

RESULT

Enhancing REServoirs in Urban deveLopment: smart wells and reservoir development, Geothermica Project Number 200317



RESULT-D6.2:

Characterization of the changes in the reservoir in the Elliðaárdalur field

Responsible author:	Helga Tulinius (ÍSOR)
Responsible WP-leader:	Helga Tulinius (ÍSOR))
Contributions by:	Sigrún Tómasdóttir (OR) Þráinn Friðriksson (OR) Bjarni Reykr Kristjánsson (OR) Helga Tulinius (ÍSOR) Kjartan Marteinnsson (ÍSOR) Íris Eva Einarsdóttir (OR) Trausti Kristinnsson (OR) Þorsteinn Ari Þorgeirsson (OR) Sigrún Sif Sigurðardóttir (OR)



Report no. ÍSOR-2022/035	Date October 2022	Distribution <input checked="" type="checkbox"/> Open <input type="checkbox"/> Closed
Report name / Main and subheadings RESULT T-D6.2: Characterization of the changes in the reservoir in the Elliðaárdalur field	Number of copies 1	Number of pages 49
	Author Helga Tulinius, Sigrún Tómasdóttir and Þráinn Friðriksson	Project manager Helga Tulinius
Classification of report	Project no. 20-0115	
Prepared for RESULT		
Cooperators OR		
Abstract <p>This report is part of the RESULT (Enhancing REServoirs in Urban deveLopmentT: smart wells and reservoir development, Geothermica Project Number 200317) project belonging to Work package 6 Design Study Volcanic Reservoirs – Production Reykjavik and is: D6.2: Characterization of the changes in the reservoir in the Elliðaárdalur field. The report presents data on the production history of the field along with changes in temperature, water level and chemical components. Cooling has been observed in the field from the very start of production. This cooling has been accompanied by significant changes in the chemical composition of the produced fluid. Rising levels of oxygen have been of special concern as oxygen causes corrosion of pipes, pumps and surface equipment. The analysis shows that the cooling and change in chemical composition is not the result of simple two fluid mixing but is a combination of different processes.</p>		
Key words Elliðaárdalur, RESULT, ÍSOR, OR, geothermal, Iceland, geochemistry, cooling	ISBN-number	
	Project manager's signature <i>Helga Tulinius</i>	
	Reviewed by Kjartan Marteinson	

Table of Content

1	Introduction	5
2	History of the Reykjavík hot water utility	5
3	Elliðaárdalur geothermal area	6
3.1	Temperature logs and revised feed zones	10
3.2	Production history	11
3.3	Analysis of changes in chemistry	21
3.4	Characteristics of the different fluid types in the Elliðaárdalur field	32
4	Conclusions/Discussion/Next steps	33
5	References	34
	Appendix 1: Temperature logs, casings, feed zones and formation temperatures	35
	Appendix 2: Changes in chemical composition for individual wells in the Elliðaárdalur field	44

Tables

Table 1.	<i>Well number, drilling year, final depth and casing information for deep wells in the Elliðaárdalur field</i>	8
Table 2.	<i>Shallow wells around the Elliðaárdalur field</i>	10

Figures

Figure 1.	<i>The origin of hot water for the capital region from 1961 until 2021</i>	6
Figure 2.	<i>Wells in the Elliðaárdalur area categorized based on current utilization</i>	7
Figure 3.	<i>Annual production from the Elliðaárdalur geothermal field and the division between wells</i>	9
Figure 4.	<i>Water level changes in well R-27</i>	9
Figure 5.	<i>Temperature gradient in the field at -100 m a.s.l.</i>	11
Figure 6.	<i>Water level data, temperature of produced fluid, average production, and concentration of Cl, SiO₂ and F in produced fluid from RG-23</i>	12
Figure 7.	<i>Water level data, temperature of produced fluid, average production, and concentration of Cl, SiO₂ and F in produced fluid from RG-26</i>	13
Figure 8.	<i>Water level data, temperature of produced fluid, average production, and concentration of Cl, SiO₂ and F in produced fluid from RG-29</i>	14
Figure 9.	<i>Water level data, temperature of produced fluid, average production, and concentration of Cl, SiO₂ and F in produced fluid from RG-30</i>	15
Figure 10.	<i>Water level data, temperature of produced fluid, average production, and concentration of Cl, SiO₂ and F in produced fluid from RG-31</i>	16
Figure 11.	<i>Water level data, temperature of produced fluid, average production, and concentration of Cl, SiO₂ and F in produced fluid from RG-36</i>	17

Figure 12. <i>Water level data, temperature of produced fluid, average production, and concentration of Cl, SiO₂ and F in produced fluid from RG-37</i>	18
Figure 13. <i>Water level data, temperature of produced fluid, average production, and concentration of Cl, SiO₂ and F in produced fluid from RG-39</i>	19
Figure 14. <i>Water level data, temperature of produced fluid, average production, and concentration of Cl, SiO₂ and F in produced fluid from RG-41</i>	20
Figure 15. <i>Temperature and concentrations of selected components in water from well RG-31 with time along with combined annual production from the Elliðaárdalur field</i>	21
Figure 16. <i>Cl concentrations in samples from the Elliðaárdalur production wells with time and total annual mass production from the field</i>	22
Figure 17. <i>Cl concentrations in the Elliðaárdalur wells from beginning of production to the end of 1992</i>	23
Figure 18. <i>Changes in chloride concentration between samples taken in 1983 and an average chloride concentration for the beginning of production</i>	24
Figure 19. <i>Changes in chloride concentration between samples taken in 1987-1988 and an average chloride concentration for the beginning of production</i>	24
Figure 20. <i>Changes in chloride concentration between samples taken in 1990-1991 and an average chloride concentration for the beginning of production</i>	25
Figure 21. <i>Changes in chloride concentration between samples taken in 2005-2008 and an average chloride concentration for the beginning of production</i>	25
Figure 22. <i>Changes in chloride concentration between samples taken in 2016-2018 and an average chloride concentration for the beginning of production</i>	26
Figure 23. <i>O₂ concentrations in the Elliðaárdalur production wells</i>	27
Figure 24. <i>pH values of water samples from the Elliðaárdalur production wells</i>	28
Figure 25. <i>Ca concentrations in samples from the Elliðaárdalur production wells with time and total annual mass production from the field</i>	29
Figure 26. <i>CO₂ concentrations in samples from the Elliðaárdalur production wells with time and total annual mass production from the field</i>	30
Figure 27. <i>SiO₂ concentrations in Elliðaárdalur production wells</i>	31
Figure 28. <i>Na concentrations in samples from the Elliðaárdalur production wells with time</i>	32

1 Introduction

This report is part of the RESULT (Enhancing REServoirs in Urban development: smart wells and reservoir development, Geothermica Project Number 200317) project belonging to Work package 6 Design Study Volcanic Reservoirs – Production Reykjavik and is: D6.2: Characterization of the changes in the reservoir in the Elliðaárdalur field. Here the production histories of the numerous wells in the geothermal field and the reservoirs' reaction to it in water level, temperature and chemistry are analysed. The water level in monitoring well R-27 follows the production; it drops quickly when production is increased and rises quickly when production is decreased or stopped. In general, there is considerable cooling in the reservoir, the average cooling in the wells drilled in the late sixties is over 30°C (R-23, 26, 29, 30, and 31) and around 12°C in the two wells drilled later (R-37 and 39). The decreasing temperature of water produced from the Elliðaárdalur field has been accompanied by significant changes in the chemical composition of the water produced from the wells. In short, the pattern seen in all wells is that the concentrations of Cl, CO₂, Ca and O₂ increase with time, as the temperature decreases. The concentrations of SiO₂ and F decrease with decreasing temperature. At the same time, other major components, such as Na, K, SO₄, remain nearly constant as the temperature of the wells decreases.

2 History of the Reykjavík hot water utility

The idea of using hot water for district heating in Reykjavík dates back to 1926. In 1928 the first borehole was drilled in the Laugardalur laundry baths, which had been used to wash laundry for decades. The Reykjavík hot water utility was then founded in 1930. To meet an increasing demand for hot water, the City Council of Reykjavík secured the geothermal energy rights for the Reykir area in Mosfellssveit in 1933 and started research in the area. In 1937, 58 houses in total were connected to the hot water utility (Reykjavík energy, n.d.).

Research in the Elliðaárdalur field started in 1932 with the drilling of well H-35. Drilling of geothermal production wells in the capital area however did not take off until the Icelandic government and the City of Reykjavík purchased steam drills in 1958 that could drill deeper wells. Deeper drilling and the use of down-hole pumps resulted in increased production. Despite that, it was clear that the geothermal systems within the capital region would not be sufficient to meet the future demand for hot water. In 1955 the City of Reykjavík bought land in Hellisheiði, 40 km east of Reykjavík, for future geothermal exploration and in 1965, land in Nesjavellir was acquired for the same purpose. By 1971, 98% of Reykjavík residents were connected to the district heating utility. The Laugarnes, Elliðaárdalur and Reykir/Reykjahlíð low temperature geothermal systems supplied the hot water for the utility until 1990 when the Nesjavellir Power plant was commissioned (Reykjavík energy, n.d.).

In 1991, the Reykjavík Electricity Utility and the Reykjavík Hot Water Utility merged into Reykjavík Energy (Orkuveita Reykjavíkur). The hot water utility is now operated by Veitur Utilities, a subsidiary of Reykjavík Energy. The Hellisheiði Power plant was commissioned in 2006 and started supplying hot water to the utility in 2010 (Reykjavík energy, n.d.). The water from Nesjavellir and Hellisheiði is heated cold groundwater and has a different chemical composition than the geothermal water from Laugarnes, Elliðaárdalur and Reykir/Reykjahlíð. Mixing of the two water types causes scaling in pipes and because of that the two water types are kept separate in the distribution system. Figure 1 shows the origin of the hot water in the utility from 1961 until 2021.

With the commissioning of Nesjavellir, production from the low temperature systems could be reduced. This was necessary because water level in the reservoirs was declining and some

wells had cooled down and/or showed changes in chemical composition. This was the case for the Elliðaárdalur system where notable cooling had been observed and oxygen in the produced water had increased.

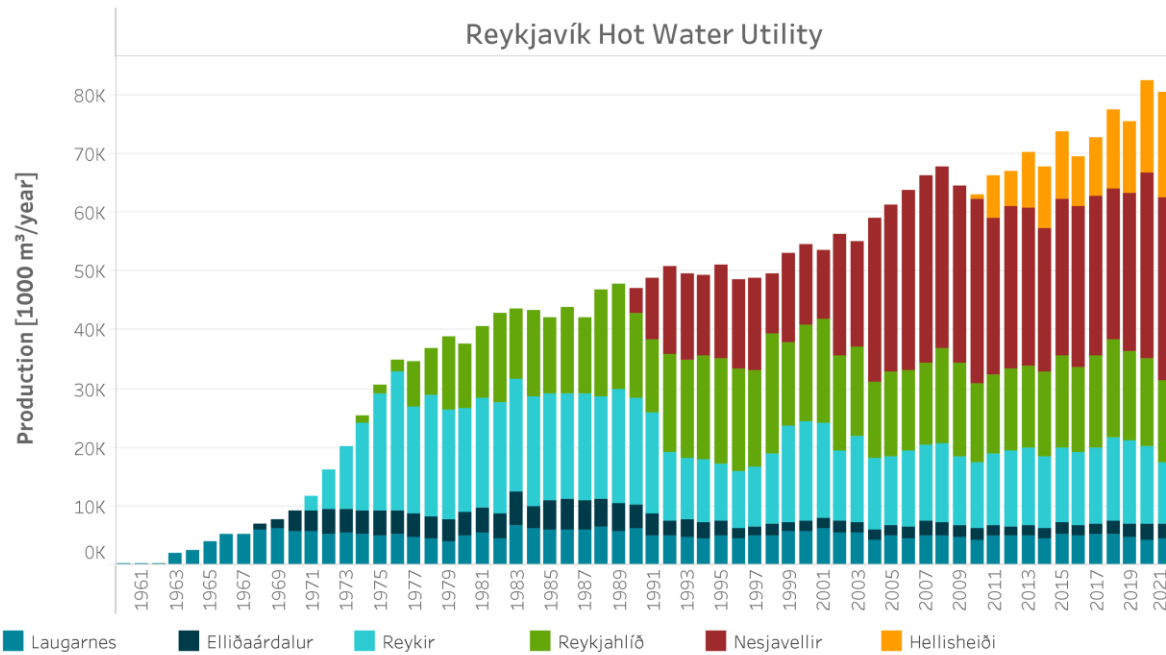


Figure 1. The origin of hot water for the capital region from 1961 until 2021.

3 Elliðaárdalur geothermal area

The drilling of production wells in the Elliðaárdalur area started in 1967 with the drilling of well R-23 (also referred to as RG-23). Between 1967 and 1984, 16 deep exploration/production wells were drilled. Production from the field started in 1968. There are currently nine active production wells in the field. These wells are called R-23, R-26, R-29, R-30, R-31, R-36, R-37, R-39 and R-41. Deep wells that were drilled in the area but not deemed suitable for production either had low productivity or were located far away from the main distribution pipes. The location of all wells within the area is shown in Figure 2.

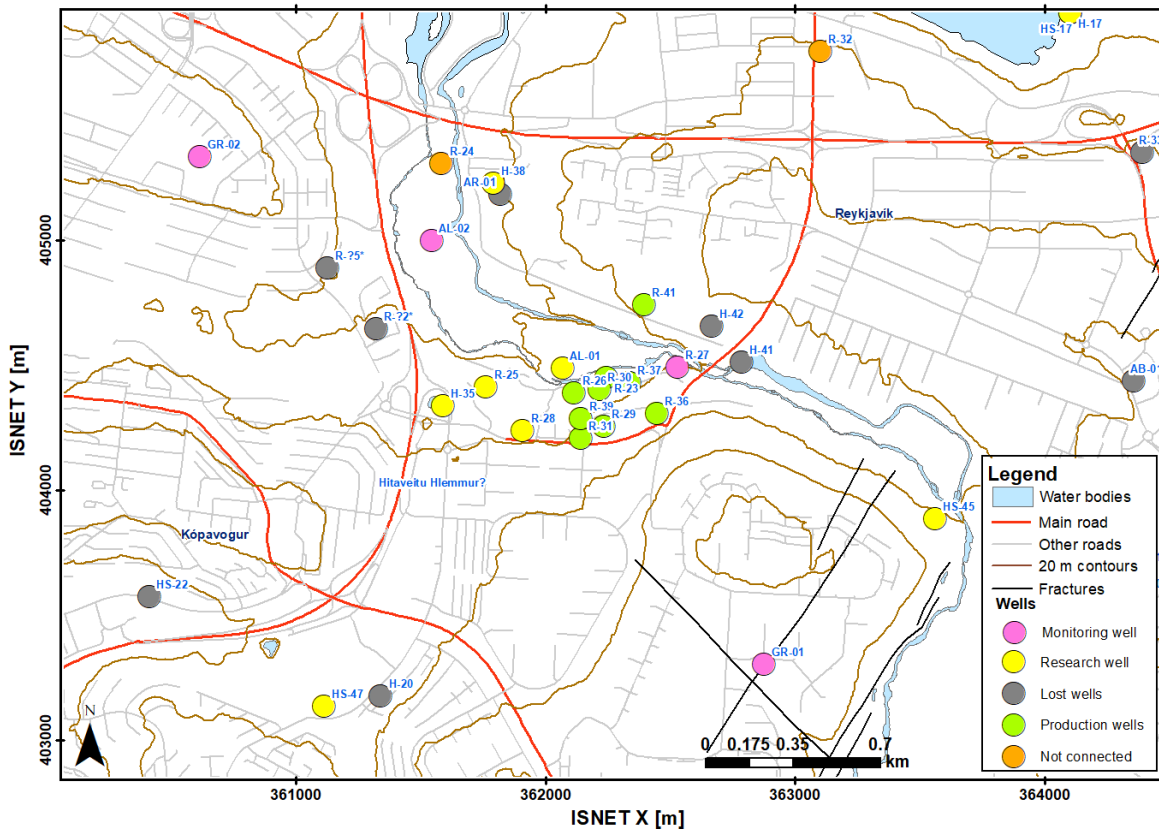


Figure 2. Wells in the Elliðaárdalur area categorized based on current utilization. R-27 is the only monitoring well for the geothermal system, the other monitoring wells are shallow cold water wells.

The production zone in Elliðaárdalur is not large (~1 km²) and lies within the geothermal system that covers 8-10 km². As listed in more detail in deliverable 6.1 (Jónsson et al., 2021), the Elliðaárdalur system has three main aquifer zones. The top one (A) in a basalt sequence reaching 300-500 m depth and with temperature between 40-90°C, the middle one (B) in a hyaloclastite sequence and includes the highest temperatures (110°C) and the lowest one (C) in another basalt sequence with temperature between 70-115°C (Tómasson, 1988). Wells within the production zone have a reversed temperature profile. Cooling has been observed in production wells in Elliðaárdalur since the start of production. Various processes are responsible for this cooling; drawdown in the hottest aquifer causing a greater portion of produced water to come from cooler aquifers, downflow of colder water from the top and inflow of cooler water from the sides (Tómasson and Thorsteinsson, 1983). The colder water entering the wells also has more oxygen content causing oxygen content in the produced water to increase with time. This is an undesirable change as oxygen leads to corrosion of pipes and surface equipment.

The wells in the Elliðaárdalur field, that were drilled before 1980, had a relatively shallow casing (< ~100 m). In an effort to decrease cooling in the reservoir, casings were deepened in some wells in the area between 1982-1992. Two wells at the western edge of the system, R-25 and R-28, were also completely plugged to stop downflow of colder water. Table 1 shows information on the deep wells drilled in the Elliðaárdalur field.

Table 1. Well number, drilling year, final depth and casing information for deep wells in the Elliðaárdalur field.

Well nr. (Id)	Drilling year	Final depth (m)	Casing depth original/final (m)
R-23 (5023)	1967	1266	35/302.2
R-24 (5024)	1968	1010	75.5
R-25 (5025)	1968	1647	79.5/1594.9
R-26 (5026)	1968	861	101.5
R-27 (5027)	1968	1450	99.5
R-28 (5028)	1968	1576	102/1515.8
R-29 (5029)	1969	1077	98/688
R-30 (5030)	1969	1316	98/709
R-31 (5031)	1969	1615	99/503.1
R-32 (5032)	1969	1359	100
R-33 (5033)	1971	1560	118.4
R-36 (5036)	1978	2312	297
R-37 (5037)	1980	2155	679
R-39 (5039)	1980	2100	1045.2
R-41 (5041)	1984	1605	437
KS-01 (9121)	1969	1504	106.5

When the Nesjavellir Power Plant was commissioned, production from the Elliðaárdalur system could be decreased. This was convenient as the operation of the area had been difficult due to cooling and chemical changes. The development of total production from the Elliðaárdalur field and the production from individual wells can be seen in Figure 3 and water level in monitoring well R-27 can be seen in Figure 4. The water level in the monitoring well seems to respond quickly to change in production from the field.

With growing population and industrial activity in Reykjavik, capacity additions are increasingly necessary to fulfil demand. As previously mentioned, additional capacity has come from development in greenfield geothermal areas outside the urban area in the past decades. However, in the last few years the focus has shifted from new fields outside the city to enhancing the utilization efficiency of currently operated mature fields within the city limits. The aim of this report is to characterize the changes in the reservoir in Elliðaárdalur throughout its production history to hopefully identify opportunities for better resource management.

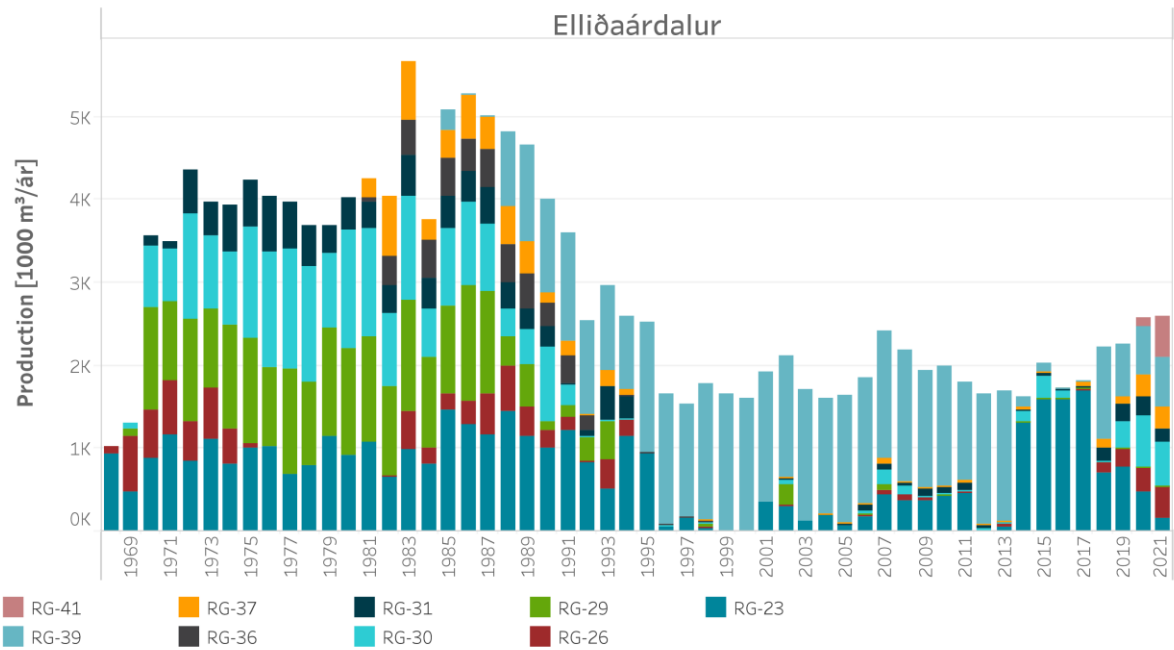


Figure 3. Annual production from the Elliðaárdalur geothermal field and the division between wells.

