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Characterization of the changes in the reservoir in the Ellidaárdalur low temperature field, Reykjavík, Iceland as a part of the RESULT project

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ABSTRACT

The RESULT project aims to demonstrate the potential for increased performance of geothermal reservoirs for direct heating in urban areas of northern Europe. One of the goals of the project is to enhance the lifetime and heat recovery of such reservoirs. The Ellidaárdalur geothermal area in Reykjavík, Iceland, contains one such reservoir. It is close to a volcanic zone, just a few kilometers west of the Krýsuvík fissure swarm, one of the fissure swarms of the Reykjanes peninsula. The area has been harnessed for district heating since 1968 and has been one of the geothermal fields providing hot water for space heating in Reykjavík and surrounding municipalities. There is a wealth of data relating to drilling, well completion, production history and temperature development available for the area. The production has varied from 1.03 GL/year in 1968 up to a high of 5.65 GL/year in 1983, but since 1983 the production from the field has decreased and in the last 10 years it has been between 1.62 and 2.60 GL/year. Substantial cooling has been observed in the field from the start of production with produced water temperature from wells in the field decreasing from over 100°C in many wells down to around 80°C or even lower in some wells. This has been accompanied by changes in chemical components. In general, the pattern seen in all wells is that the concentration of Cl, CO_2, Ca and O_2 increases with time as the temperature decreases. The concentration of SiO_2 and F decreases with decreasing temperature. The increased oxygen content in the produced water has been an issue, as oxygen causes corrosion of material and equipment. This has led to production from specific wells being decreased or stopped. Temperature measurements taken within the RESULT project in two wells that were sealed with a monitoring tube in 1991 to stop downflow of cold water show that temperature has gradually increased back to original formation temperature values. The data from the field suggests downflow of colder water from shallower aquifers through unused wells has contributed substantially to the cooling in the field, at least since production from the field was decreased. This indicates that the cooling in the field can, at least to some extent, be reversed by changing the production scheme and re-casing and/or sealing more wells.

1. INTRODUCTION

The Ellidaárdalur geothermal field is located along the river Ellidaár in the middle of Reykjavík, the capital of Iceland. Geothermal exploration in the Ellidaárdalur field started in 1932. The drilling of production wells in the field started in 1967 with the drilling of well R-23 (also referred to as RG-23). The production zone itself is not large (~1 km^2) and lies within a geothermal system that covers 8-10 km^2 (Tómasson, 1988). Between 1967 and 1984, 16 deep exploration/production wells were drilled. Production from the field started in 1968. There are currently eight active production wells in the field. These wells are called R-23, R-26, R-30, R-31, R-36, R-37, R-39 and R-41. Other 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. Production has been stopped from one well, R-29, due to cooling and scaling in the well. The location of all wells in the field is shown on Figure 1.

The Ellidaárdalur field has been, along with the Laugarnes geothermal field and the Reykir/Reykjahlíd geothermal fields, utilized by Veitur Utilities for hot water production for Iceland´s capital region. In addition to these three fields, hot water for the utility is also produced in two combined heat and power plants in the Hengill area, the Hellisheidi and Nesjavellir Power Plants. Figure 2 shows the origin of the hot water in the utility from 1961 until 2021.

With the commissioning of the Nesjavellir Power Plant, production from the low temperature fields within the capital region was reduced. This production reduction was necessary because the water level in the reservoirs had been declining and some wells had cooled down and/or showed changes in chemical composition. This was the case for the Ellidárdalur system where notable cooling and an increase in the oxygen content of the produced water had been observed.

With growing population and industrial activity in Reykjavik, capacity additions are increasingly necessary to fulfil demand. In the past decades, additional capacity has come from development in greenfield geothermal areas outside the urban area (see Figure 2). In the last few years however, increased emphasis has also been put on enhancing utilization and improving resource management of currently operated mature fields within the city limits because demand forecasts show that all available resources will be needed. The main emphasis of WP6 of the RESULT project has been to analyze the changes that have occurred in the Ellidaárdalur geothermal field and suggest ways to mitigate these issues, with the aim of increasing production, and produced water temperatures, from the field. The hope is that this work could be used to increase understanding of possible future challenges in other urban geothermal reservoirs and as a roadmap to help increase performance of such reservoirs.

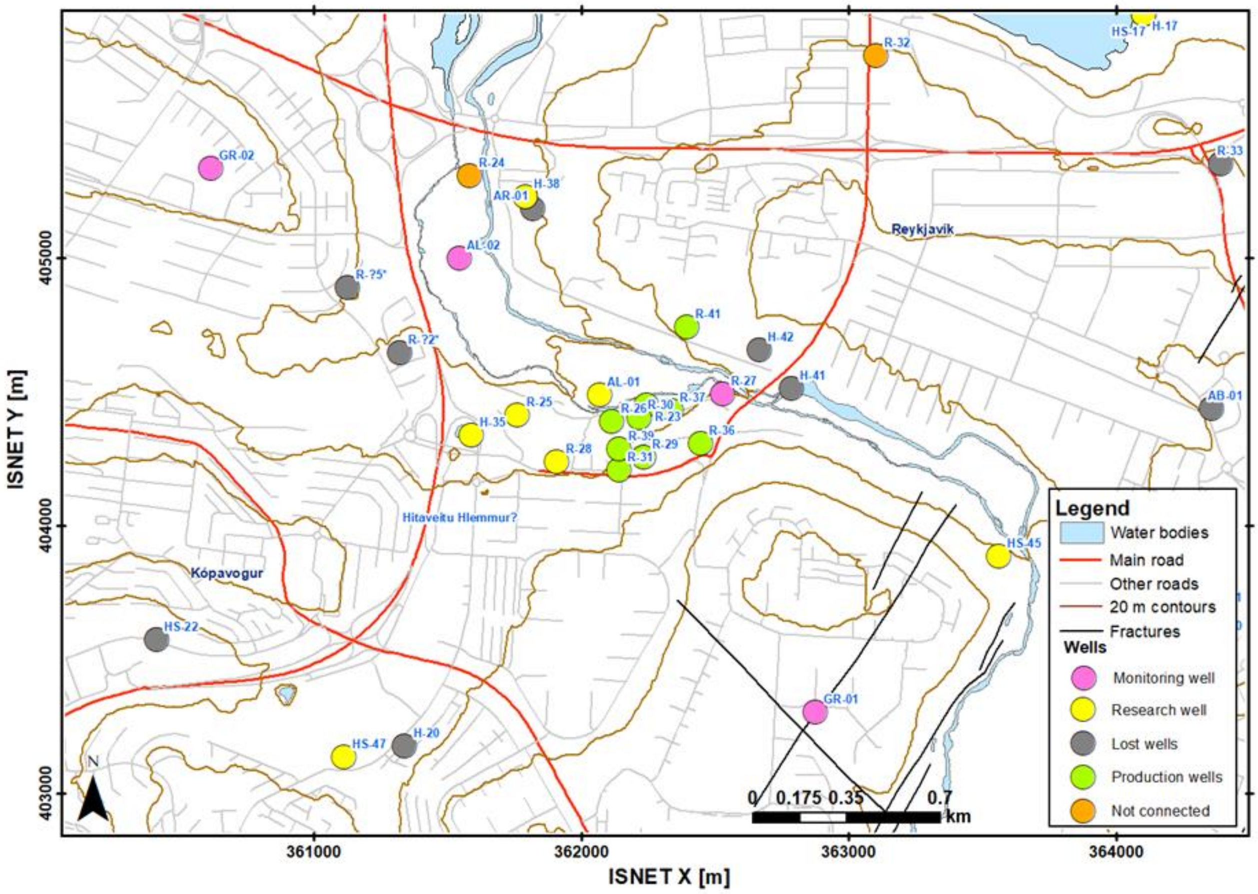

Figure 1: Wells in the Ellidaárdalur area categorized based on current utilization. Well R-27 is a monitoring well for the geothermal field. Other monitoring wells marked with a pink circle are shallow cold-water wells.

