

Geochemical monitoring of the response of geothermal reservoirs to production load –examples from Krafla, Iceland

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Abstract

Monitoring of the chemical composition of water and steam discharged from wells in exploited geothermal fields provides information on the response of the reservoir to the production load. Decrease in the Cl concentration in the discharged water indicates relative increase in recharge into producing aquifers of colder water but an increase in Cl indicates recharge from hotter zones. When a well discharge consists of components with different source temperatures, the consequence is discrepancy between geothermometry temperatures. The cause of discrepancy may also be variable departure from equilibrium for individual geothermometers.

Keywords: geochemical monitoring, response to production, geothermometers, recharge.

1 Introduction

Changes in the chemical composition of water and steam discharged from wells in exploited geothermal systems provide information on the response of the reservoir to the production load with respect to the source of the water recharging producing aquifers (Arnórsson et al., 2000). Data on fluid compositions may also provide useful information on the depth level of producing horizons in individual wells (Arnórsson, 2000). Gas compositions can be used to estimate the initial steam fraction in the aquifer fluid (D'Amore and Celati, 1983; Arnórsson et al. 1990), i.e. the steam fraction in the aquifer fluid beyond the depressurization zone that forms around producing wells.

The present contribution uses data from the Krafla geothermal system in Iceland to demonstrate how discrepancy between geothermometry temperatures and changes in Cl concentrations of well discharges can be used to identify fluid temperatures in feed zones and the source of water recharging producing aquifers. At Krafla a 30 MW geothermal power station was commissioned in 1978. In 1998 it was enlarged to 60 MW. A total of 35 wells have been drilled in the area of which 21 are productive at present.

2 Some basic concepts

Fluid discharged from wells penetrating rocks of an-isotropic permeability, such as at Krafla, is a mixture of many components that have traveled different distances at different velocities from their points of origin to the well. The concentrations of dissolved solids and gases in the discharge of wells penetrating such rocks, is the product of the chemical composition of each source component and its relative contribution to the well discharge. A change in the relative amounts of these

components will lead to a change in the composition of the discharged fluid unless their chemical composition was the same.

Dissolved solids and gases in geothermal fluids have been divided into two groups, as conservative and reactive components (Giggenbach, 1991). The aqueous concentrations of conservative components, such as Cl, are determined by their supply to the water. Once they have entered the aqueous phase they remain there. Reactive components, on the other hand, tend to equilibrate with hydrothermal minerals, which incorporate these components and provide useful information on the physical state of geothermal systems (Giggenbach, 1991).

The sources of conservative components to geothermal fluids include the rock with which the fluid has interacted but also degassing magma and the recharging water. The amount of interaction with the enclosing rock is determined by the residence time of the fluid in this rock and temperature. Increase in temperature increases the rate of fluid-rock interaction. The consequence of these processes is that geothermal fluids, particularly when of high temperature, contain higher concentrations of conservative elements than non-thermal ground waters and surface waters. A decrease in the concentrations of Cl and other conservative components in water discharged from geothermal wells is the consequence of a relative increase of water low in Cl and this is taken to be colder water (Gudmundsson and Arnórsson, 2002).

The equilibrium constants for reactions involving reactive aqueous components and hydrothermal minerals vary with temperature and pressure. Changes of fluid temperature and pressure, as fluid flows from its place of origin into a well, therefore changes its state of mineral saturation and may lead to changes in fluid composition by mineral dissolution or precipitation depending on kinetic factors. Mixing of water components has the same effect.

Changes in pressure, in the range occurring in geothermal systems, have much lesser effect on changes in the state of mineral saturation than temperature changes. This is exemplified for quartz (SiO₂) in Figure 1, a common hydrothermal mineral, the solubility of which has been well established experimentally over a wide range of temperature and pressure (Manning, 1994, Rimstidt, 1997). A drop of pressure from 300 to 0 bars at 100°C leads to a change in the saturation index by 0.016 for the quartz dissolution reaction:



This corresponds to a decrease in quartz solubility by 2 ppm. The corresponding numbers for a decrease in pressure of 200° and 300°C water from 300 bars to their vapour saturation pressures is 13.0 and 73.6 ppm, respectively. Pressure drop from 300 to 100 bars decreases quartz solubility by the same amount as a temperature increase at 300 bars from 286° to 300°C.