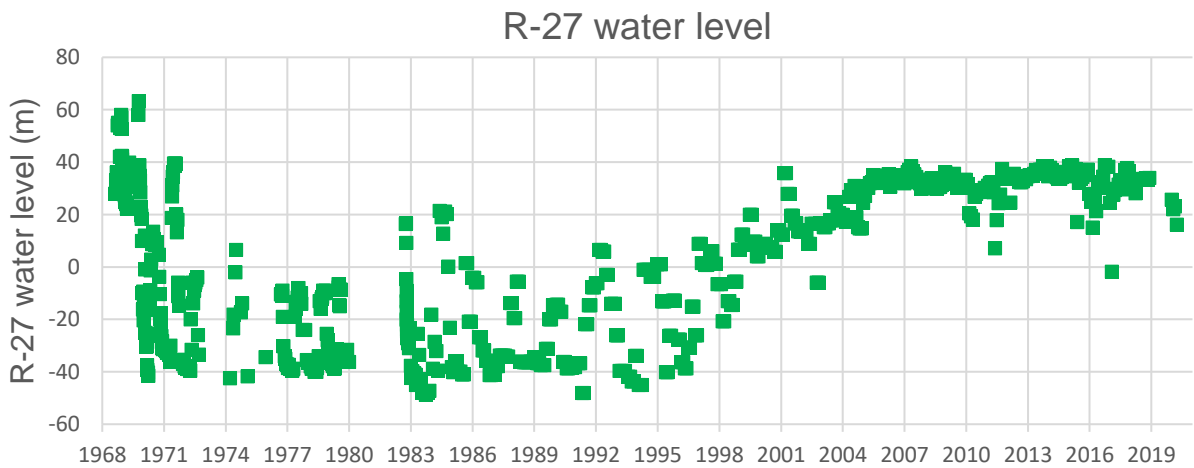


Figure 4. Water level changes in well R-27.

3.1 Temperature logs and revised feed zones

Numerous shallow wells have been drilled within and around the Elliðaárdalur geothermal field in addition to the deep wells mentioned in previous chapters. Temperature logs from shallow wells within about a 5 km radius from the centre of the Elliðaárdalur geothermal field have been analysed, feed zones located and formation temperature around the wells at the time of drilling estimated (Table 2). The shallow wells are mostly part of the H series drilled before 1967 (H-17, H-20, H-32, H-35, H-38, H-39 and H-40) along with four other wells (MM-1, MT-1, HU-1 and FH-1). These wells are research wells drilled to a depth of between 60 m to over 600 m. The HS well series were drilled to find the temperature gradient in the upper most layers, the deepest of these wells is 1265 m deep. The estimated shallow temperature gradient for the field can be seen in Figure 5. Revised temperature logs for all wells, shallow and deep, can be found in Appendix 1.

Table 2. *Shallow wells around the Elliðaárdalur field.*

Well nr.	Well name	Drilling year	Final depth (m)
1421	HS-17	1984	284.5
2411	HU-1	1963	164.6
6017	H-17	1943	271.9
6020	H-20	1955	384.5
6032	H-32	1960	606.2
6035	H-35	1932	193.5
6038	H-38	1962	326.3
6039	H-39	1963	332.7
6041	H-41	1961	272.5
6051	HS-45	1995	403.1
6052	HS-47	1996	1010
9001	HS-22	1984	302.4
9012	FH-1	1964	53.6
9091	MT-1	1960	40
9101	HS-13	1968	106.7
9121	KS-1	1969	1504
3021	MM-1	1958	60
6040	H-40	1966	251.1
1844	HS-44	1995	1265.4

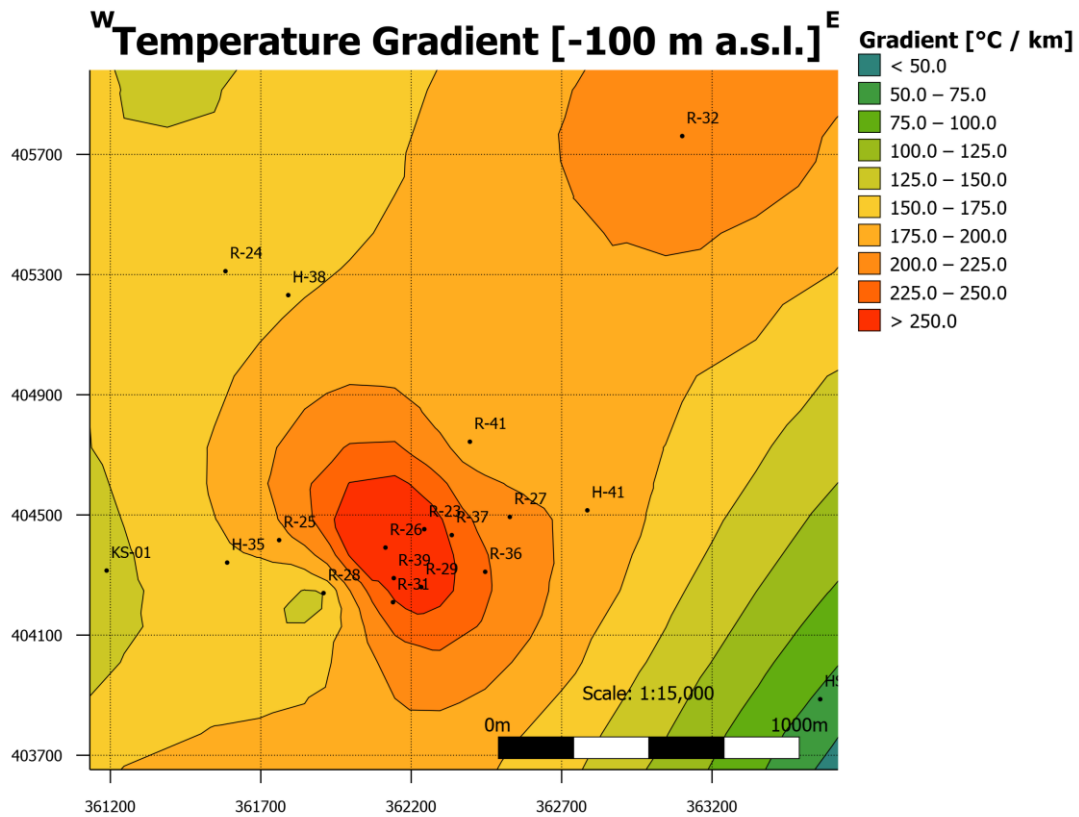


Figure 5. Temperature gradient in the field at -100 m a.s.l.

3.2 Production history

In this chapter, production rate, temperature, water level and concentration of silica, fluoride and chloride is presented for each production well (Figures 6 to 14). Chemical changes in the system are analysed further in chapter 3.3.

3.2.1 RG-23

Cooling was observed almost immediately in this well (Figure 6). The casing was deepened from 35 m down to 302.2 m in 1982. This action increased the temperature, but the cooling still continued over the next decades. The temperature seems to have stabilized around 88 °C in recent years. Temperature measurements taken shortly after pump start show a temperature of 75 °C. There are 65-70 °C feedzones around 400 m depth (see temperature logs in Appendix 1). The temperature gradually increases up to ~88 °C when the well is in use. Chloride has been increasing, mostly after 1995 when the production from the system had been decreased. Silica decreases with decreasing temperature.



Figure 6. Water level data, temperature of produced fluid, average production, and concentration of Cl, SiO₂ and F in produced fluid from RG-23.

3.2.2 RG-26

Cooling was observed almost immediately in the well. The temperature seemed to have stabilized around 90 °C in 1990 but with increased production in recent years (from 2017), the cooling seems to continue (Figure 7). Chloride has been increasing, especially after 1995, and silica decreasing. The casing depth in well R-26 is 101.5 m and has not been deepened. A temperature profile from 2019 shows cold feedzones (40-50 °C) below the casing and down to about 240 m (see temperature logs in Appendix 1). This well should be recased down to 300 m.

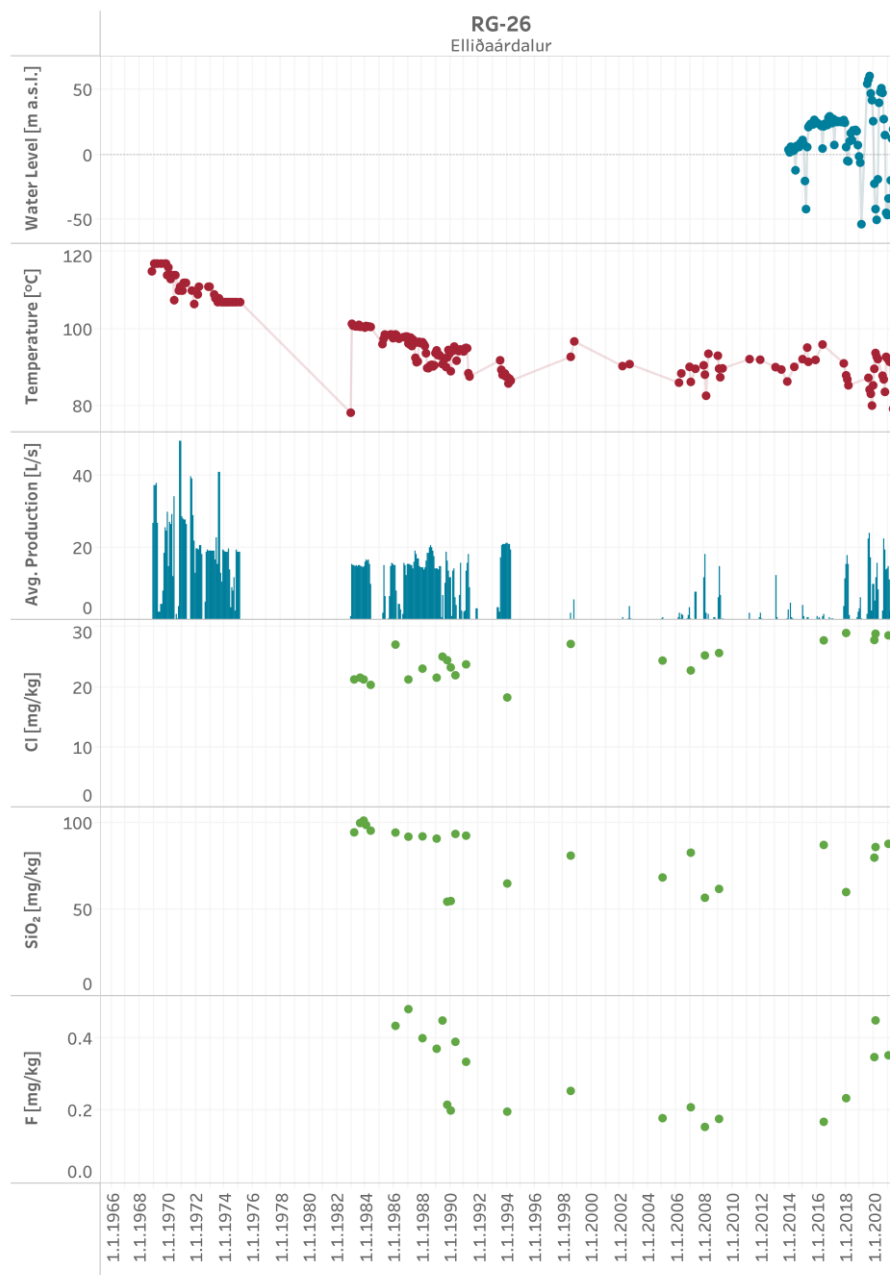


Figure 7. Water level data, temperature of produced fluid, average production, and concentration of Cl, SiO₂ and F in produced fluid from RG-26.

3.2.3 RG-29

The casing in well RG-29 was deepened from 98 m down to 688 m in 1990. The well had been rarely used in the years leading up to the re-casing which probably enhanced downflow in the well and thus cooling of the well. The re-casing slowed the cooling down but did not reverse it as the hotter feed-zones in the well were above the deepened casing depth (Sigurðsson, 1995). Silica and fluoride drastically decreased following the re-casing. Chloride concentration has increased (Figure 8). Because of the low temperature of produced fluid, the water from the well is not suitable for the distribution system. The pump has been temporarily taken out of this well.

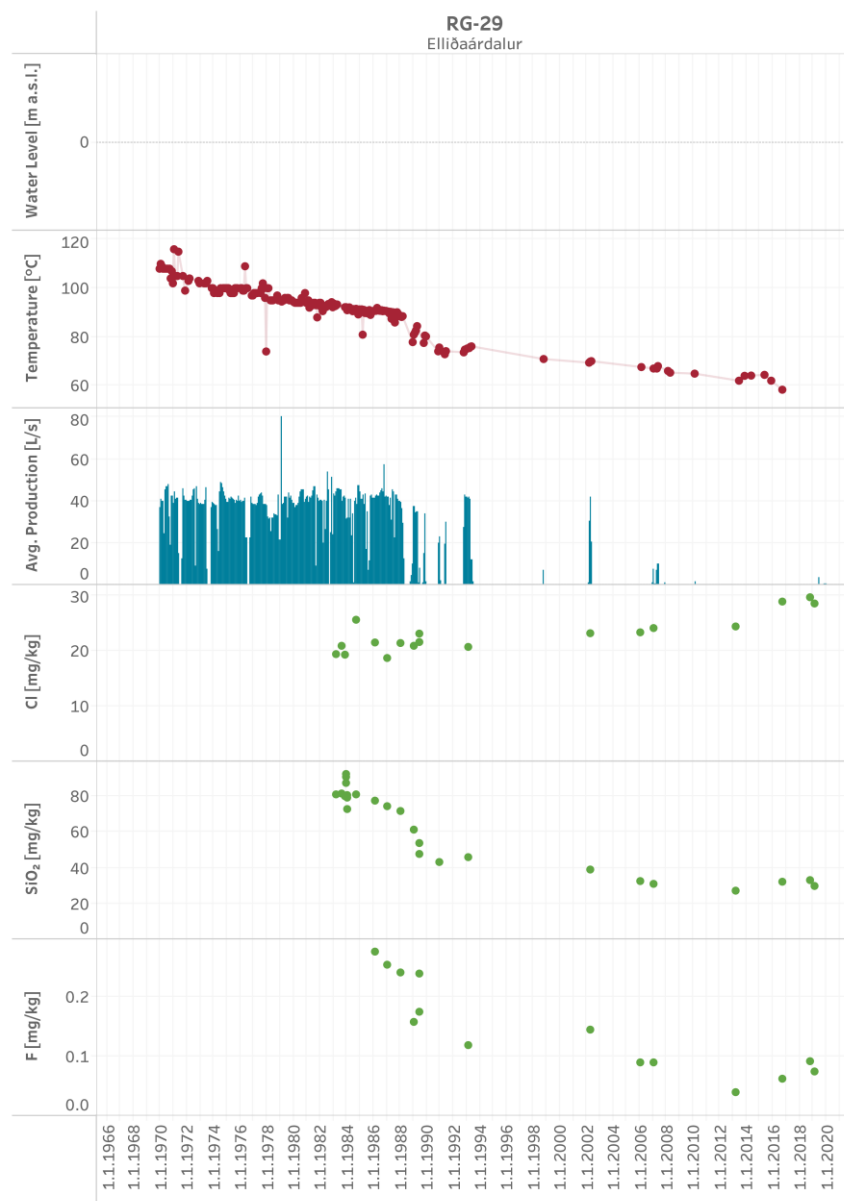


Figure 8. Water level data, temperature of produced fluid, average production, and concentration of Cl, SiO₂ and F in produced fluid from RG-29.

3.2.4 RG-30

The casing in well RG-30 was deepened from 98 m down to 709.6 m on the 31st of July 1990. The deepening of the casing slowed down the rate of cooling in this well but did not reverse it (Figure 9). Following the commissioning of Nesjavellir this well was rarely used. Stopping production did not seem to increase cooling after the re-casing. It has been used more in recent years which has caused cooling again. The temperature of the well is now below 80 °C. Chloride concentration has increased and silica concentration as well. Fluoride concentration decreased until 2016 but has since increased again.

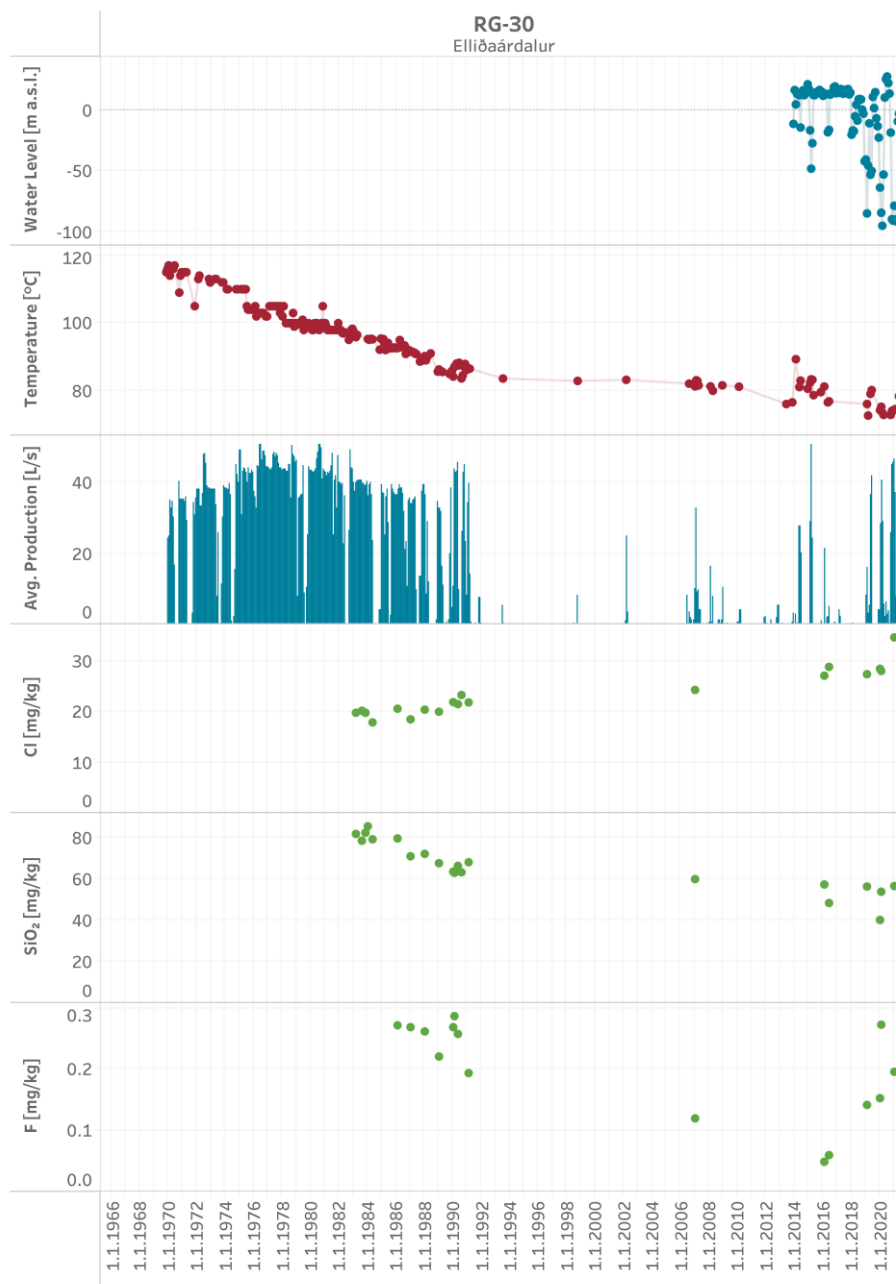


Figure 9. Water level data, temperature of produced fluid, average production, and concentration of Cl, SiO₂ and F in produced fluid from RG-30.

3.2.5 RG-31

The casing in well RG-31 was deepened from 99 m down to 503.1 m on the 25th of March 1992. The deepening of the casing stopped the cooling for the first years following the procedure when the well was very rarely used. When its usage was increased again in 2006 the cooling began again but at a slower rate. The temperature has been relatively stable since ~2010. Relatively cool feed-zones were cased off with the re-casing of well R-31 (Sigurðsson, 1995). Chloride and fluoride concentration has increased, and silica concentration decreased. The temperature of the well is around 80 °C but fluctuates (Figure 10).