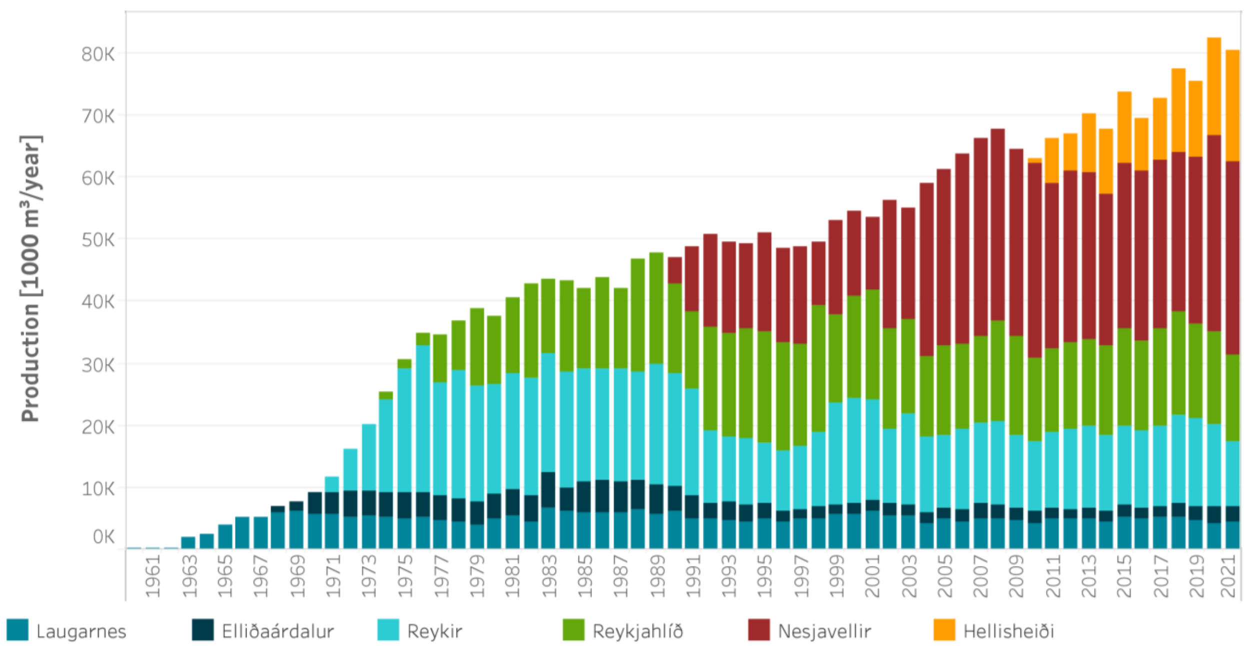

Figure 2: The origin of hot water for the capital region from 1961 until 2021.

2. GENERAL GEOLOGY

The Ellidaárdalur field is located just west of the Krýsuvík fissure swarm, which influences the fracture trends in this part of the Reykjavík area, with a main fracture trend of NNW-SSE. The area is within a zone of Quaternary rocks, characterized by lava flows, intercalated with hyaloclastites (e.g. Sæmundsson et al., 2016).

Tómasson (1988) divided the reservoir in Ellidaárdalur into three different zones, A, B and C. The topmost zone, zone A, is defined by a cold groundwater aquifer. This zone is within a series of a basalt layers referred to as upper-basalt. It reaches down to around 500 m close to the main production area, but deepens to the east, down to around 1000 m. The temperature in this cold layer has been around 40 – 90°C. Below this cold groundwater aquifer is a second zone, zone B, which is a hot water aquifer. This zone is within a series of hyaloclastite formations and reaches between 650 – 800 m in the production area. It is generally thought to contain the highest temperatures in the Ellidaárdalur area, with temperatures that used to reach up to 110°C. Finally, a second hot water aquifer zone, zone C, is found between 1000 – 1250 m. This zone is within a series of basalt layers, referred to as lower-basalt. The temperature in this zone has, in general, been slightly colder than in zone B, 70 – 115°C. This explains the characteristic reversed temperature profiles that can be seen for wells in the Ellidaárdalur geothermal area. While some feed zones have been noted in wells below this zone, the main feed zones observed in wells across the field are found within the three previously mentioned zones.

A 3D geological model of the Ellidaárdalur field was constructed within the RESULT project using data from all wells within the area. An ESE-WNW cross section through the model is shown on Figure 3 which illustrates the division of the stratigraphy into an upper basalt formation, a hyaloclastite formation and a lower basalt formation.

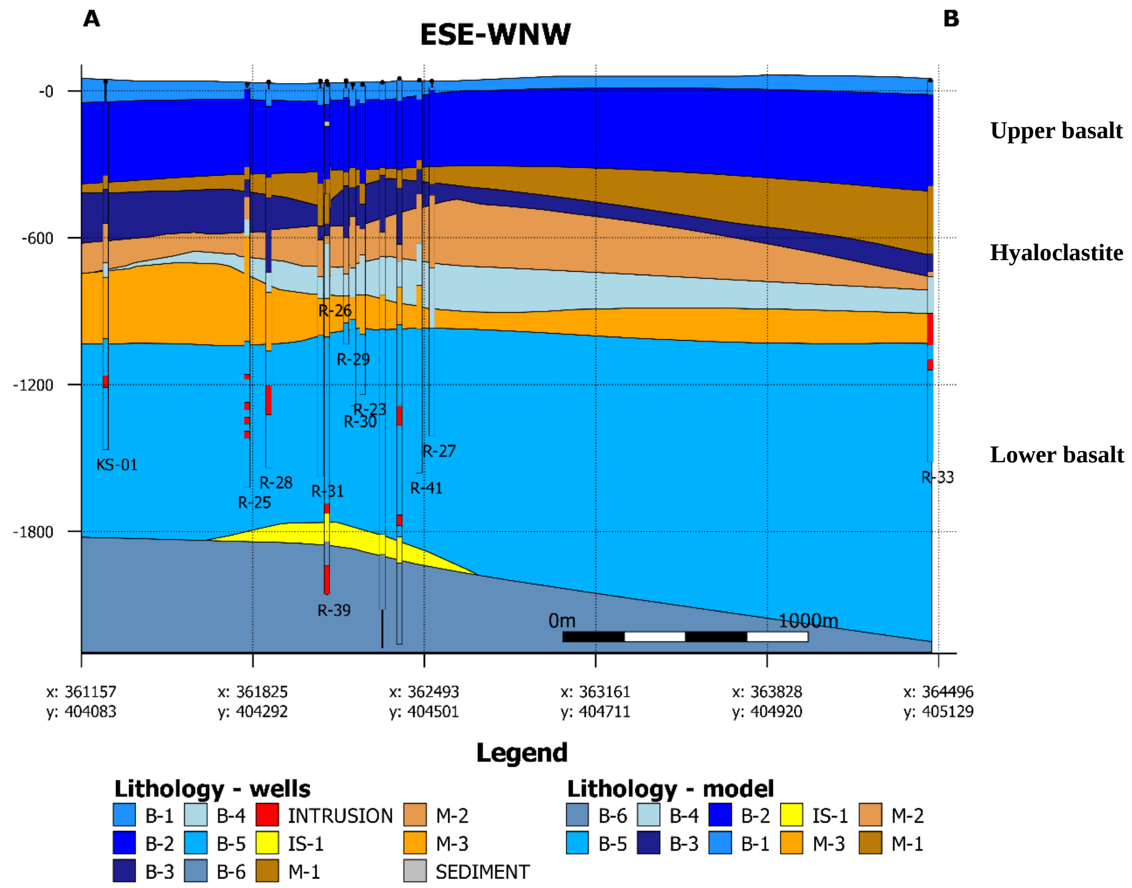

Figure 3: Geological model of the Ellidaárdalur field. B-formations are basalt lava flows and M-formations are hyaloclastite formations.