Many reactive components and reactive component ratios have been successively used as geothermometers (e.g. Fournier and Potter, 1982; Giggenbach, 1980, 1981; Arnórsson et al. 1983; Arnórsson and Gunnlaugsson, 1985). Experience indicates that many geothermometer components, such as those involved for the quartz- and Na/K-geothermometers, react slowly upon cooling and it is generally assumed that the concentration of the respective aqueous components are not affected by changes of temperature and pressure in upflow zones below springs and in aquifers producing into wells. This assumption is, of course, an approximation. Some reaction may be expected to occur, depending on kinetic factors that would affect different geothermometers to a different extent.

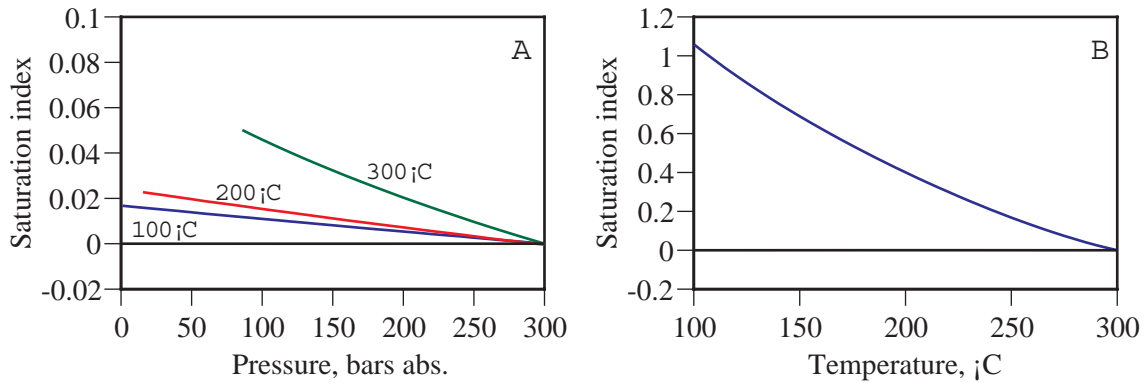


Figure 1: Changes in quartz saturation of water initially at equilibrium with quartz. A. Effect of depressurization on quartz saturation for waters at 300°, 200° and 100°C as indicated. B. Effect of temperature decrease on quartz saturation at pressure of 100 bars abs. Based on quartz solubility data of Manning (1994).

