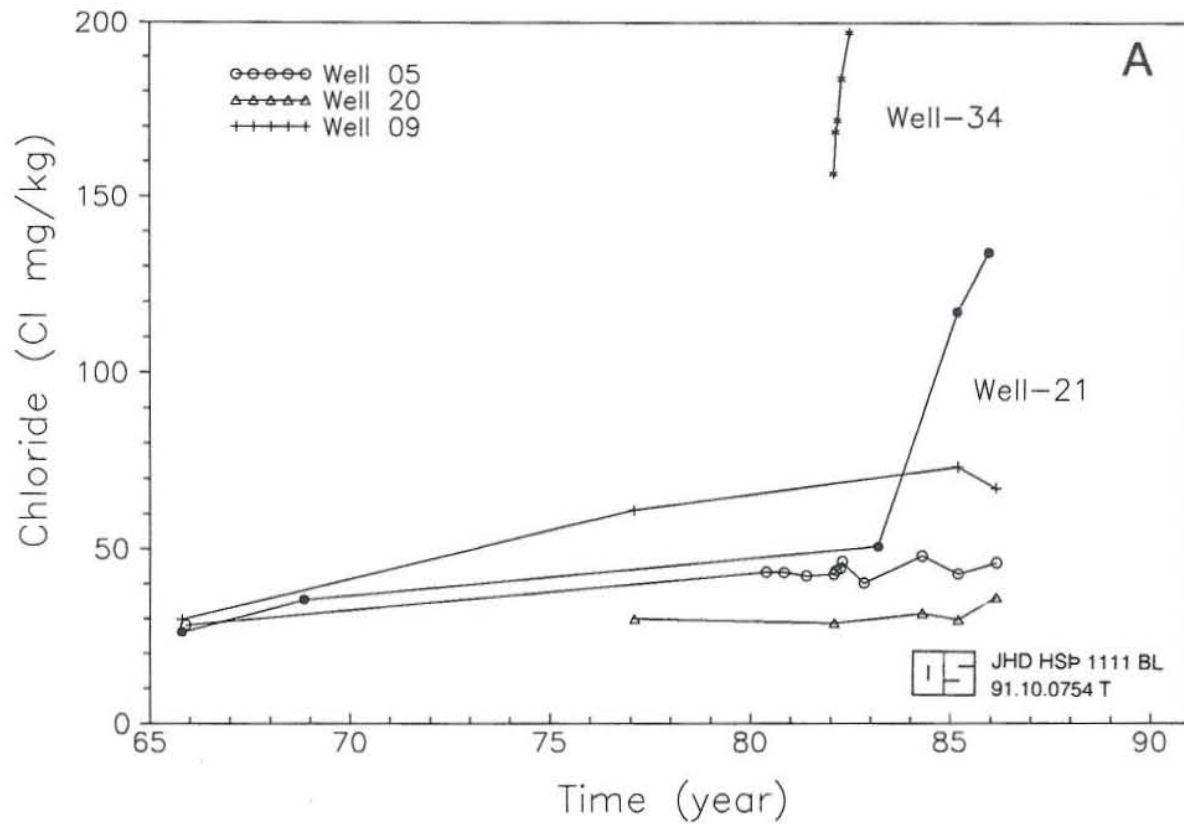
NB: (\*) Data is not in ionic balance.  
 (\*\*) Data has a large deviation from other data.  
 (\*\*\*) Data sampled shortly after initial discharge.

TABLE 5: Three types of well fluids and status of calcite scaling in Laugarnes field

Content of chloride (mg/kg)	Calcite scaling	Wells
20-30	No scaling	RV-20, 15, 17, 19
50-100	No scaling	RV-5, 9, 35, 38
> 120	Scaling	RV-21, 34

The increase in the content of chloride is caused by sea water entering the system. In this case, the content of chloride can be used as an index of scaling in this field. A comparison of the chloride content in Laugarnes wells is shown in Figure 8. It is clear that the chloride content in wells has increased with time and the largest change took place in well 21. For example, the content of chloride from sample 850328 (March 1985) is 117.2 mg/kg, without calcite scaling, and the content of chloride from sample 851218 (December 1985) is 134 mg/kg, with calcite scaling.

Figure 9 shows the relationship between the content of chloride and the calcite Saturation Index in Laugarnes geothermal field. The calcite saturation index value increases with increasing chloride. The boundary between scaling and no scaling in Laugarnes geothermal field is calcite saturation index 0.425-0.48, which occurs when the content of chloride changes from 100 to 130 mg/kg.



**FIGURE 8: Chloride ions in the well water of the Laugarnes geothermal field**  
 a) wells RV-5, 9, 20, 21 and 34; b) wells RV-10, 11, 15, 19, 21, 34, 35 and 38



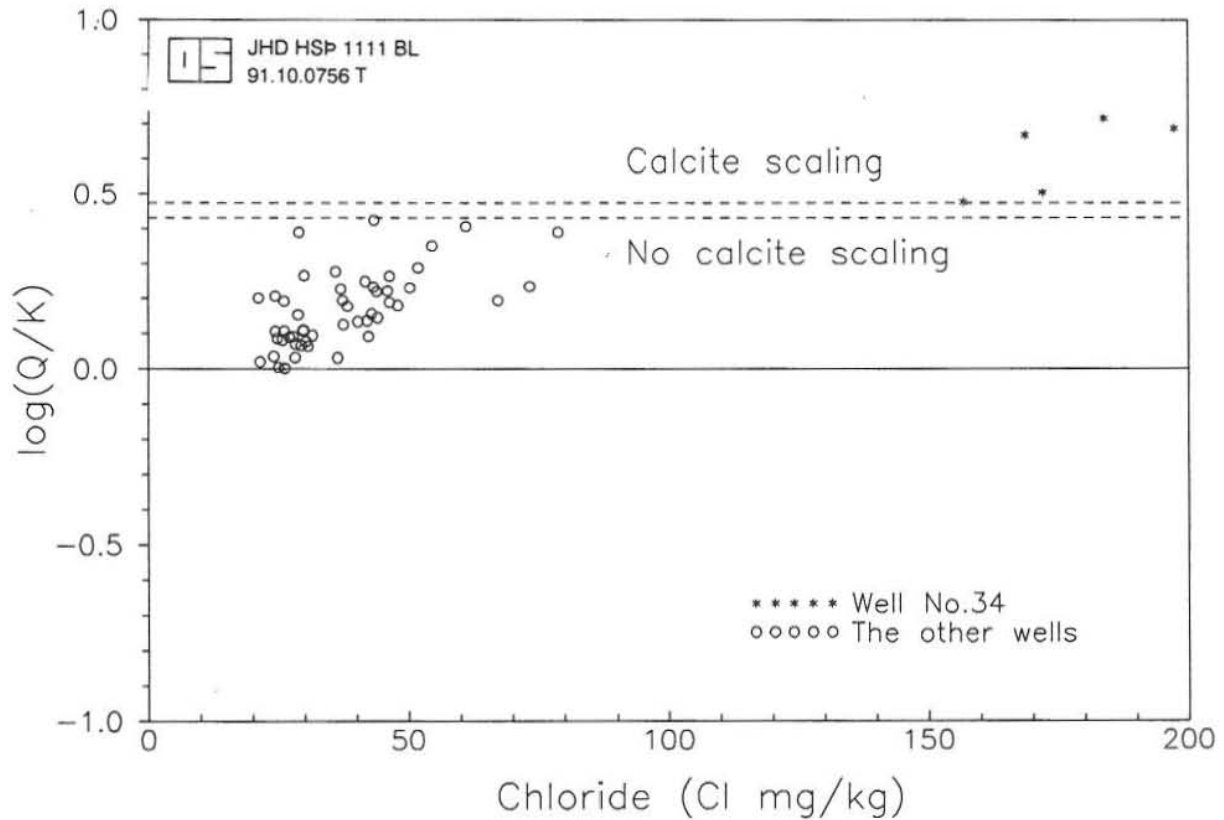


FIGURE 9: The degree of calcite supersaturation and chloride content in the Laugarnes field

### 3.2 Sudureyri

The Sudureyri geothermal field is a low temperature geothermal field situated in Northwest Iceland. At present, two wells are productive, H-2 and H-5 (Figure 10). Both of them face a calcite scaling problem. This problem has been solved by the injection of a phosphate scale inhibitor below the pump in the well. At the beginning of pumping, no calcite scaling was found in H-2. The water is used to preheat water for the district heating system at Sudureyri (population: 392).

FIGURE 10: The location of wells in the Sudureyri geothermal field

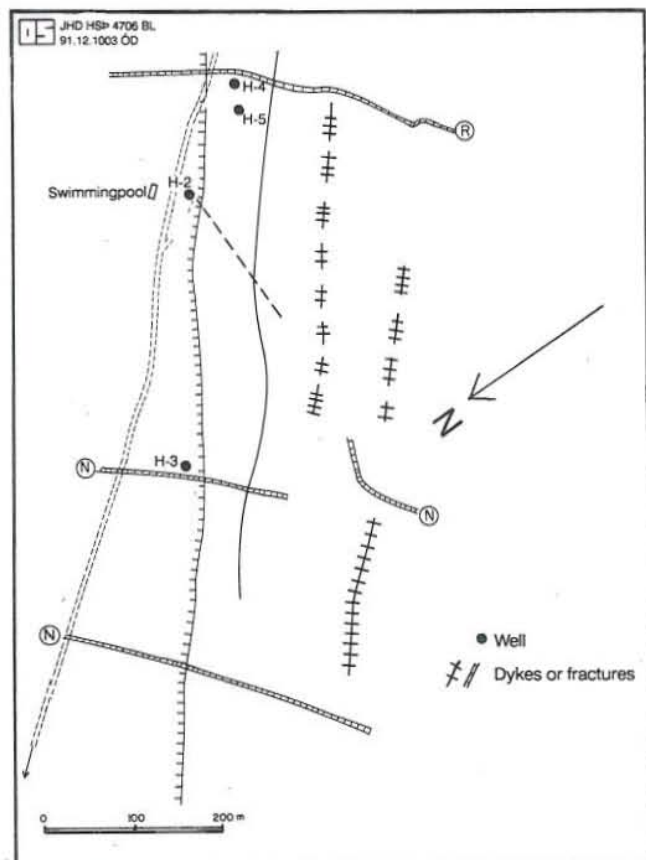
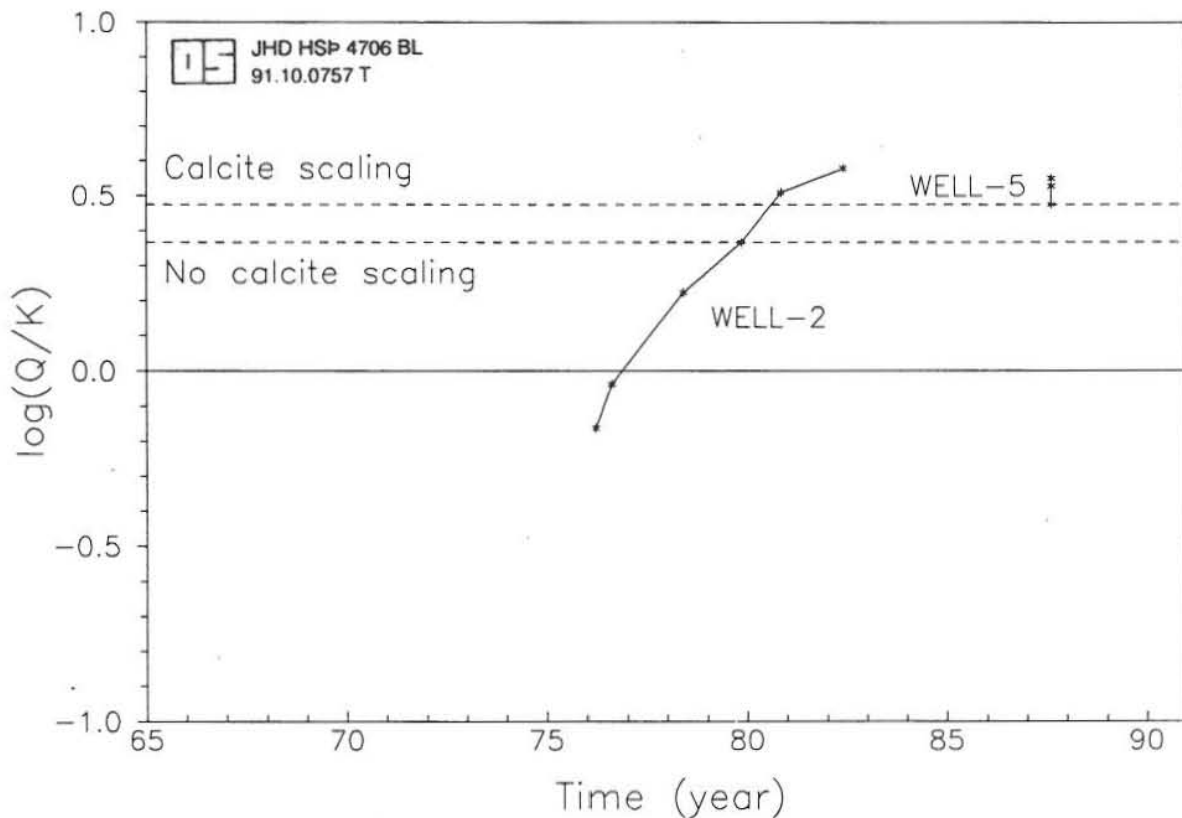