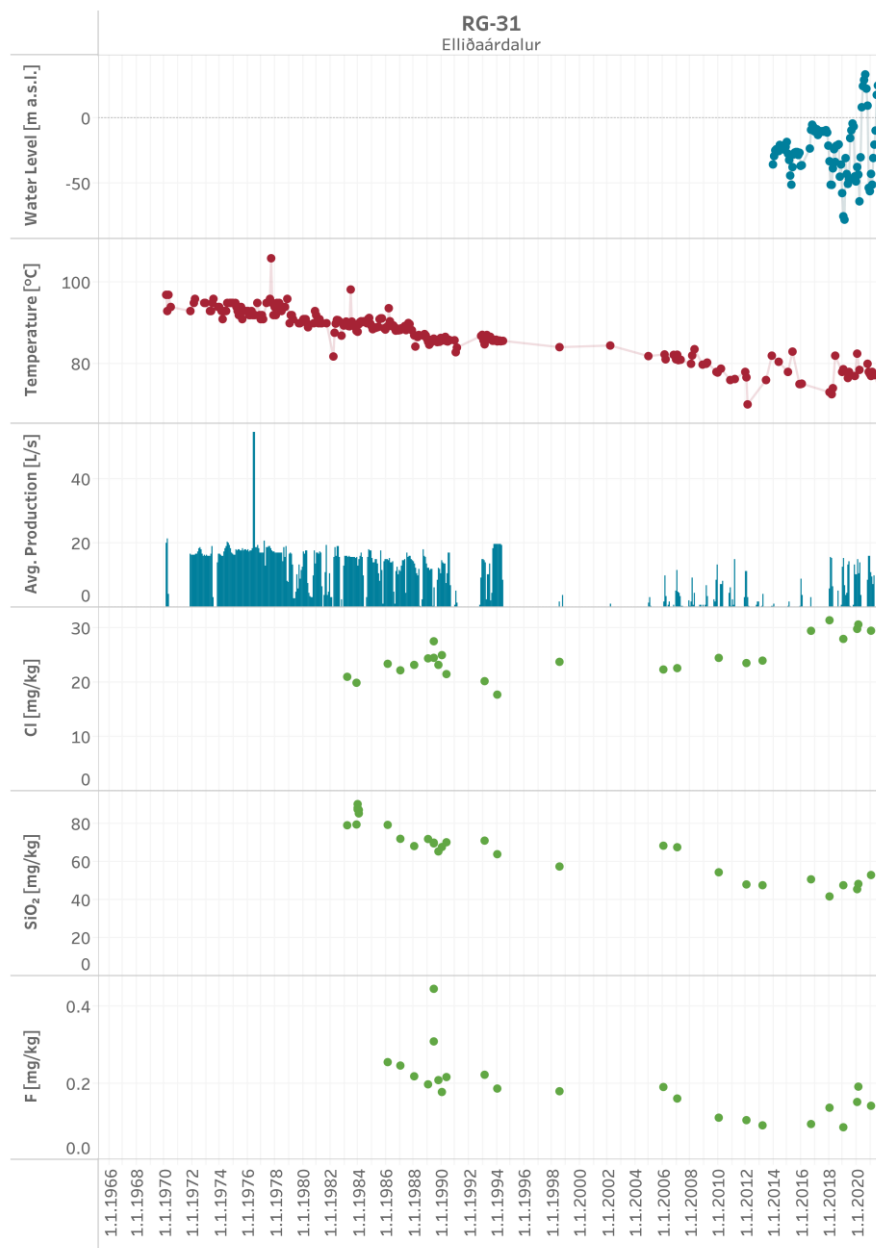


Figure 10. Water level data, temperature of produced fluid, average production, and concentration of Cl, SiO₂ and F in produced fluid from RG-31.

3.2.6 RG-36

Well RG-36 was drilled in 1978 and cased down to 297 m. It was only used for a short period of time (Figure 11). The drawdown in the well was greater than expected and it was not very productive.

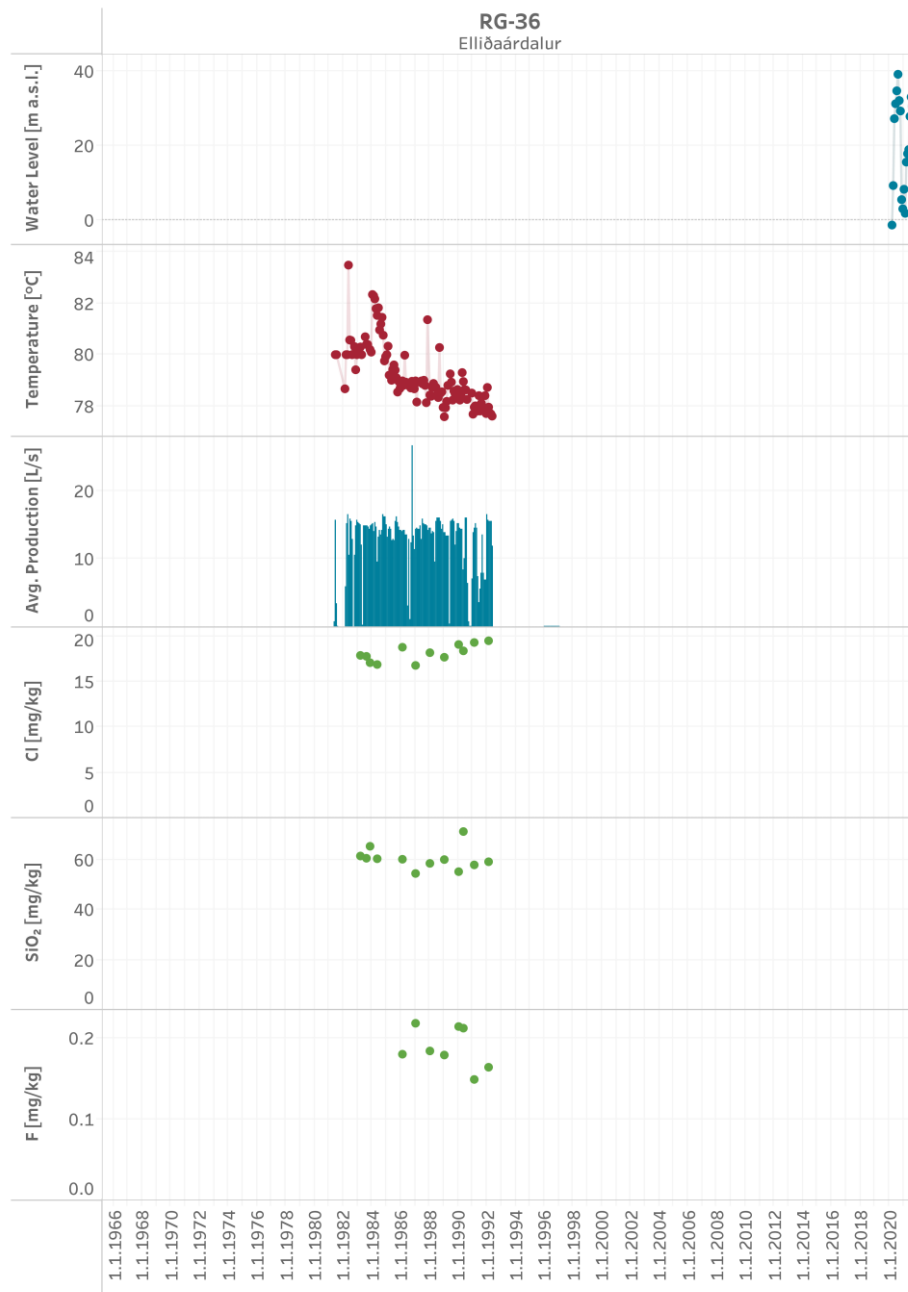


Figure 11. Water level data, temperature of produced fluid, average production, and concentration of Cl, SiO₂ and F in produced fluid from RG-36.

3.2.7 RG-37

Well RG-37 was drilled down to 2155 m in 1980 and cased down to 679 m. Temperature decreases from about 92°C in 1981 down to 87°C in 1991 (Figure 12). The cooling rate seems to decrease when the production rate declines. It increases again when the production rate is increased. Silica concentration has decreased along with cooling temperature. Chloride concentration has generally been increasing. In the last few years, with increased production, it seems to have been decreasing. Fluoride shows the same trend.

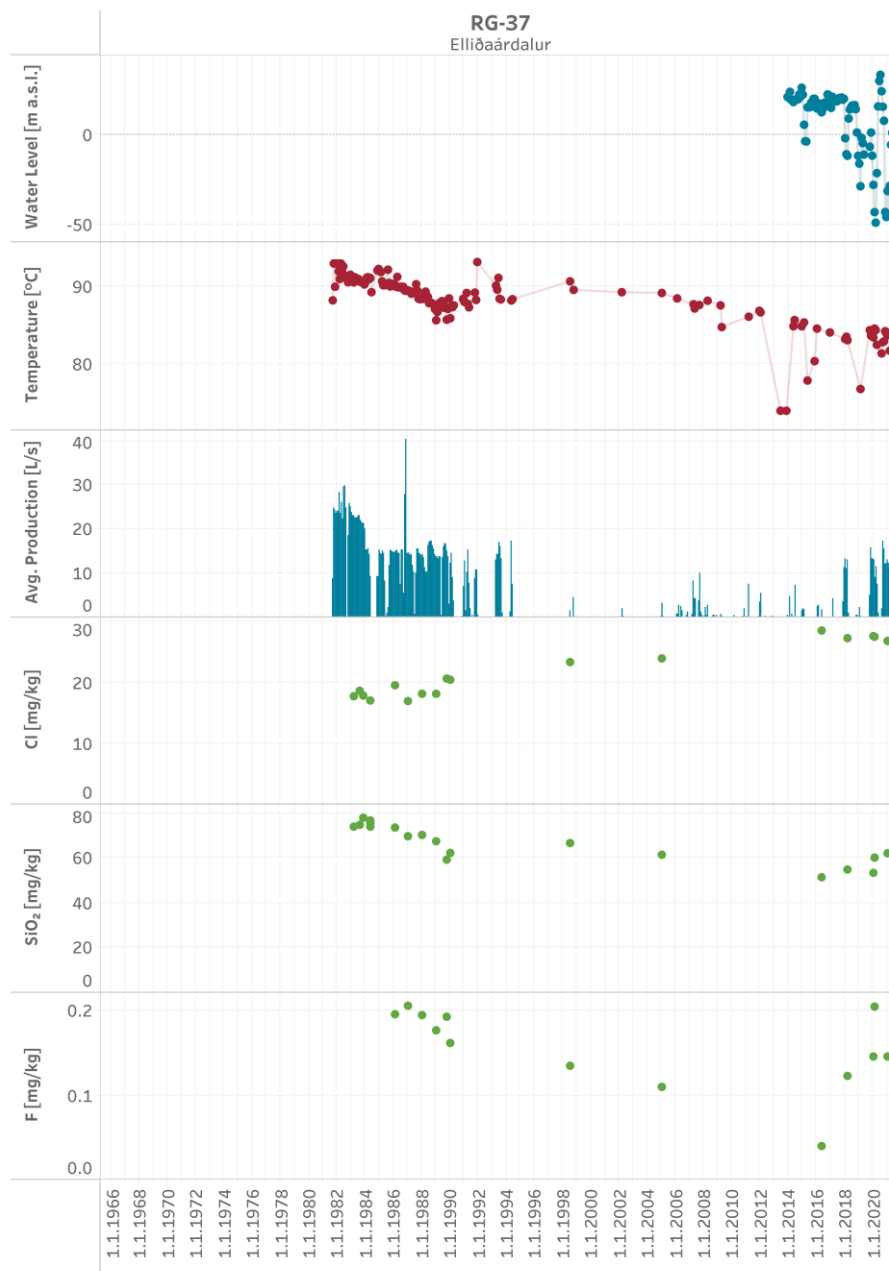


Figure 12. Water level data, temperature of produced fluid, average production, and concentration of Cl, SiO₂ and F in produced fluid from RG-37.

3.2.8 RG-39

Well RG-39 was drilled down to 2100 m in 1980 and cased down to 1045.2 m. It has been used constantly except between 2014 and 2018. Temperature has been decreasing from the start. The rate of cooling was greater during the production stop (Figure 13). Silica concentration has decreased along with cooling temperature. Chloride concentration has generally been increasing, but less than in other wells. Fluoride was generally decreasing but has increased in the last few years.

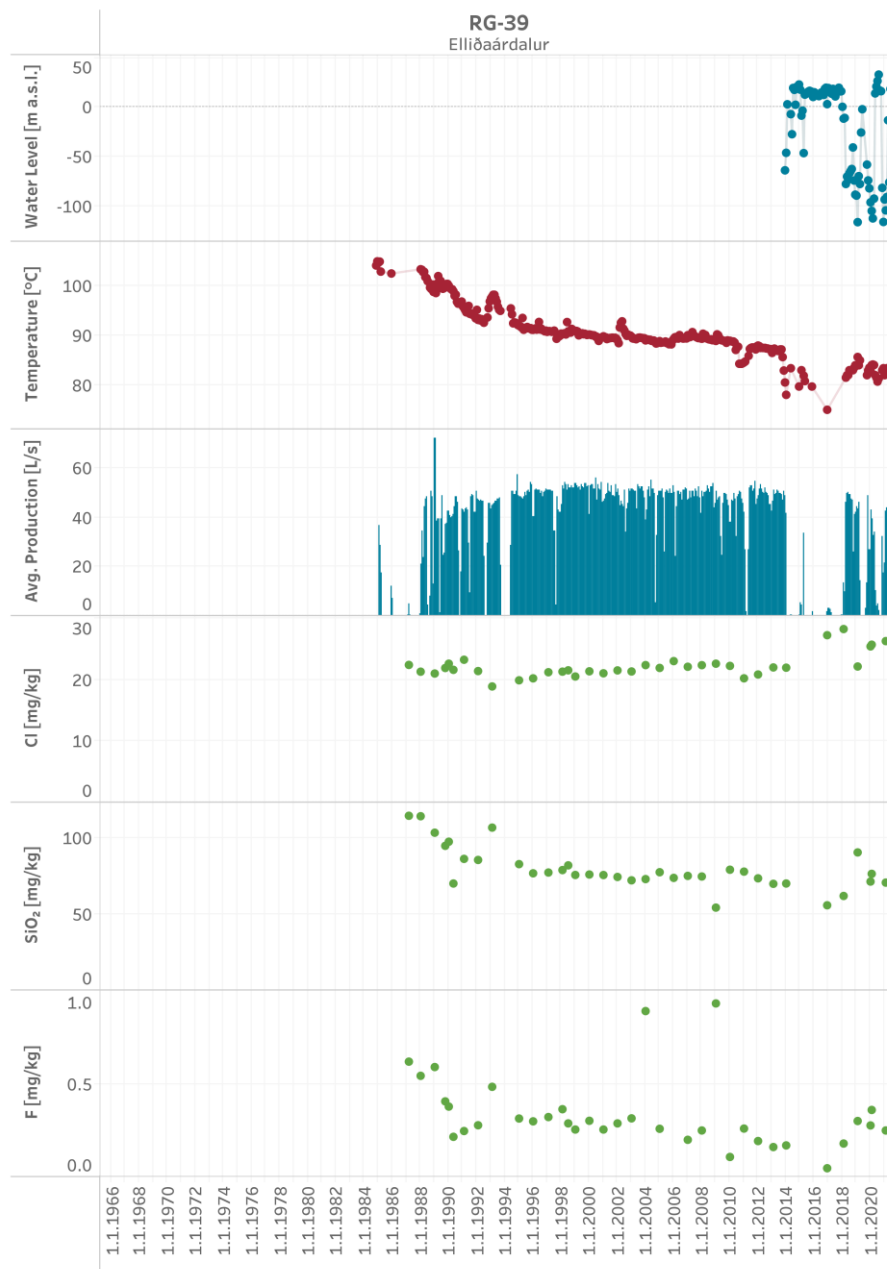


Figure 13. Water level data, temperature of produced fluid, average production, and concentration of Cl, SiO₂ and F in produced fluid from RG-39.

3.2.9 RG-41

Well RG-41 was drilled down to 1605 m in 1984 and is cased down to 437 m. It was not connected to the distribution system until 2020 because it lies on the other side of the system. It is hotter, about 92°C, compared to other wells in the field. The temperature has, however, decreased since production started in 2020 and chemical changes have also started to appear with, for example, increasing chloride concentration (Figure 14).

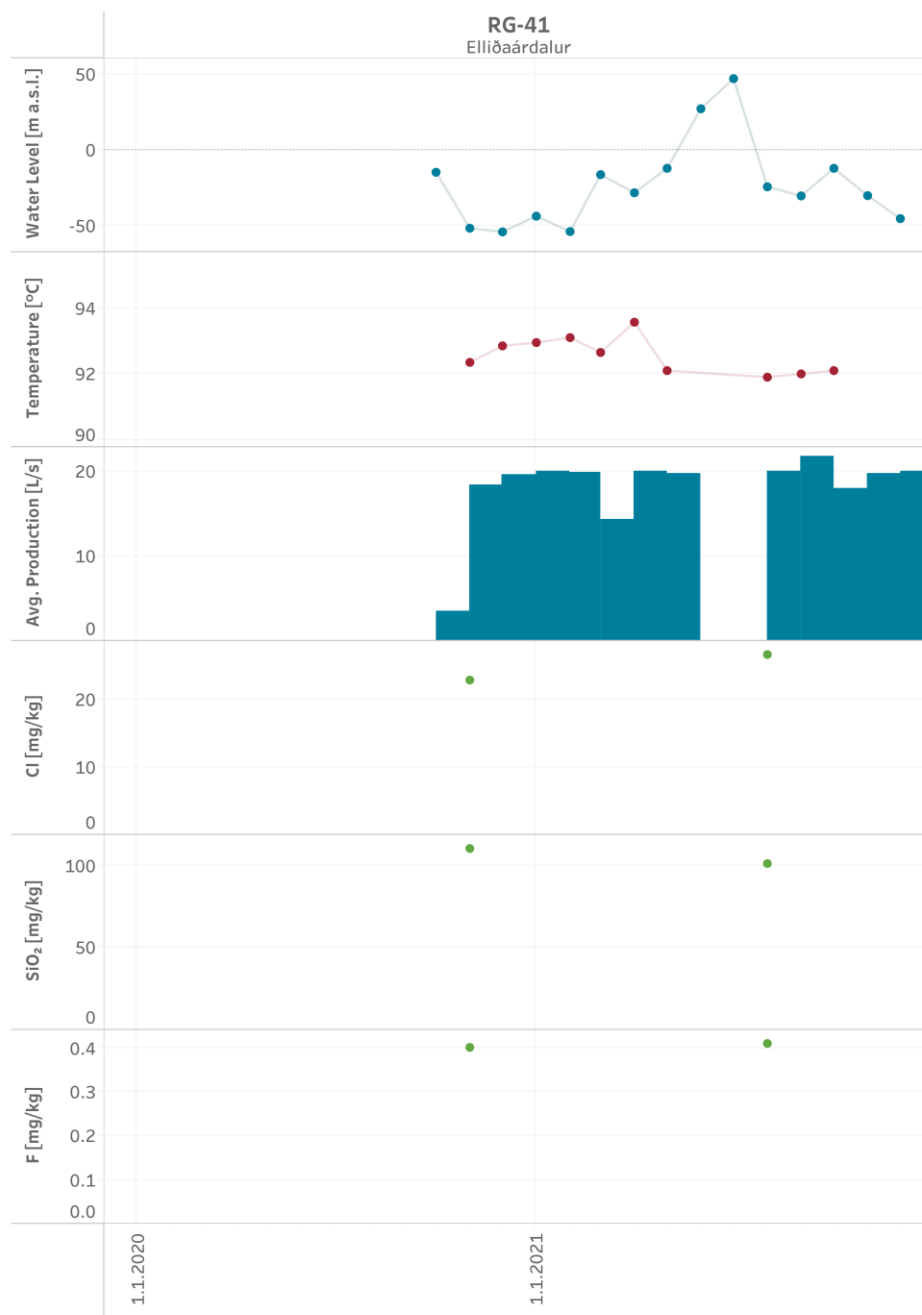


Figure 14. Water level data, temperature of produced fluid, average production, and concentration of Cl, SiO₂ and F in produced fluid from RG-41.

3.3 Analysis of changes in chemistry

The decreasing temperature of water produced from the Elliðaárdalur field has been accompanied by significant changes in the chemical composition of the water produced from the wells. Figure 15 shows how the concentration of selected components has changed over time in well RG-31. This pattern is typical for other wells in the area that have significant production history although the timing of the chemical changes varies between wells across the field. In short, the pattern seen in all wells is that the concentrations of Cl, CO₂, Ca and O₂ increase with time, as the temperature decreases. The concentrations of SiO₂ and F decrease with decreasing temperature. At the same time, other major components, such as Na, K, SO₄, remain nearly constant as the temperature of the wells decreases. The chemical changes and their relationship to changing temperature and production rate are discussed in more detail below.

