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ANALYSIS OF VARIATIONS IN THE CHARACTERISTICS OF THE GEOTHERMAL FLUID PRODUCED FROM THE SUDUREYRI LOW-TEMPERATURE GEOTHERMAL SYSTEM IN NW-ICELAND

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ABSTRACT

Problems associated with calcite scaling and drastic changes in fluid composition have limited the utilization of geothermal resources at Sudureyri in Súgandafjördur, NW-Iceland. Despite a relatively high production rate recorded during the first years of operation of the Sudureyri District Heating Service, the system showed a recovery during a later decrease in production rates. The geochemical and temperature record for this geothermal system extends from 1975 until 2014. The geochemical record suggests an intrusion of a more saline component in the producing reservoir. Comparing the characteristics of the saline fluid by a simple mixing process, it was evident that it was formed by seawater-basalt interaction. The fluid composition shows enrichment in calcium and silica, and loss of magnesium and sodium, compared with seawater. As a potential alteration product, the formation of smectite has been considered.

Knowing the system's behaviour at high production rates, a simple lumped model was used to simulate production temperature and chloride concentration, in order to predict cooling and the chemical composition of the geothermal fluid, in terms of the concentrations of some of the major species in the system; this included calcium, for different production scenarios. From the fluid characteristic predictions, it is possible to identify production scenarios that might endanger system operation. From the results of the assessment, it is believed that the system can sustain production equivalent to that recorded for 2013 (8.4 kg/s) for the next ten years. However, in those ten years the fluid is expected to reach chloride concentrations on the order of 220 ppm, and calcium concentrations of 45 ppm. At this rate of production, no significant drop is expected in the fluid temperature. For the simulation, the volume of the reservoir, porosity, the hot recharge rate and the temperature of colder inflow (saline fluid) were used as variables.

1. INTRODUCTION

The main use of geothermal energy in Iceland is for space heating; in 2010, this resource covered about 89% of the space heating requirement, through numerous district heating systems (Axelsson et al., 2010). For small communities the geothermal resource has become an accessible and affordable energy alternative to meet the heating demand, which however requires effective and reliable management to ensure energy security.

Hitaveita Sudureyrar (Sudureyri District Heating Service) utilizes the geothermal resource at Sudureyri (Laugar), located in the northwest part of Iceland, by using two production wells. One of them is well LA-2, drilled to 684 m depth in 1975, and the other is well LA-5, drilled to 1141 m depth in 1984-1985. The long term management and monitoring of Sudureyri's geothermal resource provides elements for the characterization of reservoir properties, and application of models in order to predict system responses at different rates and periods of exploitation. Relatively high rates of production during the early years of utilization of the resource showed evidence of over-exploitation, suggesting the influence of seawater intrusion, which is not unexpected as the geothermal system is partly under the ocean-fjord, Súgandafjördur.

The purpose of the project described in this report is to predict changes in the composition of the geothermal fluid to define operating limits for different utilization scenarios, based on the particular utilization experience for the field. For this purpose, the changes in the characteristics of the fluid over time were evaluated, identifying both background and natural state conditions, as well as abnormal conditions caused by the utilization. The interaction of the seawater system with reservoir fluid was first addressed through a simple mixing model and, consequently, the role of fluid-rock interaction was evaluated. Finally, a simple lumped model was used to simulate changes in production temperature and chloride concentrations and, thus, identify principal properties of the reservoir. The model was, consequently, used to calculate predictions for different future utilization scenarios. Results and conclusions are presented at the end.

2. GEOLOGICAL BACKGROUND

The Sudureyri geothermal system in Súgandafjördur is located in the West Fjords, NW-Iceland, which is the largest peninsula in Iceland. The geology of the West Fjords is mainly characterized by basic and intermediate extrusive rocks with intercalated sediments, older than 3.1 m.y. (Figure 1). Geological studies indicate that the bedrock is composed of basalts.

The lava pile is cut by dykes and faults with a dominant NW-SE orientation, parallel to the strike direction. Benjamínsson (1981) showed that hydrothermal manifestations are widespread in the area and that the location of the hot springs is controlled by dykes and faults. The surface hydrothermal activity in this part of Iceland is classified as low-temperature activity, from just above ambient temperature up to 100°C. Flow rates are also variable but natural flows extend up to ~5 L/s.

The regional thermal gradient varies from 50°C km^{-1} in the west to about 70°C km^{-1} in the east. There is, however, a temperature anomaly with gradients over 100°C km^{-1} to the south of the peninsula (Pálmason and Saemundsson, 1979).

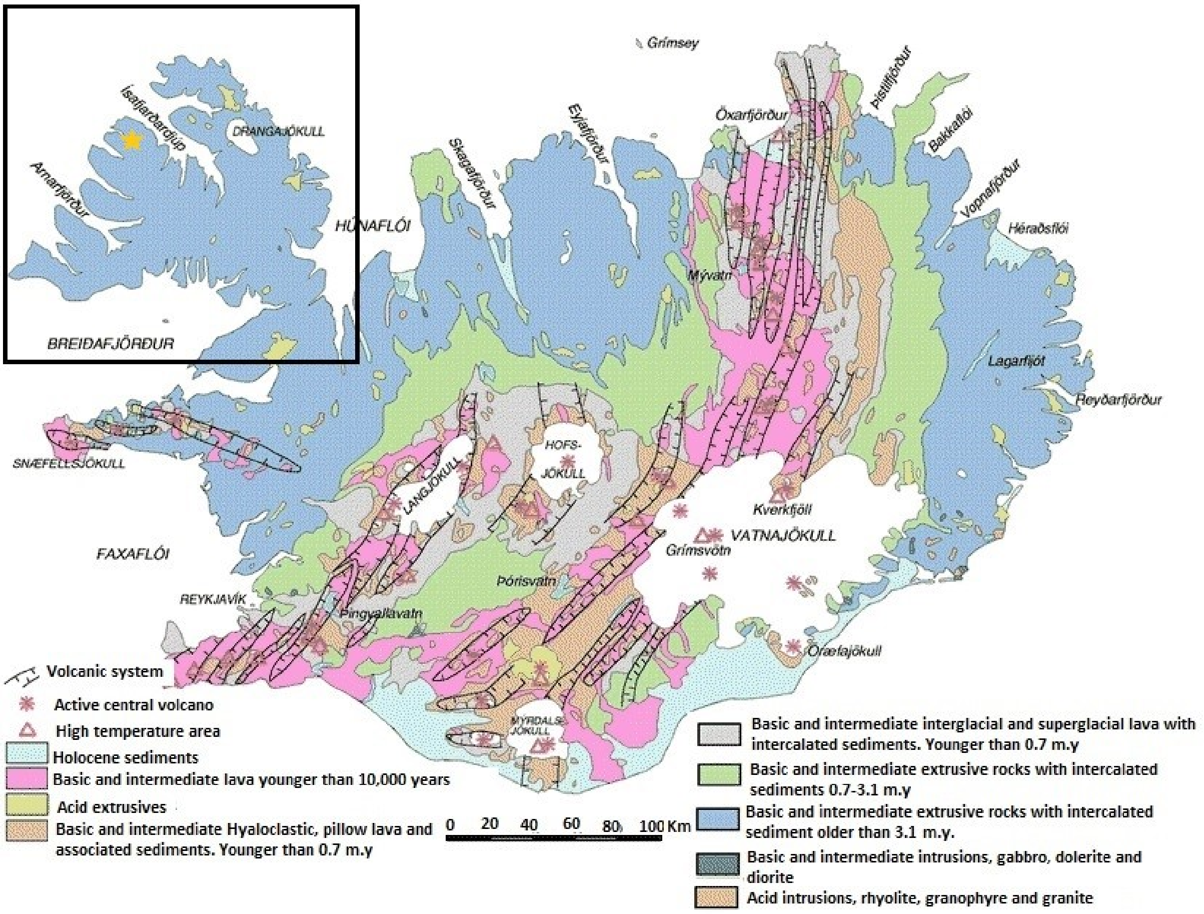

FIGURE 1: Geological map of Iceland (Jóhannesson and Saemundsson, 1999); the box marks the location of the West Fjords, the yellow star marks the location of Sudureyri

3. GEOTHERMAL EXPLORATION AND DEVELOPMENT IN SÚGANDAFJÖRDUR

The utilization of the geothermal resource at Sudureyri started by supplying hot water to a bathing pool located in the region. Studies that preceded the drilling of deep wells, including geochemical exploration and geophysical studies, aimed at increasing the flow of hot water to the pool. The temperature, calculated using a silica geothermometer for samples collected in 1960, indicated a reservoir temperature of 85°C and the chloride concentration was measured at 56 ppm. Samples collected in 1974 indicated a reservoir temperature of 69°C. In 1974, three elongated magnetic anomalies were identified, which were interpreted as dykes (Stefánsson et al., 1975).

Five wells have been drilled in the geothermal area of Sudureyri in Súgandafjördur. After successfully drilling well LA-02, Hitaveita Sudureyrar (Sudureyri District Heating Service) was founded in 1977 and put into service the following year. In the early days of the district heating system in Sudureyri, the composition of the fluid changed drastically; the chloride concentrations and calcium deposition increased, destroying the downhole pump of well LA-02 in 1978, and repeated cleaning operations were required in the well.

The successful drilling of well LA-05 in 1985 allowed for the temporary replacement of well LA-02 for the supply of hot water, from 1986 to 1998. Until 1998, the wells never operated simultaneously

(Ólafsson, 1999). Before drilling well LA-05, wells LA-03 and LA-04 were drilled in the geothermal area but neither has been used as a production well.

Basic information on the wells is presented in Table 1, and their location is shown in Figure 2. Currently, the system has two production wells: LA-02 and LA-05.

TABLE 1: Drilling operations in the Sudureyri field (Ólafsson, 1999)

Well	Year	Depth (m)	Latitude	Longitude	Description
LA-01	1967	15.5	66.111300	-23.459482	Temperature gradient
LA-02	1975	549	66.111300	-23.459482	Production well
LA-02	1976	684			Dredging production well
LA-02	1980	684			Cleaning production well
LA-02	1984	684			Cleaning production well
LA-02	1987	684			Cleaning production well
LA-03	1981	521	66.112850	-23.465134	Borehole
LA-04	1982	405	66.110384	-23.458017	Borehole
LA-05	1984-1985	1141	66.110267	-23.457883	Production well

Figure 2 shows the major faults and dikes which have been observed. It was considered likely that the main up-flow channel is connected close to well LA-02 on the east side (Gudmundsson and Flóvenz, 1981).

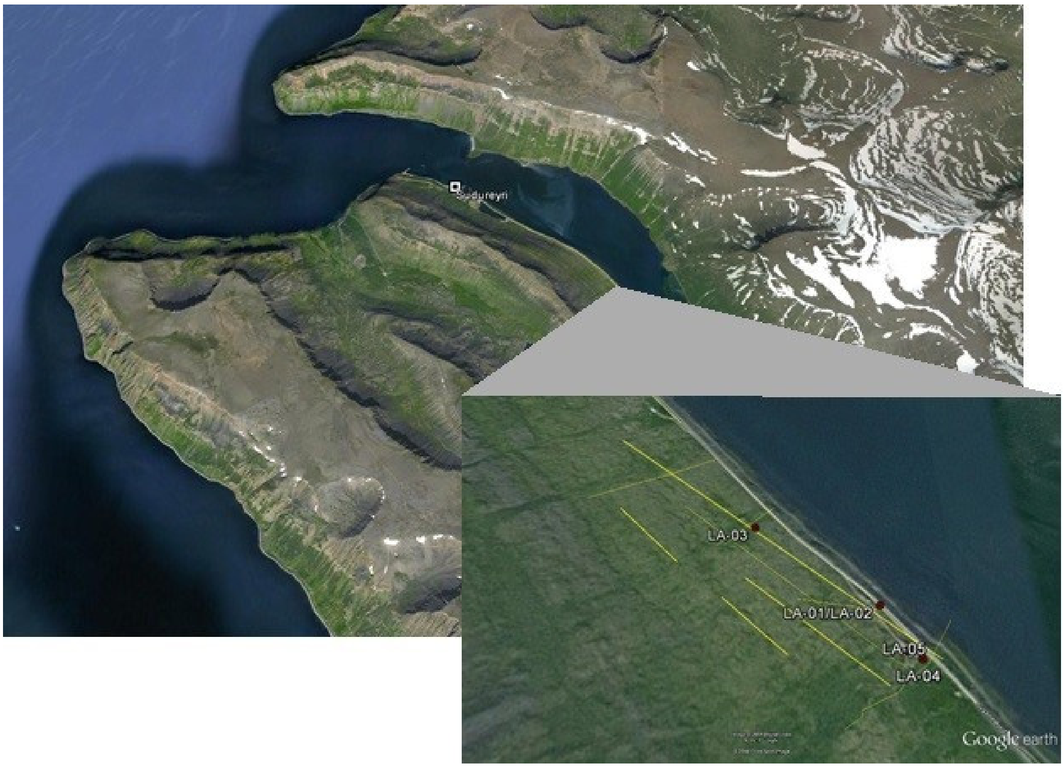

FIGURE 2: Well location and major faults and dikes in the Sudureyri fields (modified from Bai Liping, 1991)

The production data used are available in the database of Iceland GeoSurvey (ISOR). At the same time, production records indicated in geochemical monitoring reports were considered, detailed below.