TABLE 6: Calcite calculations for the Sudureyri geothermal field

Well no.	Sample no.	Ionic bal. (%)	log Q	log K	log (Q/K) (S.I.)	Cl (mg/kg)
H-2	76-0024	-1.12	-9.046	-8.883	-0.163	71.9
"	76-0111	4.43	-8.928	-8.888	-0.038	63.4
"	78-0018	-1.64	-8.616	-8.839	-0.323	168
"	78-0089	4.17	-9.302	-8.893	-0.409	127.5
"	79-0134	1.14	-8.51	-8.877	0.367	168.7
"	80-0161	-1.15	-8.367	-8.877	0.51	209
"	82-0058	-3.12	-8.298	-8.877	0.579	260
H-5	87-0085	5.2	-8.282	-8.81	0.528	339.5
"	87-0086	3.57	-8.291	-8.766	0.475	340
"	87-0087	3.38	-8.264	-8.814	0.55	336.8

Table 6 lists calcite equilibrium calculations in wells H-2 and H-5 (based on WATCH program). Figure 11 shows that the degree of calcite supersaturation in well H-2 increases with time. The saturation index, S.I. = 0.37-0.48, is a boundary between scaling and no scaling. From chemical data it was found that the chloride content in well H-2 increases with time. Calcite supersaturation can be traced to foreign water (sea water) entering the system. Figure 12 shows the chloride change in well H-2 with time. Figure 13 shows the chloride change vs. the  $\text{CaCO}_3$  supersaturation.

FIGURE 11:  $\text{CaCO}_3$  supersaturation in wells H-2 and H-5 at Sudureyri

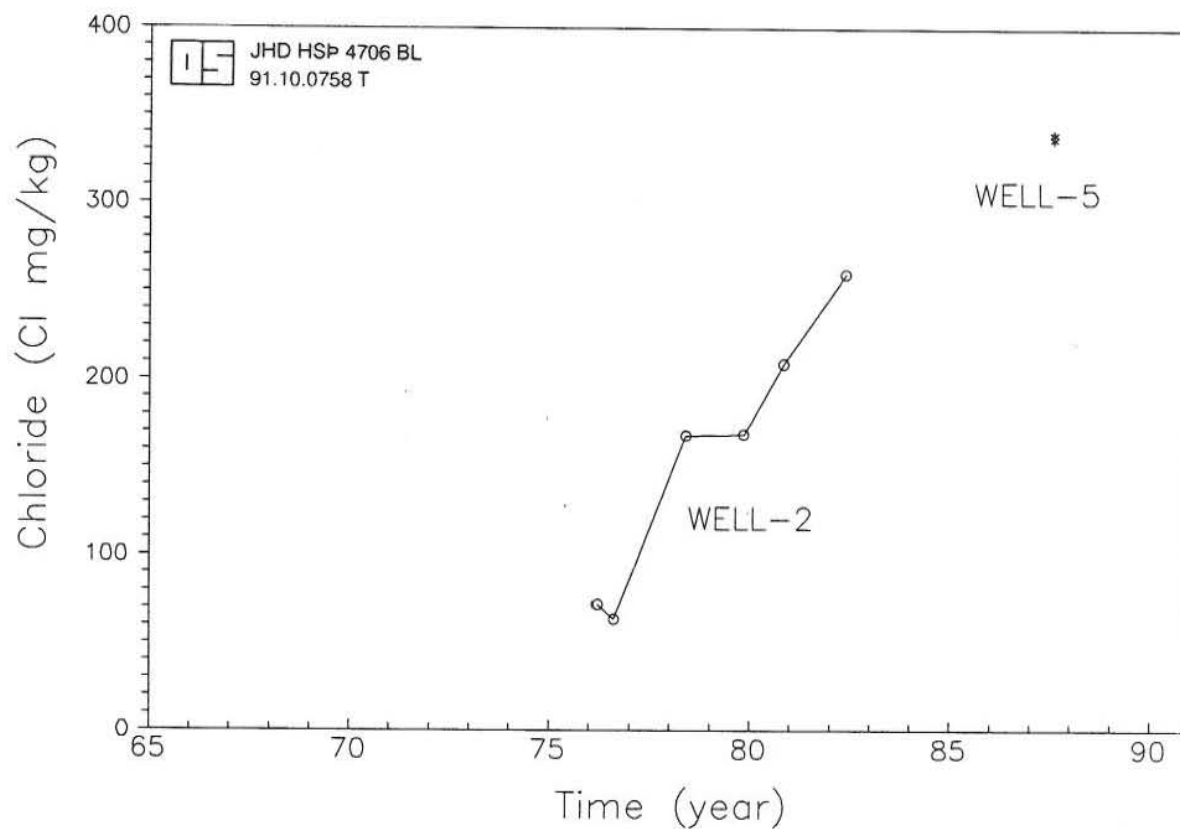


FIGURE 12: Chloride in the Sudureyri wells H-2 and H-5

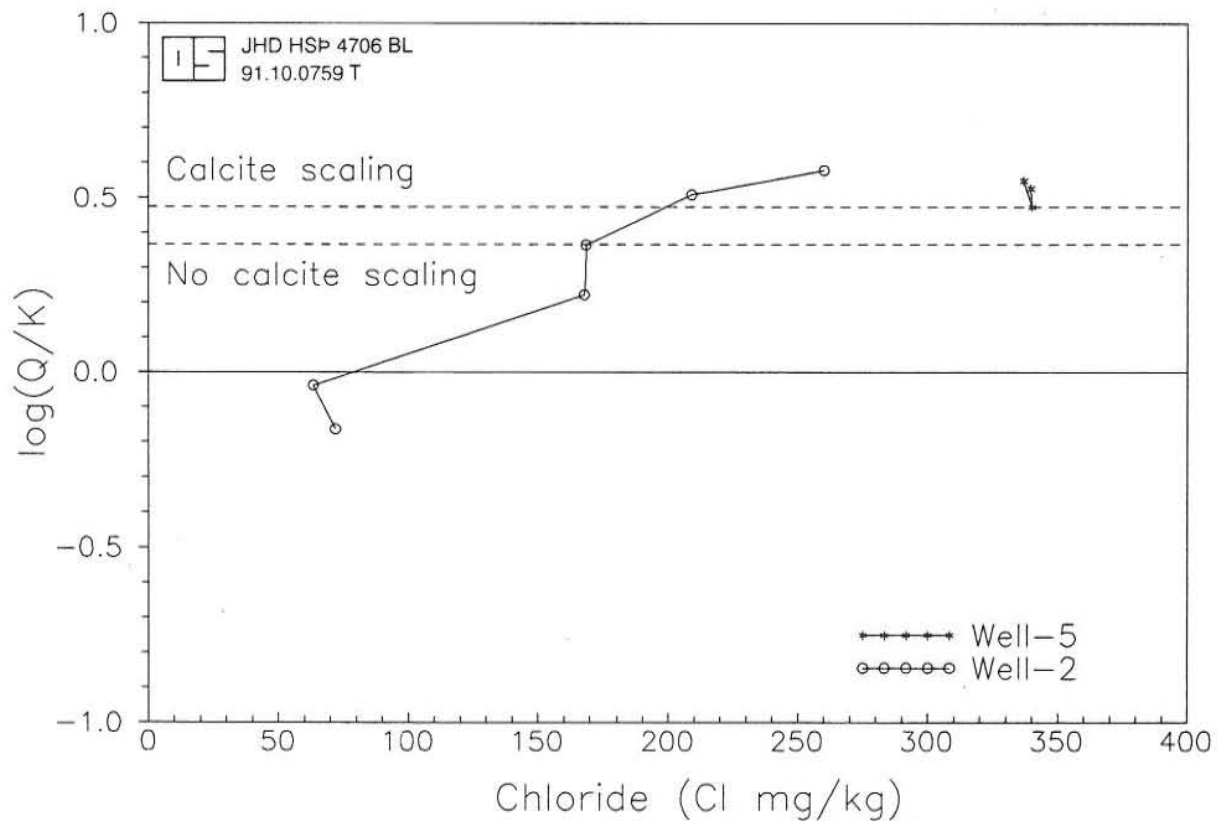


FIGURE 13: The CaCO<sub>3</sub> supersaturation and the chloride content in Sudureyri wells



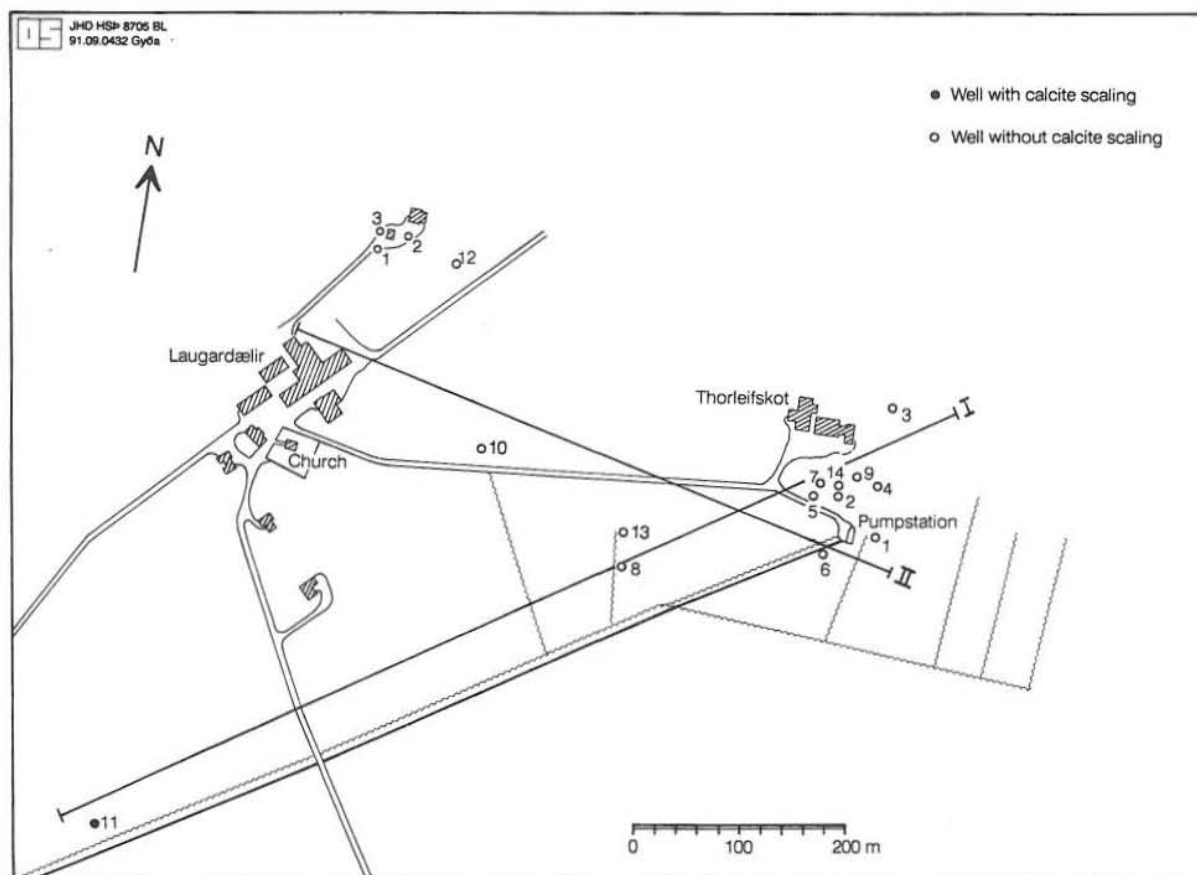


FIGURE 14: The location of wells in the Selfoss geothermal field

### 3.3 Selfoss

The Selfoss geothermal field is located in the south of Iceland. The geothermal water is used for district heating of the town Selfoss (population: 3774). A calcite scale problem is only found in well PK-11. The location of wells in Selfoss geothermal field is shown in Figure 14.

A calcite equilibrium calculation based on the WATCH program is listed in Table 7. The calcite saturation index of wells in this field is shown in Figure 15. In wells PK-08, PK-09, PK-10, PK-13 and PK-14, the calcite saturation index is lower than 0.28. In well PK-11 the saturation index is similar to other wells. It shows low supersaturation, so it is difficult to explain the presence of calcite in well PK-11 from equilibrium calculation.