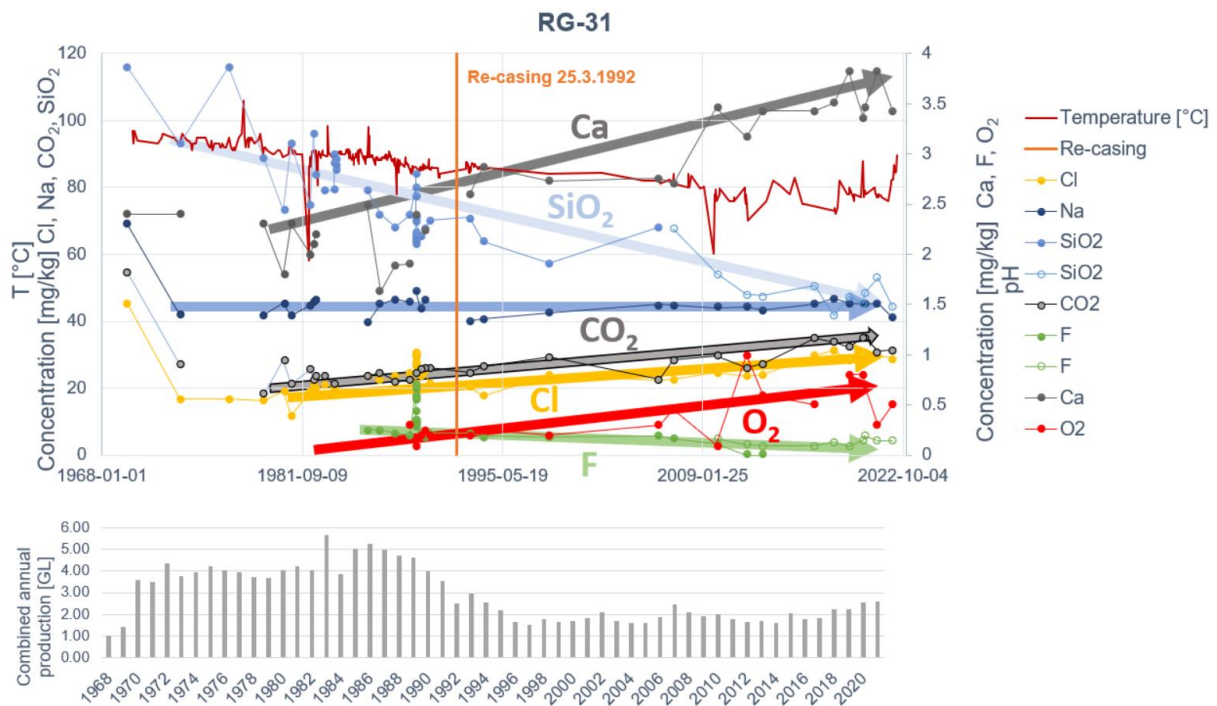


Figure 15. Temperature and concentrations of selected components in water from well RG-31 with time along with combined annual production from the Elliðaárdalur field.

3.3.1 CI

Figure 16 shows all available CI data from the production wells in Elliðaárdalur. In the first ~15 years of production (13 to 20 years, depending on the well), the CI concentrations were confined to a fairly narrow range, between 17 and 21 mg/kg. The most notable exceptions are the very first samples from wells RG-29, RG-30 and RG-31, collected in October 1969 and these will be discussed later.

When the production rate declined after 1990 there was, initially, a trend towards lower CI concentrations. Right after the point of peak production, in 1989, the range of CI concentrations was from 17.7 to 27.7 mg/kg. In 1994 this had dropped to 16.5-17.8 mg/kg. In the years following 1994 the trend towards higher CI concentrations resumed in all wells used in the field even though the annual production rate did not increase again. In 2022 the CI concentrations across the field ranged from 24 to 29 mg/kg.

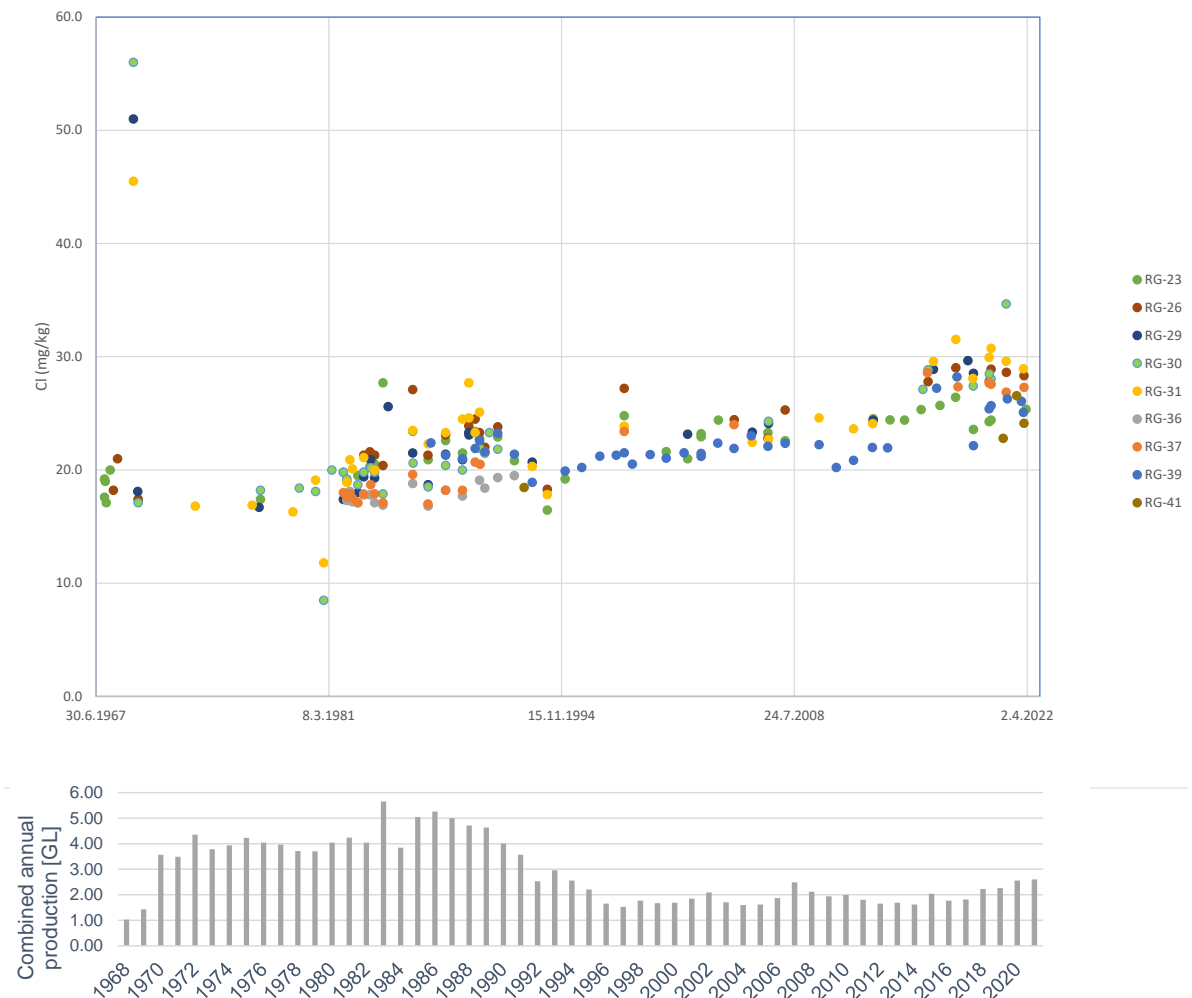


Figure 16. CI concentrations in samples from the Elliðaárdalur production wells with time (above) and total annual mass production from the field (below).

The Cl concentration changes in Elliðaárdalur did not appear uniformly across the field. First signs of increased Cl concentration start to emerge at around 1981 in samples from RG-30 and RG-31. This trend soon emerged in other wells, such as RG-23, RG-26 and RG-29, a little later. By 1989 the Cl concentrations in these wells had reached 22 to 25 mg/kg. During this time, the Cl concentrations in the two easternmost wells, RG-36 and RG-37, remained more or less constant at slightly below 17-18.5 mg/kg. The first signs of increased Cl concentration in RG-37 appear in 1989 and 1990 when the Cl concentrations reached ~20.5 mg/kg in a couple of samples. Figure 17 highlights the different timing of the Cl changes in RG-31 as compared to RG-37.

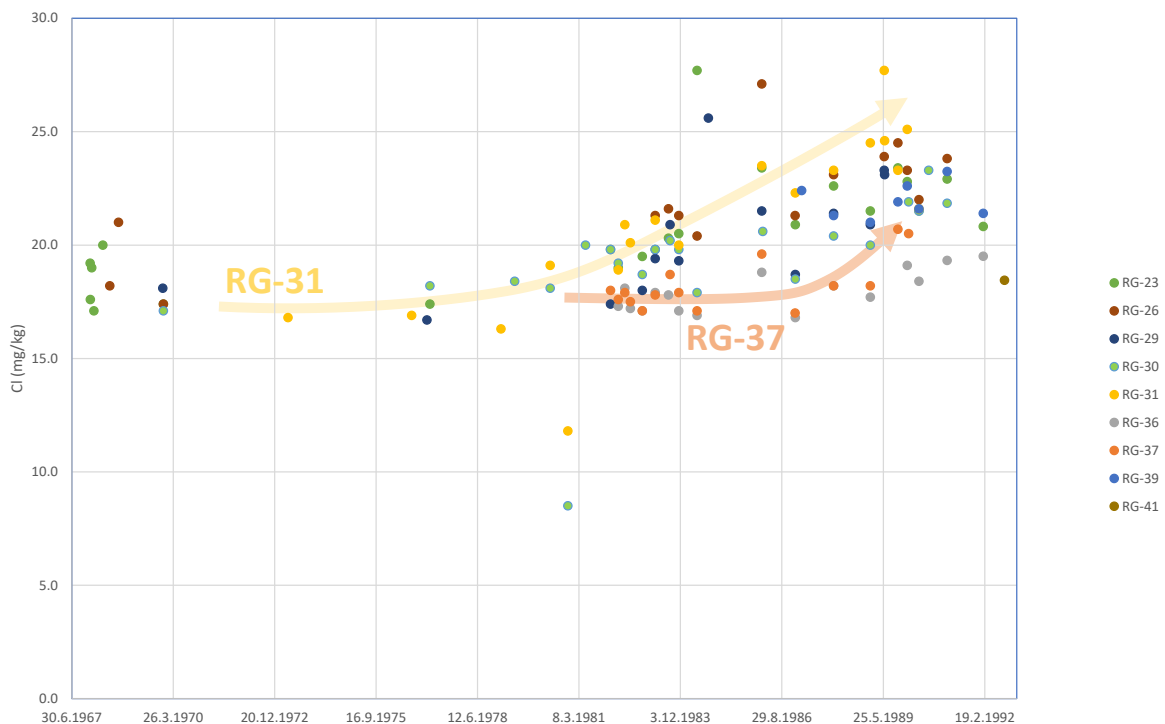


Figure 17. Cl concentrations in the Elliðaárdalur wells from beginning of production to the end of 1992. Arrows highlight how the Cl increase emerges in wells RG-31 and RG-37. The Cl increase emerges about 10 years earlier in RG-31, in the SW part of the field than in RG-37 in the NE part.

Figure 16 shows how Cl concentrations decrease slightly with decreasing mass production from the field after the production peaked in 1987. At around 1990 Cl concentrations were very similar to the initial Cl levels, i.e., slightly below 20 mg/kg. After 1995 the Cl concentrations started rising again, even though the mass production remained constant at about 40% of the production rate of 1987.

Figures 18 to 22 show maps that depict the changes in chloride concentration at different times from an average starting value for the field based on samples taken between 1967 and 1981. They show how the increased chloride concentration appears to initially enter the field from the western side and at later stages more from the south. The change between samples in 2005-2008 and the initial value is greatest in wells RG-26 and RG-30 (Figure 21). This could be due to downflow of colder water in these wells.

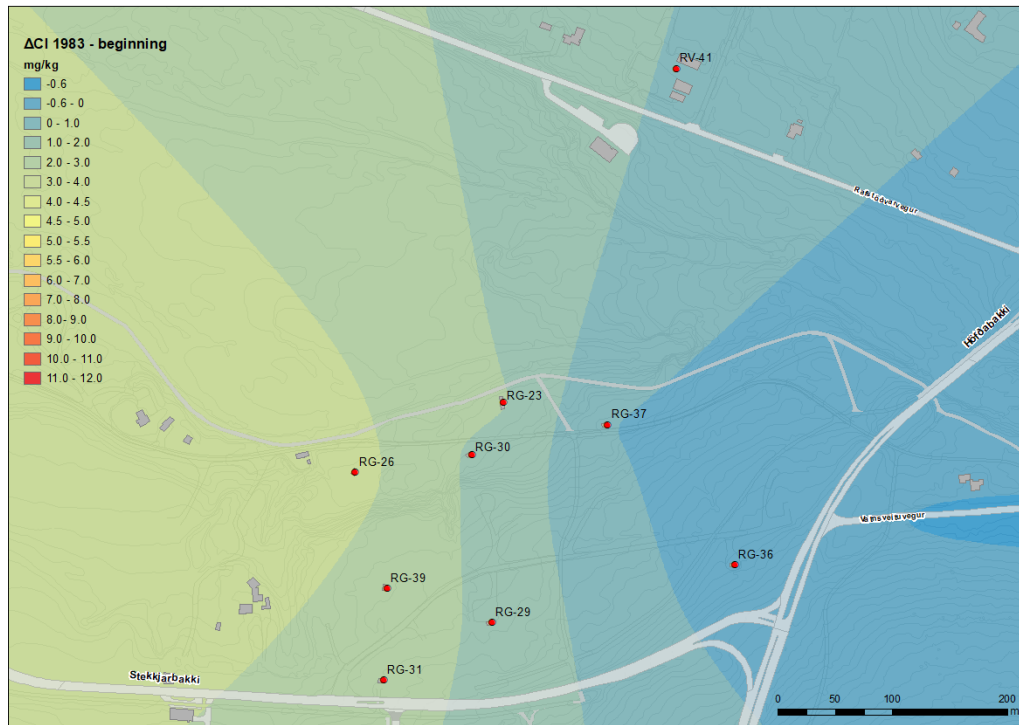


Figure 18. Changes in chloride concentration between samples taken in 1983 and an average chloride concentration for the beginning of production.

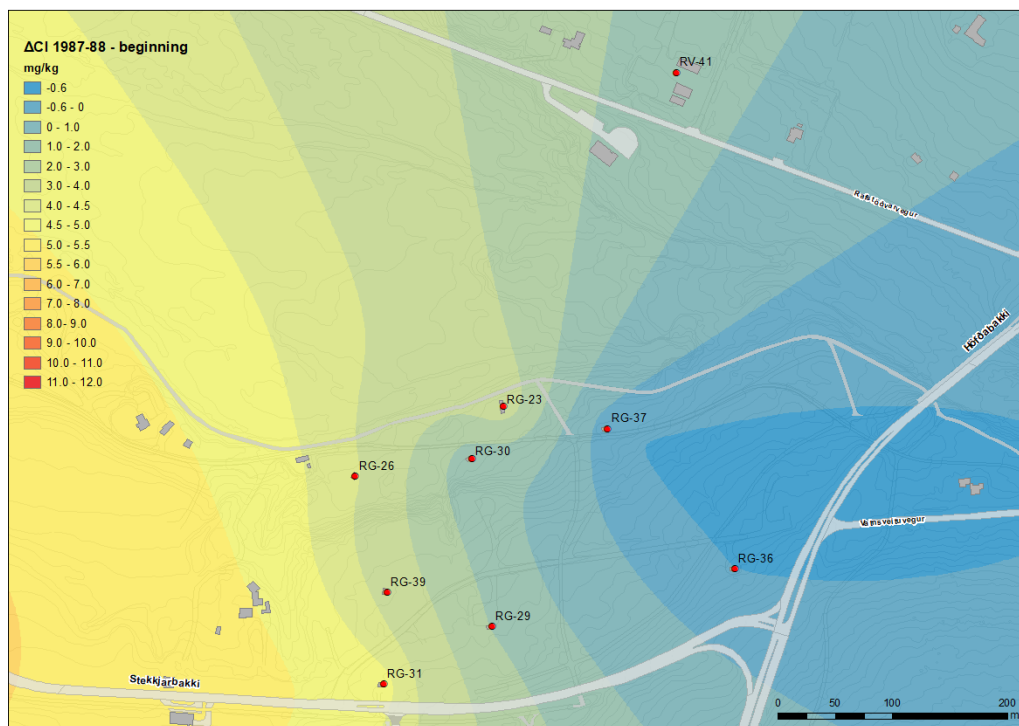


Figure 19. Changes in chloride concentration between samples taken in 1987-1988 and an average chloride concentration for the beginning of production.

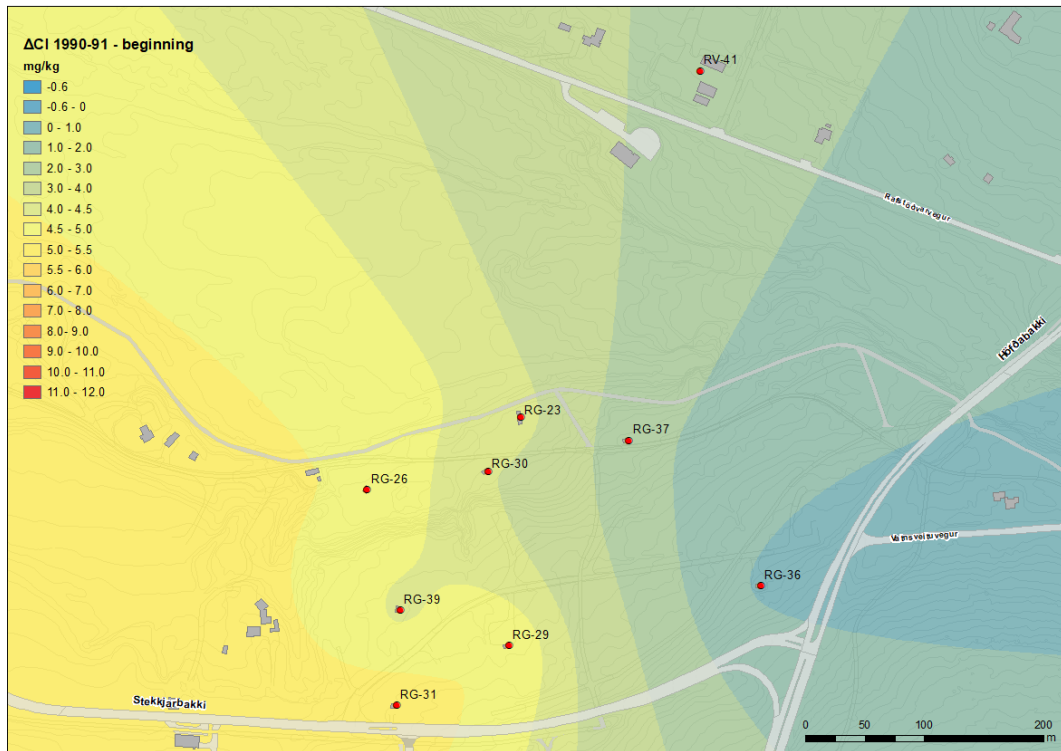


Figure 20. Changes in chloride concentration between samples taken in 1990-1991 and an average chloride concentration for the beginning of production.

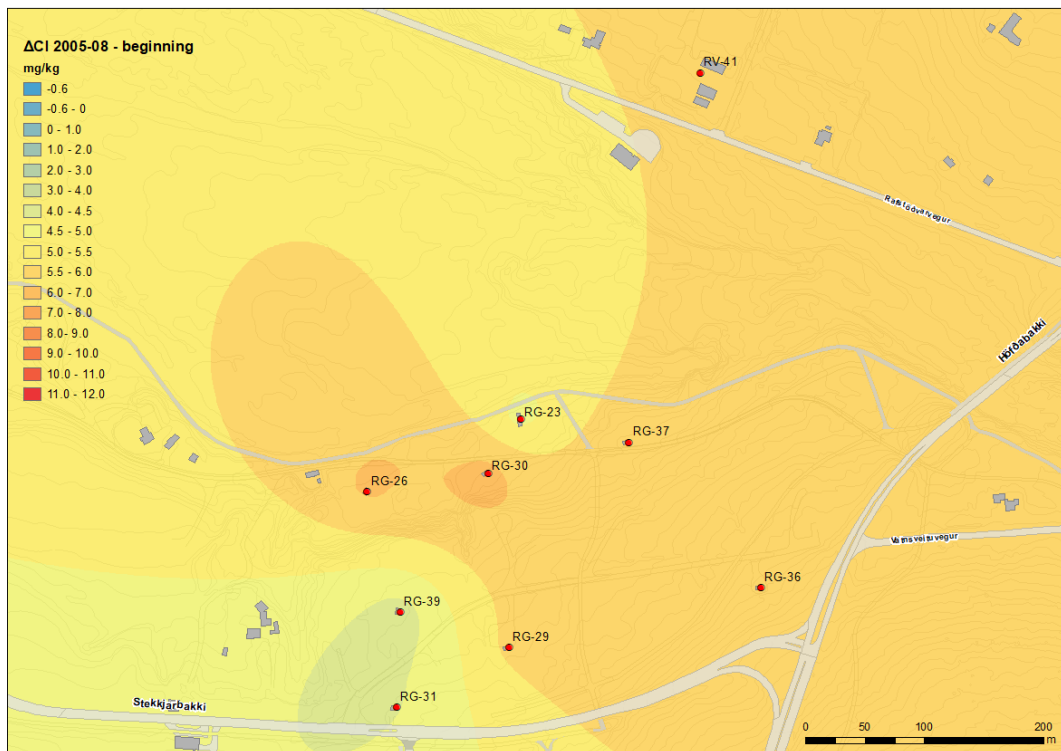


Figure 21. Changes in chloride concentration between samples taken in 2005-2008 and an average chloride concentration for the beginning of production.