3. PRODUCTION HISTORY

Production in the Ellidaárdalur field started in 1968. A history of production from the field can be seen in **Figure 4**. In the four-year span between 1967 and 1971 eleven production wells were drilled in the area, with depths between 861 m (R-26) to 1647 m (R-25). In 1972, five of these wells were active production wells, wells R-23, R-26, R-29, R-30, R-31. The other wells were either too far from the main distribution pipe grid, such as R-32, or were not connected because they had shown low productivity, such as well R-28. The five active production wells provided around 4.35 GL of hot water in 1972. Between 1971 and 1984 four additional production wells were drilled in the area, three of which have well depth exceeding 2000 m. Production in the area was 4 GL in 1990, with a peak production of 5.65 GL in 1983 (Ívarsson and Klüpfel, 2022). Table 1 shows the depth of the different wells, the drilling year and the casing depth. In 1982 the casing in well R-23 was deepened. Between 1990 and 1992, the casing was deepened in wells R-29, R-30 and R-31 and wells R-25 and R-28 were sealed with a monitoring pipe down to the bottom of the wells to prevent downflow of colder water (Sigurdsson, 1995).

With the commissioning of the Nesjavellir Power Plant in September 1990 the production from the Ellidaárdalur system was decreased. This was convenient as the operation of the area had been difficult due to cooling and chemical changes, which will be discussed in the next chapter. From 1996 until 2017 most of the produced water came from a single well, R-39 and later R-23, while other wells were more or less unused. From 2018, utilization of the field has been slowly increasing again and more wells have been in production due to increased demand for hot water (Ívarsson and Klüpfel, 2022).

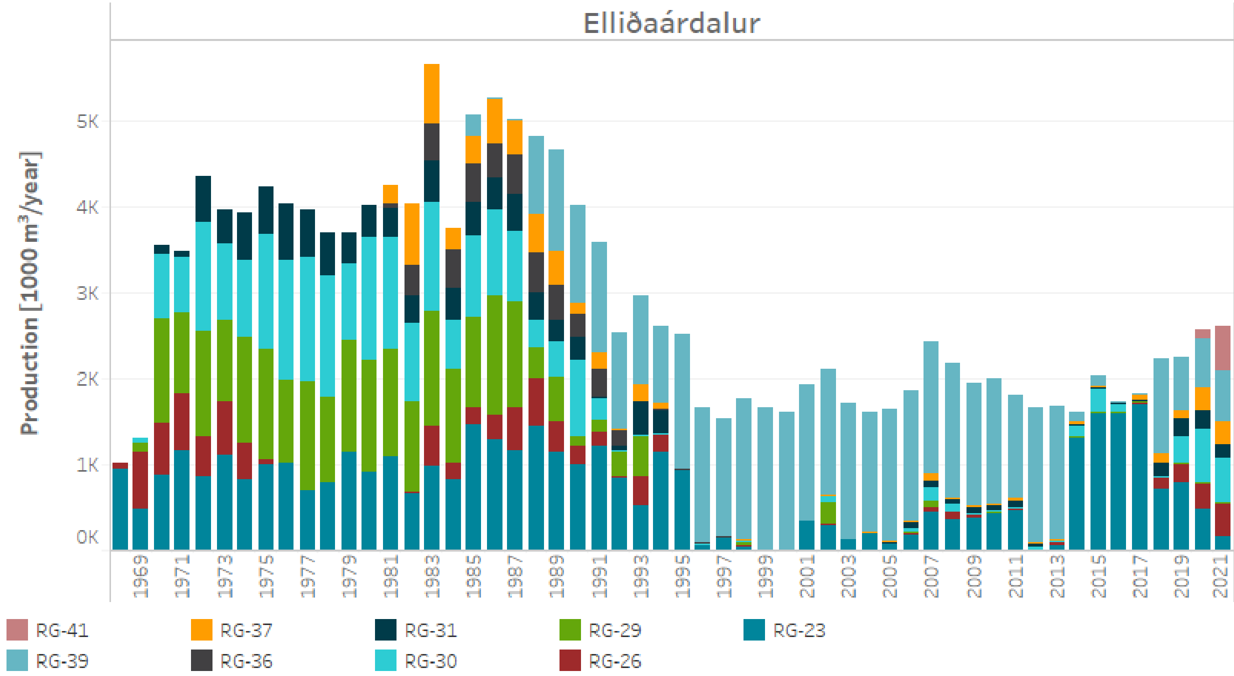

Figure 4: Annual production from the Ellidaárdalur geothermal field and the division between wells. The wells are here denoted with the prefix RG instead of R.

Table 1. Well number, drilling year, final depth and casing information for deep wells in the Ellidaárdalur field (Sigurdsson, 1995).

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

4. CHANGES IN TEMPERATURE OF THE RESERVOIR

Figure 5 shows the total production from the Ellidaárdalur field and the evolution of the annual average water level in monitoring well R-27. From start of production in the area, around 1968, to the commissioning of the Nesjavellir Power Plant in 1990 the water level in the area decreases steadily. The measured water level during this period drops around ~80 m. Since 1990, due to the decreased production, the reservoir pressure in the area has seemingly recovered, with the water level staying at around ~30m above sea level on average for the past two decades. This indicates a positive overall pressure in the reservoir. Water level responds very quickly to changes in production, it drops when production is increased but recovers quickly when production is decreased again. During the summer when the field is rested, the water level is above the ground surface.