### 3.4 Hrisey

Hrisey geothermal field is located on a small island in the northern part of Iceland (Figure 16). Geothermal development started in 1966. A total of 11 wells have been drilled, of which 4 are productive, 5 are used for observation, and 2 for reserve (Table 8). One well is used today for the Hrisey district heating system (population: 275).

TABLE 7: Calcite calculations for the Selfoss geothermal field

Well no.	Sample no.	Ionic bal. (%)	logQ	logK	log(Q/K) (S.I.)	Note
PK-08	68-3270	-4.14	-8.691	-9.101	0.41	(***)
"	73-0113	-5.08	-9.044	-9.146	0.102	
"	76-0189	-13.04	-9.276	-9.131	-0.145	
"	79-0121	-3.92	-9.109	-9.208	0.099	
"	82-0126	-0.61	-9.4	-9.158	-0.242	
"	85-0002	-0.36	-8.828	-8.949	0.121	(***)
PK-09	79-0120	-5.72	-9.741	-9.042	-0.699	
"	79-3011	-1.69	-8.919	-8.971	0.052	
"	84-0091	-1.44	-8.638	-8.917	0.279	
"	85-0003	1.12	-8.674	-8.926	0.252	
"	86-0036	2.42	-8.57	-8.778	0.208	PK-10
"	84-0090	-1.12	-9.139	-9.154	0.015	
"	85-0001	0.52	-9.17	-9.183	0.013	
"	86-0035	1.05	-9.063	-9.154	0.091	
"	87-0007	0.71	-8.992	-9.101	0.109	
"	89-0005	1.4	-8.935	-9.08	0.145	PK-11
"	82-0125	-2.06	-8.938	-8.871	-0.067	
"	85-0004	0.75	-8.739	-8.91	0.171	
"	86-0038	-1.2	-8.758	-8.809	0.051	PK-13
"	86-0037	0.77	-8.995	-9.035	0.04	
"	87-0008	1.71	-9.010	-9.045	0.035	
"	87-0100	4.7	-8.984	-9.057	0.073	
"	89-0006	0.39	-8.958	-9.086	0.128	
"	90-0258	0.64	-8.925	-9.041	0.116	PK-14
"	90-0057	1.45	-8.816	-8.959	0.143	

NB: (\*\*\*) Data sampled shortly after initial discharge.

TABLE 8: Overview of the Hrisey geothermal wells

Well no.	Type of the wells	Production history	Depth of well (m)	Depth of casing (m)	Status of calcite scaling
1	observation well	- 1977	99	2	scaling
2	production well		132	53	
3	observation well		637	4.4	
4	"	1977-1988	322	2.7	scaling
5	production well		320/1055	92	
6	reserve well for well-5		145	1.8	
7	observation well		156	6.5	
8	"		176	5	
9	reserve well for well-10	1988- 1988-	224	2	no scaling no scaling
10	production well		216	143	
11	production well		130	16.4	

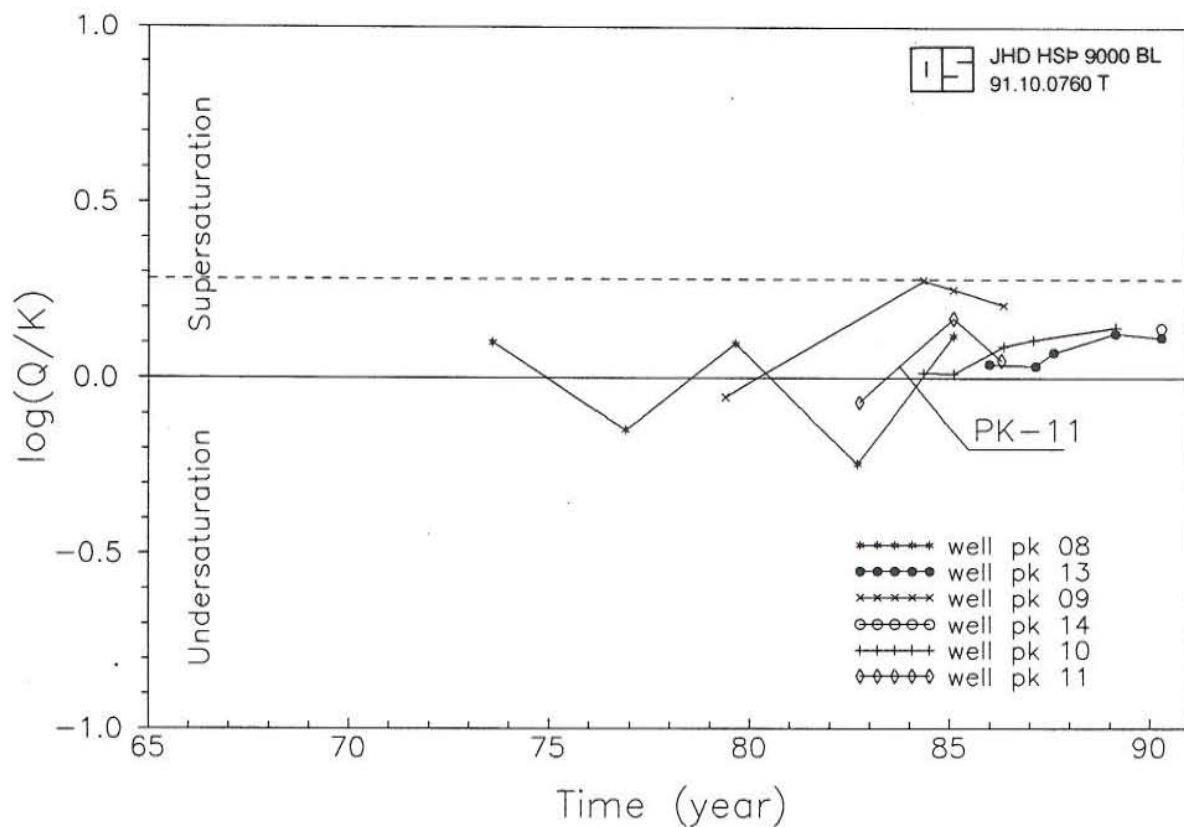


FIGURE 15:  $\text{CaCO}_3$  supersaturation in the Selfoss geothermal field

Calcite scaling occurred in surface installation using water from wells 2 and 5 (pipe system). There are two main reservoirs in the geothermal system, a deep reservoir which has a temperature of about  $82^\circ\text{C}$  and a shallow reservoir which has a temperature of about  $60^\circ\text{C}$ . The shallow reservoir is a mixture of the runoff from the deep reservoir and the cold groundwater system. Well 11 only draws water from the cold groundwater system. For well 10 the shallow reservoir is closed off by casing so it yields only water from the deep reservoir. All other wells draw water only from the shallow reservoir with minor contribution from the deep reservoir. Where there is a shallow casing there may also be minor inflow of cold water into the production wells.

The shallow reservoir is encountered as a high permeable production feedzone at about 100 m depth in all wells. This feedzone is sedimentary and interlayered between basaltic lava flows.

The mixing of the cold groundwater and runoff from the deep reservoir water appears to happen close to the well field as the produced water has not reached a chemical equilibrium at  $60^\circ\text{C}$ . In order to calculate the ratio of each component, one can use two chemically inert components such as chloride and oxygen isotope ratios and the relative temperature of the ground water and the deep reservoir.

Well 5 yields from a reservoir where the mixing of two aquifers occurs. The mixing ratio is calculated according to the chloride ion content, temperature parameter and isotope  $\delta^{18}\text{O}^+$ :



1. The mixing ratio is calculated from  $\delta^{18}\text{O}^+$ :

$$\delta^{18}\text{O}^+ \text{ in well 10} = -15.06$$

$$\delta^{18}\text{O}^+ \text{ in well 11} = -10.8$$

$$\delta^{18}\text{O}^+ \text{ in well 5} = -13.49$$

The cold water fraction is assumed to be  $x$ , so,

$$-13.09 = -15.03 \cdot (1 - x) + [-10.8] \cdot x$$

or,

$$x = \frac{15.06 - 13.09}{15.06 - 10.8} = 36.9\%$$

2. The mixing ratio is calculated from chloride ion parameters:

$$\text{Cl in well 10} = 398.5 \text{ mg/kg} \\ (881017-0174)$$

$$\text{Cl in well 11} = 20.6 \text{ mg/kg}$$

The cold water fraction is assumed to be  $x$ , so,

$$\text{Cl content of well 5} = 398.5 \cdot (1 - x) + 20.6 \cdot x$$

or,

$$x = \frac{398.5 - \text{Cl content of well 5}}{398.5 - 20.6}$$

3. The mixing ratio is calculated from temperature parameters:

$$\text{The temperature of well 10} = 77.5^\circ\text{C} \text{ (881017-0174)}$$

$$\text{The temperature of well 11} = 9^\circ\text{C}$$

The cold water fraction is assumed to be  $x$ , so,

$$\text{Temperature of well 5} = 77.5 \cdot (1 - x) + 9 \cdot x$$

or,

$$x = \frac{77.5 - \text{Temperature of well 5}}{77.5 - 9}$$

The results are listed in Tables 9 and 10, and plotted in Figure 17.

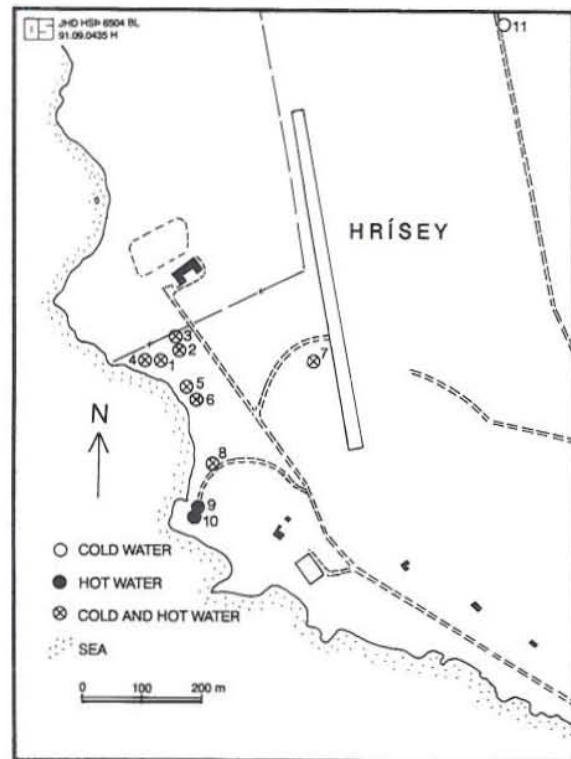


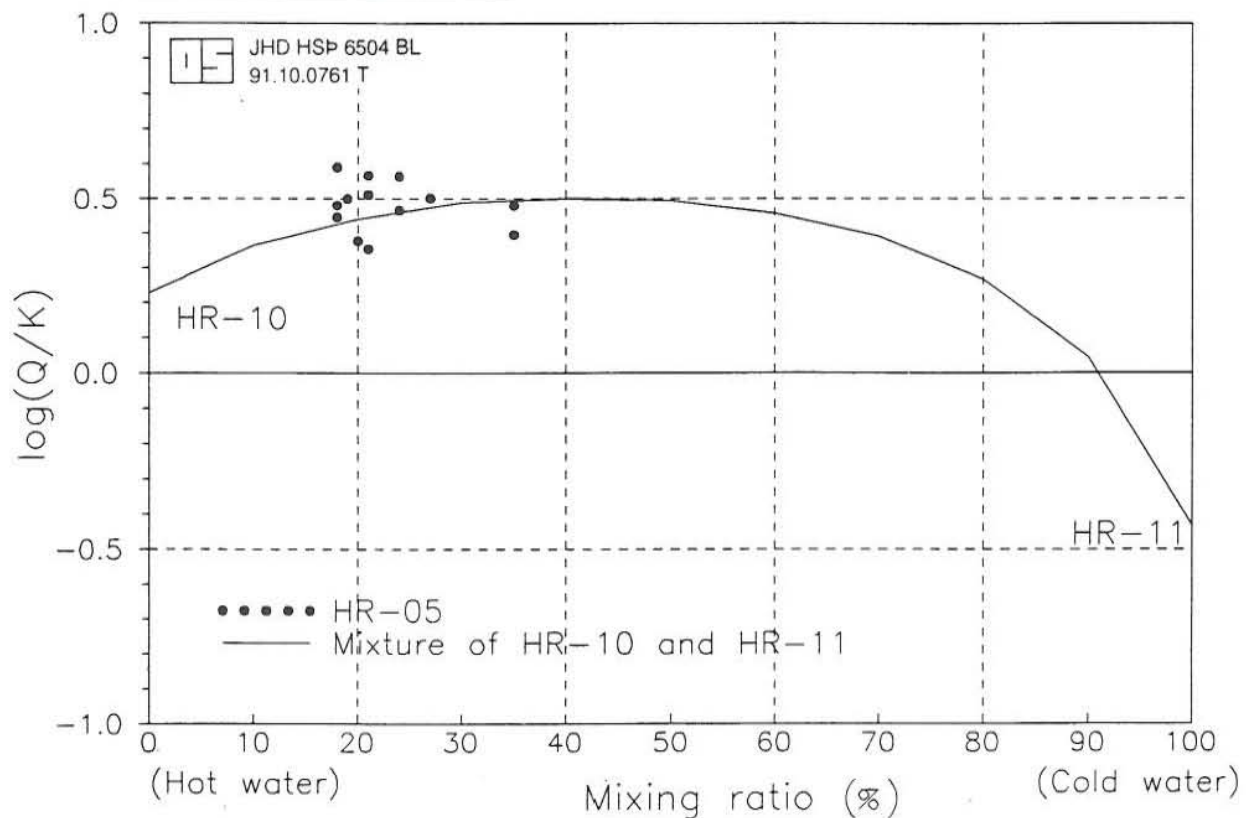
FIGURE 16: The location of wells in the Hrisey field