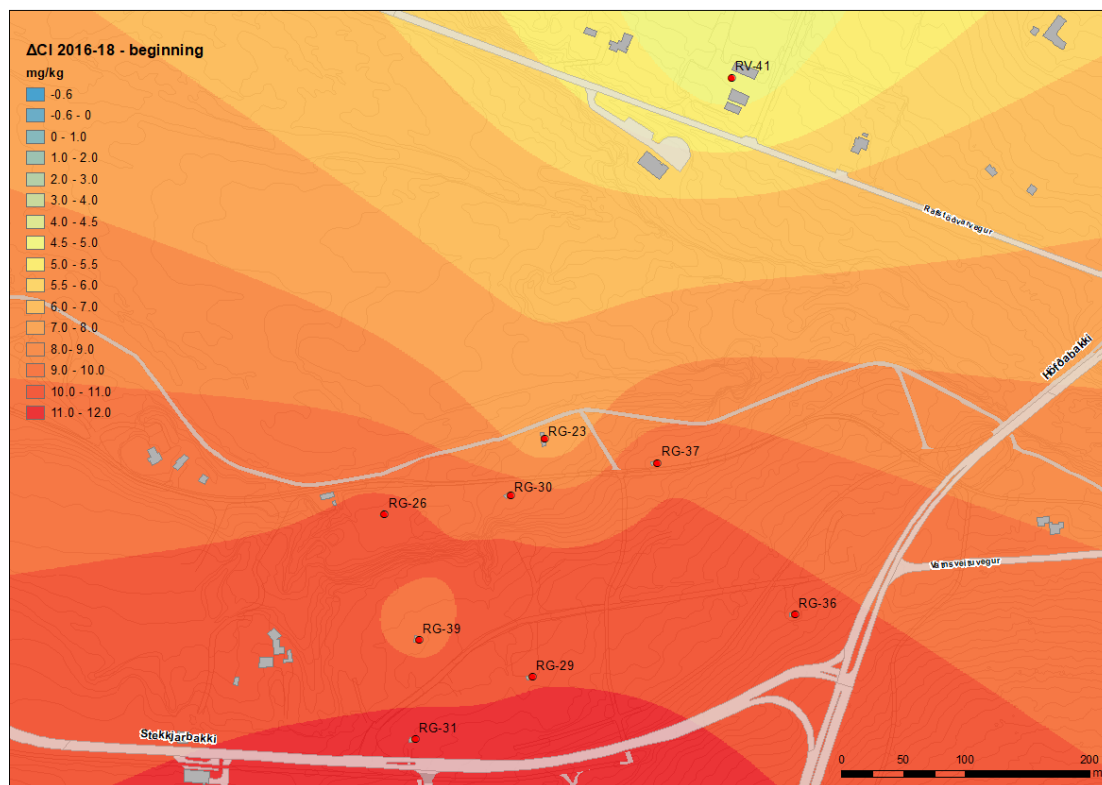


Figure 22. Changes in chloride concentration between samples taken in 2016-2018 and an average chloride concentration for the beginning of production. Well RG-41 was only taken into usage in 2020 and the sample from there is from that year.

The earliest samples from wells RG-29, RG-30 and RG-31 show anomalously high Cl concentrations compared to later samples from these wells and the field in general (Figure 16) or between 45 and 55 mg/kg. Four samples collected from wells 25 and 28 in 1982, 1985 and 1989 also show Cl concentrations between 45 and 50 mg/kg. The samples from R-25 and 28 were collected from artesian flow from the wells. The temperatures of these samples were around 41°C. The pressure conditions in the field in the 1980s and the temperature of the fluid indicate that this fluid originated in the shallow A aquifers. This confirms the presence of water with elevated Cl concentrations in the shallower aquifers of the system. It seems likely that these shallow geothermal fluids have picked up Cl from marine sediments that are present at 50 to 100 m depth in parts of the field (Guðmundsdóttir, 1989).

3.3.2 O₂ and pH

Figures 23 and 24 show the concentrations of O₂ and the pH values of all available samples from the Elliðaárdalur field, respectively. Unfortunately, O₂ and pH data are not available for samples collected before 1983. Despite considerable scatter in the O₂ data it can be clearly seen from Figure 23 that O₂ was in detectable concentrations in even the earliest samples available. Between 1983 and 1989 the O₂ concentration was moderate, between 0.05 and 0.2 mg/kg. In 1989 there was an abrupt increase in O₂ concentration in several wells (RG-26, RG-29, RG-30, and RG-31). This trend also emerged in other wells, such as RG-23 and RG-39. The only well that has been in use throughout the production history that has not exhibited this trend was well RG-37. It is worth noting that the wells that showed the most intense O₂ increase in the years following 1989 are the same wells that showed the strongest signs of Cl increase in the beginning.

The elevated O₂ concentrations observed in the Elliðaárdalur fluids are very unusual for basalt hosted geothermal systems because of the highly reduced state of the host rocks. Even at temperatures as low as 30°C oxygen has generally been effectively removed from the geothermal waters by reactions with Fe²⁺ bearing minerals in the rock. The presence of O₂ in detectable, and even substantial concentrations in geothermal waters above 70°C in Elliðaárdalur is thus a strong indication that cold, O₂ bearing water, has found a short-cut into the aquifers that feed the production wells.

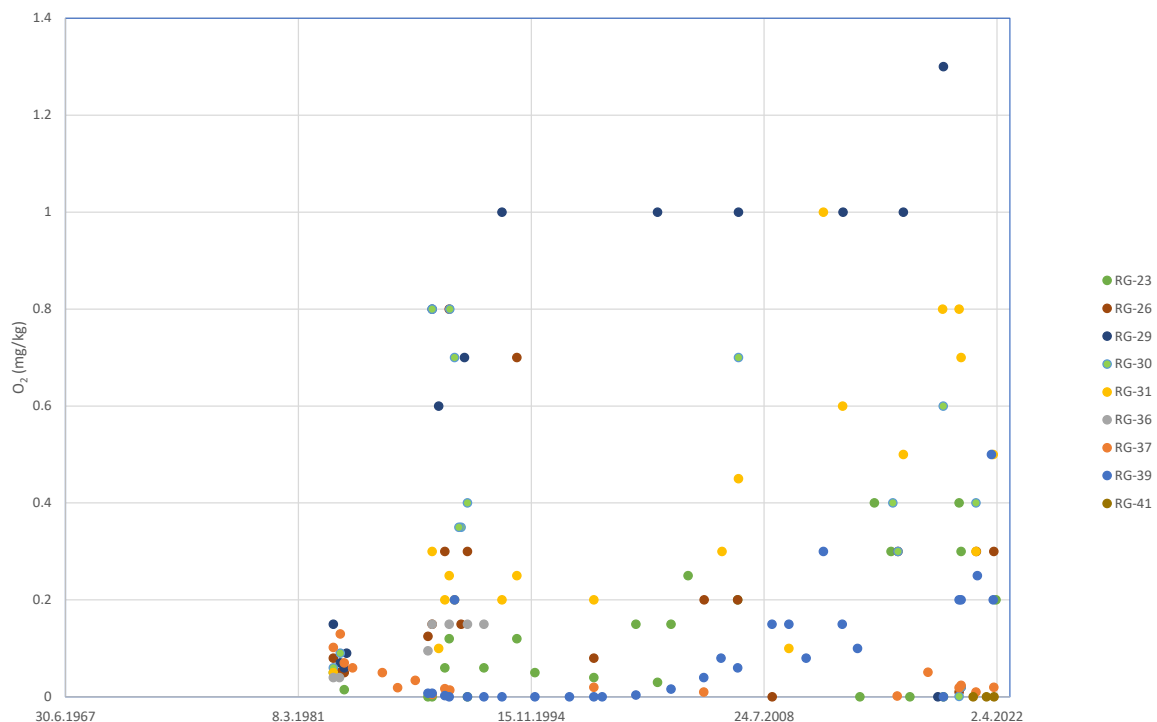


Figure 23. O₂ concentrations in the Elliðaárdalur production wells.

Figure 24 shows the pH values of all water samples collected from the Elliðaárdalur production wells. Again, the scatter is considerable as with the O₂ data but there is, nevertheless, a clear trend towards slightly lower pH values with time. This applies, in particular, to the wells that show the highest O₂ values, such as RG-29, RG-30, and RG-31. Well RG-39, on the other hand shows much more moderate shift towards lower pH values, consistent with the relatively modest O₂ increase.

It seems likely that these two components are connected through oxidation of sulphides, either H₂S in the geothermal fluid or sulphide bearing minerals in the host rock of the geothermal reservoir. Oxidation of sulphide by oxygen leads to the formation of sulphuric acid that drives down the pH.

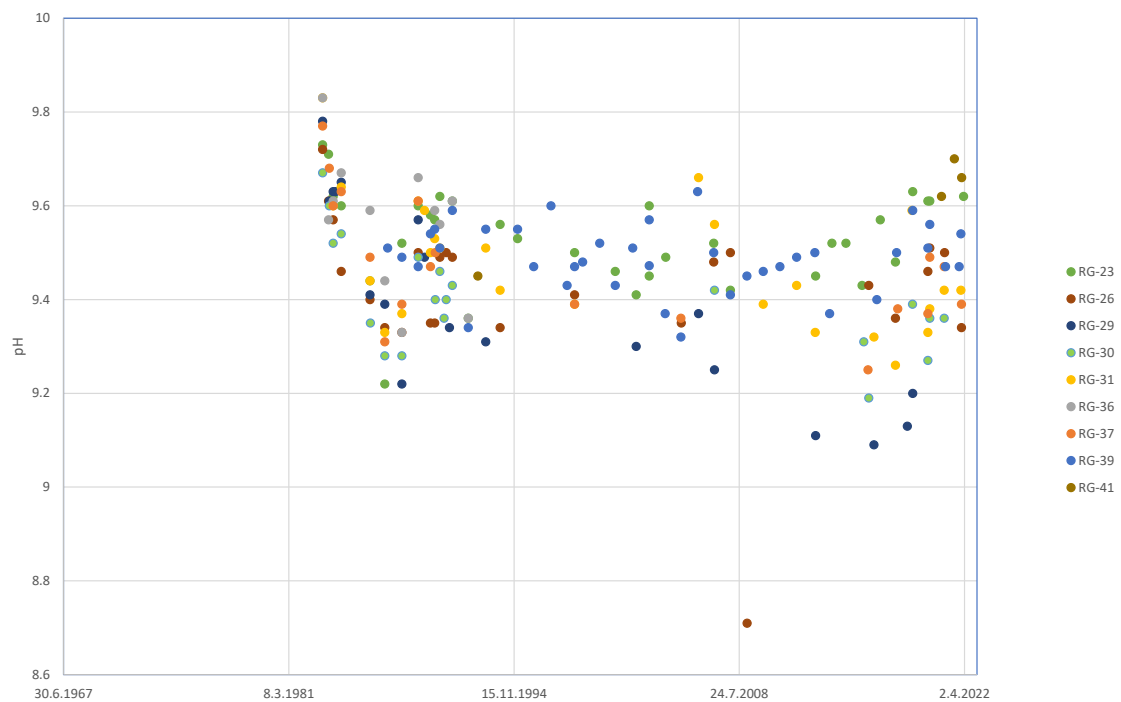


Figure 24. *pH values of water samples from the Elliðaárdalur production wells.*

3.3.3 Ca and CO₂

Figures 25 and 26 show all available Ca and CO₂ analysis, respectively, from the beginning of production to date. These figures show generally similar pattern to the Cl concentration shown in Figure 16. In both cases there is a 15-year period in the beginning, characterized by relatively constant concentration of these components. In this period the Ca concentrations range from 1.8 to 2.4 mg/kg and the CO₂ concentrations range between 20 and 30 mg/kg. During the period of maximum production, i.e., 1984 to 1989, the scatter of Ca and CO₂ increases compared to the previous 15 years, but no clear trend emerges during that period. However, once the production rates start to decline, after 1989, both Ca and CO₂ start to show clear trends towards higher concentrations. In 1989 the Ca concentrations range between 1.7 and 2.5 mg/kg whereas the corresponding values in 2020 are 2.7 to 5.1 mg/kg with most values falling between 3 and 4 mg/kg. In 1989 the range of CO₂ values was between 21 and 27 m/kg, whereas in 2020 the concentration of CO₂ ranged from 27 to 37 mg/kg.

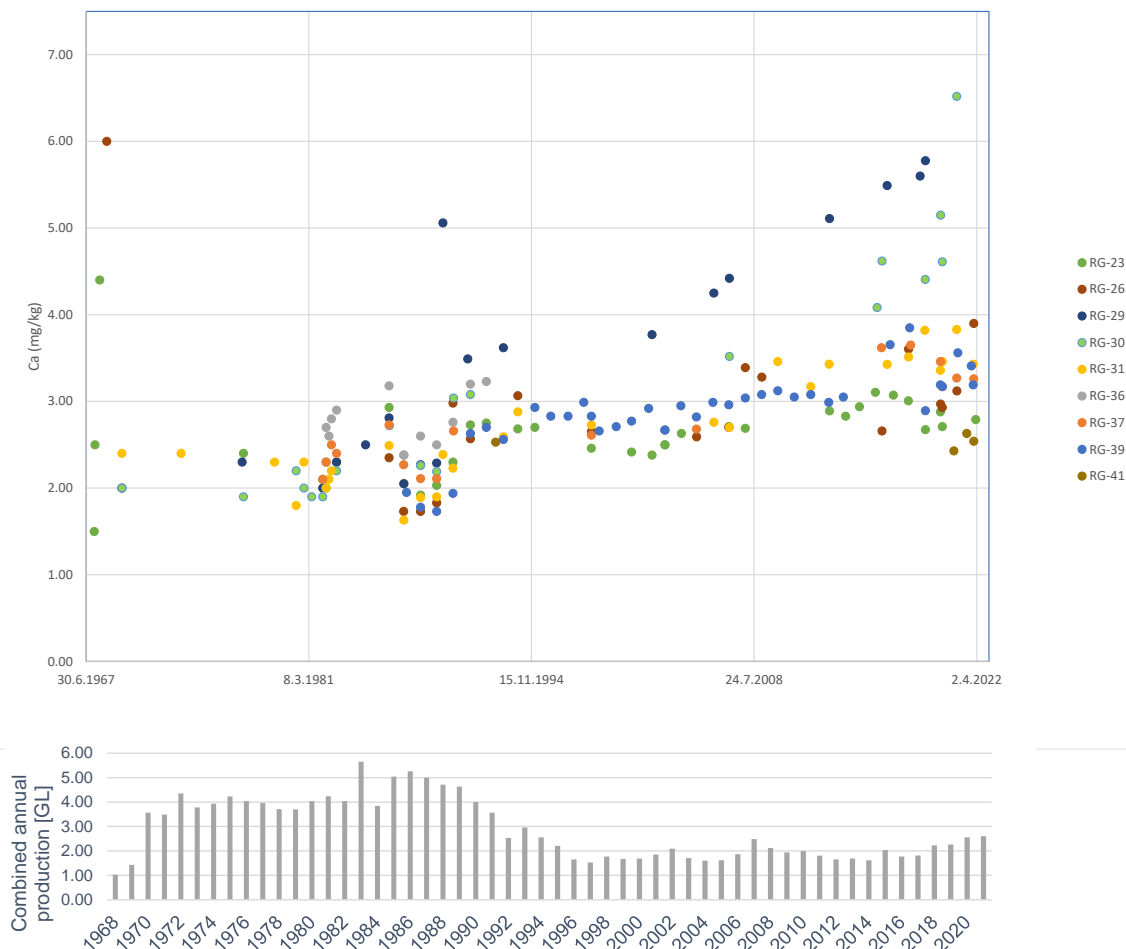


Figure 25. Ca concentrations in samples from the Elliðaárdalur production wells with time (above) and total annual mass production from the field (below).

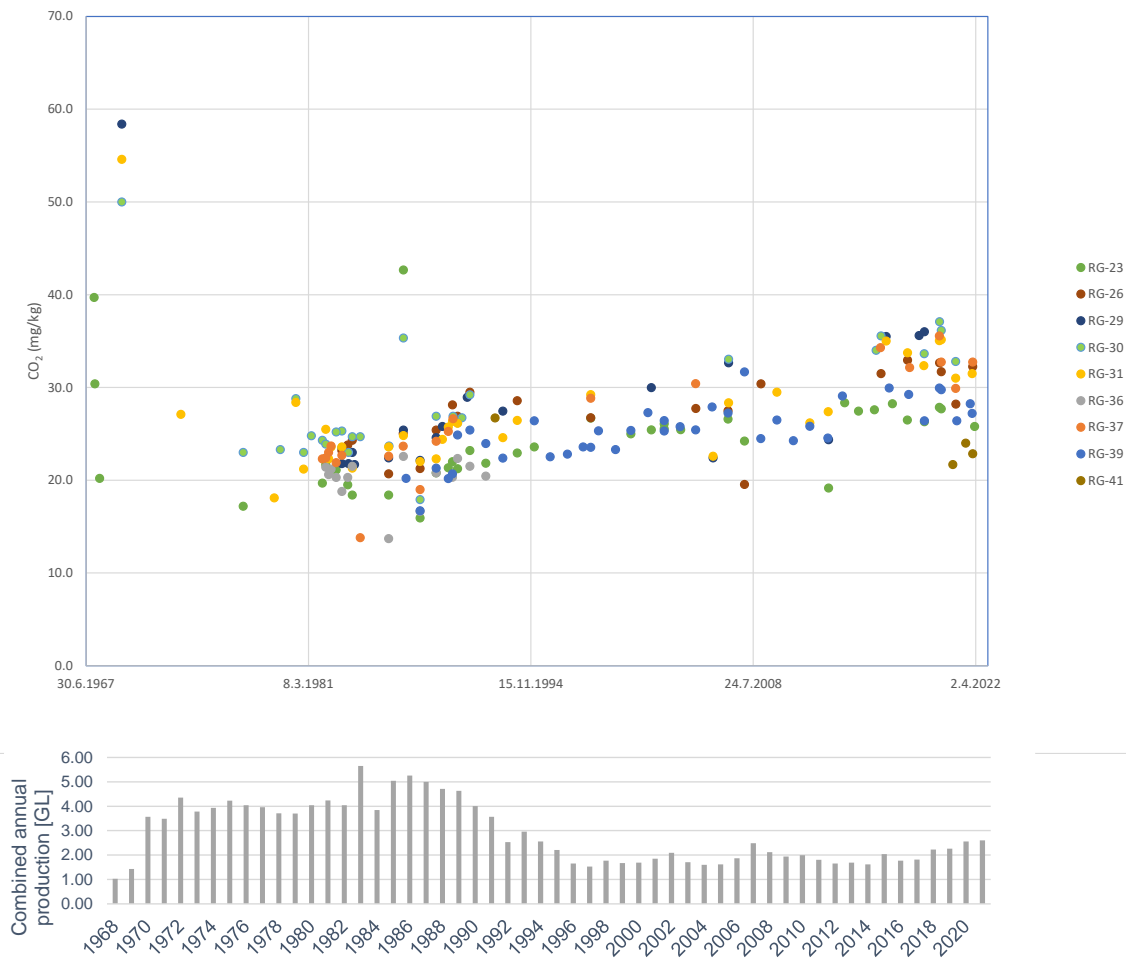


Figure 26. CO₂ concentrations in samples from the Elliðaárdalur production wells with time (above) and total annual mass production from the field (below).

It seems likely that the increase in Ca and CO₂ concentrations observed in the field from the early 1980s is a result of slightly reduced pH values of the geothermal fluids as a result of sulphide oxidation, discussed above. The authors of this report argue that the decreased pH value of the fluid, resulting from sulphide oxidation, has resulted in dissolution of calcite and other carbonates present in the host rock. This is supported by speciation calculations for selected samples from well RG-29, that showed the most distinct increase in Ca concentration and decrease in pH. These calculations show that calcite has remained very close to saturation with respect to the produced fluids despite the substantial changes in pH, Ca and CO₂ over time.