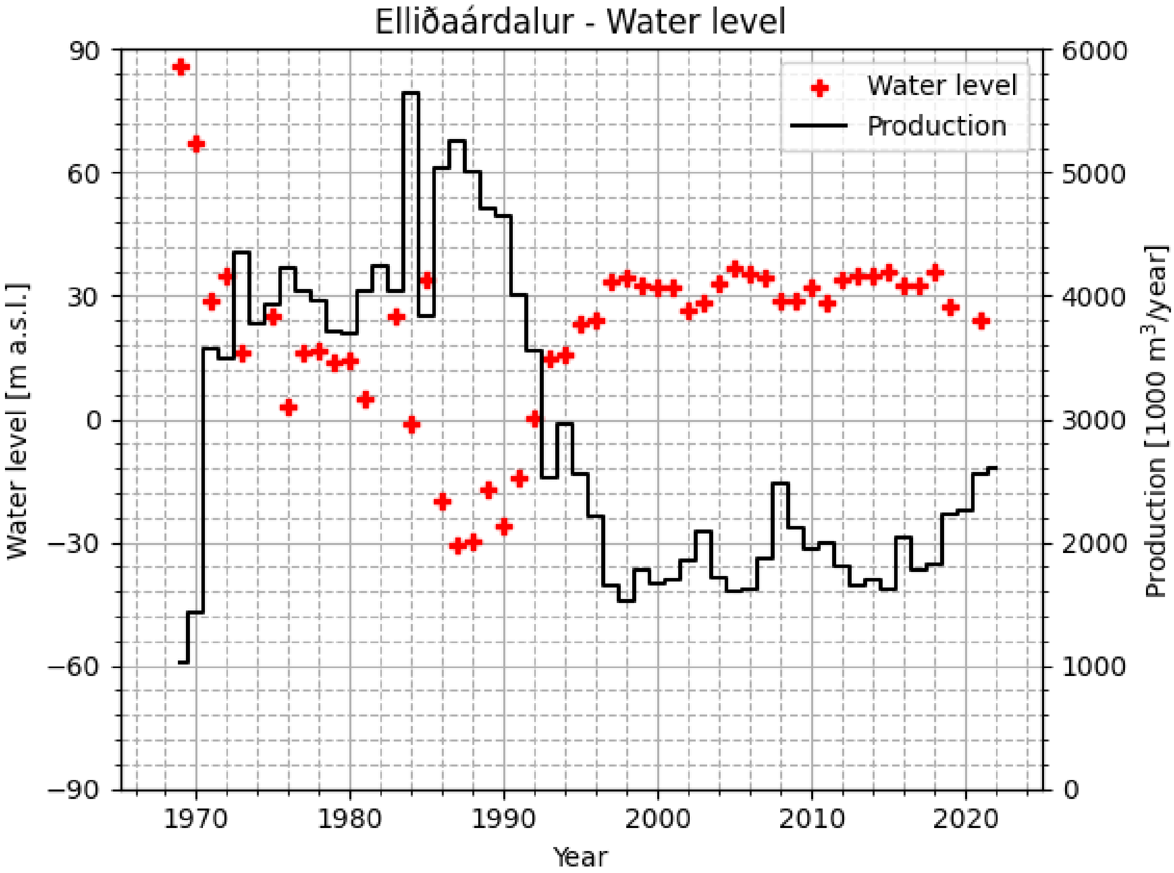

Figure 5: Annual production in the Ellidáardalur area with time. The annual average for measured water level in monitoring well R-27 is also shown. The pressure recovery due to decreased production from the field can be seen clearly around 1990.

Figure 6 shows the combined average of the annual production temperature of all production wells in the area with time, compared with the total production from the area. A temperature average weighted by the production fraction of each well, i.e. the fraction of total production that is due to the well, is also show. Like the pressure evolution, the average production temperature in the field decreased by ~20 °C between 1968 to 1990, or around 1°C / year. After the production decrease in 1990 and the deepening of casings in a few wells this cooling reversed for a few years, however since around 1995 the cooling has returned. Between 1995 and 2022 the average production temperature has decreased from 90°C down to 80°C, or 0.5°C / year. Figure 7 shows the evolution of annual production temperatures for the production wells in the Ellidáardalur field. The temperature decline is consistent between most of the wells in the area, however it seems to be the most extreme for well R-29. This would indicate that the overall cooling in the area does not seem to be biased in one part of the field. Various processes can explain this cooling, e.g., drawdown in the hottest aquifer, zone B, causing a greater portion of produced water to come from cooler aquifers, downflow of water from the colder top aquifer down into the lower, hotter, aquifers and possibly lateral inflow of cooler water from outside the system (see e.g. Tómasson and Thorsteinsson, 1983; Tómasson, 1988; Sigurdsson, 1995). Looking at specific wells in more detail can help to shed more light on the different cooling processes affecting the field.

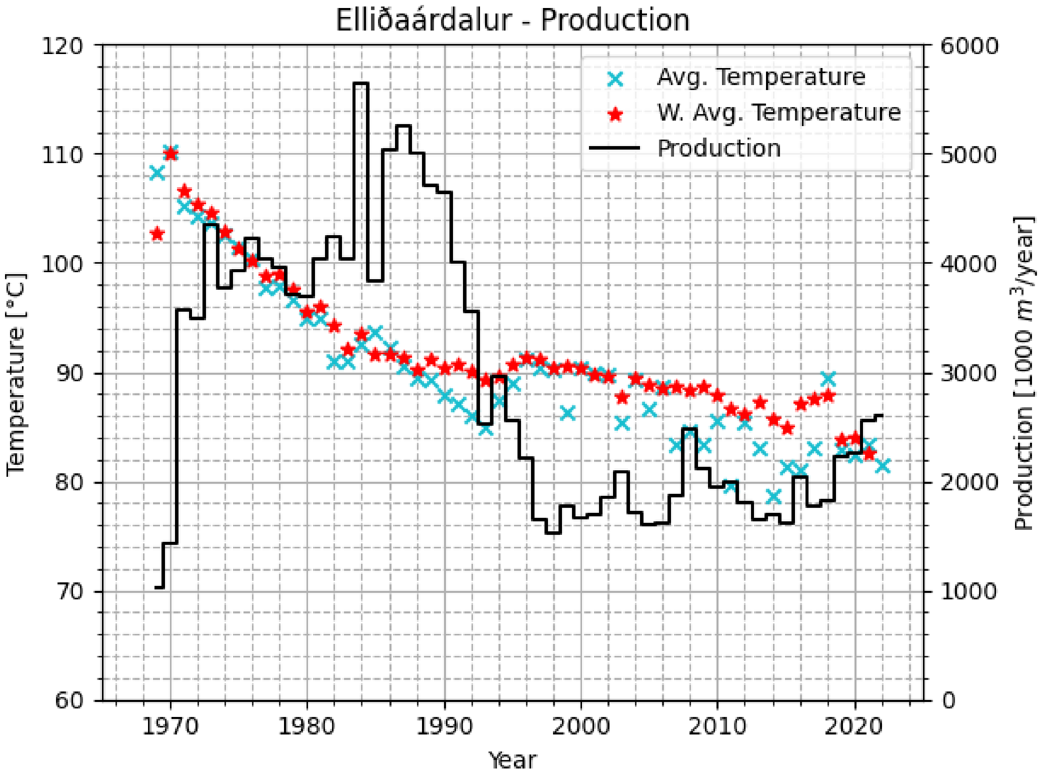

Figure 6: Annual production in the Ellidáardalur area with time. The combined average of the annual production temperature of all production wells in the field, along with the combined average weighted with the production fraction for each well, are also shown. The slow-down in cooling, along with a slight temperature recovery, due to the production reduction and well re-casings done around 1990, can be seen.