The maximum production of the field was reached during the first years of operation (Flóvenz et al., 1982). From 1990 to 1991, there was an overall reduction in field production, associated with the start-up of a boiler (Sverrisdóttir and Kristmannsdóttir, 1994); however, since 1998, with the reconnection of well LA-02, the production has been slowly increasing. The total production from the field and from well LA-02 are illustrated in Figure 3.

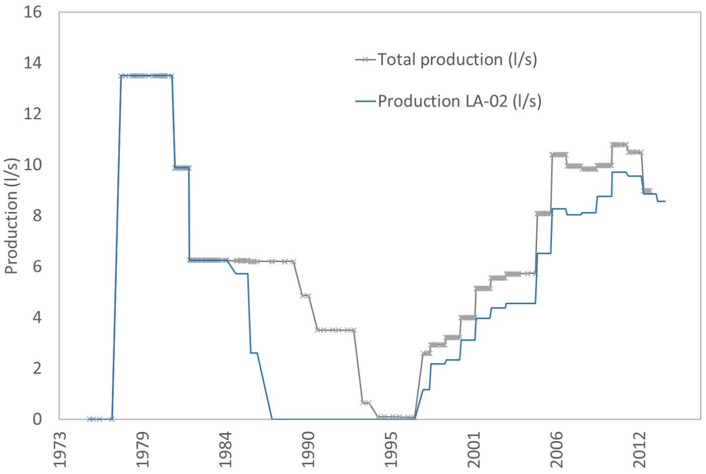

FIGURE 3: Production history

4. CHEMICAL CHARACTERISTICS OF THERMAL FLUIDS

The geochemical dataset for the Sudureyri geothermal system consists of 390 samples collected in the period from 1975 to 2014 from the field's production wells; of these, 272 were collected from well LA-02 and the remaining 118 from well LA-05. The samples were collected by personnel from Hitaveita Sudureyrar or by Iceland GeoSurvey (ÍSOR). Since 1995, the geochemical record included 6-12 samples per year for each well that is in production. Most of these samples are partial samples, for the determination of conductivity, chloride and sulphate only; this prohibits the rigorous fluid characterization of all the samples. However, for well LA-02, a number of complete samples exist, one sample per year in 1975, 1979, 1980, 1982, 1998, 2001, 2003, 2005 and 2011, and two samples per year for 1976 and 1998. The complete samples include measurements of pH, temperature, major cations (Na, K, Ca and Mg), boron, silica, chlorides, total carbonate carbon, sulphates, and other complementary parameters. For well LA-05, the complete samples are limited to those collected in 1987, 1992, 1994, 1998 and 2011. The composition of complete samples is given in Table 2.

TABLE 2: Measured chemical composition of the fluid from wells LA-02 and LA-05

Date	**Well LA**	**Sample number**	**Sample temp.**[a] **(°C)**	**Liquid phase (mg/kg)**																	
				pH[b]	**pH/T (°C)**	**SiO_2**	**B**	**Na**	**K**	**Mg**	**Ca**	**Al**	**Fe**	**F**	**Cl**	**SO_4**	**CO_2**[c]	**H_2S**	**Cond (µS/cm)**	**Cond/T (°C)**	**TDS**
17/02/2011	02	20110041	63	9.46	22.2	57.5	0.13	109.0	1.04	0.14	20.50	0.04	0.01	0.28	120	78.8	7.9		709	25.0	414.0
03/06/2005	02	20050152	64	9.63	23.2	57.1	0.08	100.0	1.09	0.04	14.10	0.04	0.02	0.30	98	78.9	9.9		584.	25.0	367.0
21/07/2003	02	20030557	64	9.57	23.8	57.0	0.09	93.2	0.79	0.02	10.30	0.04	0.04	0.31	84	77.0	9.3	0.013			252.0
12/07/2001	02	20010206	64	9.71	19.8	57.1	0.09	94.1	1.25	0.00	9.97	0.04	0.01	0.31	78	74.3	10.1	0.040	519	25.0	340.0
31/03/1998	02	19980248	64	9.74	23.4	60.9	0.06	90.6	0.88	0.01	8.70	0.05	0.01	0.41	57	78.1	9.1		496	25.0	390.0
01/05/1982	02	19820058	63	9.43	21.0	51.9		145.3	1.71	1.72	60.46			0.29	260	95.3	9.2		1075	21.7	659.9
13/11/1980	02	19800161	62	9.50	20.0	54.0		137.7	1.75	0.04	44.10			0.33	209	91.5	9.2		901	22.5	553.1
06/11/1979	02	19790134	63	9.59	20.0	56.0		126.4	2.00	0.37	33.90			0.30	169	84.7	7.0		599	14.0	484.0
14/12/1978	02	19780089	64	9.30	20.0	58.0		105.6	1.10	0.15	21.40			0.28	128	76.5	3.1		599	22.0	423.0
03/05/1978	02	19780018	60	9.66	18.0	55.0		121.0	1.20	0.26	27.80			0.39	168	75.4	5.7		671		488.0
03/08/1976	02	19760111	64	9.80	17.0	59.0		87.6	0.99	0.02	6.10			0.30	63	71.2	9.5	0.090	420		295.8
28/02/1976	02	19760024	63	9.63	19.0	60.0		83.3	1.20	0.04	6.70			0.36	72	68.6	8.3		444		327.0
03/12/1975	02	19750186	62	8.81	21.0	53.0		117.7	1.90	0.32	11.60			0.33	131	72.1	7.0		599		413.0
17/02/2011	05	20110038	53	8.88	21.2	45.0	0.15	170.0	1.41	3.06	67.70	0.01	0.00	0.21	309	86.4	9.5		1287	25.0	724.0
01/04/1998	05	19980250	57	9.56	23.6	53.6	0.04	89.7	0.77	0.07	9.22	0.02	0.01	0.36	70	71.1	14.4		500		301.0
11/07/1994	05	19940147	58	9.45	22.4	53.0	0.12	97.7	0.86	0.28	13.20			0.29	109	77.3	9.2				362.0
11/03/1992	05	19920050		9.51	19.0	53.0	0.10	126.0	1.16	1.56	28.10		0.01	0.30	169	85.0	11.0		763	25.0	398.8
28/07/1987	05	19870085	58	9.13	23.0	50.1		190.1	1.92	6.32	80.57		0.03	0.32	340	106.1	11.0		1346	23.1	807.0

a: Measured temperature; b: pH at measured temperature reported in the column to the right;
c: Total carbonate carbon as CO_2; d: Conductivity at measured temperature reported in the column to the right

The geochemical record for well LA-02 covers the following periods: 1975 and 1976, prior to the operation of Hitaveita Sudureyrar; 1978 to 1986, which marks the beginning of production from the well; and from 1998 to 2014. As mentioned above, in the period between 1987 and 1997, the production from the field was confined to well LA-05, so no geochemical records are available for well LA-02 for this period.

Well LA-05 has a continuous geochemical record from 1986 to 1989, and from 2005 to 2012. For the period between 1990 and 2005, only isolated records are available.

In addition to the monitoring record, geochemical monitoring reports published by ÍSOR exist for the periods 2012-2013 (Ólafsson, 2014), 2010-2011, (Óskarsson, 2012), 2007-2010 (Ólafsson, 2010), 2006 (Ólafsson, 2006), 2002-2003 (Ólafsson, 2003), 2000-2001 (Hardardóttir, 2002), 1999-2000 (Hauksdóttir and Ólafsson, 2000), 1998 (Ólafsson, 1999), 1997 (Ólafsson, 1998), 1995-1996 (Ólafsson, 1997) and 1994 (Sverrisdóttir and Kristmannsdóttir, 1994).

4.1 Evolution of the geochemical characteristics of the field

The high production rates recorded during the first years of operation of well LA-02, estimated to be between 13 and 14 L/s, involved a significant increase in the concentration of chloride. Inspection of Figures 4a and 4c shows that the salinity increased steadily with each year that the well was producing in the period between 1977 and 1986.

Initial Cl concentration in well LA-02 in 1976 was around 63 ppm, but in 1978 the Cl concentration had increased to 127 ppm, and in 1986 the concentration reached 290 ppm. The well's period of inactivity allowed the chloride concentration to recover to the initial value, and the production temperature of the well increased. Upon commissioning of well LA-05 as the main producer in the field (1986-1998), the chloride concentration for that well was higher than those recorded in well LA-02 (Figure 4c). The high chloride concentration initially observed decreased following the reduction of production from the field.

Geochemical monitoring reports for the field, published by Orkustofnun and later ÍSOR, attributed the high concentrations of chlorides in well LA-05, relative to the concentrations in well LA-02, to a drain in well LA-04 toward the ocean (Ólafsson, 1999), or an inflow of ocean-water into a shallow feed-zone in the latter well that consequently flowed down the well and exited through a deeper feed-zone and finally passed to well LA-02.

There are significant differences in the geothermal fluid from wells LA-02 and LA-05, including the concentration of chloride, total dissolved solids and temperature. The average temperature in well LA-02 is 65.1°C, while the average temperature in well LA-05 is 7°C lower (57.9°C). Additionally, the fluid in well LA-05 is more saline, with an average TDS (total dissolved solids) of 850 ppm. The average TDS in well LA-02 is 650 ppm. According to Arnórsson (1975), the increased chloride content in some low-temperature areas near the coast is, with little doubt, due to the percolation of sea water into the rock mixing with water of meteoric origin; nevertheless, the magnitude of the marine component in the thermal water will depend on porosity and flow rates of each geothermal system.

The variations in the chloride content were accompanied by changes in the concentrations of other major components, including calcium and sodium. Using the 1976 sample from well LA-02 as a baseline value, with a calcium concentration of 6.1 ppm, the Ca concentration increased to ten times the initial value (60.5 ppm) by 1982. Again, when well LA-05 went into operation, the Ca concentrations were even higher than those recorded in well LA-02, up to 106.2 ppm.