TABLE 9: Mixing ratio of wells 10 and 11 according to chloride ion parameter

Well 5		Cold water fraction (%)
Sample no.	Cl (mg/kg)	
81-0116	312	22.9
83-0201	315	22.1
84-0079	286.59	29.6
84-0277	312.17	22.9
84-0279	312.17	22.9
85-0267	297.96	26.6
86-0172	318	21.1
86-0173	322.38	20.1
86-0174	322.5	20.1
87-0169	259.6	36.7
87-0170	260.2	36.6
88-0024	299.3	26.3

TABLE 10: Mixing ratio of wells 10 and 11 according to temperature parameter

Well 5		Cold water fraction (%)
Sample no.	T (°C)	
81-0116	60	25.5
83-0201	60.5	24.8
84-0277	57.4	29.3
84-0279	62	22.6
85-0267	58.9	27.2
86-0174	55.5	29.2
87-0169	58	28.5
88-0024	64	19.7

FIGURE 17:  $\text{CaCO}_3$  supersaturation in the Hrisey wells (mixing of wells 10 and 11)

If the water had reached chemical equilibrium it would be near equilibrium with calcite and other secondary minerals lower in dissolved oxygen. However the concentration of dissolved oxygen in waters from well 5 was about 0.5 mg/kg. Just after mixing in the aquifer the concentration would be 3-3.5 mg/kg if the cold water fraction was 30%. The water has thus reached chemical equilibrium with the reservoir rocks to some degree, but has not reached to chemical equilibrium. The calcite saturation index shows also that chemical equilibrium in the mixture has not been fully reached. By using the VDATA program, the calcite saturation index value of mixing water of wells 10 and 11 in different ratios is calculated, shown in Figure 17.



As shown in Figure 17, the degree of calcite saturation of mixed water changes with the mixed ratio. At the beginning, the calcite saturation index increases with an increasing mixed ratio; at a certain mixed ratio, the value reaches maximum; after this mixed ratio, the calcite saturation index value decreases with an increasing mixed ratio. So, the calcite saturation index value of mixed water is higher than both wells 10 and 11 at a certain range of mixing ratio. When the water from well 5 was first used by "Hitaveita", there was excessive corrosion, but not so much scaling. When the addition of sodium sulphide started, the calcite scaling became a serious problem. The reason is probably the catalytic effect of the sodium sulphide and change in pH affecting the saturation index of calcite. So calcite saturation index is the basic but not the only factor affecting calcite scaling formation. The saturation index of actual samples taken from well 5 is calculated in the VDATA program. It is plotted in Figure 17. Saturation of well samples agrees quite well with the results from the mixed calculations.

The contents of calcium, chloride, silica, carbon dioxide and pH values of wells 5, 10 and 11 are separately shown in Figure 18. The content of every ion in well 5 is between well 10 and 11, and shows that the water in well 5 could be a mixture of two aquifers of composition similar to wells 11 and 10. A comparison of the degree of calcite supersaturation of wells 5, 10 and 11 with time is shown in Figure 19. The mean calcite saturation index value of well 5 is higher than that of wells 10 and 11. In well 5 the saturation index is 0.36-0.5, in well 10 is about 0.08-0.27, in the cold water well 11 it is -0.436. The calcite saturation index boundary between scaling and no scaling is approximately 0.36-0.5. The ionic balance of chemical data, the calcite saturation index value as well as the content of main chemical components is listed in Table 11.

TABLE 11: Calcite calculations and some components in Hrisey wells

Well no.	Sample no.	Ionic bal. (%)	log Q	log K	log (Q/K) (S.I.)	Cl (mg/kg)	CO <sub>2</sub> (mg/kg)	SiO <sub>2</sub> (mg/kg)	Ca (mg/kg)	pH	Note
HR-05	81-0116	9.09	-8.484	-8.839	0.355	312	8.2	52.66	40.28	9.3	
"	83-0201	-2.079	-8.461	-8.839	0.378	315	12.3	55	38.95	9.21	
"	84-0079	-5.13	-8.337	-8.839	0.502	286.59	14.5	52	38.31	9.25	
"	84-0277	-5.11	-8.239	-8.807	0.568	312.17	13.19	55.02	40.37	9.51	
"	84-0279	-1.07	-8.352	-8.864	0.512	312.17	11.88	55.89	42.5	9.36	
"	85-0267	-2.21	-8.358	-8.825	0.467	297.96	12.7	54.52	39.56	9.32	
"	86-0170	-2.5	-8.375	-8.822	0.447	320.82	12.7	55.64	43.43	9.34	(*)
"	86-0171	-4.19	-8.211	-8.802	0.591	321.24	17.6	55.29	43.52	9.34	(*)
"	86-0172	-3.69	-8.302	-8.802	0.5	318.91	14.5	55.46	43.52	9.34	
"	86-0173	-2.56	-8.356	-8.802	0.446	322.38	12.7	54.43	44.44	9.34	
"	86-0174	-3.01	-8.303	-8.784	0.481	322.5	14	55.38	43.33	9.34	
"	87-0169	2.46	-8.337	-8.814	0.481	259.6	16.3	51.55	34.32	9.32	
"	87-0170	2.26	-8.443	-8.839	0.396	260.2	15.8	52.41	32.04	9.27	
"	88-0024	0.87	-8.325	-8.89	0.565	299.3	11.8	55.68	39.63	9.41	
HR-10	87-0165	1.43	-8.681	-9.101	0.42	387.8	7.3	69.73	53.7	9.47	(***)
"	88-0018	0.74	-8.497	-9.042	0.545	387.1	6.4	70.32	55.44	9.58	(***)
"	88-0020	0.79	-8.571	-9.101	0.53	388.8	6	69.17	56.87	9.58	(***)
"	88-0174	1.04	-8.999	-9.079	0.08	398.5	4.6	68.64	57.77	9.3	
"	89-0064	0.2	-8.854	-9.089	0.235	398.4	3.8	68.7	59.4	9.54	
"	89-0095	0.27	-9.47	-9.086	-0.384	397.6	1.1	69.14	58.34	9.48	(**)
"	90-0281	0.67	-8.814	-9.082	0.268	403	4.8	68.4	58.8	9.46	
HR-11	87-0168	-5.54	-8.839	-8.403	-0.436	20.61	26.3	12.7	7.73	8.6	

NB: (\*\*\*) Data sampled shortly after the initial discharge  
 (\*\*) Data has a large deviation from other data,  
 (\*) Data sampled shortly after the start of pumping.



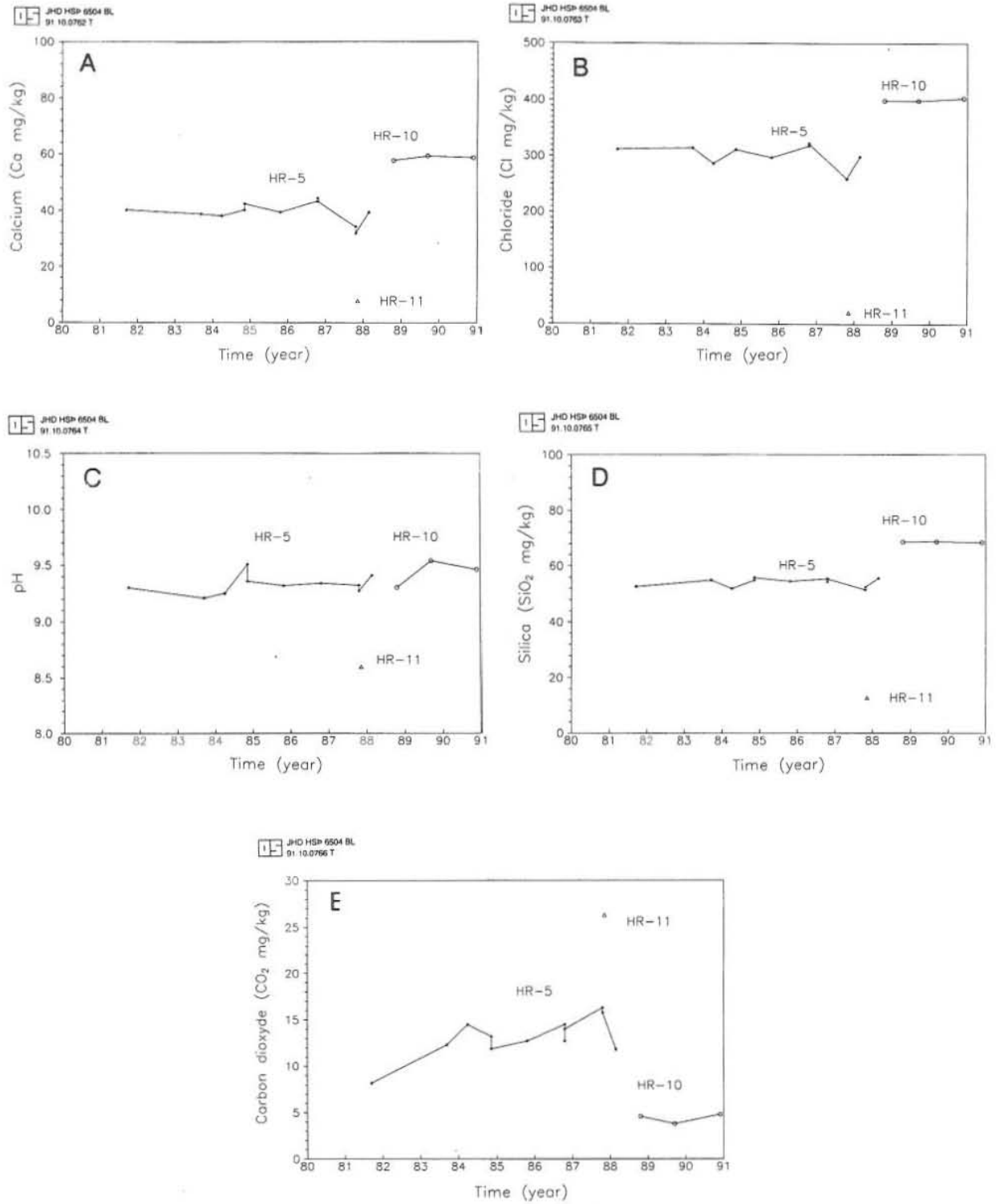


FIGURE 18: Comparison of waters in the Hrisey wells 5, 10 and 11;  
a) Ca, b) Cl, c) pH, d) SiO<sub>2</sub>, e) CO<sub>2</sub>

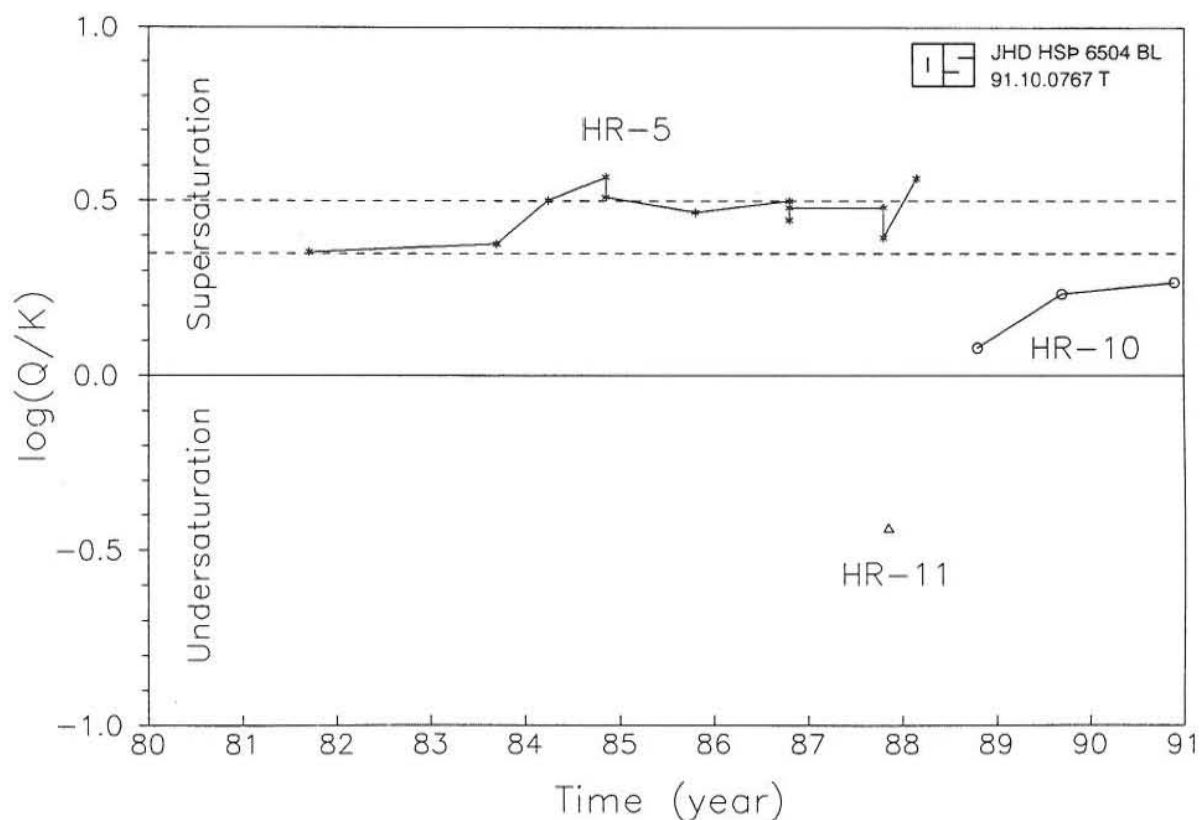


FIGURE 19:  $\text{CaCO}_3$  supersaturation in the Hrisey geothermal field

### 3.5 Seltjarnarnes

Seltjarnarnes geothermal field is located within the town Seltjarnarnes, a suburb of Reykjavik (Figure 20). The water from this field is used for heating Seltjarnarnes (population: 4174). Table 12 is an overview of the wells in the Seltjarnarnes geothermal field.