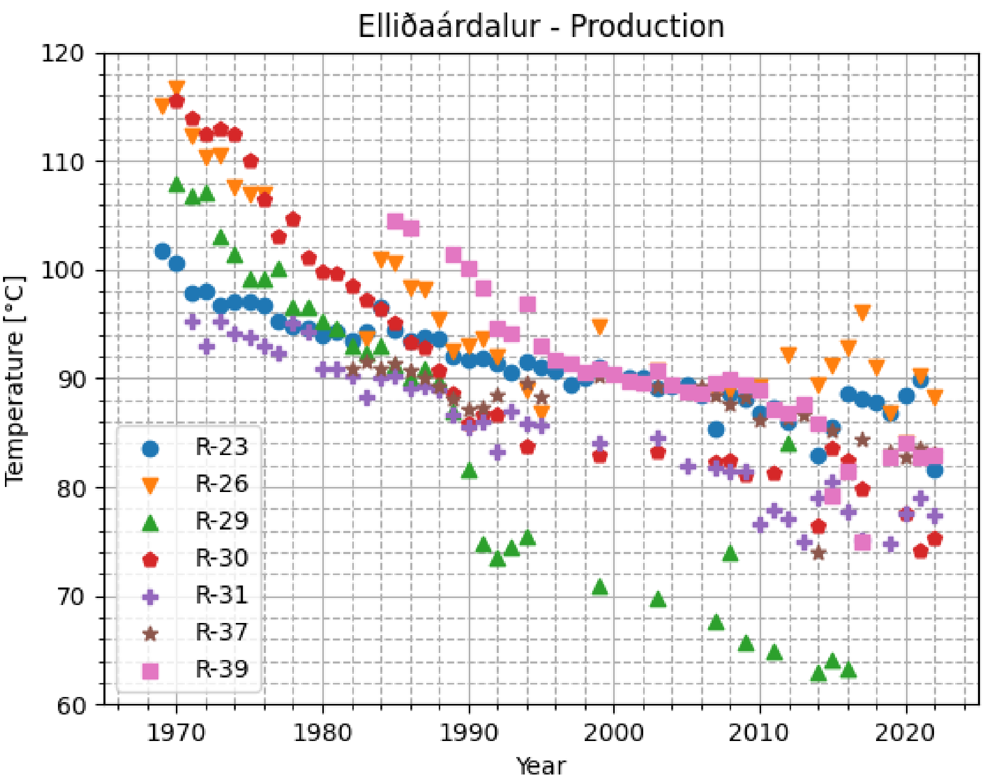

Figure 7: Average annual production temperature for each production well in the Ellidáardalur area with time. The effect of production reduction and well re-casings after 1990 can be clearly seen.

The production temperature evolution for well R-23 can be seen in Figure 8. This well is near the center of the production area and was the first production well drilled in Ellidáardalur. The well initially had casing depth of 35 m, but in 1982 the well was re-cased down to 302 m (Sigurdsson, 1995). The figure shows that since 1968 the temperature has decreased from 100°C down to 90°C in 2022. Therefore, the temperature of produced water from the well has remained consistent, compared to the field average. There is not a clear correlation between the production amount from the well and the temperature changes. Figure 9 shows downhole temperature logs for well R-23, along with the estimated formation temperature around the well. The main feed zones for the well are also indicated on the chart. The three main reservoir zones described earlier can be seen in the temperature logs. Two feed zones connected to the cold groundwater zone, zone A, can be seen around 400 m. Around 650 m ~90°C water from the hottest zone, zone B, enters the well. Finally, slightly cooler water from zone C enters the well at 1000 m. Due to the relatively shallow casing depth, around 300 m, inflow into the well of colder water from the top feed zone seems to have, over time, cooled the deeper, hotter, feed zones. The increase in temperature of produced water in the well between 2014 and 2019 might therefore be due to the increased production preventing this cold downflow from the top feed zone.

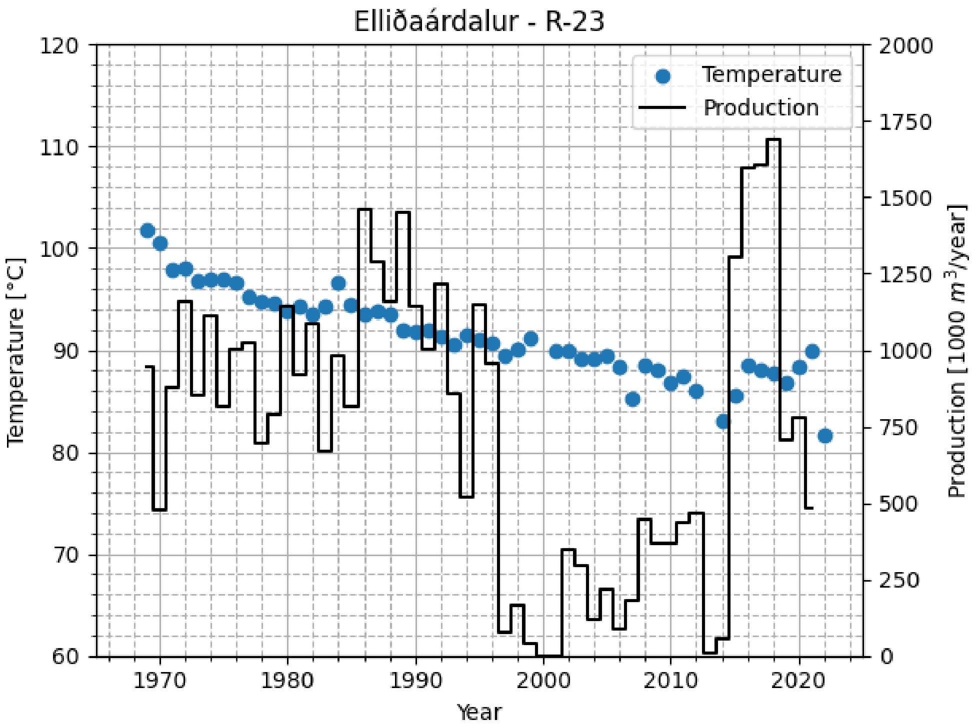

Figure 8: Average annual production temperature and annual production rate for well R-23. The re-casing of the well in 1982 and the production decrease from the field around 1990 have a negligible effect on the cooling rate of the well.

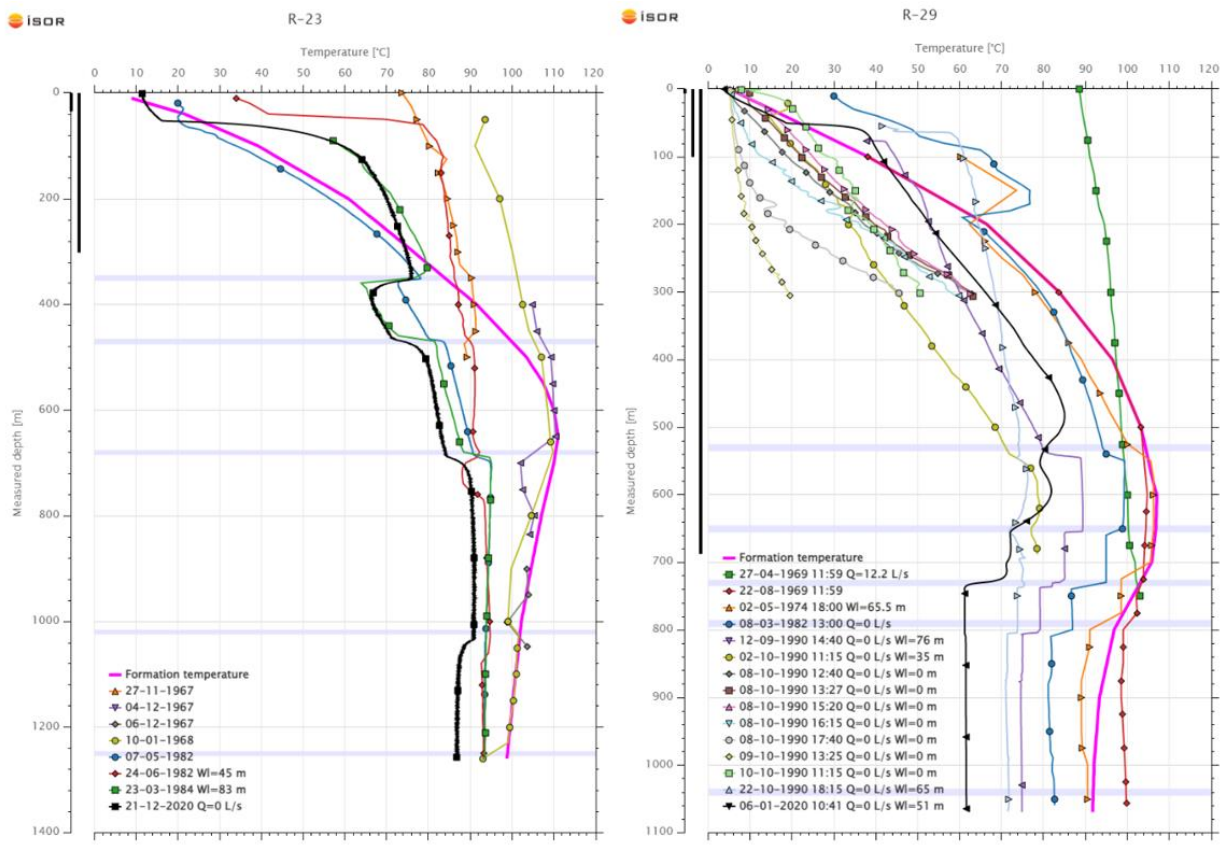

Figure 9: Downhole temperature logs and estimated formation temperature for well R-23 (left) and well R-29 (right). Estimated feed zones in the wells, along with their vertical extents, are shown as blue shading on the chart. The casing depths for the wells is shown on the left side of the chart.