3.3.4 SiO₂

Figure 27 shows the SiO₂ concentrations in the Elliðaárdalur production wells with time. The figure shows that the SiO₂ concentrations have been declining with time from the earliest days of production from the field. This trend mirrors the declining temperature of the produced fluids from the beginning. This correlation between SiO₂ and temperature is not surprising as SiO₂ is a reactive component in geothermal systems and is strongly controlled by the solubility of silica minerals (chalcedony at lower temperatures and quartz at temperatures above ~150°C).

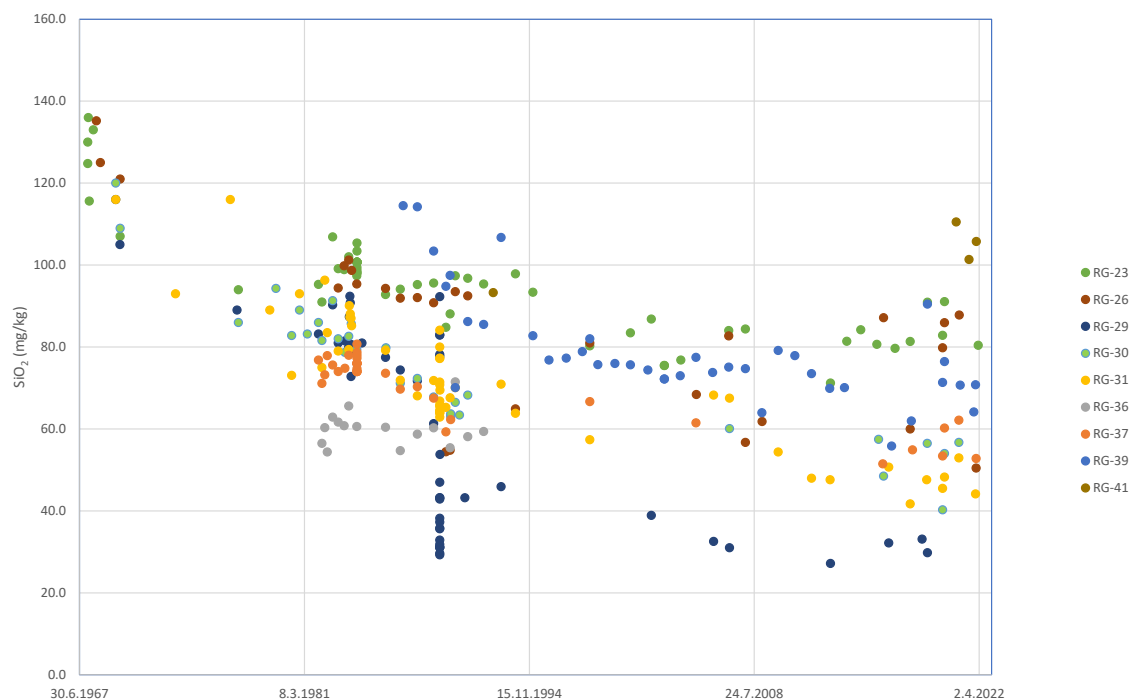


Figure 27. SiO₂ concentrations in Elliðaárdalur production wells.

The observed decline in silica concentration could either be explained by gradual cooling in an otherwise chemically uniform reservoir or by gradually increasing proportion of colder fluids entering the reservoir. Considering the pattern of other components, particularly Cl and O₂, the latter seems much more likely in this case. This variation in SiO₂ concentration with time has been explained as mixing between two components of different temperatures in earlier studies (Gunnlaugsson, 1982; Gudmundsdóttir, 1989).

3.3.5 Na

Figure 28 shows the Na concentrations of the Elliðaárdalur geothermal fluids over time. Although there seems to be a slight increase in Na concentrations from the earliest samples, the concentration of this component has remained fairly constant since the mid-1980s. There seems to be slight dip in the Na concentrations after 1990 that coincides with a dip in Cl concentrations at that time. However, the rebound seen in the Cl concentrations since the early 2000s does not seem to have been mirrored by a similar increase in the Na concentrations. This comes as a surprise as the Cl concentrations have increased over this period by some 5 mg/kg. However, a more detailed appraisal of the relationship between Na and other cations

and Cl since 2000 is needed. This requires speciation calculations of a number of samples from wells that show an increase in Cl to assess whether the charge balance has been systematically shifting since 2000. This is beyond the scope of the current work.

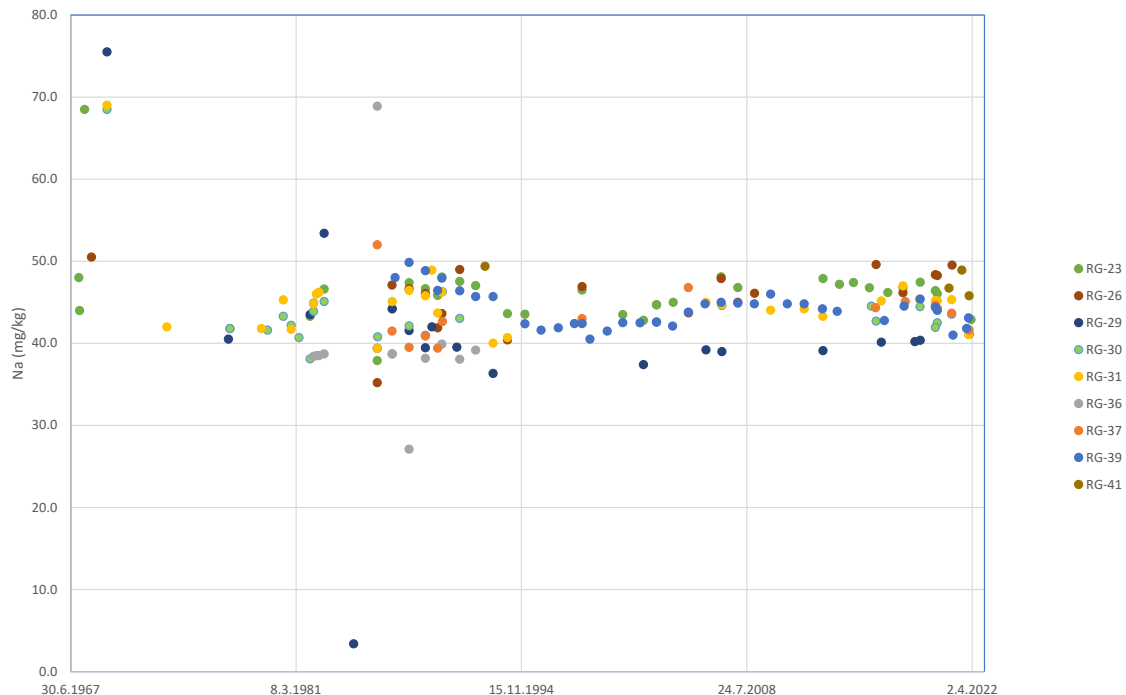


Figure 28. Na concentrations in samples from the Elliðaárdalur production wells with time.

3.4 Characteristics of the different fluid types in the Elliðaárdalur field

A full revision of the conceptual model for the Elliðaárdalur geothermal field is beyond the scope of the work presented in this report but the analysis of the geothermal fluid chemistry discussed above allows us to draw some conclusions that need to be considered when a conceptual model is developed in the next phase of this work. These observations are summarized below.

- The fluids produced from the Elliðaárdalur field appear to be mixture of two to four components
 - Low-Cl, hot geothermal fluid; <18 mg/kg Cl and >100°C. This appears to be the “original” geothermal fluid in the system. Temperature log data indicates that this fluid dominated B aquifers at 500 to 1000 m depth before production.
 - Low-Cl, slightly colder geothermal fluid; <18 mg/kg Cl and 70 to >100°C. This water is in the C aquifers below the B aquifers. Wells RG-31 and RG-36 are thought to produce predominantly from the C aquifers (Tómasson, 1988) and initial samples from these wells thus show the composition of the C aquifers. They seem to have comparable Cl concentration as the B aquifers.

- High-Cl, intermediate temperature fluid; 45-55 mg/kg Cl and ~40°C. This fluid has been referred to as peripheral water and could be a mixture of the original geothermal fluid and groundwaters that have picked up Cl from marine sediments at 50 to 100 m depth. This fluid may or may not have contained O₂ before production.
- Probably also O₂-bearing surface water, assuming that the peripheral waters were originally O₂ free.
- Declining temperature at constant Cl concentrations during the first decade of production is not consistent with a simple model of colder, high-Cl water into the producing aquifers. If that were the case the Cl increase would have preceded the temperature decline.
- This pattern can be explained if we assume that under pre-production conditions the low-Cl, hot fluids were seeping out of the isothermal and chemically homogenous B aquifers into the upper and colder A aquifers forming a zone dominated by colder, low Cl water above the isothermal B aquifers.
- When production starts the flow pattern in the system is reversed and water starts to flow from the A aquifers to the B aquifers. Initially the colder water from the A aquifers is cooled low-Cl water but with time the peripheral waters are drawn in, leading to increasing Cl concentration of the produced fluids. This flow from the A aquifers to B aquifers can be through the wells themselves or through fractures or other structural pathways.
- Another explanation lies in a greater portion of the produced water coming from the C aquifers than the B aquifers with time. These aquifer sequences seemed to have a similar chloride concentration in the beginning, but the C aquifers were colder. As more of the water came from the cooler C aquifers, the temperature of the produced fluid decreased.
- Dissolved oxygen is not stable in basalt hosted geothermal systems. The presence of O₂ in detectable concentrations and even as high as 1 mg/kg indicates that O₂ bearing water (groundwater) has found shortcuts into the producing aquifers of the geothermal system under the pressure conditions prevailing in the reservoir during production. This can for example be through downflow in the wells themselves or through fractures.

4 Conclusions/Discussion/Next steps

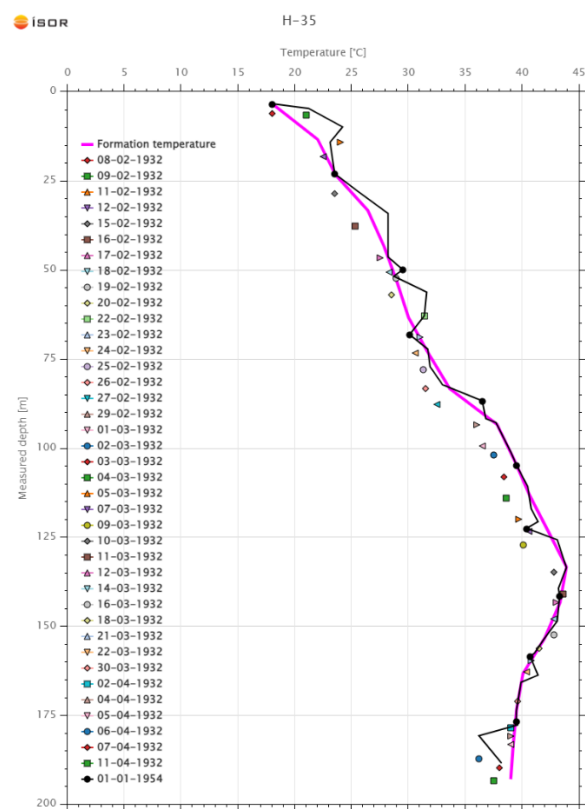
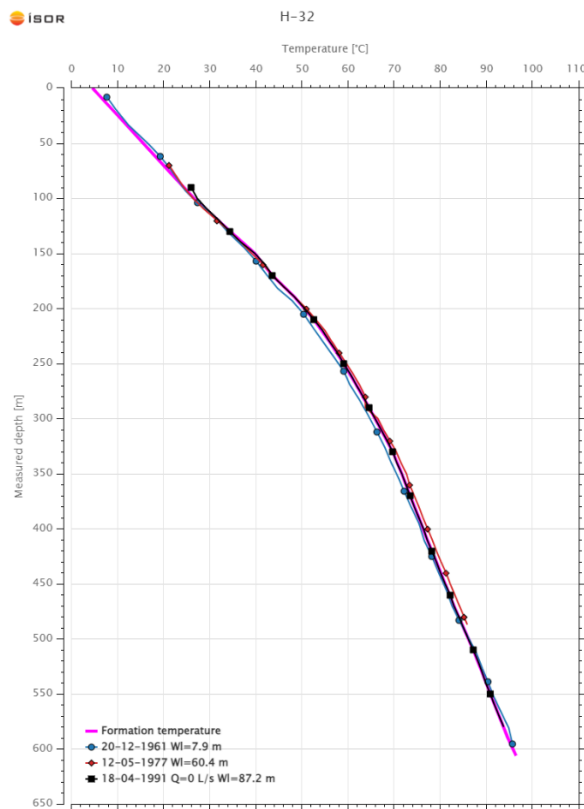
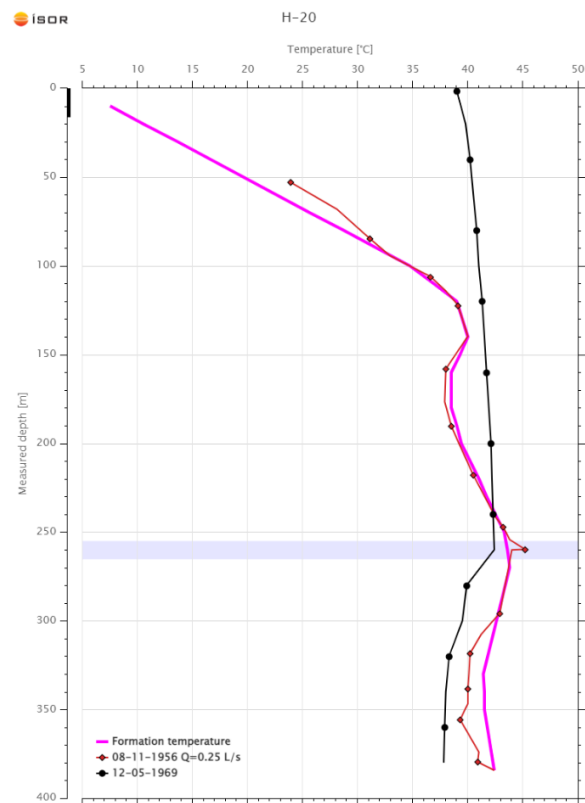
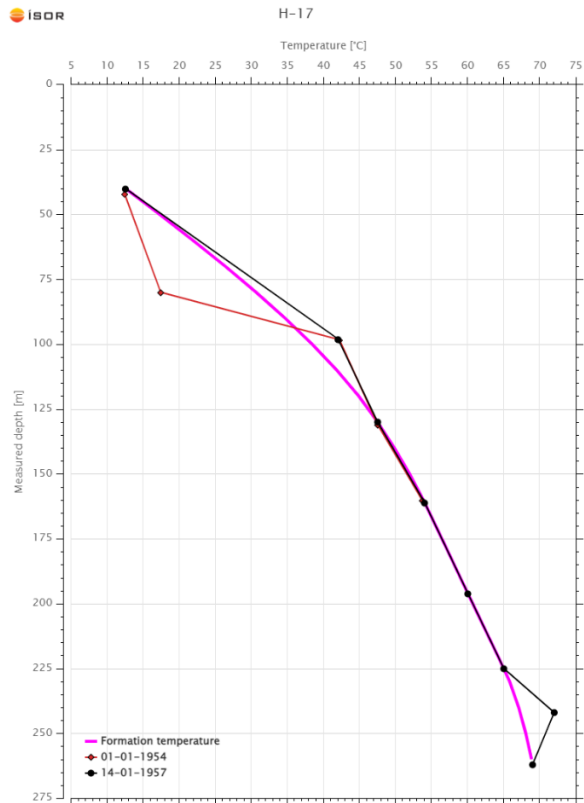
The previous chapters have described the changes in the reservoir in the Elliðaárdalur field. The decreasing temperature of the water produced from the Elliðaárdalur field has been accompanied by significant changes in the chemical composition of the water produced from the wells. In short, the pattern seen in all wells is that the concentrations of Cl, CO₂, Ca and O₂ increase with time, as the temperature decreases. The concentrations of SiO₂ and F decrease with decreasing temperature. At the same time, other major components, such as Na, K, SO₄, remain nearly constant as the temperature of the wells decreases. The analysis shows that the cooling and change in chemical composition is not the result of simple two fluid mixing but is a combination of different processes. The next steps will be to revise the conceptual model of the field and to make suggestions of improved utilization.

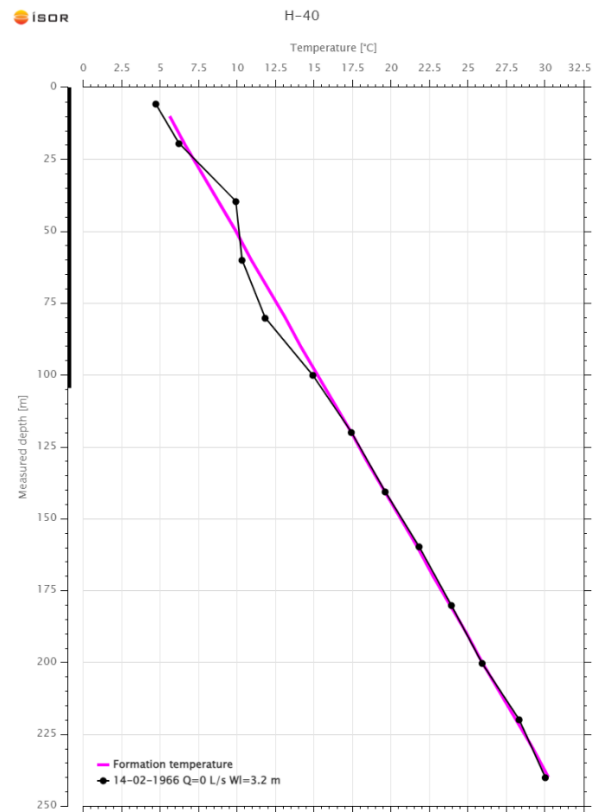
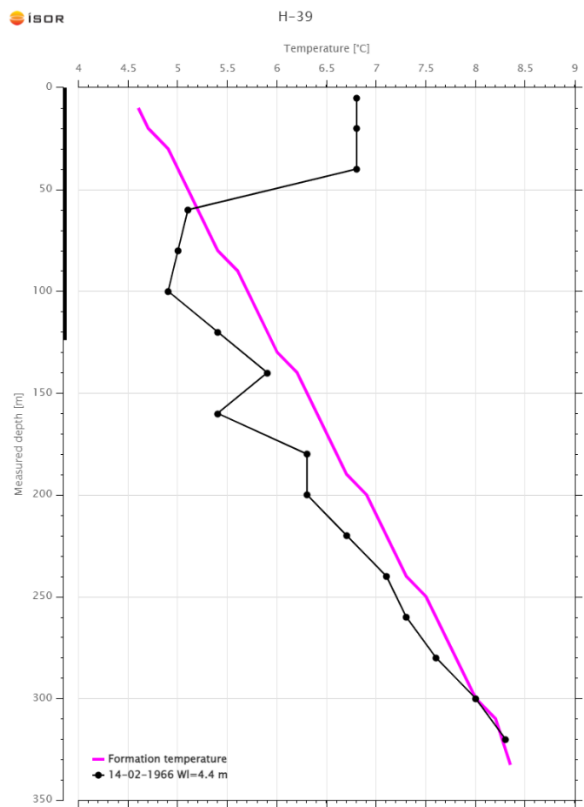
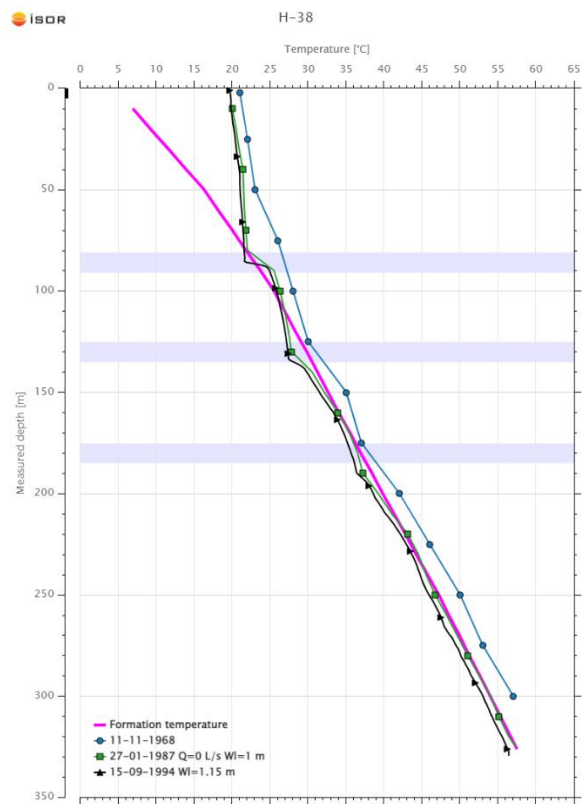
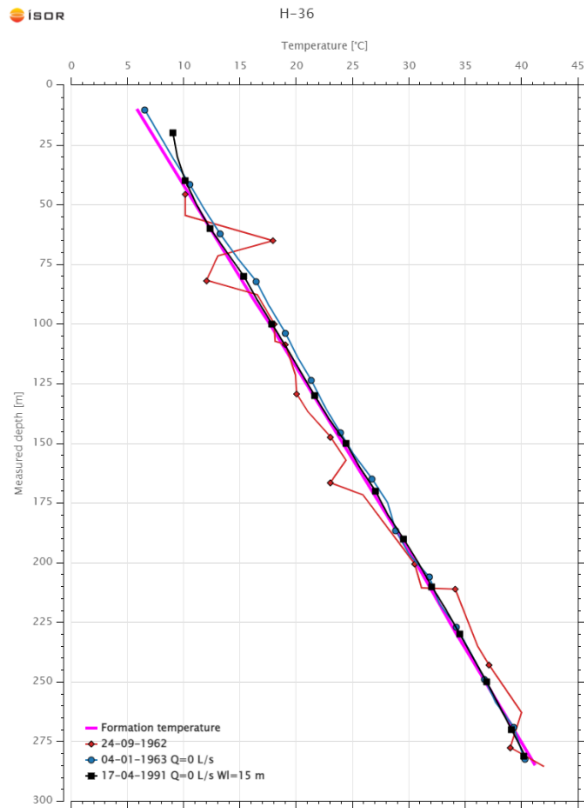
5 References