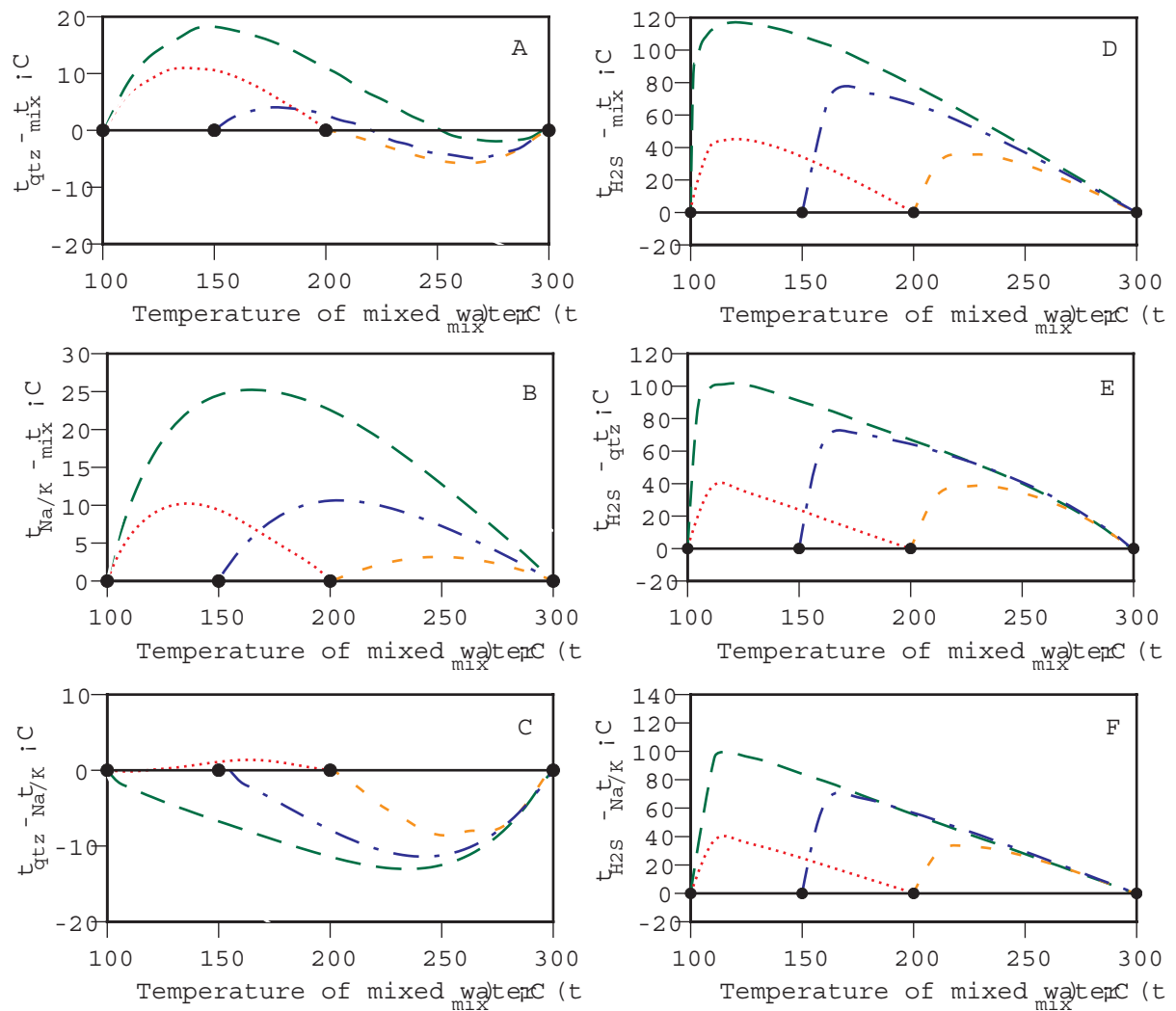


Figure 2: The difference between Na/K-, quartz- and H₂S-geothermometer temperatures and actual temperatures (t_{mix}) of variably mixed waters initially at equilibrium with quartz, low-albite and microcline (the Na/K-geothermometer) and a mineral buffer controlling H₂S. End-member components in the mixed waters are shown by dots. The quartz- and Na/K-geothermometer equations used are those given by Arnórsson (2000).

Those for H₂S are based on drillhole data below 210°C (Arnórsson and Gunnlaugsson, 1985) and the mineral buffer prehnite + epidote + pyrite + pyrrhotite above 210°C (Arnórsson et al., 1998) taking the activity of epidote in the clinozoisite-epidote solid solution to be 0.7.

If appropriately calibrated, and if all the source fluid components in a well discharge had the same temperature, all geothermometers should give about the same temperature value assuming, of course, that chemical equilibrium prevailed for all of them. When, on the other hand, a well discharge is a mixture of geothermal fluids of different temperatures, a discrepancy results between the geothermometry temperatures. The effect of such mixing is demonstrated in Figure 2 for the quartz-, Na/K- and H₂S geothermometers.