In contrast to the relatively stable temperature decrease in well R-23, the temperature decline in well R-29 is much greater, see Figure 10. Well R-29 was drilled in 1969 and is located inside the main production area of Ellidaárdalur, slightly to the south of well R-23. The well initially had a casing depth of 98 m, but was re-cased in October 1990, down to 688 m (Sigurdsson, 1995). This well shows the greatest temperature decrease of all the production wells in the area, and due to this has rarely been used for production since 1993. The temperature of the well has decreased from around 105°C in 1969 down to 65°C in 2015. The rate of cooling increased greatly when production from the well was decreased in 1988. The temperature then rose for a few years following the re-casing of the well in 1990 but started dropping again when production from the well was stopped, and when production from the field was predominantly from a single well, R-39. Figure 9 shows downhole temperature logs taken in well R-29, along with the estimated formation temperature of the well. Several feed zones have been identified in the well. The re-casing in October of 1990 seems to have closed of the feed zone with the hottest inflow, around 500 m, and thus contributed to the overall cooling of produced water from the well. The feed zones between 700 – 800 m, below the casing depth, have cooled from 100°C down to 60°C, with the cooling continuing despite reduced production from the field. The depth of these feed zones is consistent with zone B mentioned above. Since the shallow, colder feed zones in the well have been cased off, the constant cooling at depth in the well could be due to general cooling of the associated feed zone due to downflow of cold water from reservoir zone A into the deeper zones outside of individual wells, for example through fractures, or through a combination of well flow and fracture flow. The re-casing of well R-31, which lies close to R-29, cased off a feed zone with an inflow of 60°C at 300 m depth which was cooling that well. This feed zone could be connected to a feed zone in well R-29 which could then explain the cooling observed in the well. Fractures and faults in the area have unfortunately not been mapped in detail.

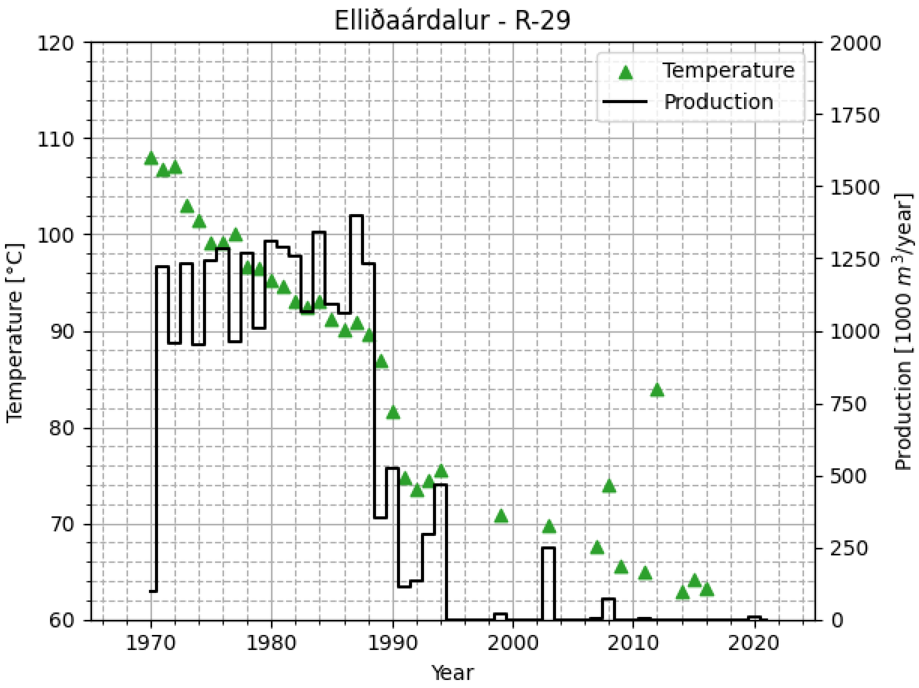

Figure 10: Average annual production temperature and annual production rate for well R-29. The rate of cooling increased when production from the well was decreased in 1988. The temperature rose for a few years following the re-casing of the well in 1990 but decreased again when production from the well was stopped and when production from the field in general is predominantly from a single well, R-39.

Figure 11 shows temperature logs for well R-25. This well was drilled in 1968 and has not been in active use as a production well. The well is slightly to the west of the main production field (see Figure 1). The well originally had a casing depth of 79.5 m but was sealed with a monitoring pipe down to 1594.9 m in late January 1991 (Sigurdsson, 1995). Prior to re-casing the well had cooled down from around 90°C at the feed zone at 820 m to around 55°C. This feed zone depth is consistent with a connection to reservoir zone B described above. Similar cooling is seen down the rest of the well. After re-casing was completed the temperature has gradually increased back to formation temperature values down the well. The rate of heating seems to indicate that the rock closest to the well has maintained the original formation temperature, despite the cooling observed in the well. This seems to indicate that the original cooling in the well was due to downflow of colder water in the well itself from the upper feed zones, rather than a cooling of the reservoir zones themselves. The same process can be seen in well R-28 (see Figure 11), which was also sealed with a monitoring pipe around the same time as R-25. In this well the newest temperature logs, undertaken as part of the RESULT project, show that the temperature below 800 m has increased beyond the estimated formation temperature in the well.

Figure 12 shows temperature models created in Leapfrog of the Ellidaárdalur geothermal reservoir based on interpolation of downhole temperature measurements over a set period of years. These models are horizontal cross sections taken in reservoir zone B, at -750m depth, with an aerial view. The earliest interval, 1967 to 1969, shows that the reservoir had relatively high temperatures around the main production zone at the start of production, with lower temperatures seen around wells R-28 and R-32, to the south and north respectively. The next interval, between 1982 to 1984, shows a decrease in the reservoir temperature to the south and west, the highest temperatures are now in the east of the production zone, around wells R-39 and R-41. The interval between 1994 to 1996, following the re-casing of the wells and reduction of production in the field, shows an increase in the average temperature of the reservoir, with the temperature in the south and west increasing to around 70°C compared to 40°C between 1982 to 1984. The most recent model, from 2018 to 2022, shows that the temperatures in the production field are still relatively high. A notable exception is R-29 which shows the lowest recorded temperature at this depth in this period. These models show that nature of cooling in the reservoir seems to have changed after 1995, with cooling coming in from the south, in the direction of R-29. Before 1995 the cooling seems to mostly have come into the reservoir from the south-west, in the direction of R-25 and R-28.