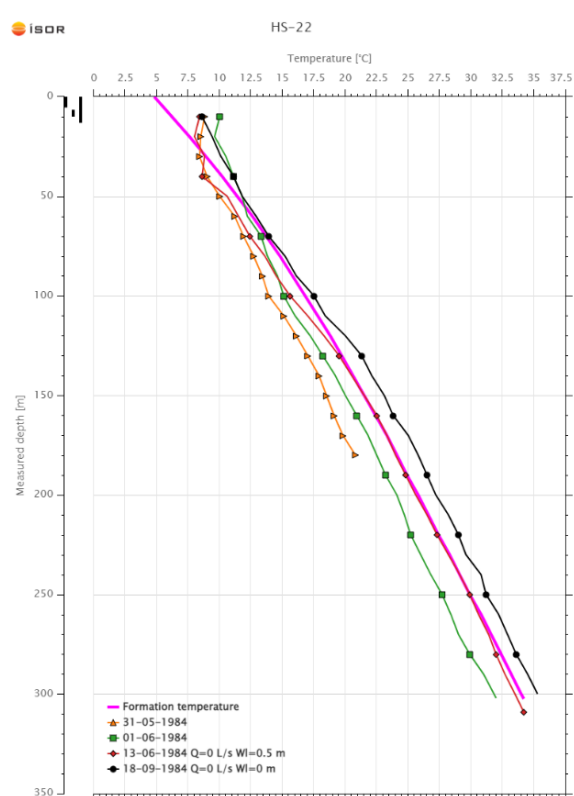
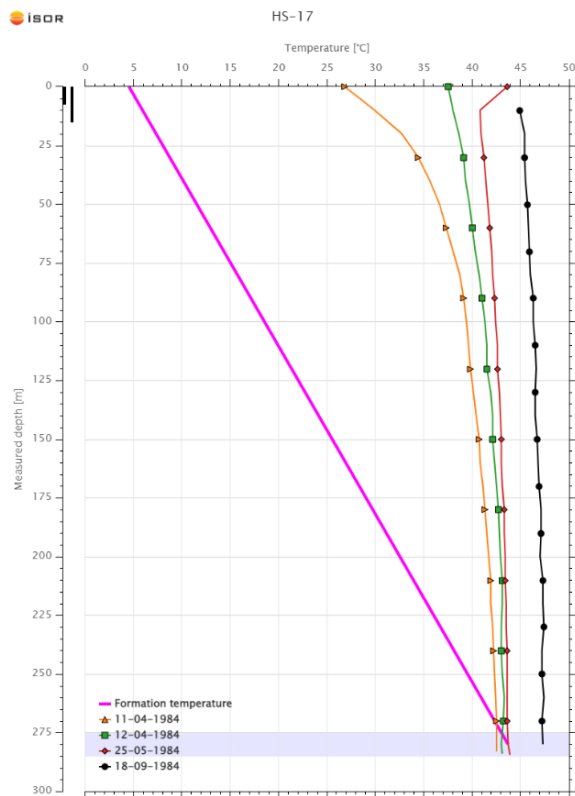
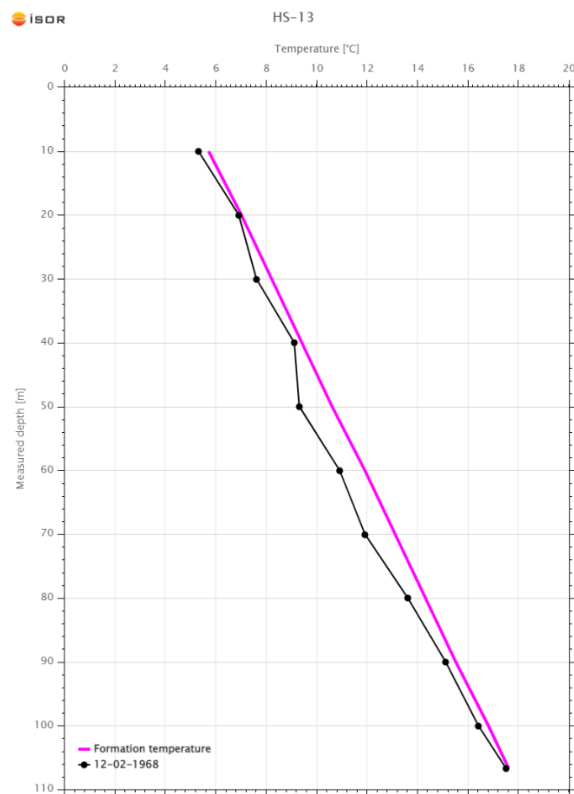
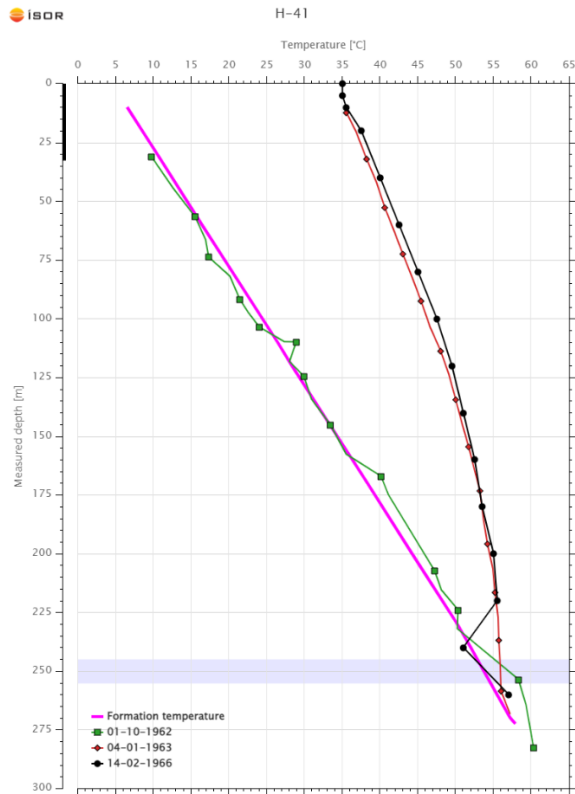
- Guðmundsdóttir, A.L. (1989). *Samantekt efnafræðigagna 1967-1989* [Chemistry data from the period 1967-1989]. Reykjavík: Reykjavík Energy
- Gunnlaugsson, E. (1982). *Efnagreiningar á vatni á Elliðaársvæði* [Chemical analysis from the Elliðaárdalur field]. Reykjavík: Reykjavík Energy
- Jónsson, J.E., Tulinius, H., Tómasdóttir, S., Richter, S.Ý., Þorgilsson, G., Kaldal, G.S., Pálsdóttir, A., Kristjánsson, B.R., and Helgadóttir, H.M. (2021). *RESULT-D6.1: Review of stimulation efforts and guidelines for drilling and completion of low temperature wells in Elliðaárdalur field*. Iceland GeoSurvey, ÍSOR-2021/038. GEO THERMICA – ERA NET Cofund, deliverable report.
- Reykjavík Energy (n.d.). *Saga OR og tímalína* [The history of OR and timeline]. Reykjavík: Reykjavík Energy. Available at: <https://www.or.is/um-or/starfsemin/saga-or-og-timalina/>
- Sigurðsson, Ó. (1995). *Berghiti og hitabreytingar á Elliðaársvæðinu* [Formation temperature and temperature changes in the Elliðaárdalur field]. Report OS-95057/JHD-37 B. Reykjavík Orkustofnun
- Tómasson, J. (1988). *Elliðaársvæðið. Uppruni og eðli jarðhitans*. [The Elliðaárdalur field. The source and nature of geothermal activity]. Report OS-88027/JHD-03. Reykjavík: Orkustofnun.
- Tómasson, J. and Thorsteinsson, Þ. (1983). *Borun R-39 og framhald borana á lághitasvæðum Hitaveitu Reykjavíkur* [Drilling of well R-39 and the continuation of drilling within Reykjavík Energy's low temperature systems]. Reykjavík: Orkustofnun.

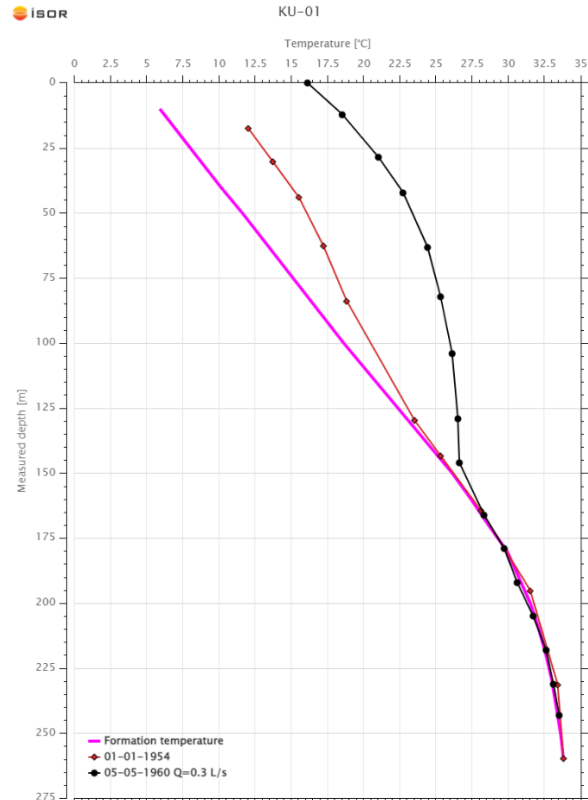
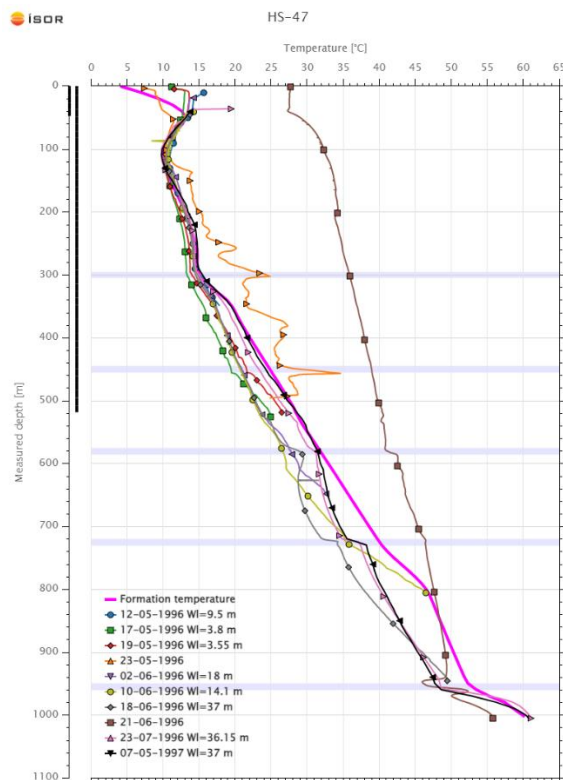
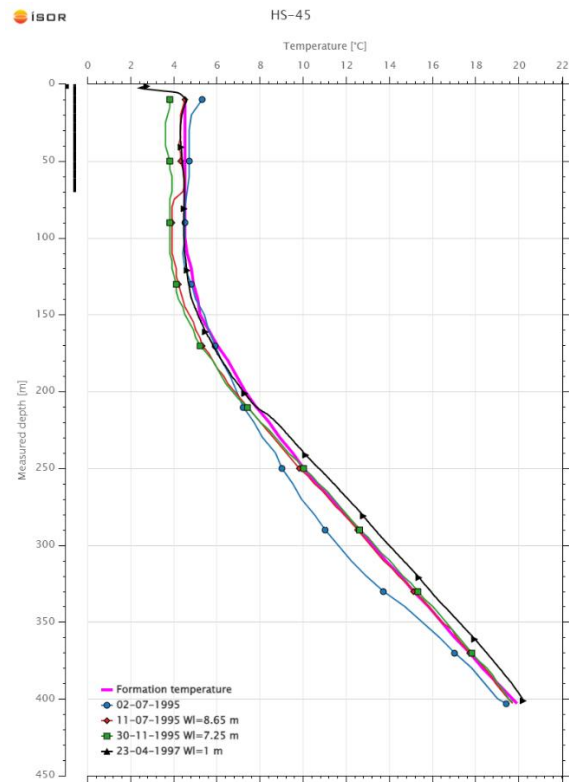
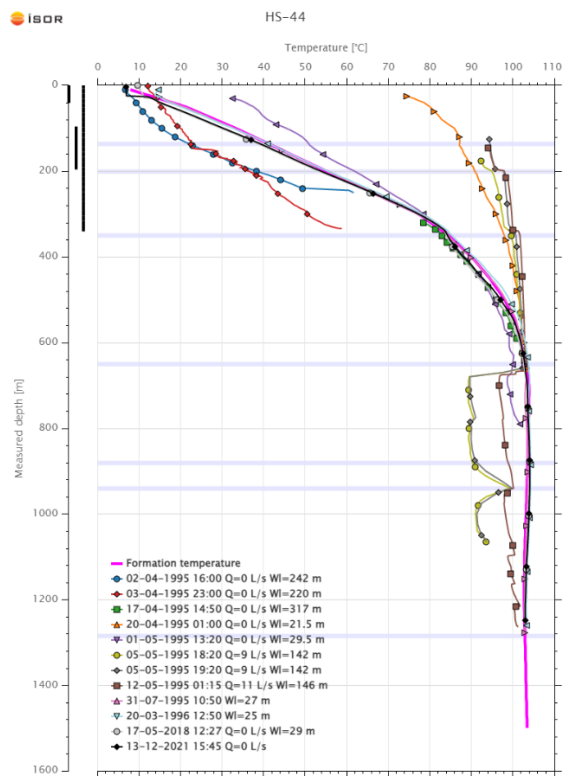
Appendix 1

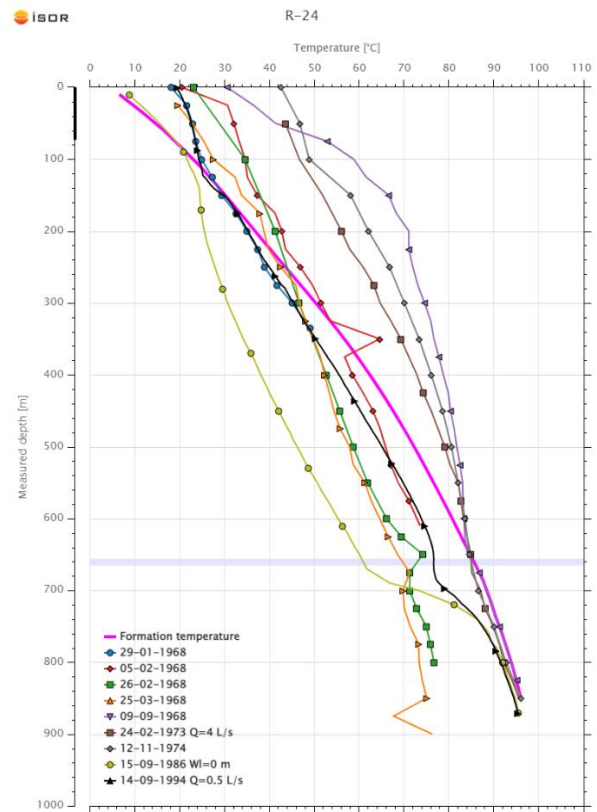
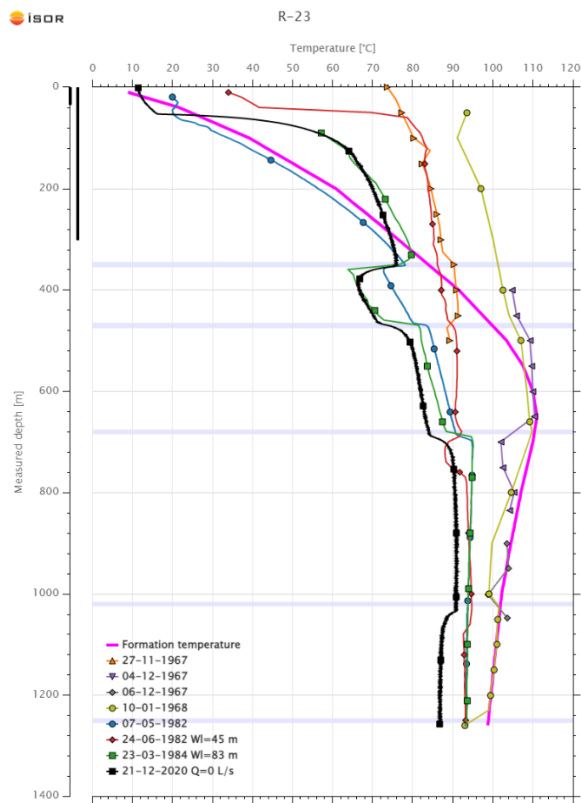
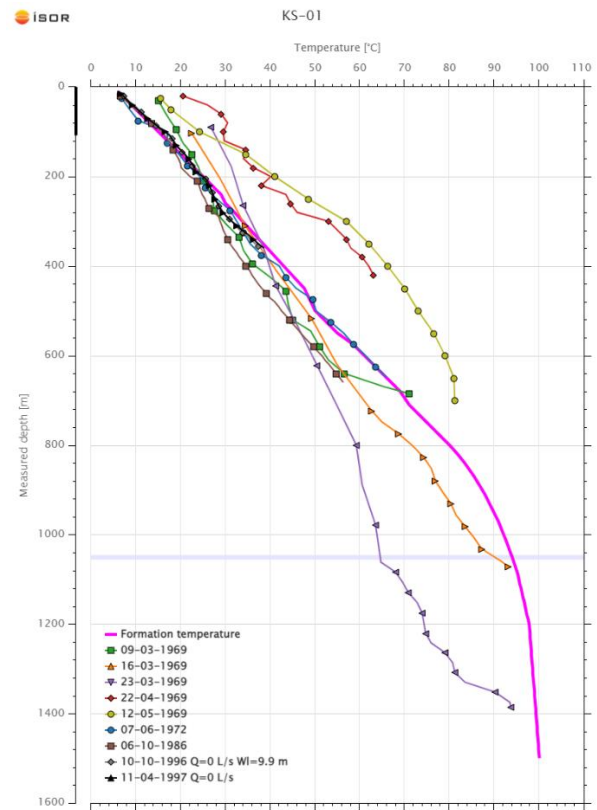
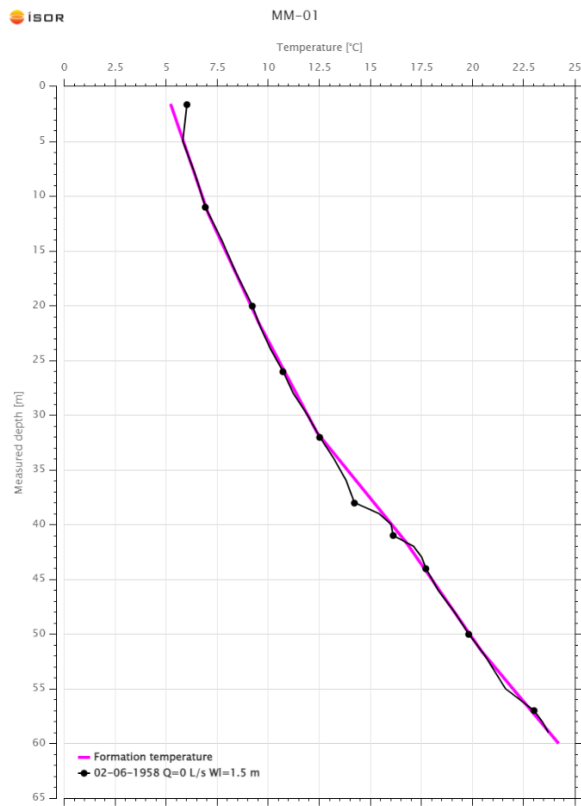
Temperature logs, casings, feed zones and formation temperatures for all wells within about a 5 km radius from the centre of the Elliðaárdalur geothermal field