3 Boiling

Many liquid dominated geothermal reservoirs are two phase. Depressurization in producing aquifers, which occurs when a well is discharged, leads to extensive boiling in the depressurization zone and a decrease in fluid temperature. Extensive boiling in producing aquifers may also occur in initially sub-boiling reservoirs, if the pressure drop is sufficient. Changes in the composition of the water, which occurs in response to steam formation and degassing, in addition to changes temperature and pressure, will lead to changes in the saturation state of the water with respect to minerals. The consequence is potential mineral precipitation or dissolution, its magnitude depending on the kinetic factors. Capillary forces and the relative permeability of flowing water and steam, which relates to the relative volume of the two fluid phases, may cause them to separate at least partly. Such phase separation may change the state of mineral saturation of the flowing water. It will also change the enthalpy of the well discharge relative to the initial aquifer fluid. Heat transfer from the rock to the flowing fluid in the depressurization zone has the same effect.

Many of the Krafla wells have “excess” enthalpy, i.e. their enthalpy is higher than that of steam saturated water at a chemical geothermometer temperature. Partial phase separation in the depressurization zone around wells is considered to be largely the cause of this “excess” enthalpy in Krafla (Gudmundsson and Arnórsson, 2002). The concentration ratios of solids dissolved in the water are not affected by phase separation. Therefore, this process does not affect geothermometers, which are based on component ratios, whereas those are that are based on aqueous or gaseous component concentrations are. The effect of phase separation on concentration based geothermometers, is minimized by calculating component concentration in water and steam at 10 bars abs. vapour pressure (Gudmundsson and Arnórsson, 2002). This has been done for the present study.

4 Examples of results

The Cl concentration in water discharged from many of the wells at Krafla has decreased with time whereas other discharges have retained constant Cl. This is demonstrated for three of the Krafla wells in Figure 3. For well 9, Cl concentrations have remained about constant in water at 10 bars abs., about 30 ppm through a 20 year observation period. Initially Cl concentrations in water from well 13 fluctuated much but then decreased and stabilized at a concentration very similar to that of well 9. In well 21 Cl concentrations have decreased to about half of the initial value, apparently fastest during the first 5 years of production but since more slowly. The decrease in Cl concentrations in the discharges of wells 13 and 21 are indicative of a

relative increase to the discharges in a Cl deficient water component, i.e. in colder water.

In harmony with a decrease in the Cl concentrations in water discharged from wells 13 and 21, t_{qtz} , t_{NaK} and t_{H_2S} have decreased considerably. A decrease is also observed for well 9.

Over a 15 year period, 1982-1997, t_{qtz} has decreased by about 10°C in well 9 and t_{NaK} and t_{H_2S} a little more. Prior to 1982 decreases in the geothermometry temperatures were more rapid. T_{qtz} is systematically higher than t_{NaK} and t_{H_2S} , or by about 20°C. This discrepancy is not considered to be due to an erroneous calibration of the geothermometers. It cannot be explained by mixing of water components of different temperatures. Such mixing would cause t_{H_2S} to be highest and t_{qtz} lowest. The difference is too large to be explained by variable effects of pressure on the various geothermometer mineral-solution equilibria but their calibration is valid at vapour saturation pressures but the producing aquifer of well 9 is sub-boiling. It is considered most likely that the cause of the discrepancy is variable departure from equilibrium of the water recharging the producing aquifer.

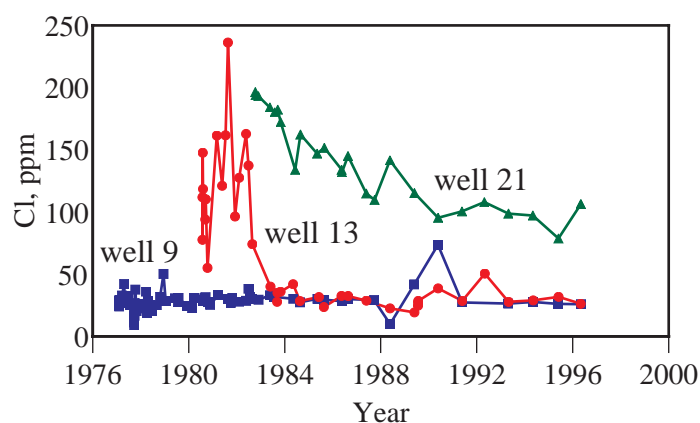


Figure 3: Changes in Cl concentrations in water at 10 bars abs. vapour pressure discharged from wells at Krafla, Iceland.