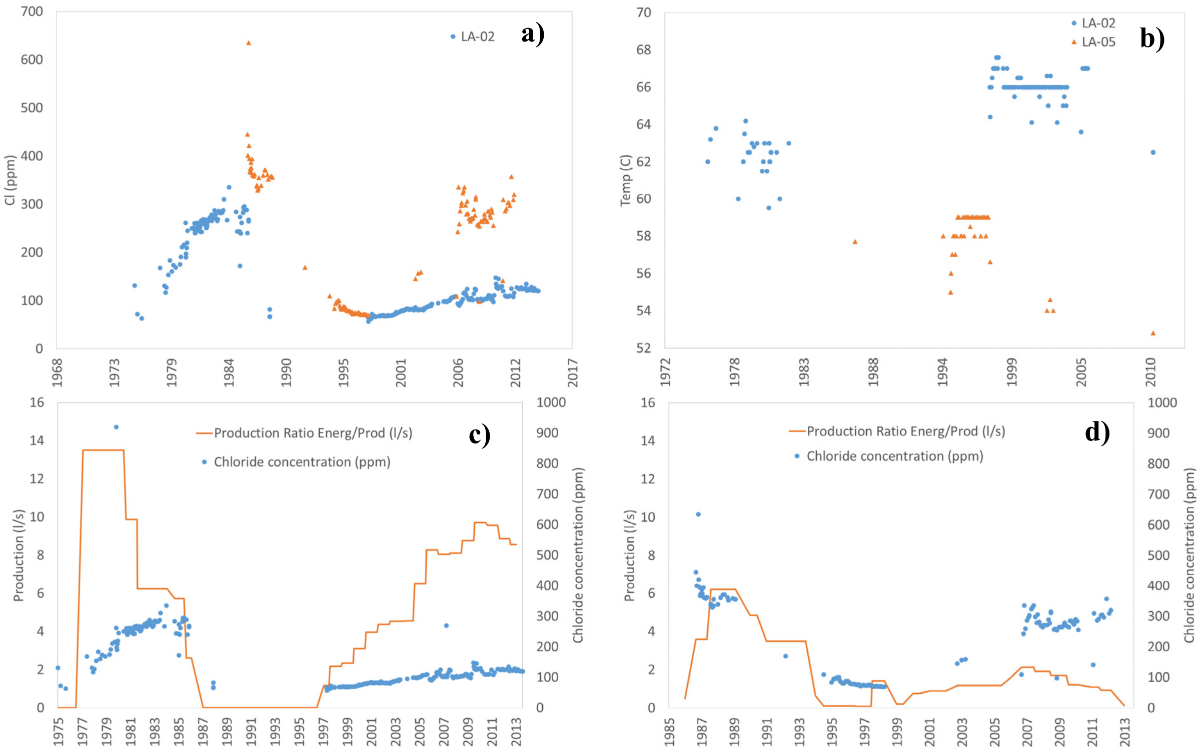

FIGURE 4: Development of: a) Chloride concentration in wells LA-02 and LA-05; b) Calcium concentration in wells LA-02 and LA-05; c) Chloride in well LA-02 along with production values; d) Chloride in well LA-05 along with production values

The fluid shows systematic changes in chemical composition with time. Therefore, it is difficult to establish a mechanism to describe the different populations. With the purpose of illustrating the behaviour of fluid composition, Table 3 gives the concentrations of the main components at different moments in the development of the field, and at different production rates. Also, in Figure 4, the historical behaviour of chloride and temperature is shown.

TABLE 3: Chemical composition of geothermal waters from wells LA-02 and LA-05 in Sudureyri

	Well LA-02	**Well LA-02**	**Well LA-05**	**Well LA-05**
Production (L/s)	0	9.9	6.2	1.4
Date	03/08/1976	01/05/1982	27/07/1987	01/04/1998
Temperature (°C)	63.8	63.0	57.7	56.6
pH/°C	9.80 / 17	9.43 / 21	9.13 / 23	9.56 / 24
CO_2 (t) (ppm)	9.5	9.2	11.0	14.4
SiO_2 (ppm)	59.0	51.9	50.1	53.6
Na (ppm)	87.6	145.3	190.1	89.7
K (ppm)	0.99	1.71	1.92	0.77
Mg (ppm)	0.02	1.72	6.32	0.067
Ca (ppm)	6.10	60.46	80.57	9.22
F (ppm)	0.30	0.28	0.32	0.36
Cl (ppm)	63.4	260.0	339.5	69.7
SO_4 (ppm)	71.2	95.3	106.1	71.1
TDS (ppm)	295.8	659.9	807.0	301

A continuous, but not significant, decline has been identified in the pH value for the period between 1976 and 1982, with coefficients of variation for the evaluation period being 2.7% for well LA-02, and

2.8% for well LA-05. The average pH values recorded were 9.53 and 9.29 for wells LA-02 and LA-05, respectively.

In temperature, the most significant changes are an increase of 3.7°C in the average temperature recorded for the period 1998-2013 (66.0°C), relative to the average temperature between 1975 and 986 (62.3°C), for well LA-02. The increase in temperature was noted after a period of less production from the well.

4.2 Classification of geothermal waters

A classification of the waters was carried out on the basis of the relative content of the three major anions Cl-SO_4-HCO_3 and a diagram based on the relative Na+K, Ca and Mg concentrations. Figure 5 depicts ternary diagrams showing these cation and anion concentration ratios for the Sudureyri geothermal waters. Additionally, Figure 5b illustrates the composition of different types of thermal waters: mature waters, steam-heated waters, volcanic waters and peripheral waters.

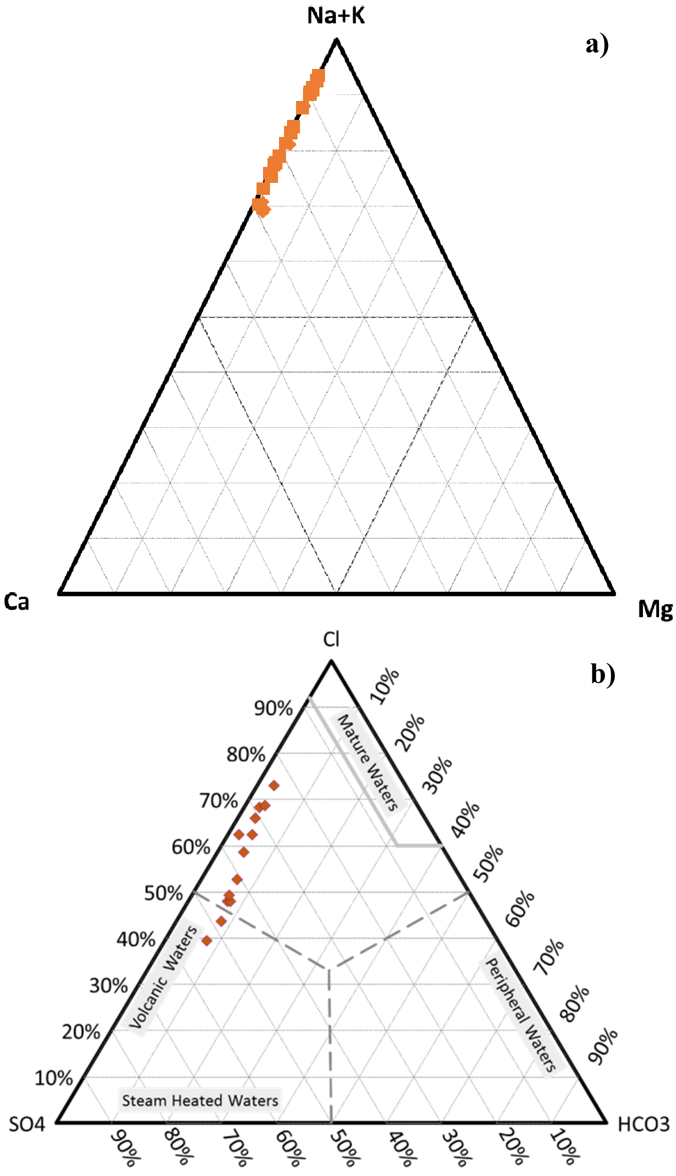

FIGURE 5: Classification for complete samples from wells LA-02 and LA-05: a) (Na+K)-Ca-Mg ternary plot; b) Cl-SO_4-HCO_3 ternary plot (Giggenbach, 1991)

Chloride-rich waters are generally found near the up-flow zones of geothermal systems. High SO_4 steam-heated waters are often encountered over the more elevated parts of a field. This diagram can also be used to assess possible mixing of groundwater and geothermal fluid, as the degree of separation from the Cl corner towards the HCO_3 corner is the result of interaction of the CO_2 charged fluids at lower temperatures (Arnórsson, 2000).

Figure 5a shows that sodium and potassium are the dominant cations in the system, but mixing with a more calcium-rich component is evident. Figure 5b shows that chloride is the predominant anion in most samples, but there are a few samples where sulphate is the predominant anion and, again, the pattern indicates mixing with a more SO_4-rich component.

This behaviour in the distribution of the anions is commonly associated with volcanic systems, however, in the Sudureyri geothermal waters, it is more likely due to the contribution and mixing of seawater into the system, given the abundance of these ions in the waters. The mixing trend seen for the cations supports this interpretation.

Giggenbach's Na-K-Mg triangular diagram allows a clear distinction to be made between waters suitable for the application of ionic solute geothermometers and, at the same time, allows deeper equilibration temperatures and the effects of a variety of processes such as re-equilibration and mixing of waters of different origins (Giggenbach, 1988). The temperature dependant equations adopted for the construction of the ternary diagram are (Giggenbach, 1988):

$$\log\left(\frac{c_{K^+}^2}{c_{Na^+}}\right) = 1.75 - (1390/T) \tag{1}$$

$$\log\left(\frac{c_{K^+}^2}{c_{Mg^{2+}}}\right) = 14.0 - (4410/T) \tag{2}$$

where T is the absolute temperature in K.

The intersection of the isotherms corresponding to the K-Na and K-Mg subsystems corresponds to the composition of water in equilibrium with the two mineral systems and is labelled as "full equilibrium curve" (Figure 6).

Most of the samples show that the water composition shifts to lower temperatures and falls below the full equilibrium line (partial equilibration zone), reflecting the addition of magnesium in different amounts. These waters have probably been mixed with colder water. This behaviour is consistent with the potential intrusion of seawater into the system. A few samples are located in the "immature waters" area and are, therefore, considered unsuitable for the evaluation of K/Na-feldspar equilibrium temperatures. It should, however, be noted that the ternary diagram reflects temperatures between 60 and 100°C, consistent with the measured temperatures for the wells.

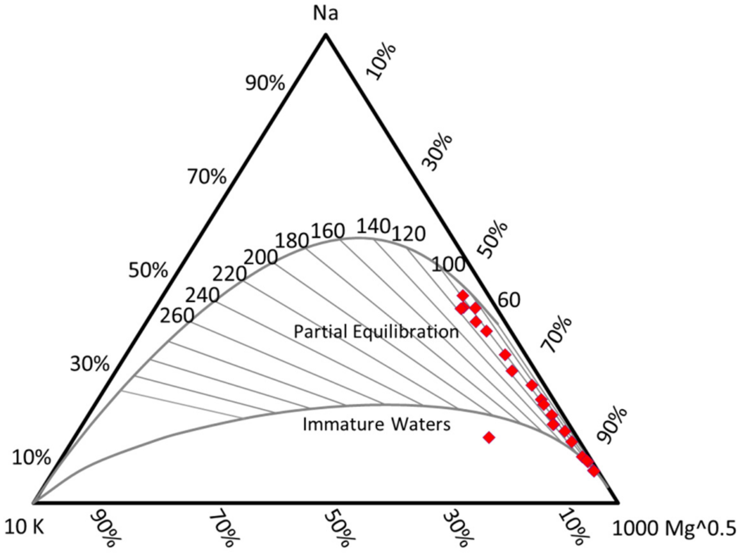

FIGURE 6: Na-K-Mg equilibrium diagram (Giggenbach, 1988) with data from the Sudureyri geothermal system (red diamonds)

4.3 Seawater-basalt interaction and the mixing process

When sea water and groundwater mix, the concentration of components such as sodium, potassium, calcium, chloride, magnesium and sulphate in the water increases, relative to the groundwater concentration, but concentrations of other components such as silica and fluoride could decrease.

Chloride is considered to be a conservative species in the system, i.e. it does not take part in the formation of secondary minerals and, therefore, can be used for characterizing potential mixing processes in the reservoir. If the variation in the concentration of chloride is due to the mixing of cold and hot water in the upflow, a linear correlation between the chloride concentration and the concentration of other components is expected, also dominated by the mixing process.

The relationship between the concentrations of chloride on one hand, and individual components on the other, was studied, using the available samples from both wells, in order to identify relative changes. Pearson´s correlation coefficient was used as a measure of the strength of the correlation between the concentrations. The results are given in Table 4.