Table 13 lists the main aquifers in wells SN-04 - SN-06. Calcite saturation indices of production wells SN-04, SN-05 and SN-06 were calculated. The results are listed in Table 14 and shown in Figure 21. Calcite saturation index increases with time in wells SN-04 and SN-05.

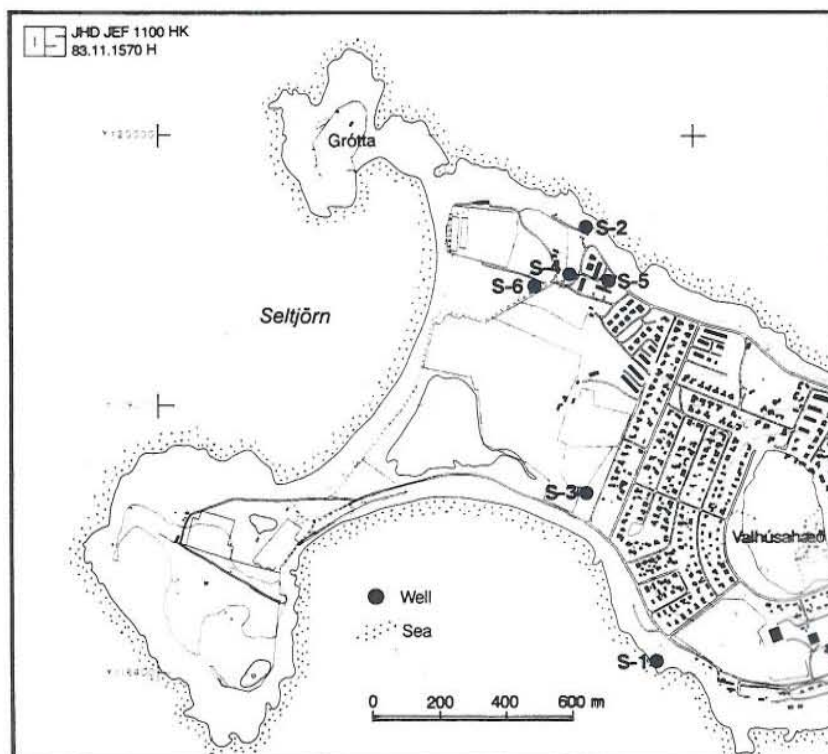


FIGURE 20: The location of wells in the Seltjarnarnes field

TABLE 12: Overview of the Seltjarnarnes geothermal wells

Well no.	Year drilled	Depth (m)	Casing (m)	Water temperature (°C)
SN-01	1967	1282	18.5	101-106 108-116 90-105 115-117
SN-02	1965	856	81.5	
SN-03	1970	1715	99	
SN-04	1972	2025	172	
SN-05	1981	2207	168	
SN-06	1985	2701	414	

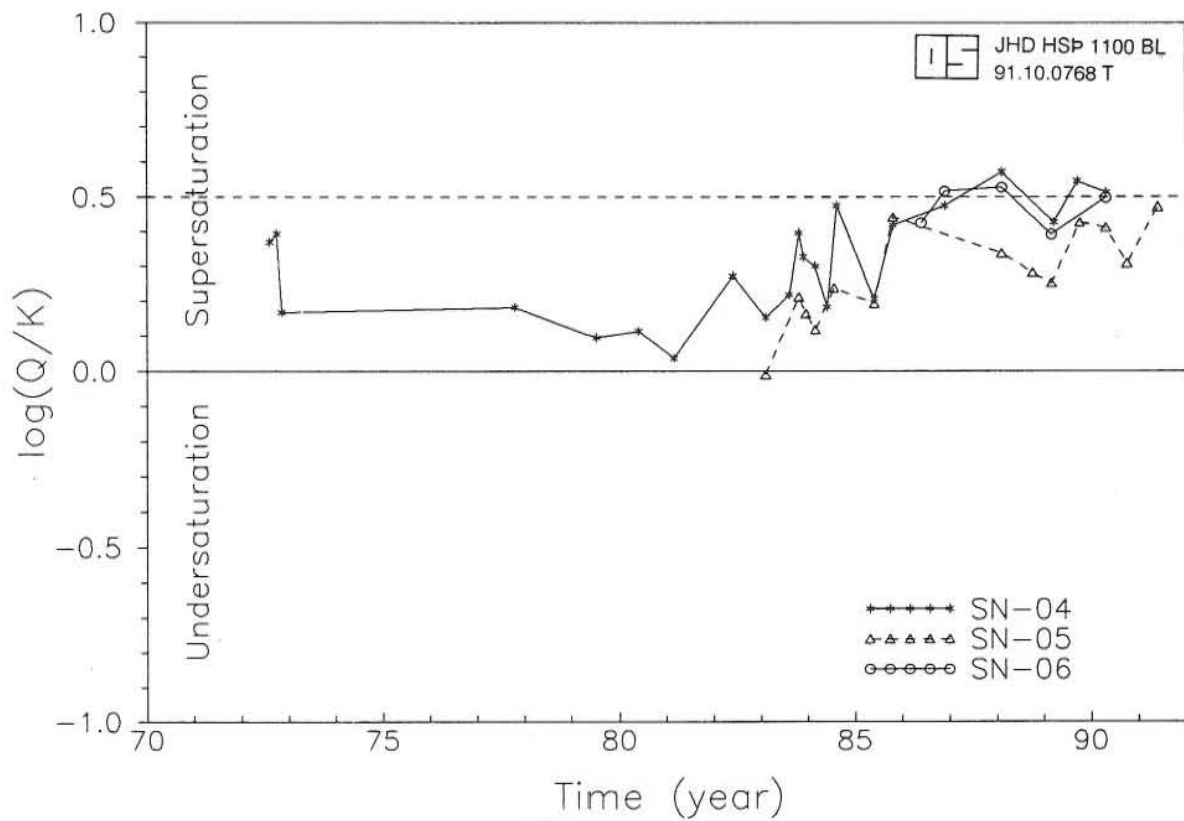
FIGURE 21:  $\text{CaCO}_3$  supersaturation in the Seltjarnarnes geothermal field



TABLE 13: Main aquifers in wells SN-04 - SN-06

Well	Depth (m)	Temperature (°C)	Cl concentration 1984-1985 (mg/kg)	Production 1984-1985 (%)
SN-04	370	75	2000	15
SN-04	1180	104	900	5
SN-04	1840	122	900	40
SN-04	1950	126	900	40
SN-05	430	75	1800	30
SN-05	700	90	800	>40
SN-05	2090	>120	800	<30
SN-06	440-700	80	2100	30
SN-06	2060	133	1000	70

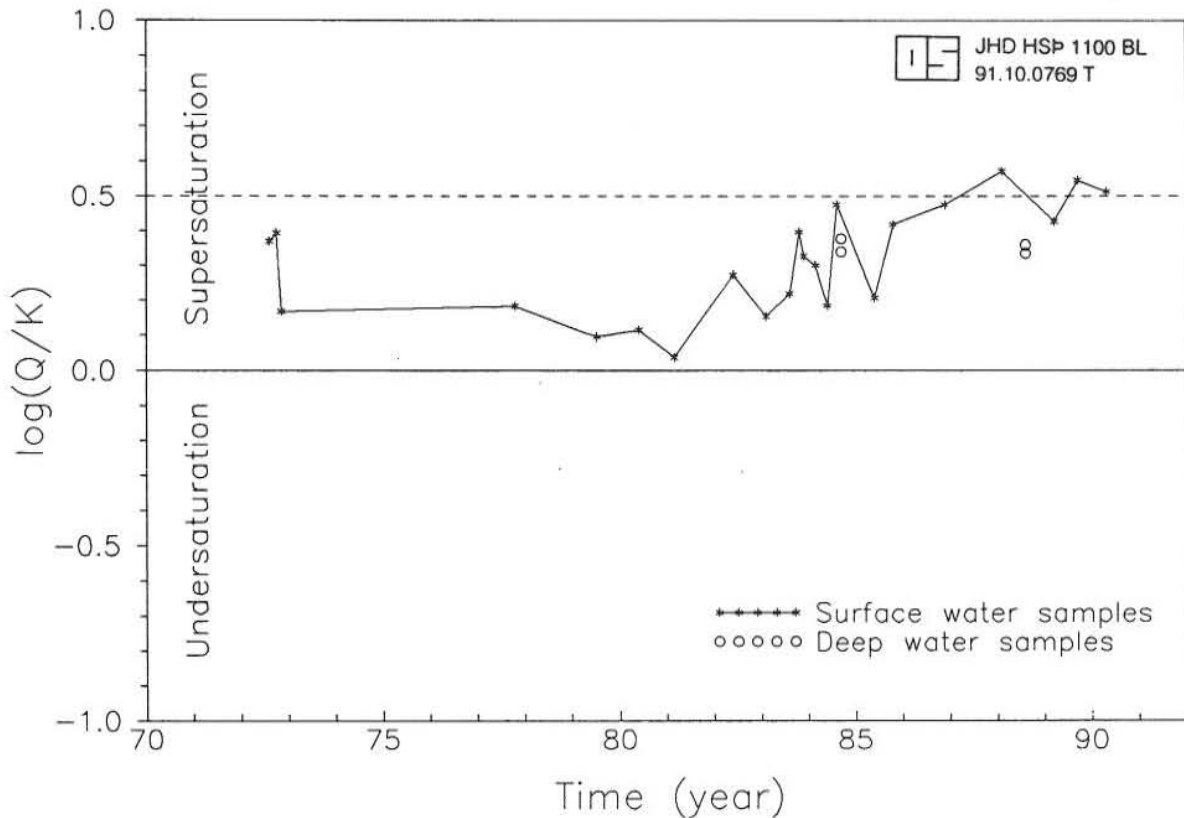


FIGURE 22: Comparison of deep waters and surface water in well SN-04

Deep samples from well SN-04 are used to compare with the surface samples. As shown in Figure 22, the calcite saturation index of deep water samples did not change, whereas the calcite saturation index from surface samples increases with time. This is explained by a change in the relative yield of the aquifers in well SN-04 after the drilling of well SN-06 and also a collapse of the bottom 100 m in well SN-04 after 1984. Thus, well SN-04 is drawing more water from shallow, cooler and more saline aquifers with time. A temperature drop in well SN-04 also confirms this explanation (Figure 23).