Data on the chemical composition of hot spring and fumarole discharges in Iceland, such as in the Geysir Area, in Hveragerdi at Hveravellir and in Landmannalaugar show that t_{qtz} is typically higher than t_{NaK} and t_{H_2S} (Arnórsson, 1985; Arnórsson and Gunnlaugsson, 1985). This is attributed to variable reaction rates for the different geothermometer components in the upflow where cooling occurs. These observations, when transferred to data from well 9, imply a relative increase of water into the producing aquifer of the well from shallower and cooler horizons in the reservoir.

Temperature measurement in well 13 during thermal recovery after drilling indicated three permeable horizons, at 1000, 1400 and 1500 m depth (Gudmundsson and Arnórsson, 2002). The geothermometry temperatures for this well are consistent with contribution from feed zones having significantly different temperatures, as the H_2S geothermometer yields the highest temperature (Figure 4). In line with the data interpretation for well 9, the discrepancy between t_{qtz} and t_{NaK} indicates recharge from shallow zones in the reservoir. It is envisaged that the discharge of well 13 consists of a “bleed” from relatively deep hot zone, as indicated by t_{H_2S} and increasing recharge from shallow and relatively cold zone as indicated by decreasing t_{qtz} and t_{NaK} and by increasing discrepancy between these geothermometers

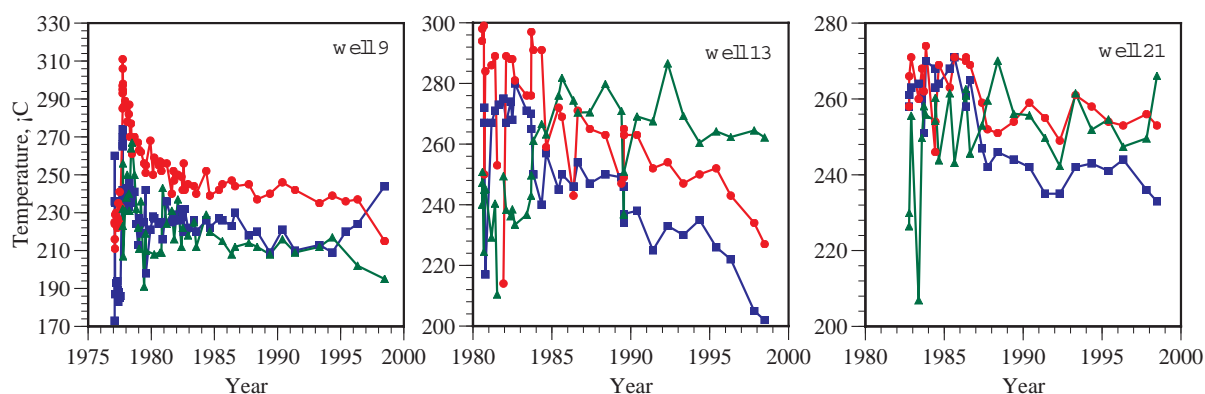


Fig. 4: Variations in geothermometry temperatures with time for 3 wells at Krafla. Squares t_{NaK} ; dots t_{qtz} , and triangles $t_{\text{H}_2\text{S}}$.