TABLE 4: Pearson´s correlation coefficient indicating the relationship between the concentrations of different species with respect to chloride concentration, for the period between 1978 and 2014 in wells LA-02 and LA-05

	CO_2	**SiO_2**	**Na**	**K**	**Mg**	**Ca**	**F**	**Br**	**SO4**
R	0.0681	-0.7759	0.9889	0.7252	0.8321	0.9884	-0.6018	0.9976	0.8825

A linear relationship between two components in mixing geothermal waters, where one component is certainly conservative, suggests the other component is also conservative. Bromide shows this behaviour, in accordance with it being considered conservative, in advance. Nevertheless, sodium and calcium also show a strong correlation with the chloride concentration in the system. For low-temperature systems, which involve fluid-rock interaction, some of the major components (Ca, Mg, Na, K, HCO_3, SO_4, SiO_2) are expected to be reactive. The reactive nature of all of these components is due to their tendency to precipitate from solution, forming secondary minerals (Arnórsson, 2000).

It should be noted that silica and fluoride show negative coefficients. This indicates that if the concentration of chloride in the system increases, then the concentration of these components will decrease. On other hand, total carbonate and fluoride have low correlation coefficients, to some extent the behaviour of the reactive components.

The high correlation shown by sodium and calcium concentrations, with that of chloride, allows the development of empirical equations for the mixing (Table 5). Regarding the content of sulphate, Figure 7 shows that wells LA-02 and LA-05 exhibit behaviour slightly offset relative to each other, so that empirical equations for the system, and both wells, are proposed.

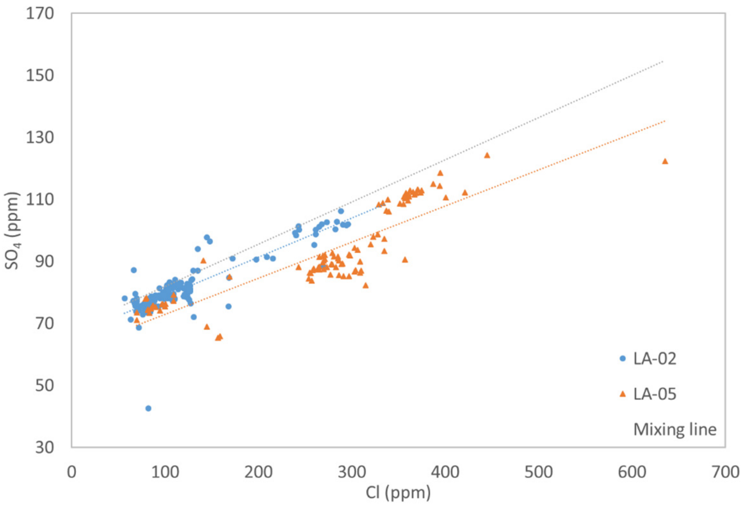

FIGURE 7: Relationship between sulphate and chloride concentrations in wells LA-02 and LA-05, along with the proposed mixing line for geothermal water and seawater

TABLE 5: Empirical relationship between concentrations of different constituents, with respect to chloride

Equations	**R^2**	**Equat. no.**
$[Na] = 0.3536 * [Cl] + 64.474$	0.9779	(3)
$[Ca] = 0.2639 * [Cl] - 11.262$	0.9769	(4)
$[SO_4] = 0.0994 * [Cl] + 68.018$	0.7788	(5)
$[SO_4] = 0.1263 * [Cl] + 66.074$	0.7558^a	(6)
$[SO_4] = 0.1166 * [Cl] + 61.184$	0.7624^b	(7)

a) Well LA-02; b) Well LA-05

A mixing process was simulated in terms of concentrations in the dilute geothermal fluid at baseline (undisturbed state), and seawater composition. As a reference value, the values for the geothermal fluid concentration measured in 1998 for well LA-02 (after a period of less use for 12 years) were considered, which defines the minimum chloride content for the period. The seawater concentration published by Arnórsson (1978) was assumed.

TABLE 6: Expected geothermal and seawater composition in Sudureyri

	Geothermal water	**Seawater**
Na	90.61	10556
K	0.88	380
Mg	0.011	1272
Ca	8.7	400
SiO_2	60.9	3
SO_4	76.07	2649
F	0.41	1.3
CO_2	9.06	114
Cl	56.68	18980

The equation for the mixing line is given by the following expression:

$$[C_i] = \frac{[C_{seawater}] - [C_{geothermalw}]}{[Cl_{seawater}] - [Cl_{geothermalw}]}([Cl_i] - [Cl_{geothermalw}]) + [C_{geothermalw}] \qquad (8)$$

where C_i represents the concentration of the species of interest, under the assumption of a perfect mixing process, and Cl_i represents the respective concentration of chloride.

The results are shown in Figure 8. Note, that the sulphate distribution trends towards the mixing line (Figure 7), whereas the sodium, potassium, magnesium and calcium concentrations show a deviation from the geothermal-seawater mixing line. The content of sulphates in fresh cold groundwater in Iceland is generally less than 5 ppm (Arnórsson, 1975). It is also estimated that the sulphate content in water, where the temperature is less than 100°C, is governed by the leaching of the rock (Arnórsson, 1975).

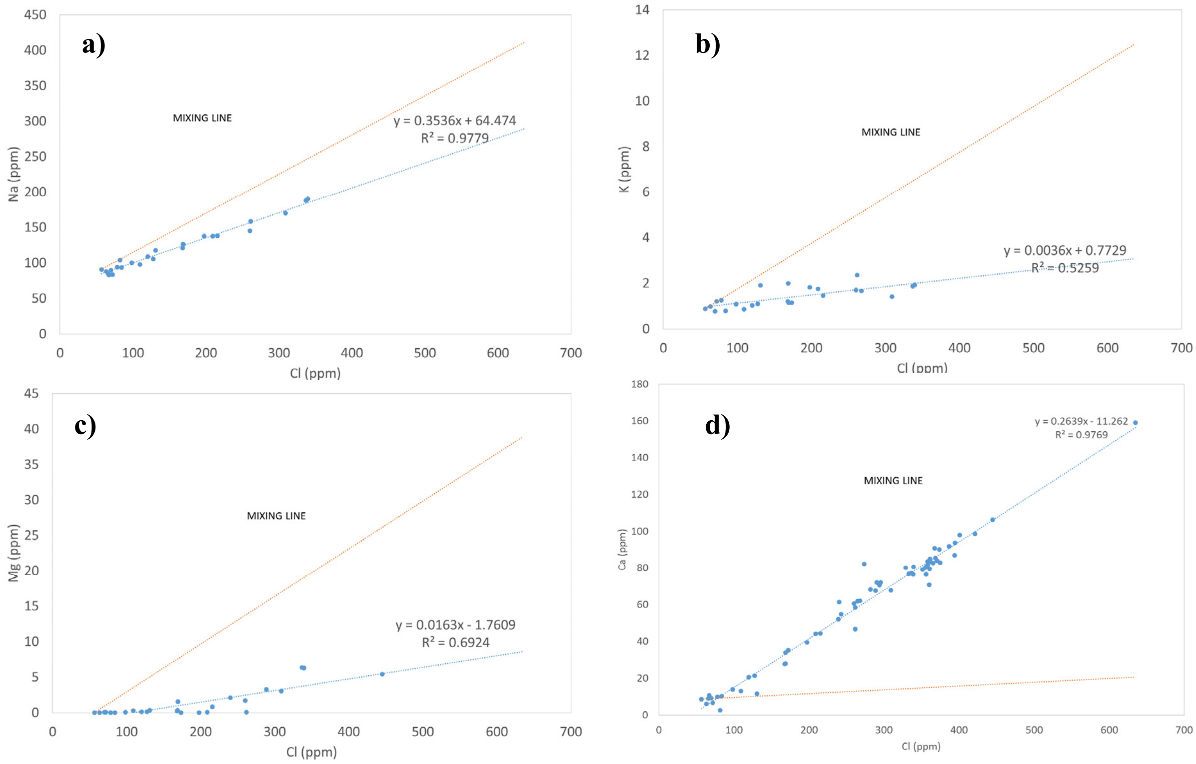

FIGURE 8: Concentrations of Na, K, Mg and Ca, as a function of Cl concentration in wells LA-02 and LA-05 (a, b, c and d, respectively), along with the proposed mixing line for geothermal water and seawater

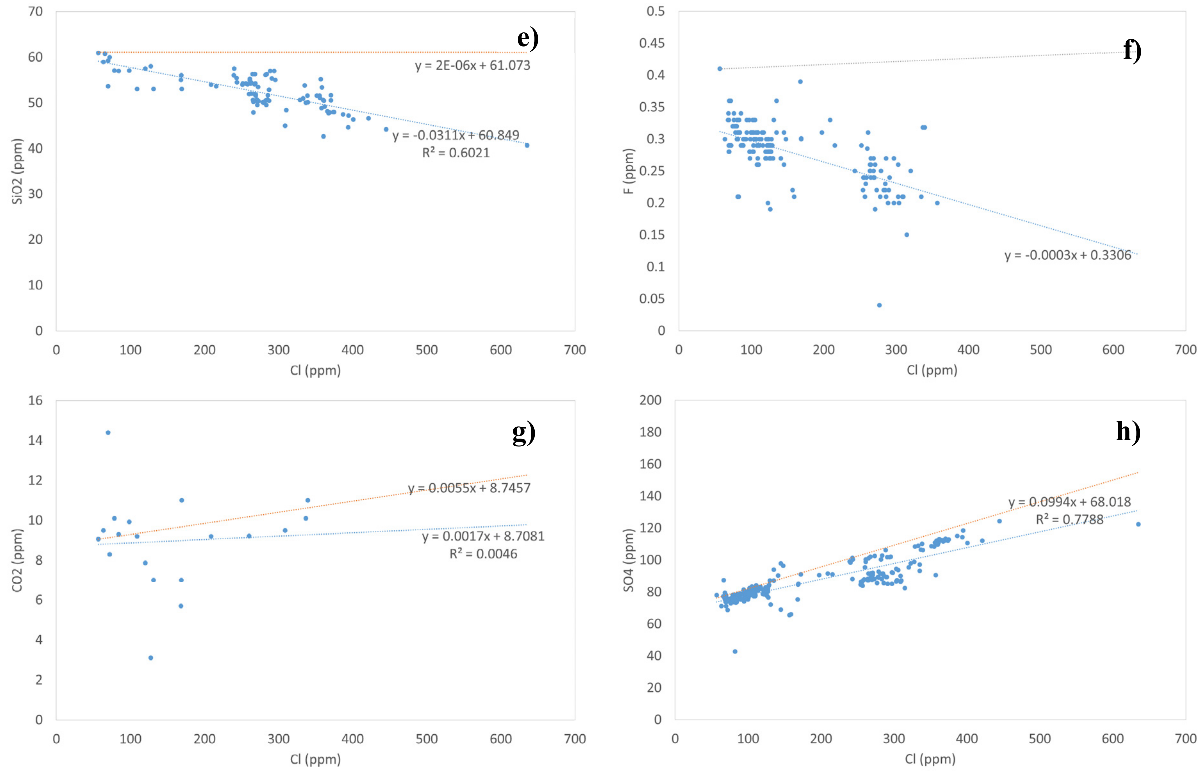

FIGURE 8 cont.: Concentrations of SiO_2, F, CO_2 and SO_4, as a function of Cl concentration in wells LA-02 and LA-05 (e, f, g and h, respectively), along with the proposed mixing line for geothermal water and seawater

The Sudureyri system has quartz temperatures between 90 and 101°C, and sulphate concentrations ranging between 10.6 and 92.7 ppm. The enrichment of sulphate is clearly associated with a mixing process.

The measured concentration of calcium is above the geothermal-seawater mixing line, possibly associated with higher values of calcium in the cold fluid fed into the system than the seawater values. Moreover, the concentrations of sodium, magnesium, potassium, fluoride and silica are lower than estimated by the mixing process. When a fluid, such as seawater, is being modified through chemical reactions with the rock, the conservative components such as chloride remain constant, so when some cations decrease in concentration, others increase.