TABLE 14: Calcite calculations for the Seltjarnarnes geothermal field

Well no.	Sample no.	Ionic bal. (%)	log Q	log K	log(Q/K) (S.I.)	Cl (mg/kg)	T (°C)	Note
SN-04	72-0100	10.51	-9.326	-9.696	0.37	488	114.5	
"	72-0131	0.35	-9.33	-9.724	0.394	542	116	
"	72-0155	10.46	-9.541	-9.709	0.168	554	115.2	
"	75-0070	-6.76	-9.852	-9.705	-0.147	585.8		(*)
"	77-4059	5.52	-9.522	-9.705	0.183	565		
"	79-3020	-3.54	-9.592	-9.687	0.095	670.8	114	
"	80-0077	3.23	-9.555	-9.669	0.114	655		
"	81-0030	1.59	-9.632	-9.669	0.037	662.5	113	
"	81-0156	-0.96	-9.211	-9.737	0.526	735	116.7	(**)
"	82-0071	2.57	-9.432	-9.705	0.273	752		
"	83-0008	0.36	-9.552	-9.705	0.153	850		
"	83-0199	-4.59	-9.088	-9.705	0.617	933.7	115	(**)
"	83-0215	-5.63	-9.459	-9.678	0.219	989.8	113.5	
"	83-0246	-3.3	-9.253	-9.65	0.397	967.5	112	
"	83-0293	-7.37	-9.382	-9.709	0.327	970	115.2	
"	84-0007	-0.11	-9.41	-9.711	0.301	972.5	115.3	
"	84-0099	-1.98	-9.54	-9.724	0.184	1036	116	
"	84-0114	-6.39	-9.228	-9.704	0.476	1085	114.9	
"	84-0182	-17.77	-9.248	-9.43	0.182	1117	99.5	(*)
"	85-0185	1.58	-9.462	-9.669	0.207	1302.5	113	
"	85-0259	-1.65	-9.288	-9.707	0.419	1325.37	115.1	
"	86-0214	-5.29	-9.142	-9.618	0.476	1368.3	110.2	
"	88-0003	0.25	-9.039	-9.611	0.572	1387.4	109.8	
"	89-0013	0.85	-9.148	-9.576	0.426	1440	107.9	
"	89-0052	-0.29	-9.043	-9.589	0.546	1525	108.6	
"	90-0060	-0.94	-9.086	-9.6	0.514	1629	109.2	
"	84-0146	-5.05	-9.743	-9.402	0.341	929.3		(1)
"	88-0091	2.16	-9.743	-9.407	0.336	1052.2		(2)
"	84-0147	-3.35	-9.743	-9.366	0.377	901.4		(3)
"	88-0090	0.65	-9.743	-9.383	0.36	1209.8		(4)
SN-06	86-0064	-4.09	-9.748	-9.322	0.426	1488.6		
"	86-0215	-4.13	-9.643	-9.126	0.517	1540.2		
"	88-0004	0.35	-9.743	-9.215	0.528	1616.8		
"	89-0014	-1.23	-9.741	-9.348	0.393	1730		
"	90-0061	-1.45	-9.756	-9.258	0.498	1810		
SN-05	83-0009	1.88	-9.364	-9.373	-0.009	662.09		
"	83-0248	-0.2	-9.543	-9.331	0.212	575		
"	83-0294	-2.4	-9.423	-9.259	0.164	682.5		
"	84-0008	0.52	-9.384	-9.266	0.118	780		
"	84-0115	-0.39	-9.399	-9.161	0.238	865		
"	85-0186	-1.86	-9.337	-9.143	0.194	1022.7		
"	85-0260	0.86	-9.372	-8.929	0.443	1044.06		
"	88-0005	-0.22	-9.354	-9.015	0.339	1044.1		
"	88-0130	-2.28	-9.359	-9.076	0.283	1151		
"	89-0015	2.36	-9.336	-9.083	0.253	1070		
"	90-0062	-0.28	-9.352	-8.94	0.412	1154		
"	89-0051	0.03	-9.387	-8.959	0.428	1160		
"	90-0239	0.08	-9.392	-9.082	0.31	1403		
"	91-0116	0.46	-9.367	-8.894	0.473	1340		

NB: (1)-(4): Deep water samples, (1) 1820 m, (2) 1810 m, (3) 1920 m, (4) 1170 m.

(\*) Water is not in ionic balance.

(\*\*) Data has a large deviation from other data.

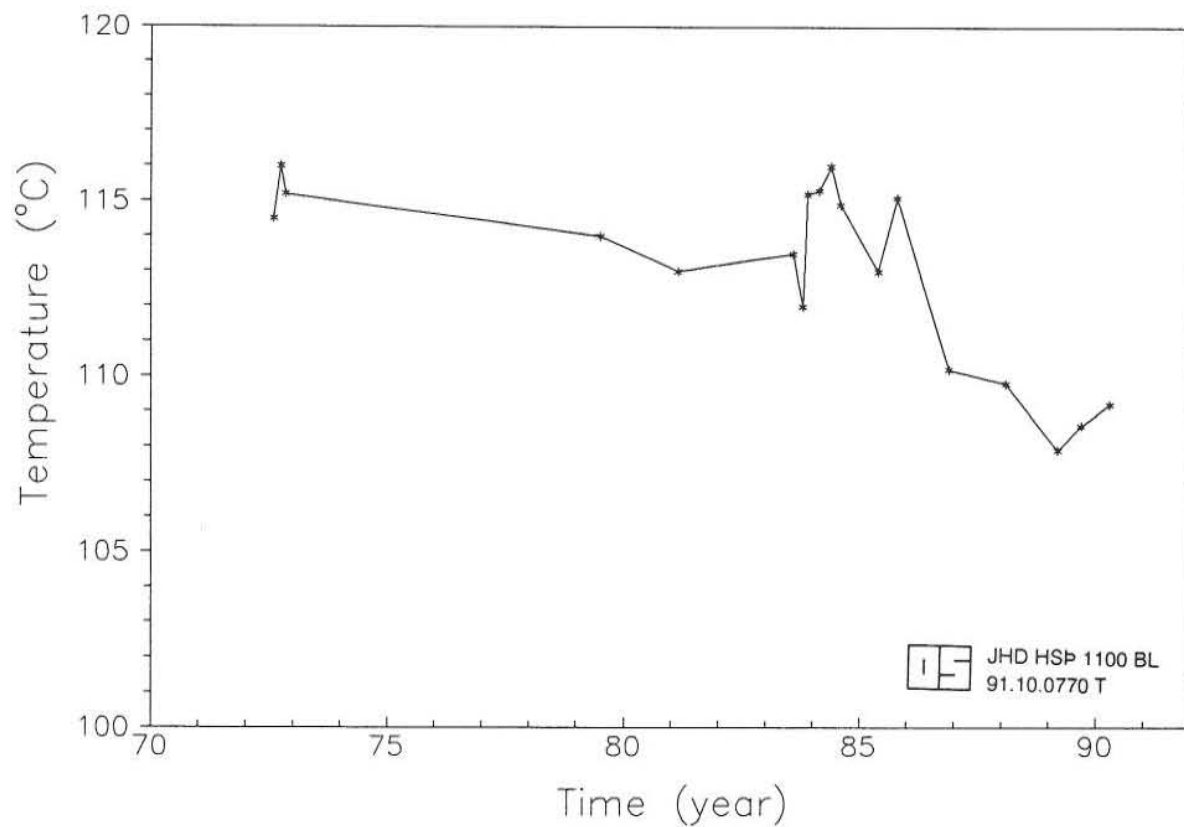


FIGURE 23: The temperature change in the Seltjarnarnes well SN-04

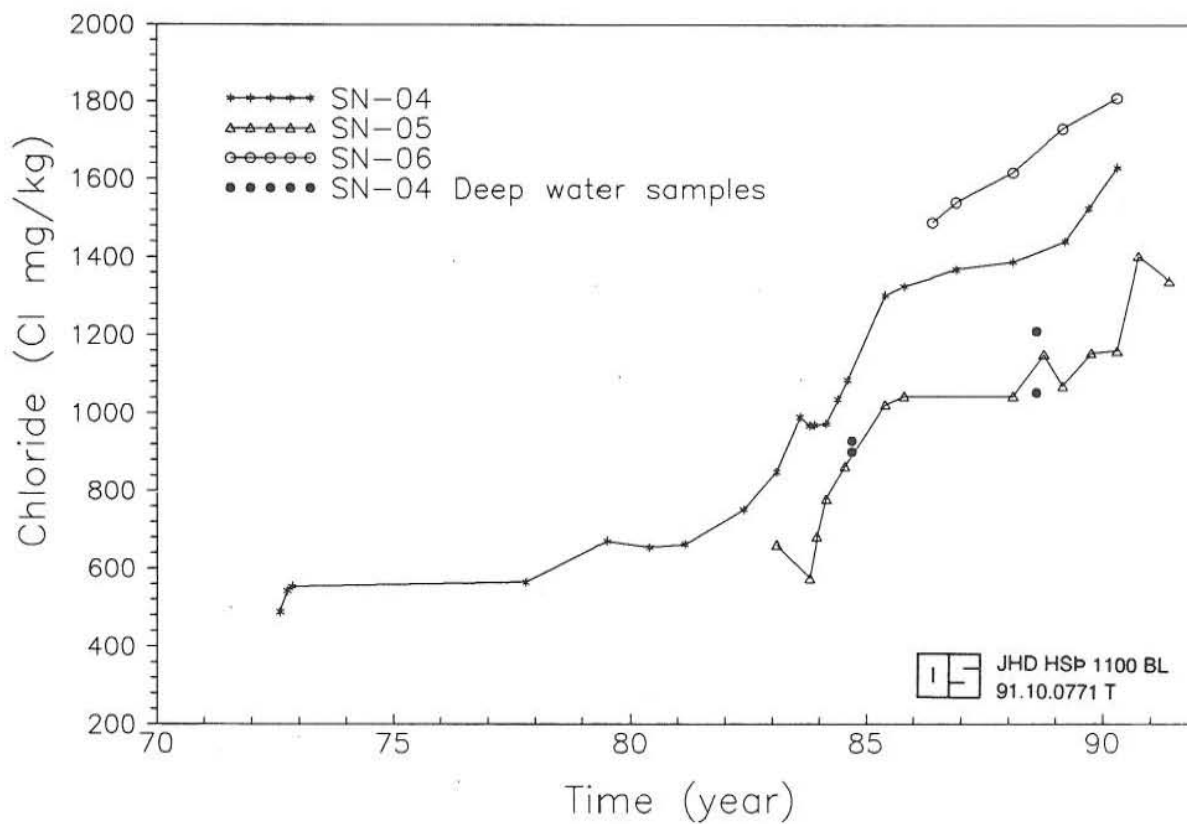


FIGURE 24: Chloride in the Seltjarnarnes wells SN-04, 05 and 06



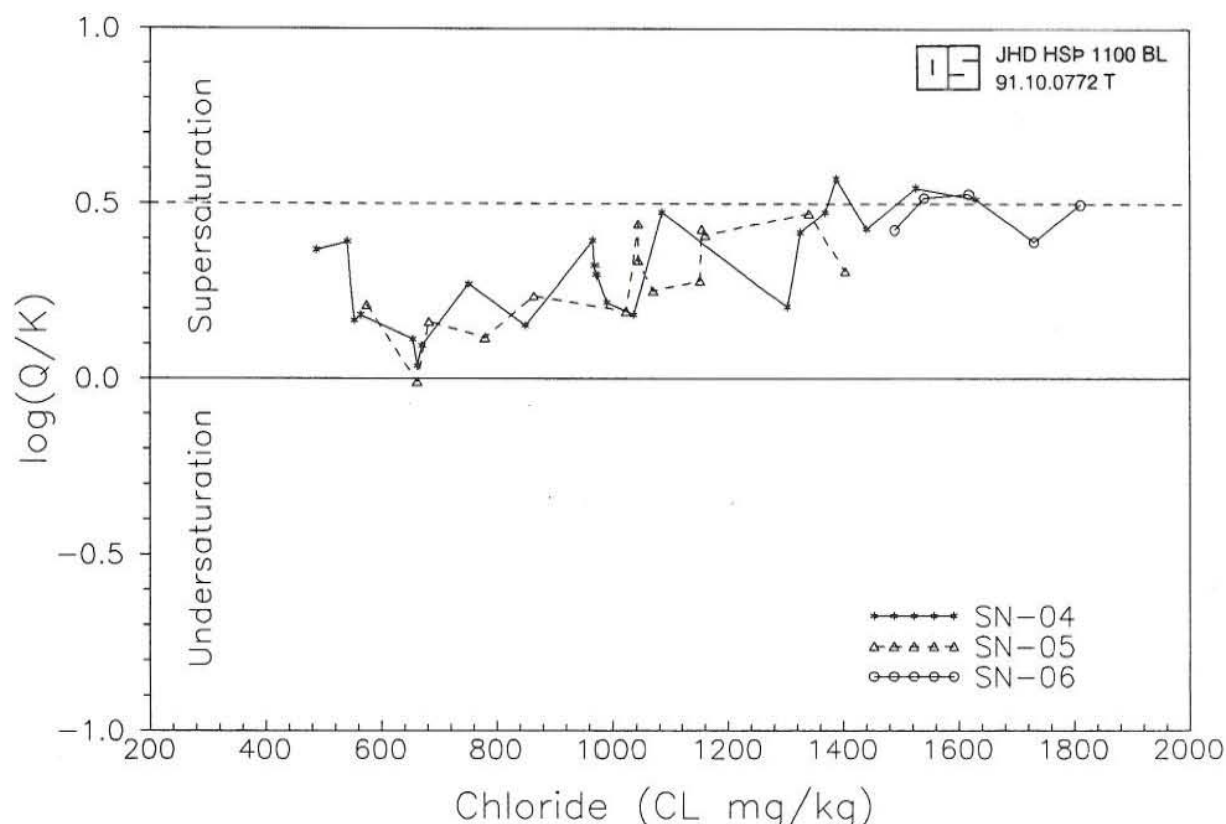


FIGURE 25:  $\text{CaCO}_3$  supersaturation and the chloride content in the Seltjarnarnes wells

Figure 24 shows that the chloride content in wells SN-04, SN-05 and SN-06 increases with time and also that the chloride content from deep water samples is lower than from surface samples. Figure 25 shows how the change of chloride concentration affects the calcite saturation index in the wells. The calcite saturation index appears to increase with an increase in the chloride content. The calcite saturation index of water from well SN-06 has not changed over time although the salinity has increased. The temperature of the production water has remained almost unchanged during the production time in this well. Well SN-05 shows oscillations in the calcite saturation index and perhaps a general increase over time. This well shows a big change in temperature throughout production. When it is rested for a few months water temperature may rise by  $10^\circ\text{C}$  and then gradually go down. The oscillations in calcite saturation index are most certainly linked to those production periods and also subsequent temperature changes. At present, the calcite saturation index,  $\log(Q/K)$ , in wells SN-04 and SN-06 reaches about 0.5, but no scaling problems have been noticed yet.

