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2.2.
APPENDIX 1

EXAMPLE OF CHEMICAL MONITORING OF GEOTHERMAL WATER USED FOR DISTRICT HEATING IN REYKJAVÍK

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District heating in Reykjavík the capital of Iceland started in 1930 on a small scale and has extended, so to day it is serving all inhabitants in Reykjavík and surrounding communities all together about 160.000 people. The district heating is utilizing three low temperature geothermal fields and one high-temperature geothermal field. These are:

- Laugarnes low-temperature field
- Elli_aár low-temperature field
- Reykir-Reykjahlí_ low-temperature field
- Nesjavellir high-temperature field

All the low temperature fields were to some extent over exploited in the years 1985 to 1990.

The exploration of the *Elli_aár* geothermal reservoir began in 1967 with the drilling of the first wells in the area. Sixteen wells have been drilled into the area, which cover about 0.08 km^2 although some manifestation can be seen in 8-10 km^2 area.

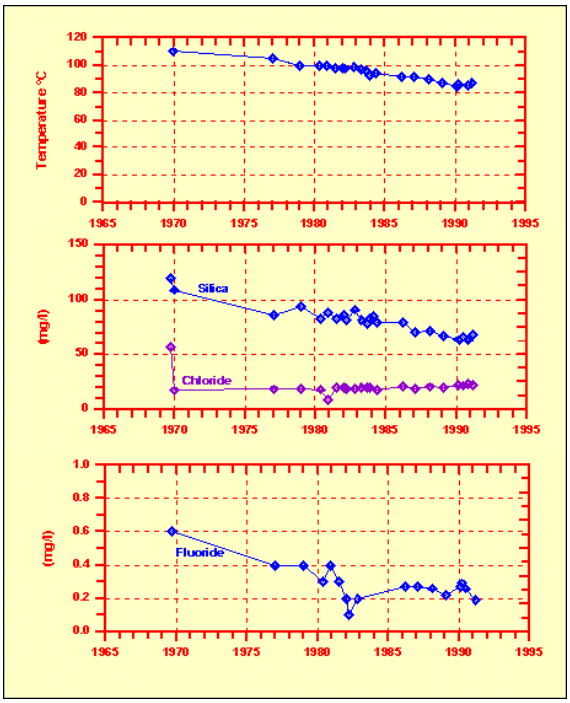

Figure 1. Changes in temperature, silica, chloride and fluoride in well 30 at Elli_aár field

Production from the field started in January 1968 and since 1970 the annual production has been in the range of 4 to 5 Gl. The peak-pumping rate from the 8 production wells has been about 200 l/s.

The pressure history of the field shows a rapid draw down or recovery each time the pumping from the field is changed. At a constant pumping rate for couple of months, pressure stabilization occurs, indicating a massive recharge of fluid to the reservoir. Monitoring of production, temperature and chemistry shows that the recharge is of groundwater origin. Figure 1 shows the changes in temperature, silica, chloride and fluoride content with time for one of the drill hole in the area. Cooling of up to 20 °C has been observed since 1968. The concentration of silica and fluoride has decreased at the same time. Only slight changes have on the other hand be in the concentration of chloride where the chloride concentration in the groundwater and in the geothermal water is similar. Prior to exploitation geothermal water may be in equilibrium with the alteration minerals. Mixing with cooler groundwater may cause deviation from equilibrium and that have to be studied by interpretation of the monitoring data.

Initially the geothermal water was close to chalcedony saturation but with time it has become progressively more under-saturated as the water temperature has fallen (fig. 2). The recharge water has been heated up before mixing with no or very slight leaching of silica from the rock.

Due to the recharge the concentration of dissolved oxygen has increased drastically making the water corrosive to steel. The corrosion has been avoided by mixing the geothermal water from the Elli_aár field with water from other geothermal fields containing hydrogen sulphide (H_2S). Hydrogen sulphide reacts fast with dissolved oxygen until either of the components is dissipated.

Drilling began in the ***Laugarnes*** field now in mid Reykjavík in 1928 and exploitation was initiated in 1930. Available artesian flow rate was 14 l/s of water at 87°C. Deep drilling began in 1958 and the first down hole pump was installed a year later. Artesian flow ceased in 1965 and since then down hole pumps have been operated in the wells. To day 10 exploi-tation wells are in operation but total of 26 deep wells have been drilled in the field, the deepest one reaching down to 3085 m. Since 1968 the produc-tion from the field has averaged at 5-6 Gl per year of 125-130°C water. The maximum production du-ring the coldest part of the year is about 330 l/s. The fluid from the field was low in total dissolved solids, about 350 mg/kg, of which about 35 mg/kg was chloride.