The temperature increase in wells R-25 and R-28 in recent years strongly suggests that the B and C reservoir rocks themselves have not cooled down due to production in the area or due to lateral inflow of cooler water. This fact, along with the continued cooling in the field after production was decreased and mainly taken from a single well, along with temperature models of reservoir B, seems to indicate that downflow of cold water in the wells themselves has contributed substantially to the cooling of production wells and produced water from the field, especially since 1995. Increased portion of produced water originating in the cooler aquifers played a large role in decreasing the temperature of produced water in the first decades of production when many wells with shallow casings were in operation (Tómasson, 1988).

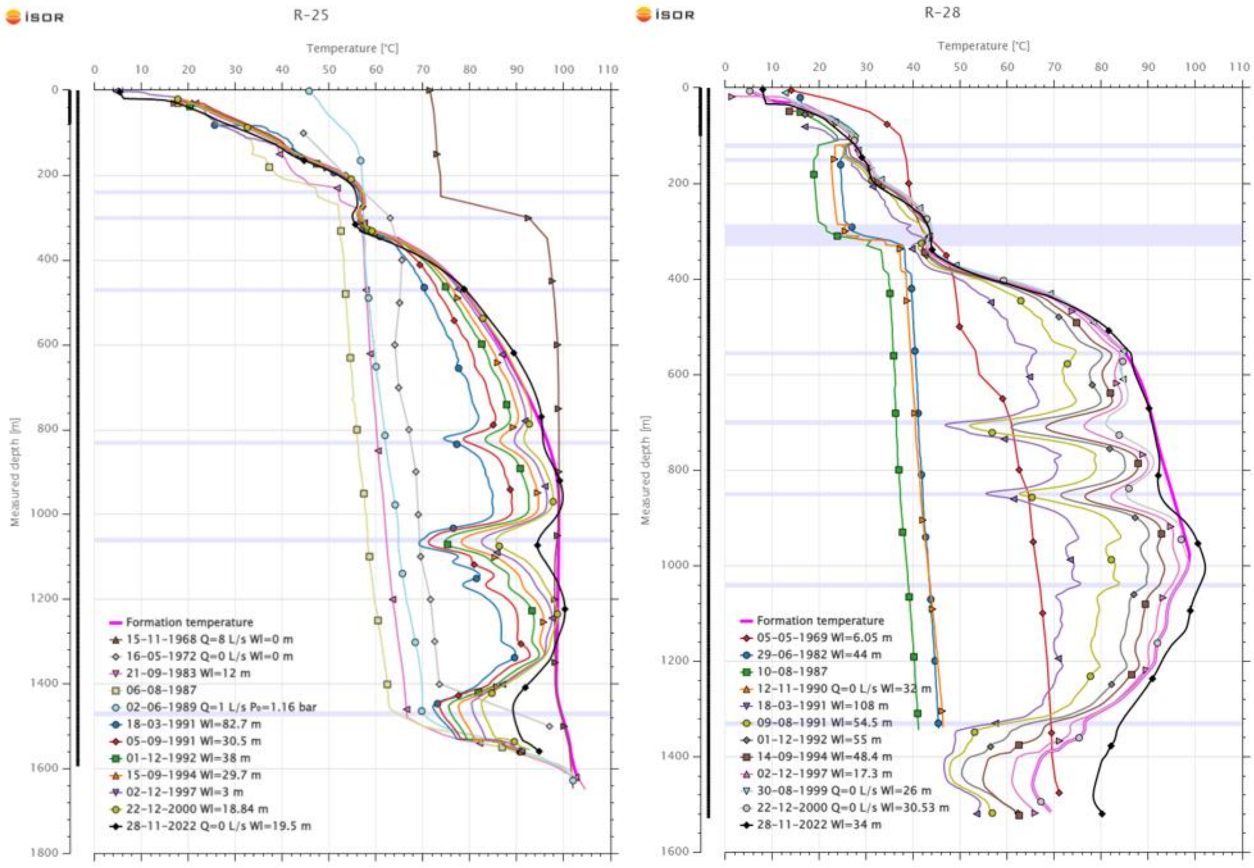

Figure 11. Downhole temperature logs and estimated formation temperature for well R-25 (left) and well R-28 (right). Estimated feed zones in the wells, along with their vertical extents, are shown as blue shading on the chart. The casing depths for the wells is shown on the left side of the chart. These well were sealed with a monitoring pipe in 1991.

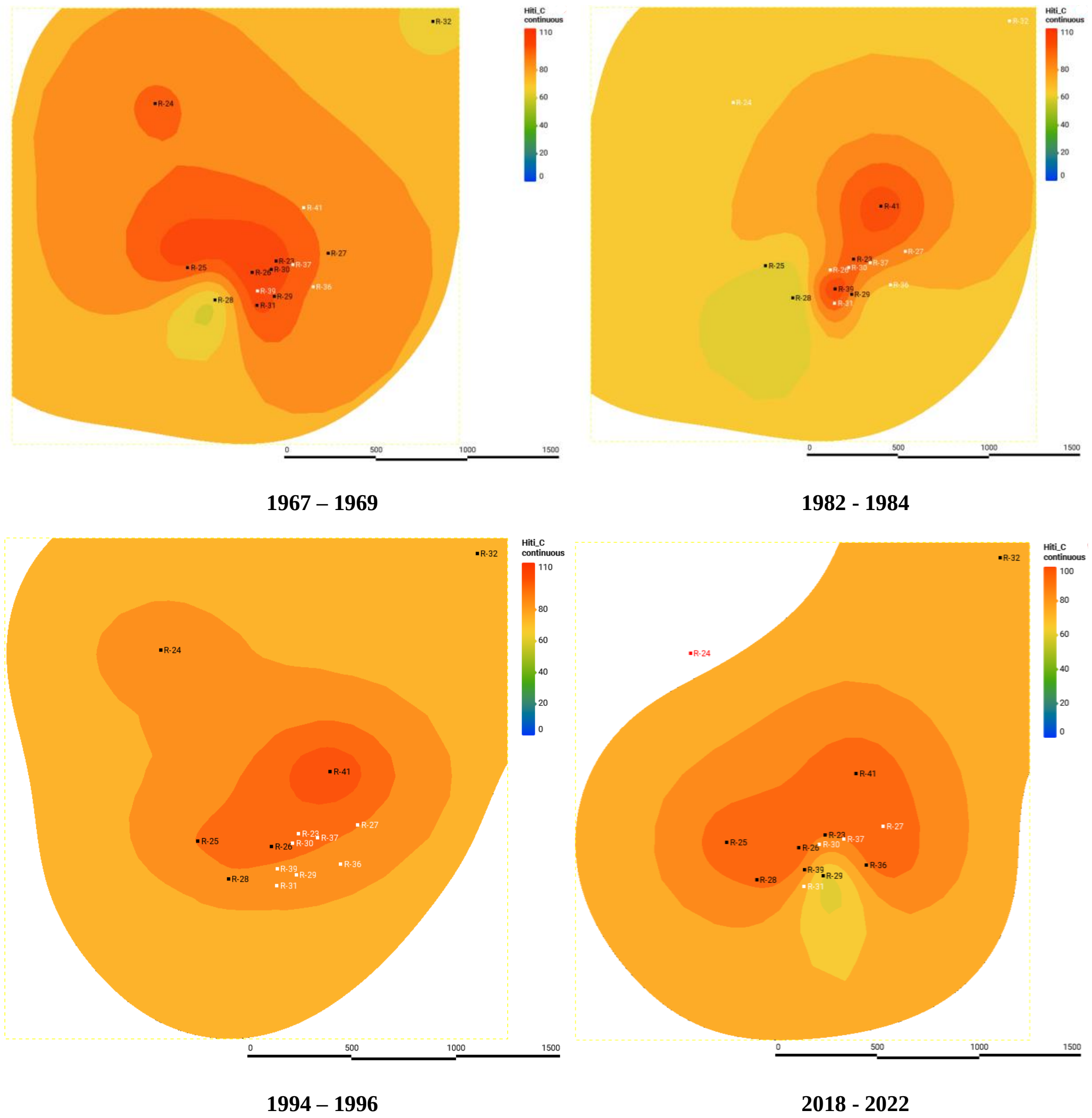

Figure 12. Temperature models of zone B in the Ellidaárdalur geothermal reservoir during different time intervals; 1967-1969 (top left), 1982-1984 (top right), 1994-1996 (bottom left) and 2018-2022 (bottom right). These horizontal cross-sections at -750m depth show wells with downhole temperature measurement in a given interval in black.