### 3.6 Calculating calcite scaling tendency by using Ryznar index

The Ryznar index was calculated for the following wells:

Hrisey - wells 05, 10 and 11; Sudureyri - H-2 and H-5, Selfoss - PK-11 and PK-13

The results are shown in Figure 26. Based on the Ryznar index the calcite scaling tendency is evaluated, as well as a comparison between the evaluated scaling tendency based on the Ryznar index and the actual scaling status (listed in Table 15). The actual scaling status conforms to evaluated scaling tendencies.

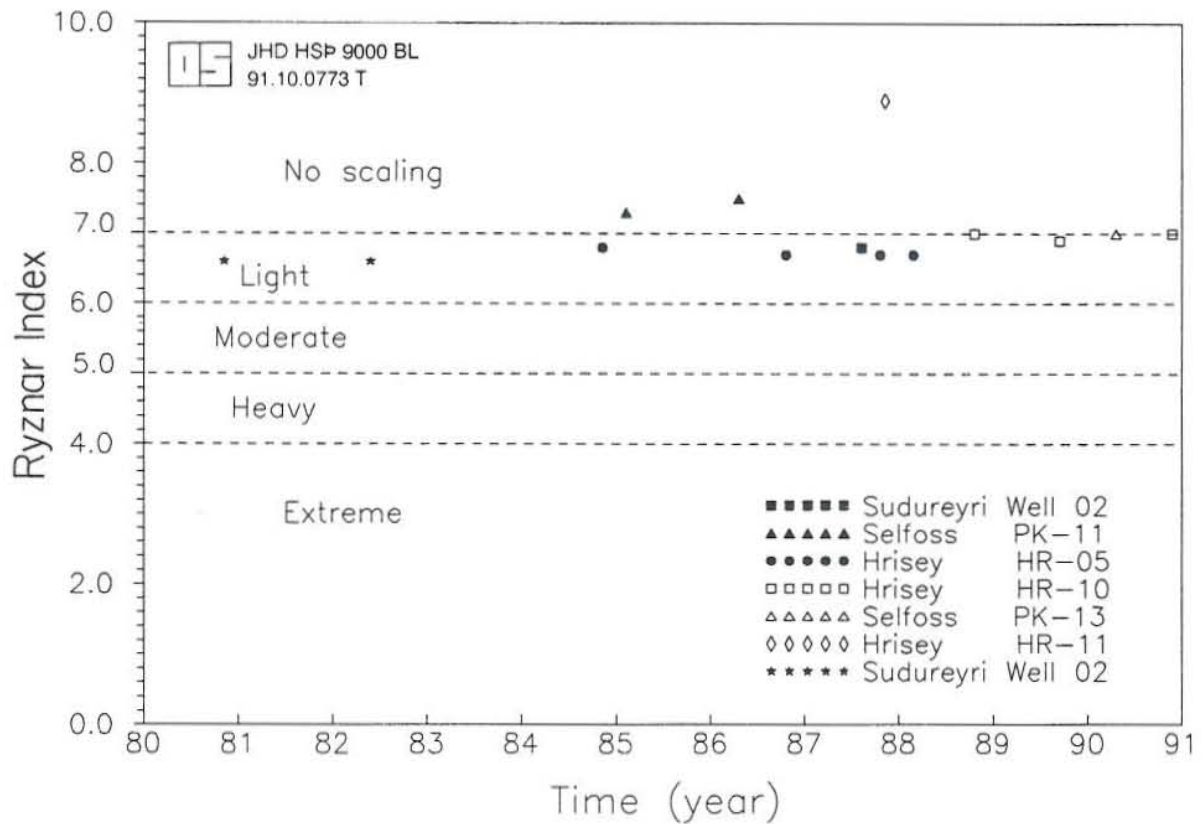


FIGURE 26: The Ryznar index in selected wells

TABLE 15: Ryznar index and calcite scaling

Wells no.	Sample no.	R.I.	Scaling tendency	Actual status
Hrisey-05	84-0279	6.8	light	light
"	86-0172	6.7	"	"
"	87-0169	6.8	"	"
"	88-0024	6.7	"	"
Hrisey-10	88-0174	7	no	no
"	89-0064	6.9	"	"
"	90-0281	7	no	"
Hrisey-11	87-0168	8.9	no	no
Sudureyri-2	80-0161	6.6	light	light
"	82-0058	6.6	"	"
Sudureyri-5	87-0087	6.8	"	"
Selfoss-11	85-0004	7.3	no	scaling
"	86-0038	7.5	no	"
Selfoss-13	90-0058	7	no	no

## 4. DISCUSSION

### 4.1 Comparison of WATCH program, VDATA program and Ryznar index

Three models were used to analyze calcite scaling potential in low temperature wells in Iceland. A comparison was given.

The WATCH program is a good way to study solution and calcite equilibria, especially chemical changes in water chemistry accompanying boiling, and variable degassing, and how these changes affect the calcite/solution equilibria.

The VDATA program is specifically suited to study the equilibrium condition between solution and calcite and in what way the mixing of different waters will lead to calcite departure from equilibrium. It is based on the same thermodynamic database as the WATCH program.

The Ryznar index gives a qualitative estimate of the calcium carbonate scaling tendency of water. It can be used in the temperature interval 0-93.3°C.

Figure 27 shows that the Ryznar index decreases with an increase in the calcite saturation index. Calcite scaling occurs at low Ryznar index values and high calcite saturation index values. The results from the WATCH program confirm the results from the Ryznar index.

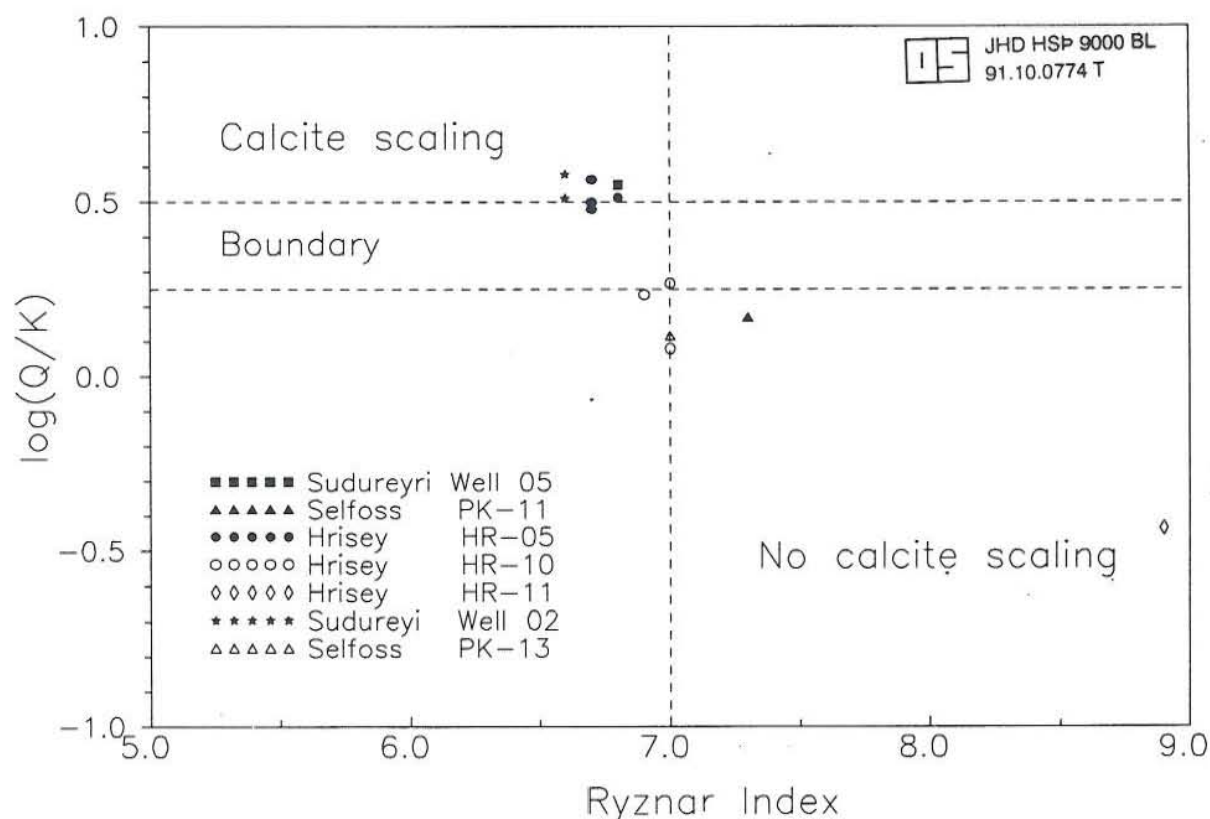


FIGURE 27: Comparison of Ryznar index and saturation index ( $\log Q/K$ )



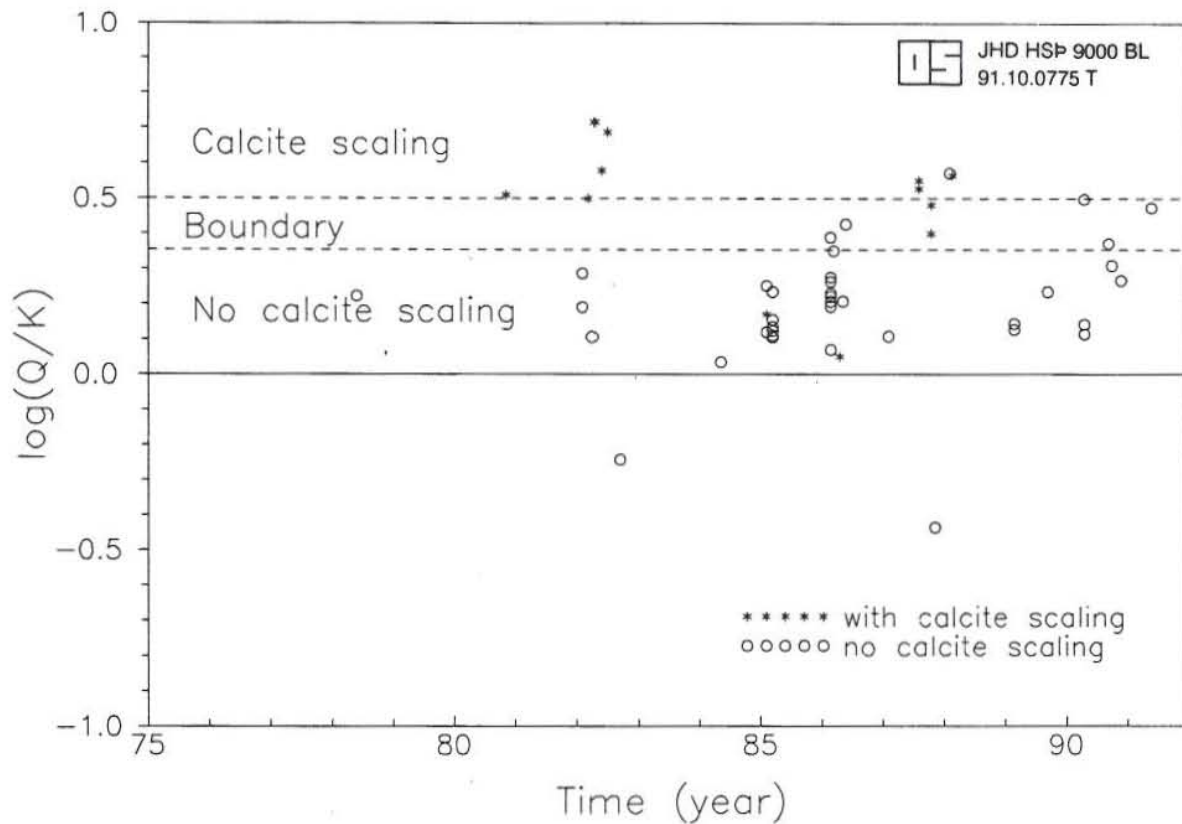


FIGURE 28:  $\text{CaCO}_3$  supersaturation in selected wells

#### 4.2 Supersaturation criterion for calcite scaling formation

A determination of a criterion for the formation of calcite scaling was attempted based on the WATCH and VDATA programs. Figure 28 shows the relationship between the degree of calcite supersaturation and calcite scaling in the Hrisey, Laugarnes, Sudureyri and Selfoss geothermal fields.