The mixing trends shown in Figure 8 suggest that the saline component has been modified through reactions with the rock at geothermal temperatures. The saline component has gained calcium and lost magnesium, sodium, and potassium relative to seawater. The consistency of the mixing trends furthermore indicates that there is a substantial amount of saline fluid with a fairly constant chemical composition. These chemical changes suggest the probable formation of a magnesium-rich alteration phase, possibly smectite. The reaction, considering the interaction of seawater with basalt glass, could be described according to the following equation (Seyfried and Bischoff, 1979):

$$\begin{aligned} 2.0Na_5(Ca_{12}Mg_{12}Fe_{10})Al_{17}Si_{49.6}O_{160\,(s)} + 23.3H_2O + 10H^+{}_{(ac)} + 13.96Mg^{2-}_{(ac)} \rightarrow \\ 28.33Na_{0.15}Ca_{0.28}(Mg_{1.34}Fe_{0.71}Al_{0.65})(Al_{0.55}Si_{3.45})O_{10}(OH)_{2\,(s)} + 5.76Na^+_{(ac)} \\ + 16.07Ca^{2+}_{(ac)} + 1.66SiO_{2(ac)} \end{aligned} \tag{9}$$

To further explore the effects of smectite formation, the difference between the concentrations of magnesium, resulting from direct mixing of geothermal water with seawater, and the measured magnesium concentrations was assumed to correspond to the amount of magnesium consumed in the reaction process. For a direct mixing process in which chloride concentrations of 200 ppm are reached, magnesium concentrations levels should be around 9.6 ppm. Measured concentrations, corresponding to the same chloride concentrations, are on the order of 5 ppm, indicating that about 4.6 ppm of magnesium was removed from the liquid phase.

On the other hand, the measured concentration of calcium is higher than what corresponds to the mixing process between geothermal water and seawater. For a chloride concentration of 200 ppm, a calcium concentration of 12 ppm would be expected. The product of the smectite reaction with calcium is estimated to add 8 ppm (considering Mg as the limiting reactant), giving a total of 20 ppm. Even though the reaction process shows considerable enrichment of calcium in the aqueous phase, the measured calcium concentrations in samples with chloride concentrations of 200 ppm are even higher, in the range of 64 ppm (Figure 9).

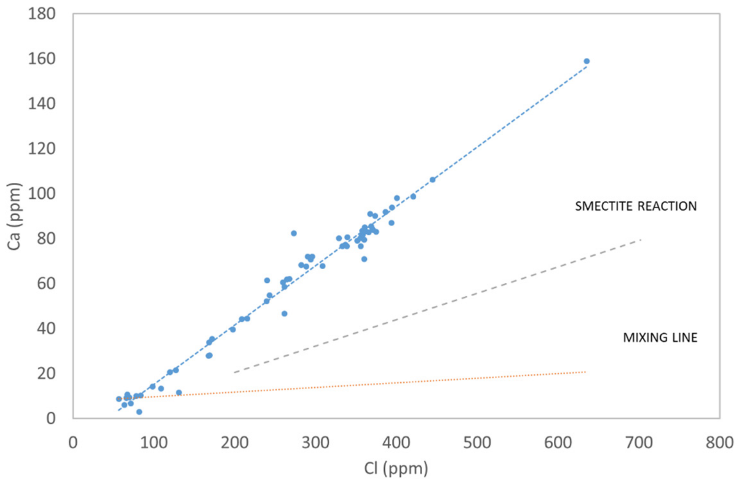

FIGURE 9: Relationship between calcium and chloride concentrations in wells LA-02 and LA-05, along with the proposed mixing line for geothermal water and seawater without (red) and with (green) the smectite formation reaction

The formation of smectite in the system explains the magnesium consumption, compared to that originally available in the fluid. At the same time, the calcium enrichment in the fluid is only partially explained. However, the stoichiometric generation of smectite, based on the magnesium available, is not sufficient to explain the measured values. This suggests the potential formation of other species rich in magnesium, ion exchange reactions, or an additional contribution associated with the dissolution of anhydrite by the inflow of cold seawater to the system.

The reaction of smectite suggests a small, but not negligible, sodium gain. Also, a gain of silica is observed. The enrichment of these components is inconsistent with the behaviour of the fluid shown in historical records. For these species, it is necessary to consider the temperature dependence of the solubility of these components, in particular with respect to chalcedony and alkali feldspars.

One of the phenomena noted, as a result of the interaction of basalt with seawater in low-temperature systems, is a drop in pH associated with the removal of magnesium, and the corresponding formation of hydrogen ions (Seyfried and Bischoff, 1979). This has also been seen here where, associated with the mixing process, there has been a slight decrease of pH values. The lowest pH measured was 8.8 and the highest was 9.8.

5. ANALYSIS OF MINERAL EQUILIBRIA

The saturation index (SI) for a given mineral dissolution reaction is defined as:

$$SI = \log(Q/K) \tag{10}$$

where Q is the quotient of ionic activities and K is the solubility product for the mineral under consideration (function of temperature).

If $SI = 0$, the system is in equilibrium, but if SI is positive, the solution is super-saturated and the mineral may precipitate.

Q is given by:

$$Q = \frac{a_C^c \cdot a_D^d}{a_A^a \cdot a_B^b} \qquad (11)$$

for the reaction:

$$aA + bB \rightarrow cC + dD \qquad (12)$$

where the reactants are the species A and B and the products the species C and D. The lower case letters designate the stoichiometric coefficients of the respective chemical species.

The relationship between concentration and activity is given by:

$$a_i = m_i \gamma_i \qquad (13)$$

where a_i is activity, m_i the molal concentration, and γ_i the activity coefficient.

The individual activity coefficients for charged aqueous species were calculated from the extended Debye-Hückel equation:

$$-log\gamma_i^* = \frac{AZ_i^2\sqrt{I}}{1 + åB\sqrt{I}} + B^*I \qquad (14)$$

where I is the ionic strength, å is the effective diameter of aqueous ions, and A, B and B^* are temperature dependent parameters.

The saturation index of calcite and other minerals was evaluated for the Sudureyri data, using the WATCH speciation program (Arnórsson and Bjarnason, 1993) for the complete water samples from Well LA-02. The results are illustrated in Figure 10.

Calculations show that the system is slightly super-saturated for low albite and microcline (stable K-feldspar at low temperatures). This coincides with indications in the literature for low temperature systems, up to 150°C (Arnórsson et, al., 1983).

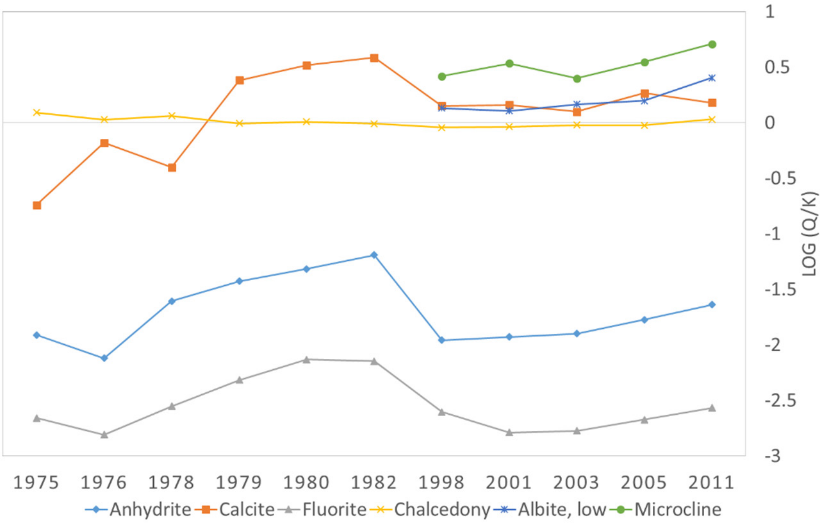

FIGURE 10: Mineral equilibrium calculated for well LA-02

Chalcedony is very close to saturation for all samples. In young basalt hosted geothermal systems at temperatures below ~180°C, it is expected that silica be controlled by the solubility of chalcedony (Fridriksson and Ármannsson, 2007). However, mixing of cold groundwater with thermal water may lead to silica super-saturation in the mixture if the original thermal water was in equilibrium with chalcedony. This is because the solubility of chalcedony increases more rapidly than the temperature (Arnórsson, 1975).

The historical record does not give any evidence of super-saturation with chalcedony, which might result from a mixing process with cold water. However, because of the limited temperature decay in the system, one should not expect drastic changes in the solubility and the mineral equilibrium after the mixing process.

5.1 Calcium saturation state

Calcite is super-saturated for the period between 1978 and 2011 (Figure 10). Experience in Iceland of utilization of low-temperature reservoirs has shown that geothermal waters are, in general, slightly super-saturated with respect to calcite but, in most cases, scaling problems are not encountered as long as the water has a saturation index (log(Q/K)) below about 0.4 (Bai Liping, 1991). The calcite saturation index exceeded this critical level for the samples collected between 1978 and 1982.

It is noteworthy that other factors have been identified that promote the deposition process, such as salinity. It is expected that if the total concentration of dissolved solids in the water is high, then precipitation will occur faster than in more diluted water (Sverrisdóttir and Kristmannsdóttir, 1994).

The solubility of calcite can be described by the following reactions:

$$CaCO_{3\,(s)} = Ca^{2+}_{(aq)} + CO^{2-}_{3\,(aq)} \tag{15}$$

$$CaCO_{3\,(s)} + H^{+} = Ca^{2+}_{(aq)} + HCO^{-}_{3\,(aq)} \tag{16}$$

The average pH value for well LA-02 was 9.53, and 9.29 for well LA-05. At these pH levels, inorganic carbon is mainly present as bicarbonate (HCO_3^-) and carbonate (CO_3^{2-}).

By observing in detail the behaviour of fluorite, calcite and anhydrite, depending on the concentrations of calcium and ionic species of carbonate, it is observed that the concentration of the bicarbonate ion describes the general trend of the saturation indices of these minerals (Figures 11 and 12). The concentration of Ca^{2+} shows an increasing trend from 1976 to 1982, however the rise in the saturation index is not of the same magnitude.

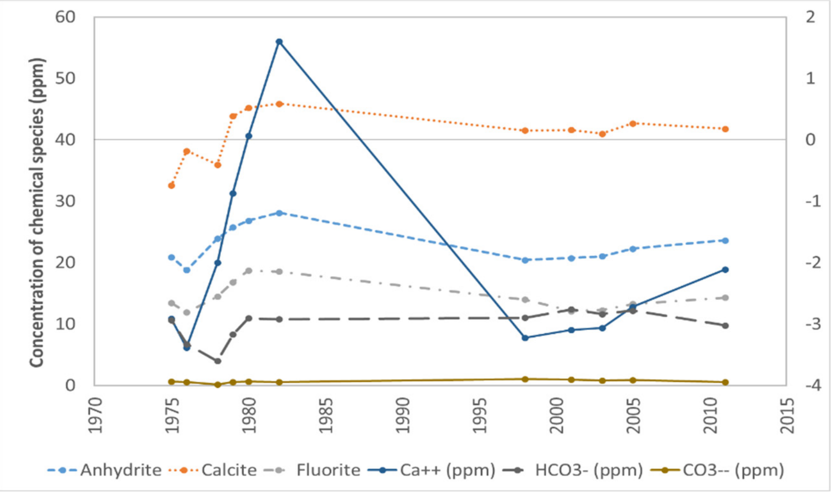

FIGURE 11: Saturation indices of anhydrite, calcite and fluorite along with concentrations of calcium and carbonate species in well LA-02

When evaluating a function of the activities of the calcium carbonate and bicarbonate species, a minimum was observed in 1982. While the concentrations and activities of the species are directly proportional (Equation 13), in this case there is an increase in the concentration of calcium and most of the other main components, thus increasing the ionic strength of the system and reducing the associated activity coefficient, as shown in Figure 13.

Calcite ($CaCO_3$) formation prevails over the formation of other calcium minerals. The reduced availability of calcium ions, limits the concentrations of other calcium minerals such as fluorite (CaF_2) and anhydrite ($CaSO_4$) and, consequently, the saturation index of these species. Fluorite (CaF_2) and anhydrite ($CaSO_4$) are under-saturated for all samples considered. Anhydrite saturation is generally linked to high-temperature systems (Arnórsson, 1975).

By modelling, the conductive cooling process (Figure 14) shows that with the decline in temperature, the solubility of anhydrite increases, while the solubility of the feldspars decreases. Note that low albite and microcline described the same trend, suggesting that the mineral balance of these species is not independent.