Production from the field has caused pressure draw down within the production well field and vicinity. The initial pressure potential of the field is unknown. Since 1963 the well head pressure and later the water level in observation wells has been monitored carefully. The total draw down is in the order of 120 m.

The exploitation of the field has not had any effect on the production temperature, but some gradual changes have been measured in the fluid chemistry after 1980 when production was increased in the western part of the field. The concentration of chloride has doubled in some of the wells while other remain as initially. Two wells produced water in excess of 100 ppm chloride concentration. The concentration of silica and fluoride has on the other hand showed a small decline during the exploitation years. The changes in chemistry are most likely caused by infiltration of highly saline water into the uppermost part of the reservoir.

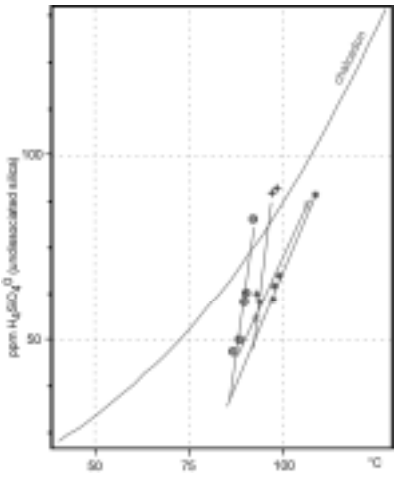

Figure 2. The variation with time of the degree of calcedony saturation in water discharge form different wells in the Elli_aár field.

The mixing of the reservoir fluid with more saline water has caused calcite deposition in down hole pumps where the chloride concentration has

reached 100 ppm. Figure 3 shows equilibrium curve for calcite as a function of temperature and comparison of calculated activity product for calcite for water samples from all wells in the Laugarnes field to the equilibrium. Most samples are close to equilibrium at given temperature but those higher in chloride concentration (filled dots) show deviation from equilibrium.

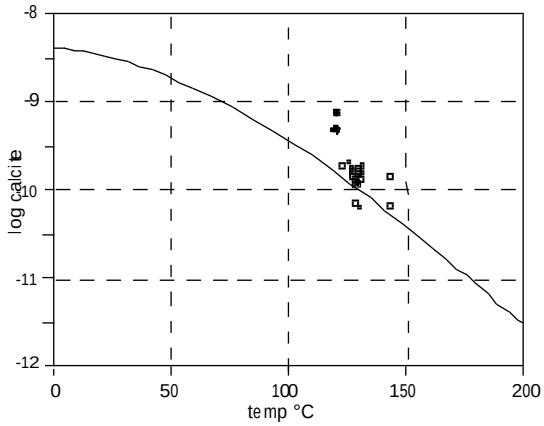

Figure 3. Solubility of calcite and degree of saturation of water from the Laugarnes field

Figure 4 shows a graph where the solubility product of calcite for samples from one well (no. 34) is plotted against chloride concentration. The calculations are performed at 120 °C and the equilibrium constant for calcite at that temperature is shown on the graph as horizontal line. The degree of uncertainty for the equilibrium constant is shown shaded. Initially the water from this well had chloride concentration about 50 mg/kg and close to equilibrium. As mixing increases the water calculates to be super-saturated and calcite depositions are formed.

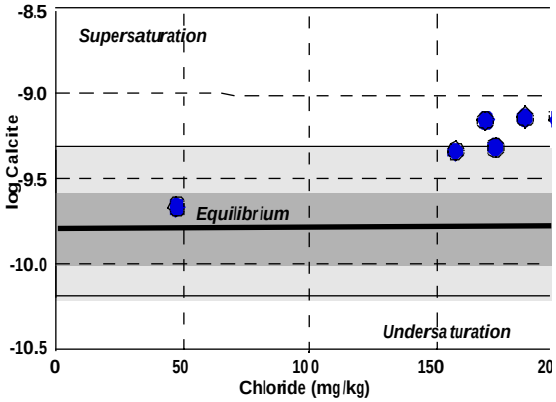

Figure 4. Changes of the solubility product of calcite with increasing chloride concentration for samples from well RV-34 at Laugarnes field.

Some of the saline water enters the reservoir through wells due to shallow casings. Steps have been taken to stop the leakage of saline water in the reservoir. Observation wells, which showed down-flow of saline water, have been plugged with cement and some production wells have been re-cased. New production wells will be cased deeper than present production wells.

Chemical monitoring during geothermal utilization cover more than just monitoring of the geothermal field and how the utilization changes reservoir parameters. Regular monitoring of production related parameters have to be carried out. These parameters are determining the quality of the water and steam used in different applications. Examples of these are dissolved oxygen, hydrogen sulphide (H_2S) and pH in low temperature water in direct use applications and gas composition and carry-over of high temperature steam.