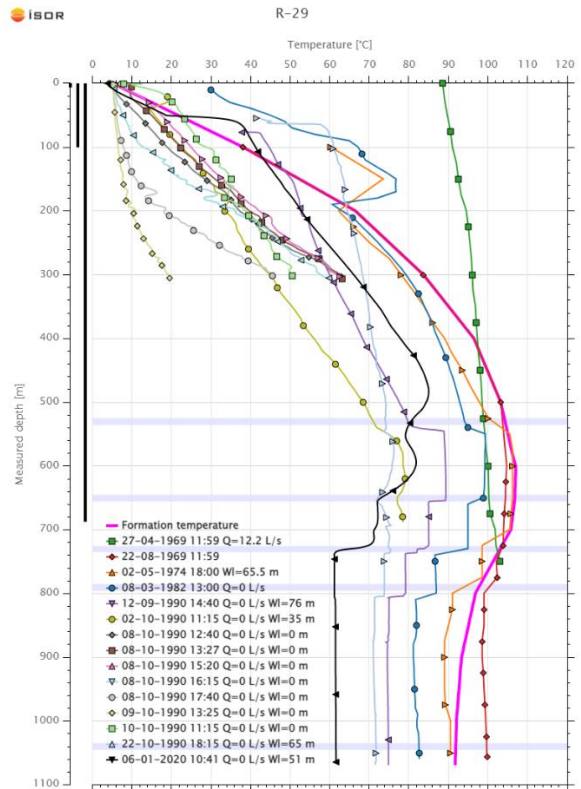
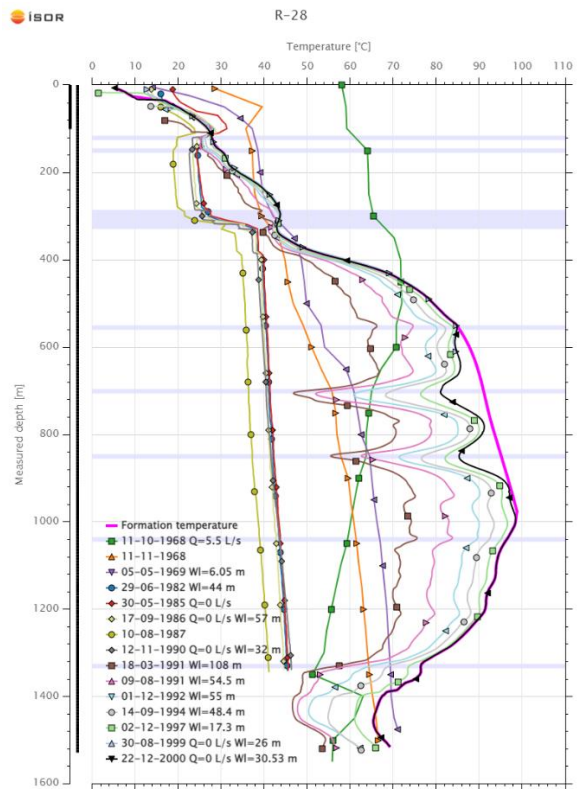
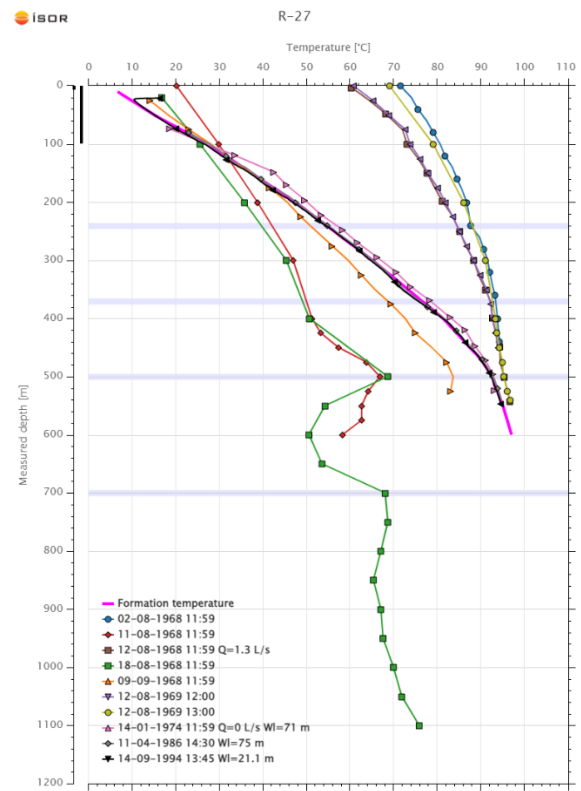
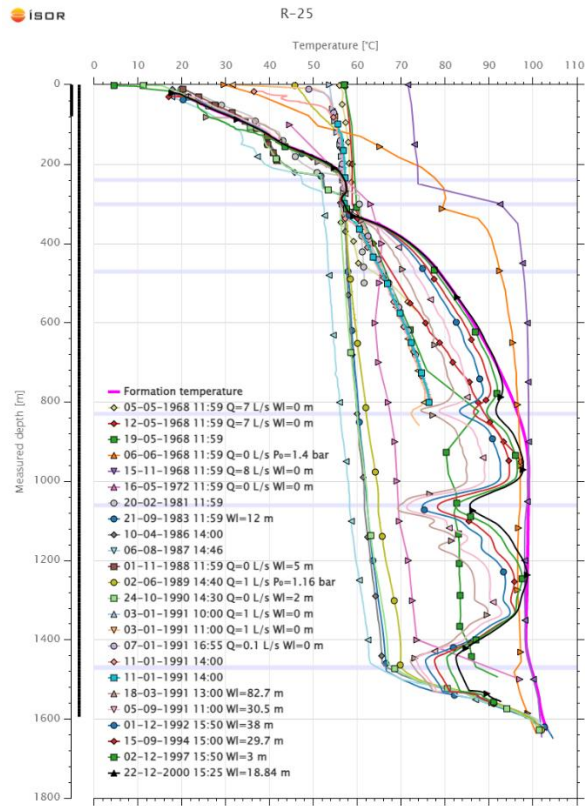


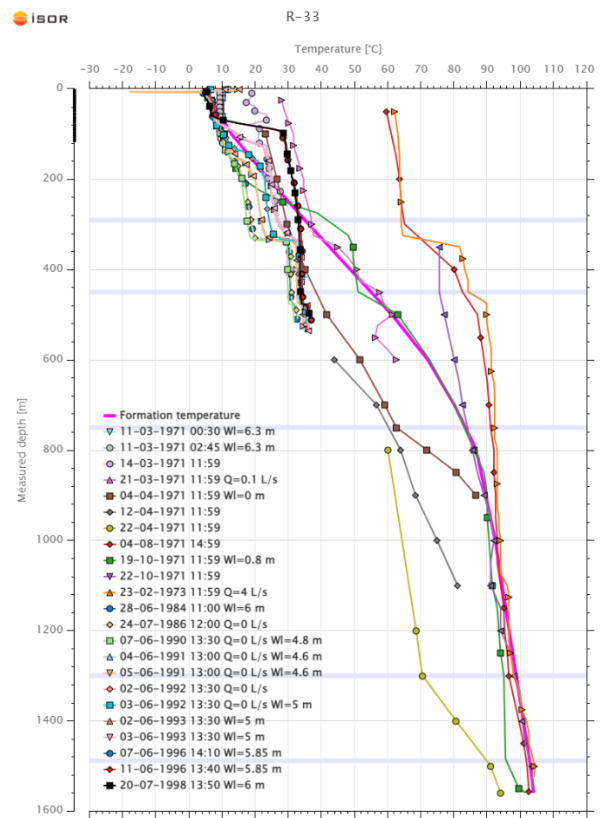
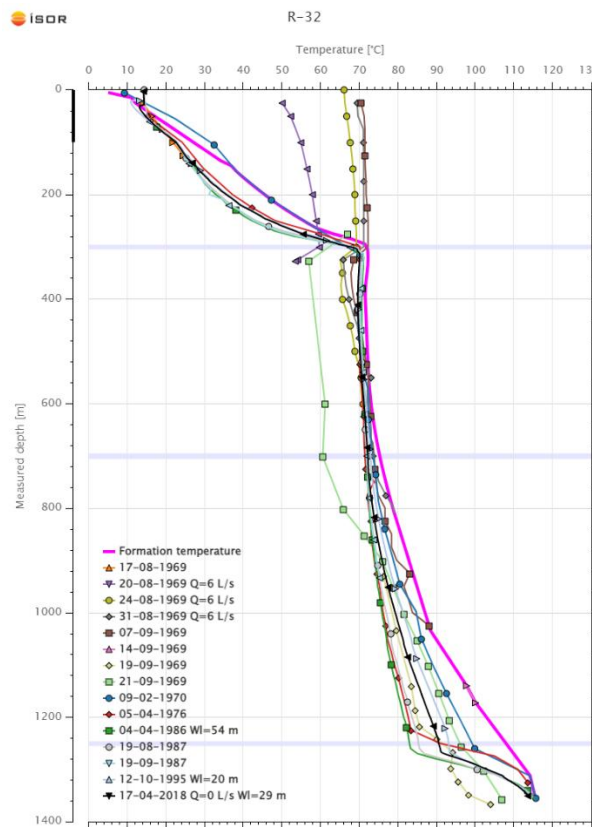
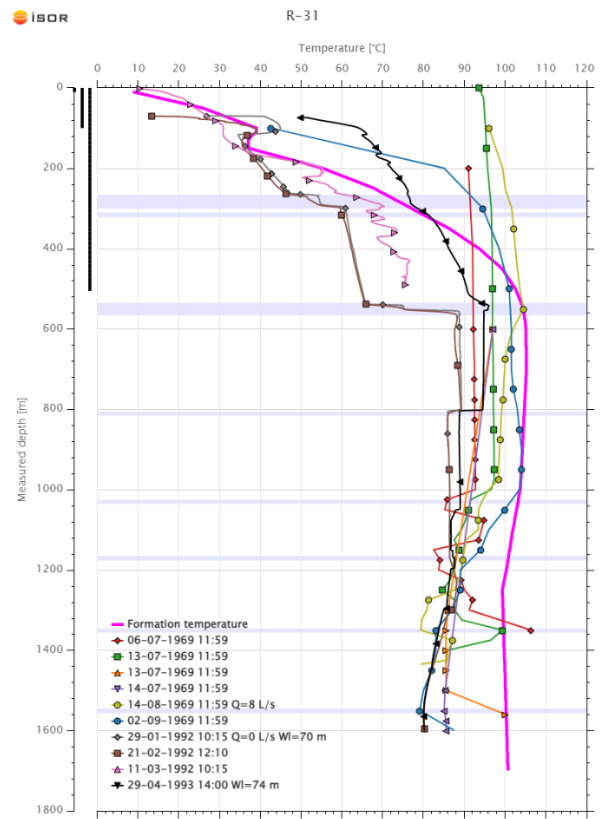
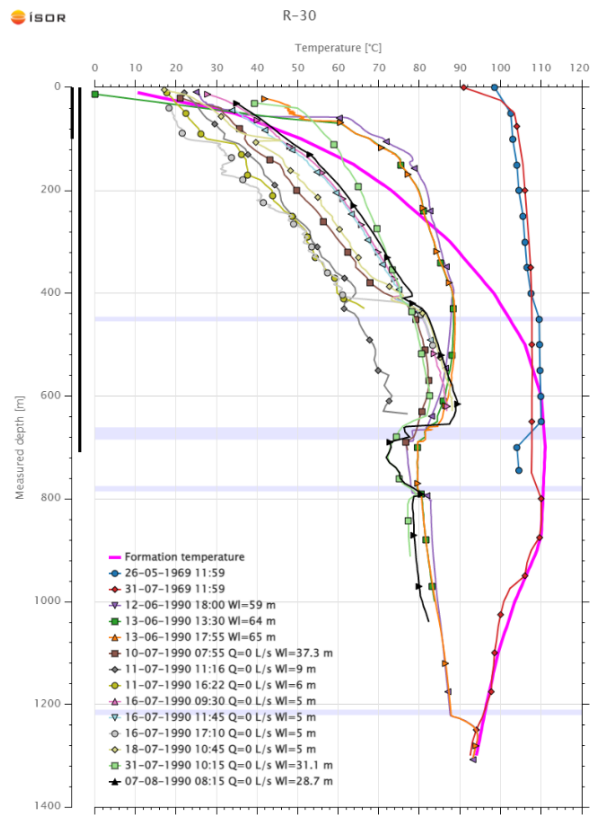


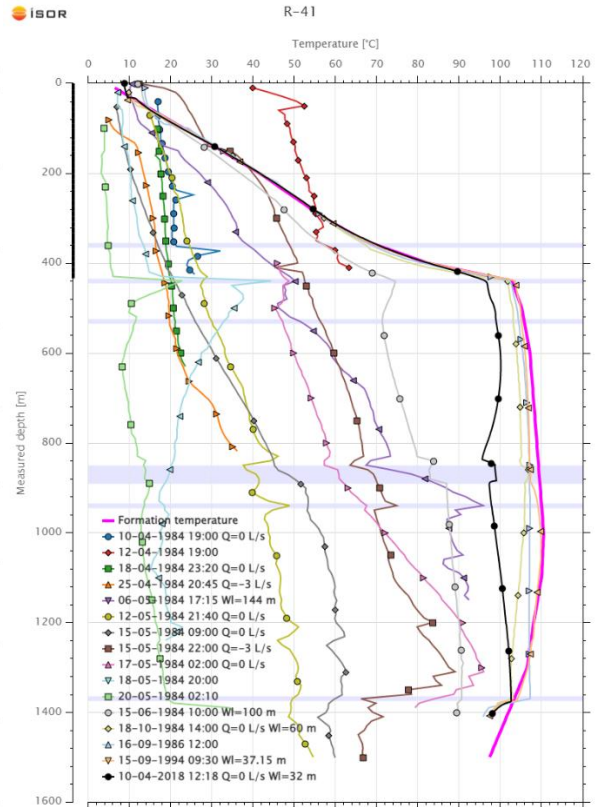
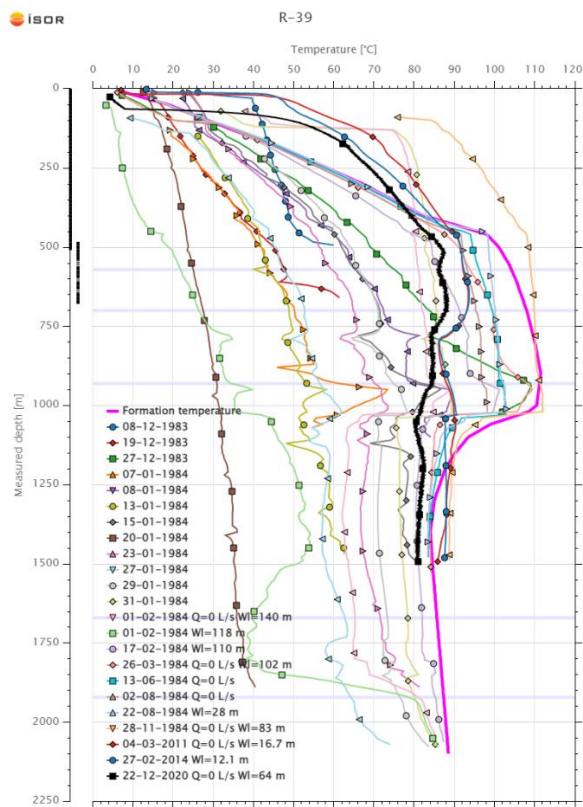
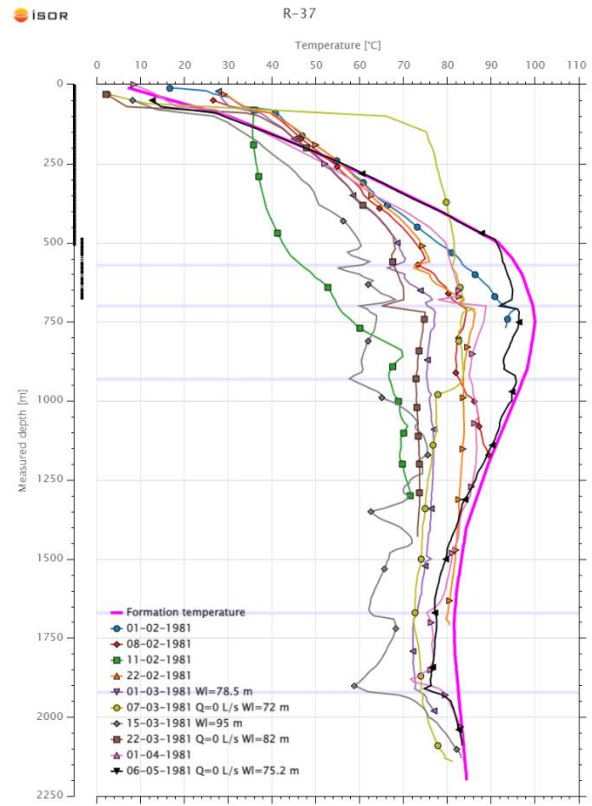
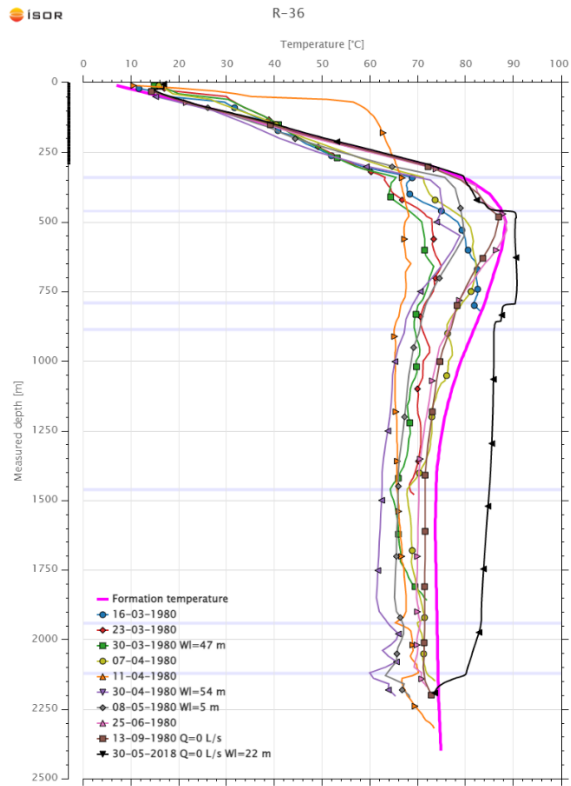








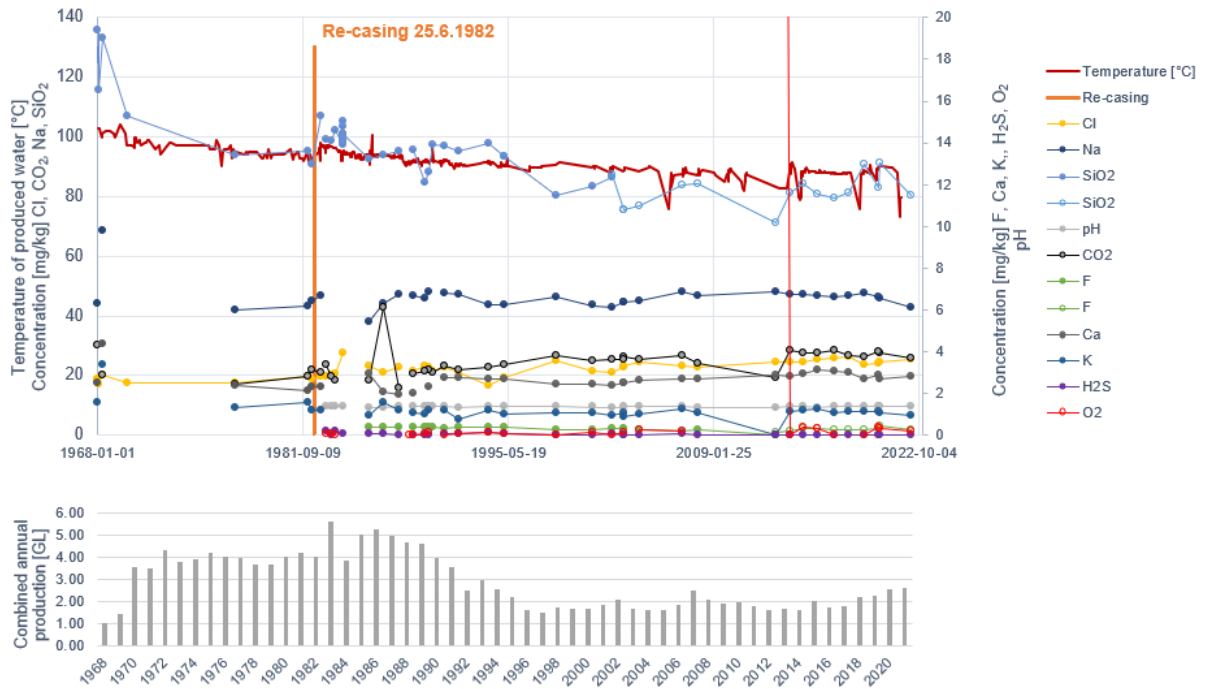




Appendix 2:

Changes in chemical composition for individual wells in the Elliðaárdalur field

R-23



R-26