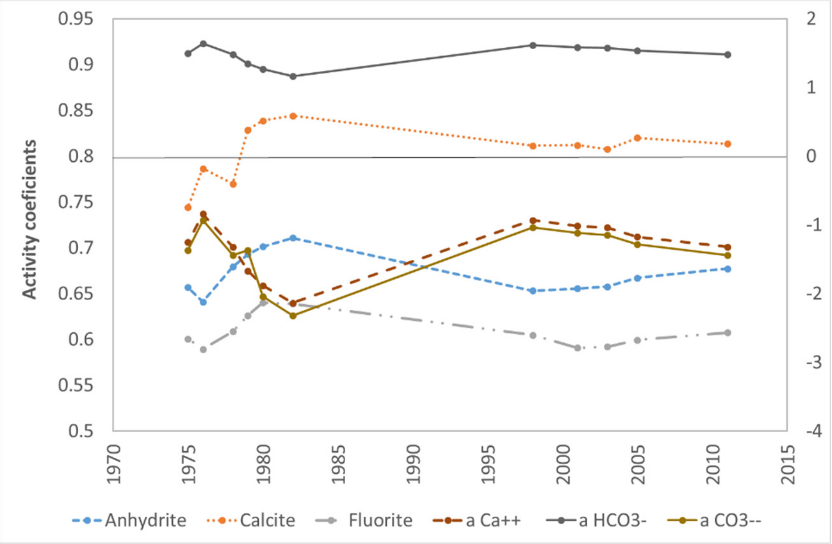

FIGURE 12: Saturation indices of anhydrite, calcite and fluorite along with activity coefficients of calcium and carbonate species in well LA-02

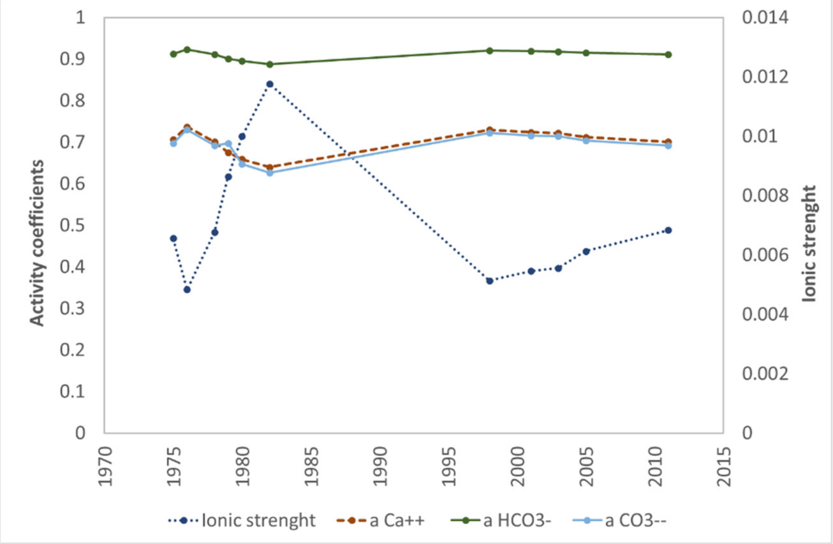

FIGURE 13: Ionic strength along with the activity coefficients of calcium and carbonate species in well LA-02

6. GEOTHERMOMETER TEMPERATURE

Geothermometers were applied in order to identify those that best described the behaviour of the Sudureyri system, and because there are systematic variations between the estimated temperatures. The quartz-, chalcedony- and Na/K-geothermometers were considered. The expressions are given below:

$$T_{Na/K}(°C) = \frac{1319}{1.666 + \log\frac{Na}{K}} - 273.15 \tag{17}$$

$$T_{chalcedony}(°C) = \frac{1112}{4.91 + \log SiO_2} - 273.15 \tag{18}$$

$$\begin{multline} T_{quartz}(°C) = -42.2 + 0.28831\, SiO_2 - 3.6686 \times 10^{-4}\, {SiO_2}^2 + 3.1665 \\ \times 10^{-7}\, {SiO_2}^3 + 77.034 \log(SiO_2) \end{multline} \tag{19}$$

The Na/K and chalcedony geothermometers were retrieved from Arnórsson et al. (1998), and the quartz geothermometer from Fournier and Potter (1982).

The average temperature recorded for well LA-02 is 65.1°C. As the geothermal water is not boiling at these conditions, the measured temperature at the wellhead is expected to correspond to the temperature of the reservoir. Analyses of spring waters by independent methods have suggested that at temperatures below 190°C, the reservoir temperature should be estimated using the chalcedony geothermometer (Henley et al., 1984).

By comparing the results with the measured temperature, it is observed that the estimated chalcedony geothermometer temperature has the smallest deviation from the temperature in the reservoir (Figure 15). This is consistent with the results of mineral balance. It can therefore be concluded that the chalcedony geothermometer is not significantly affected by the effects of mixing in the reservoir, i.e. that dissolved SiO_2 readily reaches equilibrium with chalcedony after mixing.

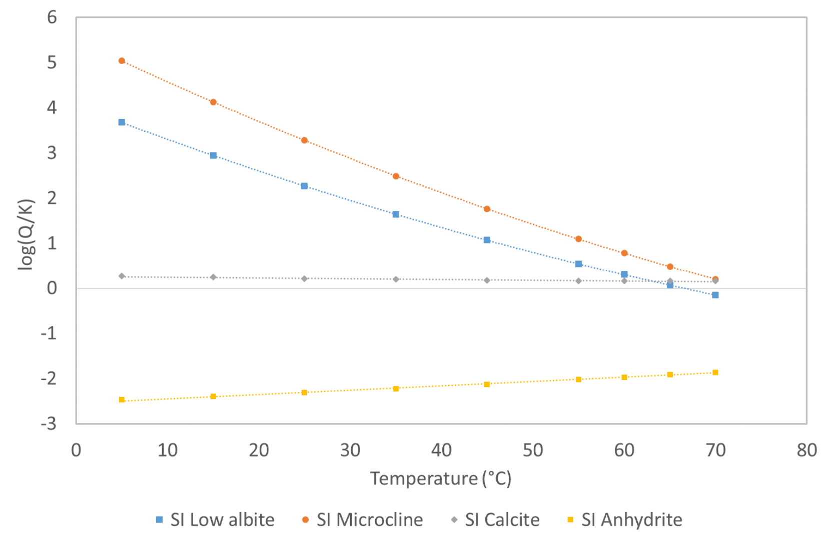

FIGURE 14: Saturation indices of low albite, microcline, calcite and anhydrite against temperature

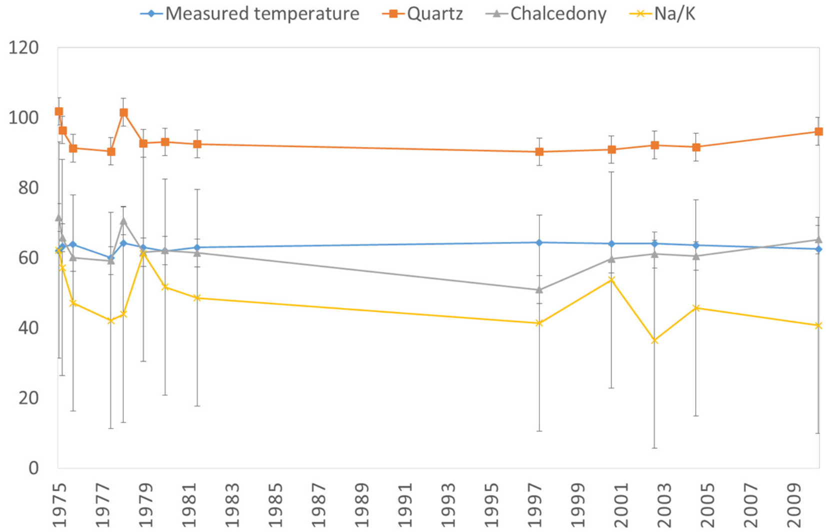

FIGURE 15: Comparison between geothermometer temperatures and observed temperature for well LA-02

Also, the minimum and maximum temperatures given by the quartz, chalcedony and Na/K geothermometers were evaluated, using the concentrations of silica, sodium and potassium corresponding to the average value and one standard deviation (μ ± σ). Figure 15 shows the quartz, chalcedony and Na/K temperatures, along with the measured temperature.

The error bars in Figure 15 show the evaluated minimum and maximum temperature calculated by the quartz, chalcedony and Na/K geothermometers, using the concentrations of silica, sodium and potassium corresponding to μ ± σ.

The Na/K geothermometer, while yielding lower temperatures than those measured, magnifies variations in fluid temperature. This is a rather unusual behaviour, but is probably due to the considerable changes in concentrations of these ions when mixing with seawater and the slow kinetics of Na-K exchange between feldspars and aqueous alkali solutions below 300°C (Marini, 2000).

7. SIMULATION OF TEMPERATURE AND CHEMICAL COMPOSITIONAL CHANGES BY A COLDER INFLOW MODEL

7.1 Description of the model

A simple lumped parameter model was used to simulate the observed changes in temperature and chloride concentration at Sudureyri, which is part of the effect of inflow of saline fluid into the geothermal system (seawater modified through reactions with the basalt), observed during production.

A graphical representation of the system, illustrated in Figure 16, shows an infinite groundwater system (sea water in this case), with water temperature *T'*, and solute concentration *C'*. The Sudureyri system constitutes a sea-water reservoir. The production part of the geothermal system has a volume *V*, variable temperature *T(t)* and solute concentration *C(t)*. The initial temperature and concentration are denoted by T_O and C_O, respectively. In addition, there is a constant inflow of *R* kg/s from the outer and deeper parts of the geothermal system, with temperature T_R and concentration C_R (Björnsson et al., 1994).

The expressions used for modelling the behaviour of the conservative species concentrations and temperatures were presented by Björnsson et al. (1994) and are listed below.

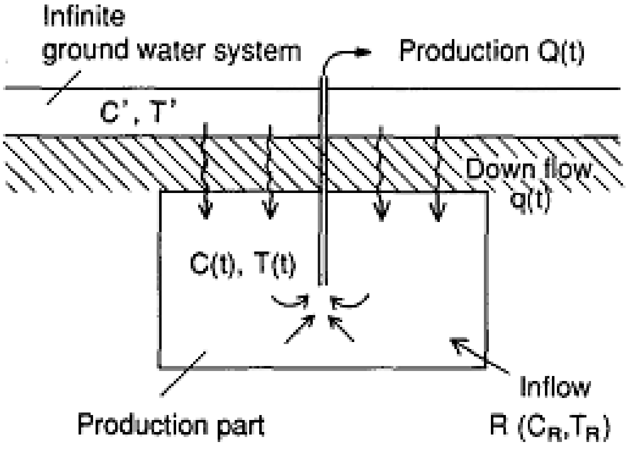

FIGURE 16: Simple model used for simulating inflow of saline fluid (Björnsson et al., 1994). A variable production of *Q* kg/s starts at time *t* = 0. The down-flow of groundwater (in this case seawater) is *q* kg/s, which is also variable. In the natural state, before *t* = 0, the production is assumed to be zero.

7.2 Chemical changes

The conservation of a chemical substance that does not react with the reservoir rock, is given by:

$$V\frac{d(\rho_w \varphi C)}{dt} + QC = qC' + RC_R \tag{20}$$

where ρ_w = Density of the geothermal fluid (water);
φ = Porosity of the rocks in the production part of the system.

Rewritten, the equation becomes:

$$\frac{dC}{dt} + \alpha(q+R)C(t) = \alpha qC' + \alpha RC_R \tag{21}$$

with

$$\alpha = \frac{1}{V\varphi\rho_w} \tag{22}$$

Considering $q = Q\text{-}R$, and solving for a constant production, we obtain:

$$C(t) = C_0 e^{-\alpha t} + \left[\frac{(Q-R)C' + RC_R}{Q}\right](1 - e^{-\alpha t}) \tag{23}$$

In the case of variable production, the time-series can be discretised in time, resulting in:

$$C_i(t) = C_{i-1} e^{-\alpha Q_i \Delta t_i} + \left[\frac{(Q_i - R)C' + RC_0}{Q_i}\right](1 - e^{-Q_i \Delta t_i}) \tag{24}$$

7.3 Energy balance and temperature

According to Wang Guiling (1991), the conservation of energy, or heat, in this lumped model can be expressed by:

$$V < \rho c > \frac{dT}{dt} = C_v(qT' - QT + RT_R) \tag{25}$$

where <*ρc*> is the volumetric heat capacity of the reservoir, and C_v is the heat capacity of water.