Table 16 lists the saturation index boundary between calcite scaling and no scaling in the Hrisey, Laugarnes and Sudureyri geothermal fields.

TABLE 16: The Saturation index boundary between calcite scaling and no scaling

Geothermal fields	Saturation index boundary (S.I.)
Hrisey	0.36-0.5
Laugarnes	0.43-0.48
Sudureyri	0.37-0.48
Selfoss	<0.28 (except PK-11)
boundaries	0.36-0.5

The results show that if the saturation index,  $\log Q/K$  is higher than 0.5, a calcite scaling problem occurs; if the calcite saturation index is lower than 0.36, there is no calcite scaling, and between 0.36 - 0.52 calcite scaling may and may not occur, depending on the flow factor, corrosion factor, etc. This implies a calcite supersaturation ratio ( $Q/K$ ) of 2.3-3.2. According to this study, geothermal waters can contain 2.3 times more  $\text{CaCO}_3$  in solution than the theoretical amount.

#### 4.3 Data used for analysis

As mentioned in section 2.4, good chemical data is very important for any calculation and analysis. In this report, the following kinds of data were not used:

1. Data that is not in ionic balance.
2. Data that was sampled shortly after initial discharge.
3. Data that has a large deviation from other group data.

In the second case, data is considered not to be of a steady status. For example, Figure 29 shows how the chloride content changed with the start of pumping in Laugarnes wells RV-5, 21, 34 and 35. Sampling at the start of pumping did not give data that reflected the actual water composition. All samples are, however, listed in the tables, including those not reported according to the above criteria.

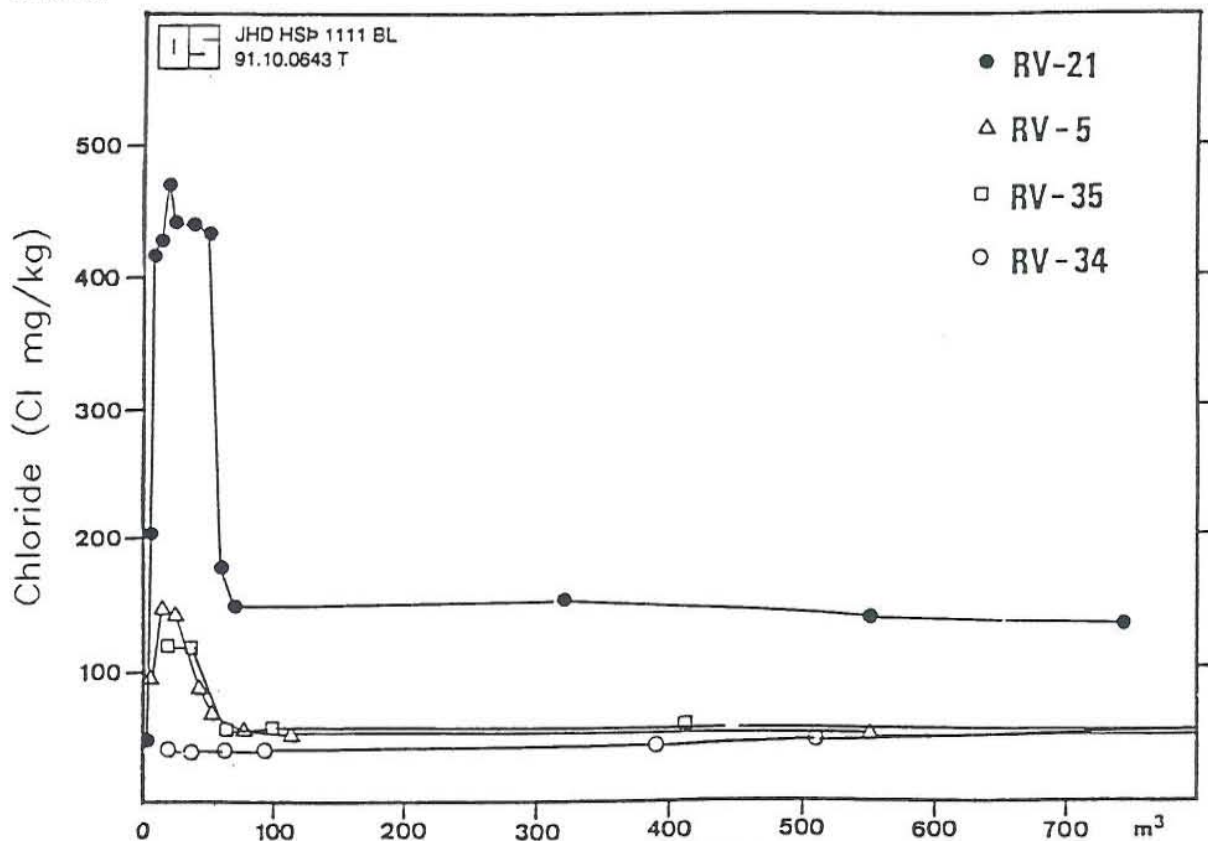


FIGURE 29: Chloride change after start of pumping in Laugarnes wells RV-5, 21, 34 and 35

## 5. CONCLUSIONS

The main results of this study are:

1. The saturation index boundary between calcite scaling and no scaling in the selected wells is 0.36-0.5 based on the WATCH program and VDATA program. If the saturation index ( $\log Q/K$ ) is higher than 0.5, a calcite scaling problem occurs, if it is lower than 0.32, no calcite scaling will occur. Between 0.36-0.5 calcite scaling may and may not occur, depending on other factors. This implies that a calcite supersaturation ratio ( $Q/K$ ) of 2.3-3.2 and, thus, geothermal waters can contain 2.3 times more  $\text{CaCO}_3$  in solution than the theoretical amount.
2. Mixture of different waters is the main reason causing calcite scaling in the low temperature wells selected for this study. In Sudureyri well H-2, Laugarnes wells 21 and 34 as well as Seltjarnarnes wells SN-04, SN-05 and SN-06, a high degree of calcite supersaturation is led by the mixing of geothermal water with high salinity water (sea water origin). In this case, the chloride content can be an index of calcite scaling. The degree of calcite supersaturation increases with increasing chloride concentration in solution. All of these wells are within 1 km distance from the shore and the drawdown has caused the reservoir pressure to become lower than the hydrologic pressure in the surrounding sea. In Hrisey well HR-05, a high degree of calcite supersaturation is mainly caused by the mixing of geothermal water and cold water.
3. The results from the WATCH program agree with the results from the Ryznar index. The calcite saturation index increases with the decreasing of the Ryznar index. Calcite scaling occurs at high calcite saturation index values and low Ryznar index values.



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**APPENDIX:**

**Typical raw chemical data used in this study**

=====

	YR	MO	DAY	NO
SAMP. NO	82	05	31	5091

LOCATION: Laugarnes, RV-34

=====

WATER COMPOSITION (mg/kg)			
TEMP. °C	119.8	SO4	35.4
PH/°C	9.30/25.	H2S	.1
OHMM/°C	/	CL	197.3
SIO2	127.5	F	.40
B		DISS.	
NA	129.3	FE	
K	5.1	AL	
CA	23.8	NH3	
MG	.010		
CO2	14.8		

=====

=====

	YR	MO	DAY	NO
SAMP. NO	86	02	10	

LOCATION: Laugarnes, RV-5

=====

WATER COMPOSITION (mg/kg)			
TEMP. °C	130.2	SO4	22.5
PH/°C	9.43/23.	H2S	.1
OHMM/°C	31.8/ 0.	CL	46.0
SIO2	155.0	F	.90
B		DISS.	
NA	63.3	FE	
K	2.5	AL	
CA	3.6	NH3	
MG	.070		
CO2	17.8		

=====

=====

	YR	MO	DAY	NO
SAMP. NO	78	05	03	0018

LOCATION: Sudureyri, H-2

=====

WATER COMPOSITION (mg/kg)			
TEMP. °C	60.0	SO4	75.4
PH/°C	9.66/18.	H2S	
OHMM/°C	671.0/ 0.	CL	168.0
SIO2	55.0	F	.39
B		DISS.	488.0
NA	121.0	FE	
K	1.2	AL	
CA	27.8	NH3	
MG	.260		
CO2	5.7		

=====

=====

	YR	MO	DAY	NO
SAMP. NO	82	05	01	0058

LOCATION: Sudureyri, H-2

=====

WATER COMPOSITION (mg/kg)			
TEMP. °C	63.0	SO4	95.3
PH/°C	9.43/21.	H2S	
OHMM/°C	1075.0/22.	CL	260.0
SIO2	51.9	F	.28
B		DISS.	659.9
NA	145.3	FE	
K	1.7	AL	
CA	60.5	NH3	
MG	1.720		
CO2	9.2		

=====

=====

	YR	MO	DAY	NO
SAMP. NO	86	04	10	0038

LOCATION: Selfoss, þK-11

=====

WATER COMPOSITION (mg/kg)			
TEMP. °C	57.6	SO4	54.7
PH/°C	8.72/23.	H2S	
OHMM/°C	917.0/23.	CL	229.1
SIO2	62.4	F	.25
B	.2	DISS.	570.5
NA	149.6	FE	
K	4.3	AL	
CA	28.5	NH3	
MG	.050		
CO2	19.3		

=====

=====

	YR	MO	DAY	NO
SAMP. NO	89	01	30	0005

LOCATION: Selfoss, þK-10

=====

WATER COMPOSITION (mg/kg)			
TEMP. °C	77.6	SO4	54.3
PH/°C	8.62/23.	H2S	
OHMM/°C	833.0/23.	CL	206.3
SIO2	64.4	F	.22
B	.1	DISS.	511.6
NA	146.0	FE	
K	4.5	AL	
CA	25.8	NH3	
MG	.078		
CO2	27.2		

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YR MO DAY NO  
SAMP. NO 90 04 03 0060  
LOCATION: Seltjarnarnes, SN-04

WATER COMPOSITION (mg/kg)

TEMP. °C	109.2	SO4	283.0
PH/°C	8.47/22.	H2S	.1
OHMM/°C	4490.0/24.	CL	1629.0
SIO2	99.2	F	5.67
B		DISS.	3607.0
NA	622.0	FE	
K	14.7	AL	
CA	490.0	NH3	
MG	.760		
CO2	10.0		

YR MO DAY NO  
SAMP. NO 88 07 12 0091  
LOCATION: Seltjarnarnes, SN-04

WATER COMPOSITION (mg/kg)

TEMP. °C		SO4	228.5
PH/°C	8.48/24.	H2S	
OHMM/°C	3840.0/21.	CL	1052.2
SIO2	100.1	F	.73
B		DISS.	2420.0
NA	466.1	FE	
K	11.7	AL	
CA	298.0	NH3	
MG	.080		
CO2	7.5		

YR MO DAY NO  
SAMP. NO 89 08 31 0064  
LOCATION: Hrisey, HR-10

WATER COMPOSITION (mg/kg)

TEMP. °C	78.2	SO4	50.6
PH/°C	9.54/18.	H2S	
OHMM/°C	1401.0/21.	CL	398.4
SIO2	68.7	F	.25
B		DISS.	936.0
NA	222.8	FE	
K	4.7	AL	
CA	59.4	NH3	
MG	.005		
CO2	3.8		

YR MO DAY NO  
SAMP. NO 87 10 27 0169  
LOCATION: Hrisey, HR-05

WATER COMPOSITION (mg/kg)

TEMP. °C	58.0	SO4	37.5
PH/°C	9.32/17.	H2S	
OHMM/°C	977.0/19.	CL	259.6
SIO2	51.5	F	.22
B		DISS.	575.3
NA	163.8	FE	
K	2.4	AL	
CA	34.3	NH3	
MG	.100		
CO2	16.3		

YR MO DAY NO  
SAMP. NO 87 10 27 0168  
LOCATION: Hrisey, HR-11

WATER COMPOSITION (mg/kg)

TEMP. °C	9.0	SO4	8.3
PH/°C	8.60/17.	H2S	
OHMM/°C	150.0/19.	CL	20.6
SIO2	12.7	F	.04
B		DISS.	76.2
NA	19.4	FE	
K	.2	AL	
CA	7.7	NH3	
MG	.770		
CO2	26.3		