5. CHANGES IN THE CHEMISTRY OF THE RESERVOIR

The decreasing temperature of water produced from the Ellidaárdalur field has been accompanied by significant changes in the chemical composition of the water produced from the wells in the area. Rising levels of oxygen have been of special concern as oxygen causes corrosion of pipes, pumps and surface equipment. Figure 12 shows how the concentration of Ca, SiO_2, CO_2, Cl, O_2 and F has changed since 1968 in well R-31. The total production from the area is also shown for comparison. The pattern seen in well R-31 is typical for other wells in the area that have significant production history although the timing of chemical changes varies between wells across the production area. In general, the pattern seen in all wells is that the concentration of Cl, CO_2, Ca and O_2 increases with time as the temperature decreases. The concentration of SiO_2 and F on the other hand decreases with decreasing temperature. Data shows that the concentration of other major components such as Na, K and SO_4 remains nearly constant over the production period. When the production rate declined after 1990 there was, initially, a trend towards lower Cl concentrations. In the years following 1995 when production decreased and was predominantly from one well, however, the trend towards higher concentrations resumed.

Samples taken from wells R-29, R-30 and R-31 in October 1969 showed anomalously high values for Cl compared to other data points for these components, with values between 45 and 56 mg/kg (Gunnlaugsson, 1982). Four samples collected from wells 25 and 28 in 1982, 1985 and 1989, before the wells were sealed, also showed Cl concentrations between 45 and 50 mg/kg (Gunnlaugsson, 1982; Gudmundsdóttir, 1989). The temperature of these samples was around 41°C. This temperature indicates that this fluid originated in the shallow A aquifers which in turn confirms the presence of water with elevated Cl concentrations in the shallower aquifers of the system (Tulinius (ed.), 2022). Gudmundsdóttir (1989) stated that the explanation could be that these shallow geothermal fluids picked up Cl from marine sediments that are present at 50 to 100 m depth in parts of the field. Samples taken in the fall of 2022 in well R-26, the only production well in the field that is still open in the A aquifer zone, also showed elevated Cl concentrations (up to 70 mg/kg). The samples were taken following a production stop in the well, allowing downflow. Based on the above, increasing chloride concentration in the field is likely due to downflow of water from the shallow A aquifer, at least partially through wells that are not in production. This is consistent with the decrease in temperature seen in the field and described above.

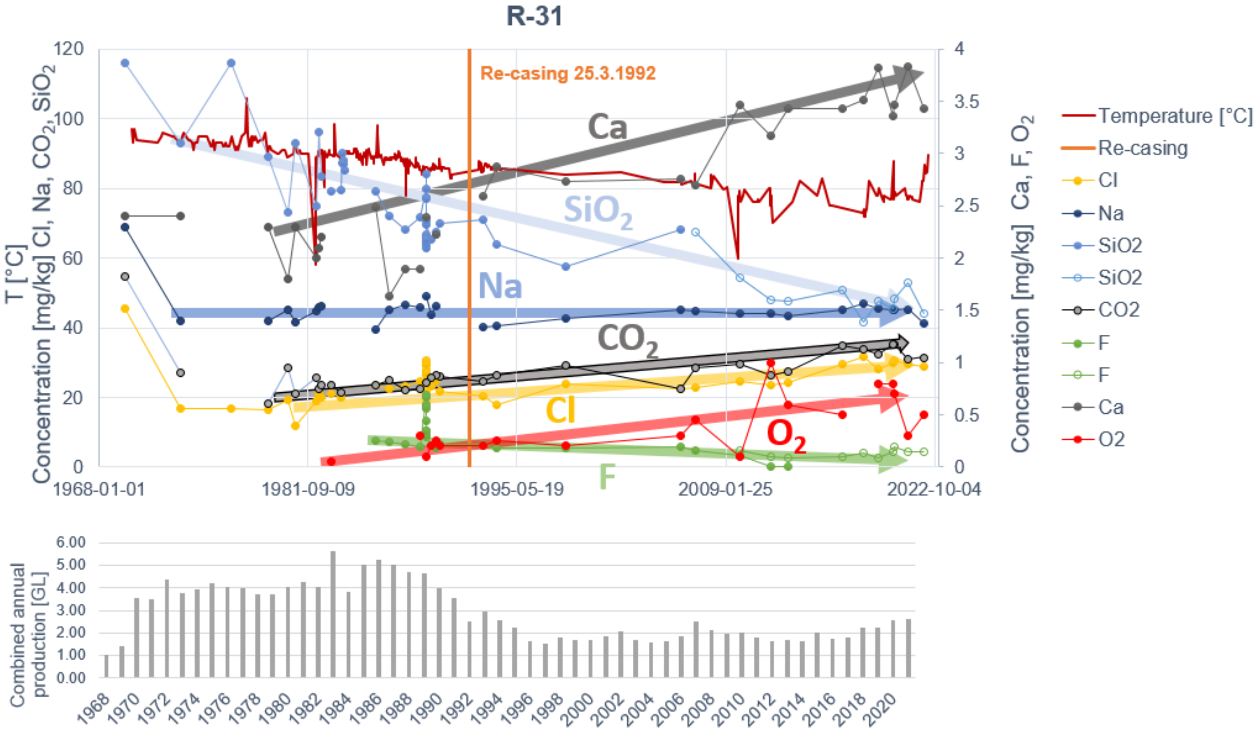

Figure 12 Temperature and concentrations of selected components in water from well R-31 with time along with combined annual production from the Ellidaárdalur field.

6. CONCLUSIONS

The Ellidaárdalur geothermal field is a mature field that has been in production since 1968. Water temperature produced from wells in the field has decreased from over 100°C in many wells at the start of production down to around 80°C or even lower in some wells. This has been accompanied by changes in chemical components. As a part of the RESULT project, data on the geology, production history and changes in temperature and chemistry have been reviewed and analyzed. The aim was to improve understanding of the system and the different processes that control the system behavior and response to utilization. A 3D geological and temperature model of the field was constructed in the Leapfrog software using data from all wells within the area. New temperature and chemical measurements were done within the project to shed light on cooling in the area and the origin of different water types. The data from the field suggests that in the first decades, increased portion of produced water originating in cooler aquifers played a large role in decreasing the temperature of produced water. In recent decades however, since production in the field was decreased, downflow of colder water from shallower aquifers through unused wells within the well field seems to be the primary driver of cooling in the field. This indicates that recent cooling in the field can, at least to some extent, be reversed by changing the production scheme and re-casing and/or sealing more wells.

The hope is that this work could be used to increase understanding of possible future challenges in other urban geothermal reservoirs and as a roadmap to help increase performance of such reservoirs.

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