Approximating the value of *q* as above results in the following:

$$T(t) = T_0 e^{-\beta t} + \left[\frac{(Q-R)T' + RT_R}{Q}\right]\left(1 - e^{-\beta t}\right) \tag{26}$$

where

$$\beta = \frac{Q}{V < \rho_c >} \tag{27}$$

At the same time, <*ρc*> is given by the following expression:

$$< \rho c >= (1 - \varphi)\rho_r C_r + \varphi \rho_w C_w \tag{28}$$

Discretizing by intervals for a variable production results in:

$$T(t) = T_{i-1} e^{-\beta Q_i \Delta t_i} + \left[\frac{(Q_i - R)T' + RT_0}{Q_i}\right]\left(1 - e^{-\beta Q_i \Delta t_i}\right) \tag{29}$$

7.4 Methodology

The measured chloride concentrations were adjusted to reflect a single annual value. For the years in which multiple samples are available, the first measured value during the second half of each year is selected for this purpose.

The equations suggested by the model (Equations 20-29), were developed in an Excel spreadsheet. Model fitting was performed by varying the relevant parameters to minimize the sum of the squared deviations between measured values and simulated concentrations, for chloride and temperature simultaneously, according to the following equation:

$$\sum A(T_{sim} - T_{measured})^2 + A([Cl]_{sim} - [Cl]_{measured})^2 \tag{30}$$

The optimization method uses the GRG Nonlinear Solving method and Evolutionary algorithms, both in the Solver Package of Microsoft Excel.

The optimization variables considered were: producing reservoir volume, porosity, hot recharge of the system and temperature of the colder inflow. According to the developers (Frontline Systems, 2014), the GRG method is capable of finding a *locally optimal* solution. Therefore, there should be no other set of values, for the decision variables, close to the current values that yields a better value for the objective function. Thus, conditions for local optimality have been satisfied (to within a certain predefined tolerance). In order to evaluate different local solutions, the order of magnitude of the pivot value of reservoir volume was changed.

How the variables were constrained is listed in Table 7. The limits for the recharge rate are fixed; they were established by considering the historical field production.

TABLE 7: Constraints of the inflow model

Variable		Unit	Lower limit	Upper limit
V	Volume of production part of geothermal reservoir, or the mixing volume	m^3	1000	
R	Recharge	kg/s	2.00/0.10	100.00/6
φ	Porosity of reservoir	-	0.05	0.15

8. SALINE INFLOW SIMULATION RESULTS

8.1 Chloride concentrations, measured and simulated

Assessing the behaviour described by Equations 24 and 29, it is seen that for zero production, the functions are undefined. Also, a very low production value is simply a break-point approach.

For well LA-02, in which the period of analysis incorporates a long period of inactivity (1986-1998) and the subsequent recovery period, the model does not converge to a reliable fit (r^2=0.6019). The measured and modelled concentrations are presented in Figure 17. For this reason, the time series for well LA-02 is split into two periods, 1975-1986 and 1998-2013. The production values in 1975 and 1997 correspond to the initial production (t_0) for both periods. Results of the modelling are presented in Table 8 and Figure 18.

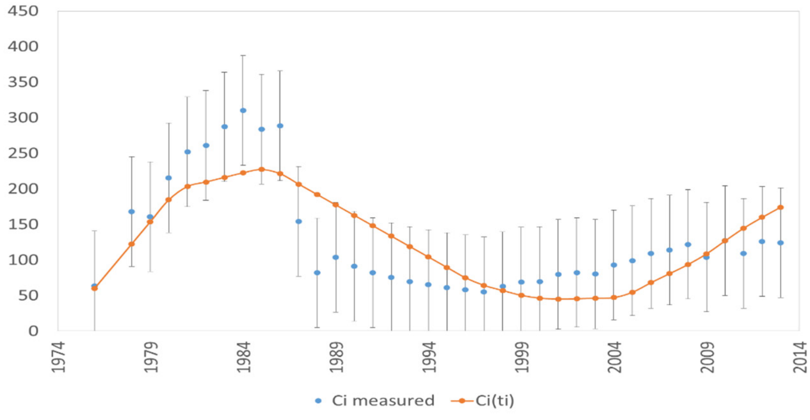

FIGURE 17: Chloride concentrations for well LA-02, measured and simulated, for the period 1975-2013

TABLE 8: Results of the iterative simulation process for well LA-02

Variable		Unit	1975-1986	1997-2013
V	Volume of production part of geothermal reservoir, or the mixing volume	m^3	1.23×10^9	9.10×10^9
R	Recharge	kg/s	2.89	2.00
φ	Porosity of reservoir	-	0.127	0.050

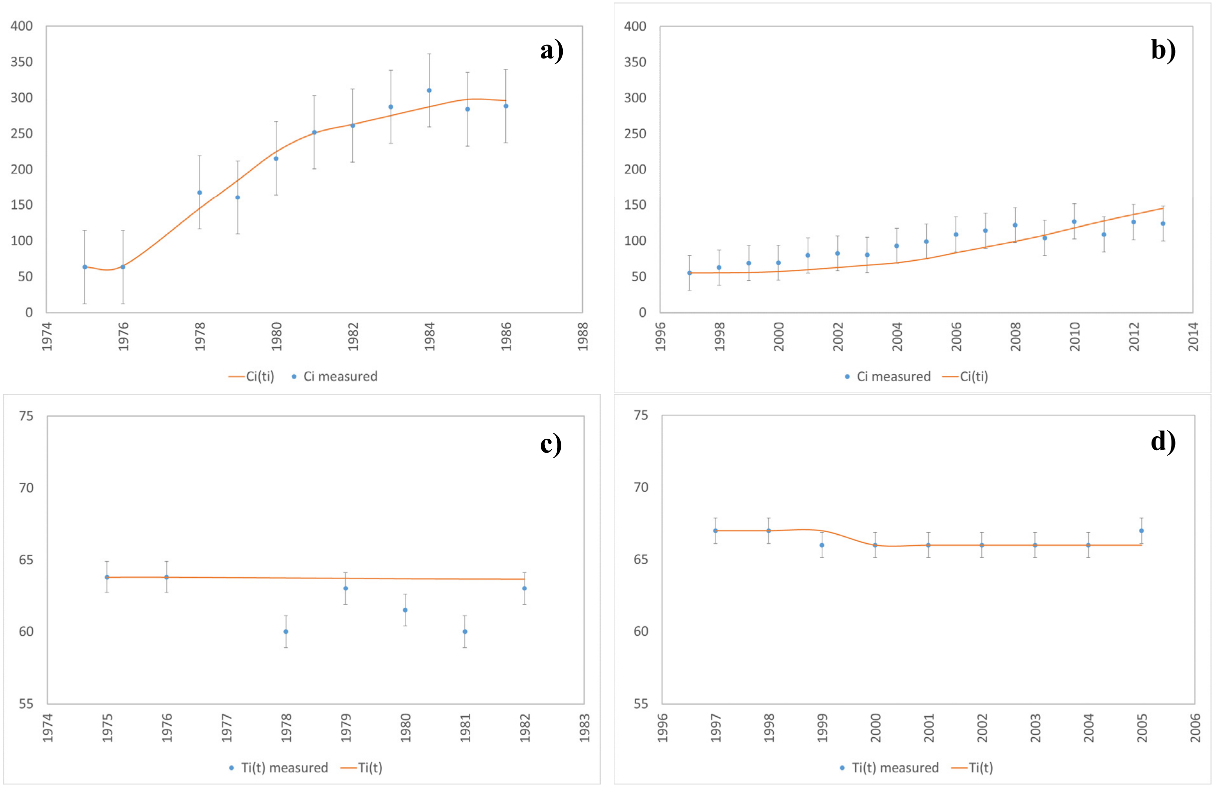

FIGURE 18: Results of the modelling of well LA-02: a) Chloride concentrations (ppm) 1975-1986; b) Chloride concentrations (ppm) 1997-2013; c) Temperature (°C) 1975-1986; d) Temperature (°C) 1997-2013; error bars show the standard deviation of concentrations and temperatures for the respective period

The average production for the period 1976-1986 is 7.91 kg/s, and 5.90 kg/s for the period 1998-2013. Recharge rates correspond to 37% and 34% of the average yield for each period, respectively.

It is of note that the model for the more recent period suggests a greater reservoir volume, as well as a reduction in the estimated porosity and hot system recharge. Reduction in porosity, if it were real, could be associated with depositional processes associated with the super-saturation of species through the intrusion of seawater. The coefficients of determination and correlation to the concentration of chlorides for each of the periods are shown in Table 9.

TABLE 9: Correlation and determination coefficients for measured and simulated chloride concentrations in well LA-02

		1975-1986	**1997-2013**
Pearson´s correlation coefficient	r	0.9865	0.8767
Determination coefficient	r^2	0.9732	0.7686

In well LA-05, for which there are no long periods of disuse, the fluctuations in production levels (0.12-6.20 L/s) prevent a good fit of the model (Figure 19). The production record, concentration and temperature records are, therefore, segmented into two periods, the first 1985-1998, and the second 2001-2013. The results of the simulation for well LA-05 are presented in Table 10 and Figure 19.

TABLE 10: Results of iterative simulation process for well LA-05

Variable		Unit	1985-1998	2002-2013
V	Volume of production part of geothermal reservoir, or the mixing volume	m^3	4.46×10^8	1.15×10^8
R	Recharge	kg/s	6.00	0.7653
φ	Porosity of reservoir	-	0.1173	0.1500

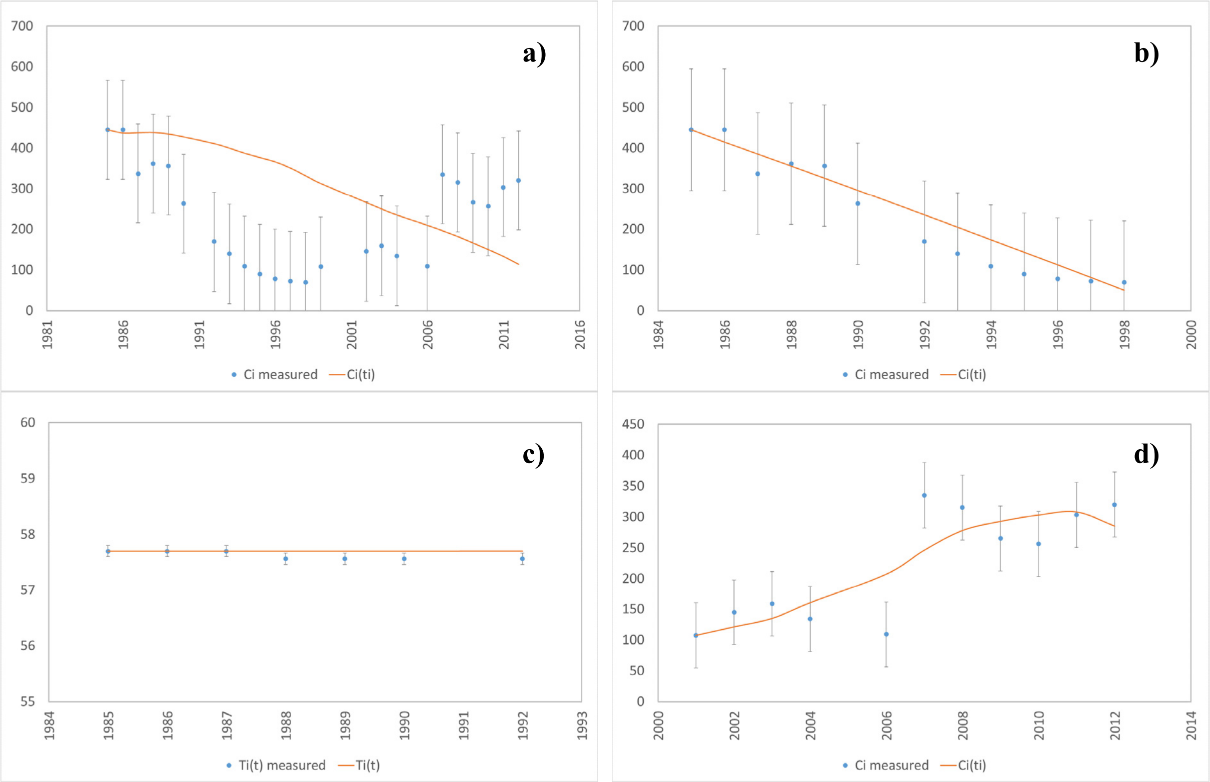

FIGURE 19: Results of the modelling of well LA-05; a) Chloride concentrations (ppm) 1985-2013; b) Chloride concentrations (ppm) 1985-1998; c) Temperature (°C) 1985-1998; d) Chloride concentrations (ppm) 2002-2013; error bars show the standard deviation of concentrations and temperatures for the respective period

The simulation of well LA-05 (Table 11) yields a smaller volume of the producing reservoir, or mixing volume, relative to that estimated for well LA-02. The constant reduction in the chloride content of the fluid in the period between 1986 and 1998 masks the recharge values, and suggests a greater contribution from the hot recharge to the system. However, it must be considered that for the period in question, there was an overall reduction in field production, mainly through well LA-02, which could affect well LA-05 if an interconnection exists between the wells.