During the first 4 years of discharge of well 21 all the geothermometers considered yielded about the same temperature, the averages for t_{qtz} , t_{NaK} and $t_{\text{H}_2\text{S}}$ being 263° , 264° and 265°C , respectively. This corresponds well with the measured temperature in the well when thermally stabilized at the depth level (570 m) of the main permeable horizon, 260°C . In 1986-88 t_{qtz} fell considerably and t_{NaK} even more whereas $t_{\text{H}_2\text{S}}$ has remained about constant. Since 1988 t_{qtz} has remained about constant but t_{NaK} has decreased slightly, by about 10°C . These changes are considered to indicate a small relative increase in a colder water component in the discharge of well 21. The strong decline in Cl concentrations indicates, by contrast, a substantial relative increase in colder water recharge into the producing aquifer of the well. It is considered that the chemical geothermometers indicate only a limited increase in colder water recharge because this water component has had sufficient time to approach chemical equilibrium quite closely at the temperature of the producing aquifer.

5 References

- Arnórsson, S. (2000). The quartz- and Na/K geothermometers. II. Results and application for monitoring studies. *World Geothermal Congress 2000*, pp. 935-940.
- Arnórsson, S. (1985). The use of mixing models and chemical geothermometers for estimating underground temperatures in geothermal systems. *J. Volc. Geothermal Res.*, Vol. 23, pp. 299-335.
- Arnórsson, S. and Gunnlaugsson, E. (1985). New gas geothermometers for geothermal ex-ploration-calibration and application. *Geochim. Cosmochim. Acta*, Vol. 49, pp. 1307-1325.
- Arnórsson, S., Björnsson, S., Muna, Z.W. and Ojiambo, S.B. (1990). The use of gas chemistry to evaluate boiling processes and initial steam fractions in geothermal reservoirs with an example from the Olkaria field, Kenya. *Geothermics*, Vol. 19, pp. 497-514.
- Arnórsson, S., D'Amore, F., and Gerardo, J. (2000). *Isotopic and chemical techniques in geothermal exploration* (Ed. S. Arnórsson). Vienna, Intern. Atomic Energy Agency, 351pp.
- Arnórsson, S., Fridriksson, Th., and Gunnarsson, I. (1998). Gas chemistry of the Krafla geothermal field, Iceland. In: Proc. *International Symposium on Water-Rock Interaction*, Auckland, New Zealand, pp. 613-616.

- Arnórsson, S., Gunnlaugsson, E. and Svavarsson, H. (1983). The chemistry of geothermal waters in Iceland. III. Chemical geothermometry in geothermal investigations. *Geochim. Cosmochim. Acta*, Vol. 47, pp. 567-577.
- D'Amore, F. and Celati, C. (1983). Methodology for calculating steam quality in geothermal reservoirs. *Geothermics*, Vol. 12, pp. 129-140.
- Fournier, R.O. and Potter, R.W. (1982). A revised and expanded silica (quartz) geothermometer. *Geotherm. Resour. Council Bull.*, Vol. 11, pp. 3-9.
- Giggenbach, W. F. (1980). Geothermal gas equilibria. *Geochim. Cosmochim. Acta* Vol. 44, pp. 2021-2032
- Giggenbach, W. F. (1981). Geothermal mineral equilibria. *Geochim. Cosmochim. Acta* Vol. 45, pp. 393-410.
- Giggenbach, W.F. (1991). Chemical techniques in geothermal exploration. *Application of Geochemistry in Geothermal Reservoir Development*. (Ed. F. D'Amore) UNITAR/UNDP Centre on Small Energy Resources, Rome, pp. 119-144.
- Gudmundsson, B.Th. and Arnórsson, S. (2002). Geochemical monitoring of the Krafla and Námafjall geothermal areas, N-Iceland. *Geothermics*, Vol. 31, pp. 195-243.
- Manning, C.E. (1994). The solubility of quartz in H₂O in the lower crust and upper mantle. *Geochim. Cosmochim. Acta*, Vol. 58, pp. 4831-4839.
- Rimstidt, J.D. (1997). Quartz solubility at low temperatures. *Geochim. Cosmochim. Acta*, Vol. 61, pp. 2553-2558.