TABLE 11: Correlation and determination coefficients for measured and simulated chloride concentrations in well LA-05

		1985-1998	2002-2013
Pearson´s correlation coefficient	r	0.9051	0.8258
Determination coefficient	r^2	0.8191	0.6820

The average production from well LA-05, for the period 1986-1998 is 3.4 kg/s, and 1.2 kg/s for the period 2001-2013. Recharge rates correspond to 179% and 65% of the average yield for each period, respectively.

8.2 Predicted temperature and chemical composition changes for well LA-02

The main objective of modelling a geothermal system is to assess its production potential, which can be seriously restricted by changes in temperature and chemical composition. For this purpose, the simulation model parameters: reservoir volume, porosity, recharge and temperature of colder inflow were used to predict future changes in the characteristics of the fluid produced at Sudureyri. The model developed for well LA-02 for the period 1978-1986 reflects closely the concentration and temperature measured; nevertheless, it does not describe the behaviour for the period 1998-2013 as well.

To define future variations in production, the period 1997-2013 was considered for well LA-02. The prediction modelling was performed by assuming constant production for 5, 10 and 15 years. The constant production rates considered corresponded to the average production reported for the period 2012-2013 (8.38 kg/s), a production of 10 kg/s, corresponding to a previously planned expansion in production and a production of 13.21 kg/s, corresponding to the maximum historical production. Also, scenarios of reduced production were evaluated, assuming half the production reported for the period 2012-2013, 4.19 kg/s, (under this scenario, the contribution of the hot recharge would be equivalent to 48% of the production) and the production equivalent to the calculated recharge (2.0 kg/s). The estimated chloride concentration and the predicted behaviour of the fluid are presented in Table 12 and Figure 20.

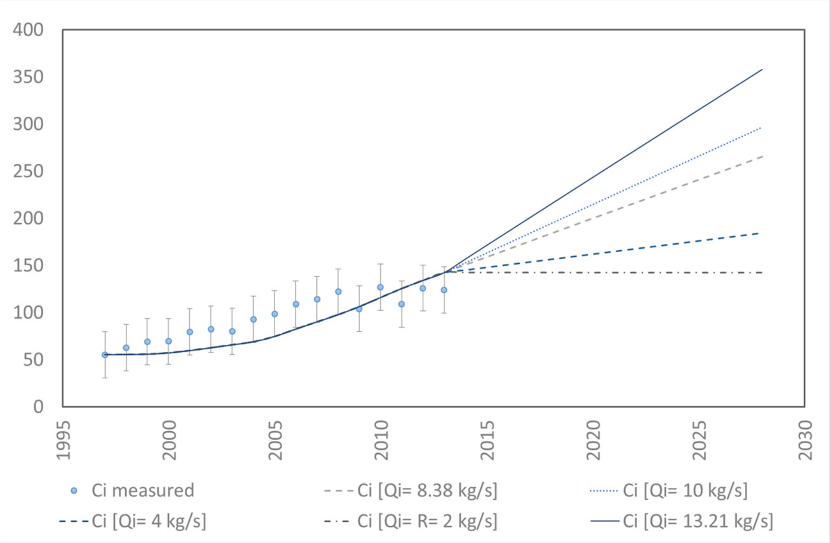

FIGURE 20: Predicted chloride concentrations for well LA-02 for different future scenarios described in the text; error bars show standard deviation in the chloride concentrations for the period 1998- 2013

TABLE 12: Predicted chloride concentrations in well LA-02

Scenarios	Q_i=13.21 kg/s	Q_i=10.00 kg/s	Q_i=8.38 kg/s	Q_i=4.19 kg/s	Q_i=2.00 kg/s
5 years	215	194	183	156	142
10 years	286	245	224	171	142
15 years	358	296	265	185	142

At a production rate equal to the estimated recharge, no effects are expected, according to the simulated values. For a production equivalent to the production in the period 2012-2013, an increase of 48% in chloride concentrations in the system (to 183 ppm) is expected within five years. Similar values are projected after fifteen years with production of 4.19 kg/s.

It is expected that the maximum values in chloride concentrations, measured during the period 1980-1986 in well LA-02 (approximately 260 ppm, with peak values up to 335 ppm), will be encountered within fourteen years at a production of 8.38 kg/s, within twelve years at a production of 10 kg/s, and within eight years at a production rate of 13.21 kg/s. Such chloride concentrations did precede the discontinuation of well operations in the 1980s. At lower production rates for the modelled scenarios, these chloride concentrations are not encountered, according to the predictions.

Using the correlation between the calcium, sodium and sulphate concentrations and chloride concentration (Equations 3-7, Section 4.3), the predicted concentrations of these species for different scenarios were calculated. The results are presented in Tables 13-15:

TABLE 13: Predicted sodium concentration in well LA-02

Scenarios	**Q_i=13.21 kg/s**	**Q_i=10.00 kg/s**	**Q_i=8.38 kg/s**	**Q_i=4.19 kg/s**	**Q_i=2.00 kg/s**
5 years	140	133	129	120	115
10 years	166	151	144	125	115
15 years	191	169	158	130	115

TABLE 14: Predicted calcium concentration in well LA-02

Scenarios	**Q_i=13.21 kg/s**	**Q_i=10.00 kg/s**	**Q_i=8.38 kg/s**	**Q_i=4.19 kg/s**	**Q_i=2.00 kg/s**
5 years	43	38	35	28	25
10 years	61	51	46	32	25
15 years	80	64	56	36	25

TABLE 15: Predicted sulphate concentration in well LA-02

Scenarios	**Q_i=13.21 kg/s**	**Q_i=10.00 kg/s**	**Q_i=8.38 kg/s**	**Q_i=4.19 kg/s**	**Q_i=2.00 kg/s**
5 years	93.2	90.6	89.2	85.8	84.0
10 years	102.3	97.0	94.4	87.6	84.0
15 years	111.3	103.5	99.6	89.4	84.0

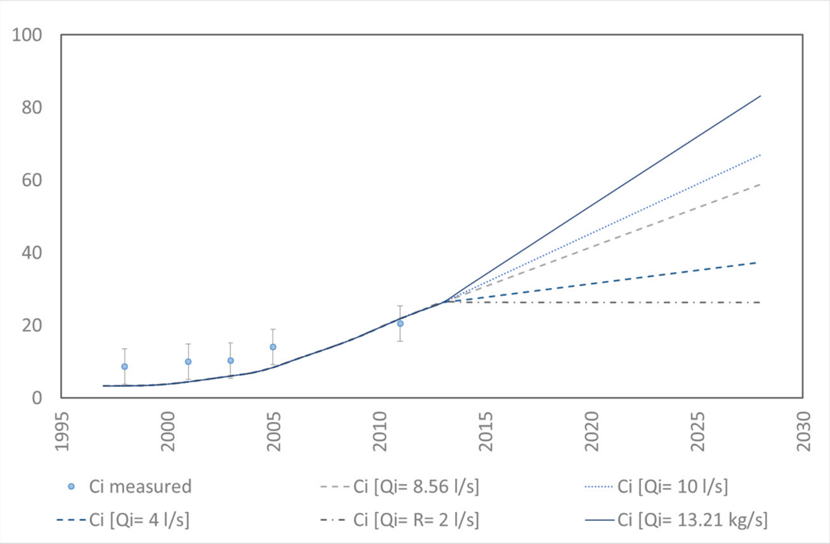

FIGURE 21: Predicted calcium concentration in well LA-02 for different future prediction scenarios

Figure 21 presents the calcium concentration predicted by the simulation model for different future production scenarios. Error bars show the standard deviation in the measured concentration of calcium for the period 1998-2013.

The calculation of the saturation index of calcite requires the activity of the carbonate ion in the system, but this could not be determined, as no correlation has been identified between the concentrations of chloride and the inorganic carbon species. On the other hand, for the determination of the activities of species, it is necessary to consider all components to properly include the effects of ionic strength.

9. DISCUSSION AND CONCLUSIONS

Systematic changes in the chemical composition of geothermal fluid, during the operation of Hitaveita Sudureyrar, have been associated with an additional recharge of fluid with a high content of sodium, calcium, chloride and sulphate, which are the components that have the most dramatic changes. Given the proximity of producing wells to the coastline, historically the recharge fluid has been considered to be heated seawater. The variations in the properties of the geothermal fluid have posed operational constraints for resource exploitation in Sudureyri, which has led to decreased production and the requirement for backup heating systems.

Production wells, LA-02 and LA-05, operated alternately from 1977 to 1998. The evaluation of the historical behaviour of the fluid during the transition intervals between wells shows similar values in the chemical compositions of the geothermal fluid, and suggests interconnection between the two wells. The historical averages reveal significant differences in the characteristics of the fluids from these wells, associated with temperature and salinity, indicating that well LA-05 has a higher relative contribution of seawater recharge.

Mixing models reveal that seawater recharge to the system interacts with the basaltic bedrock at geothermal temperatures, based on the enrichment of calcium, and loss of magnesium and sodium. Smectite is considered a potential alteration product.

The formation of smectite in the system may explain the magnesium consumption and the partial enrichment of calcium in the fluid. However, the stoichiometric generation of smectite, based on the available magnesium, is not sufficient to explain the measured values. This suggests the potential precipitation of other minerals rich in magnesium, such as magnesium silicates, ion exchange reactions or an additional contribution associated with the dissolution of anhydrite, by the inflow of cold seawater to the system. Mineralogical evaluation, enabling the identification of alteration products formed during the interaction of basalt and seawater, is therefore required.

Simple models were set up to evaluate the properties of the reservoir, on the basis of variations in production, the concentration of chloride and the temperature, for the periods 1975-1986 and 1997-2013 for well LA-02, and the periods of 1985-1998 and 2002-2013 for well LA-05. The models, based on the most recent records, suggest a production volume of the geothermal reservoir for well LA-05 to be 0.1 km^3, and for well LA-02 to be 9 km^3. The recharge rate for the most recent periods suggests a hot recharge of 0.76 kg/s for well LA-05 and 2 kg/s for well LA-02. These properties, coupled with higher temperature measured in the well, suggest that well LA-02 is located closer to the recharge zone.

By comparing simulation scenarios, the estimated properties of the reservoir for the periods 1976-1986 and 1998-2013, indicate a possible reduction in porosity. This could be a consequence of the reduction in production rates, as a consequence of deposition of minerals such as calcite in the interstitial spaces of the reservoir rock.

Operational limits were assumed for systematic variations in fluid composition, mainly the chloride concentration, based on maximum values measured during the period 1980-1986 in well LA-02 (approximately 260 ppm) which preceded the temporary replacement of the well. These values are predicted to be reached again within 14 years at a production of 8.4 kg/s, 12 years at a production of 10 kg/s, or 8 years at a production of 13.2 kg/s. For lower production rates for the modelled scenarios, these values are not reached. The lumped inflow simulation does not suggest changes in the temperature of the fluid entering the system, despite changes in the composition of the fluid.

The gaps in the existing production records limit the development of a more accurate model, so implementing a more comprehensive and continuous monitoring programme, with the development of resource management tools for greater accuracy, is required.

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