

Geochemical methods in geothermal exploration and exploitation

Magnús Ólafsson
Iceland GeoSurvey (ÍSOR)

- The focus in the talk will be on the role of geochemistry in exploring and exploiting high-temperature geothermal systems ($T > 180^{\circ}\text{C}$)
- I will emphasize the need of careful sampling of geothermal fluids
- And say a few words about data interpretation
 - Geothermometers
 - Fluid qualities, scaling

Geochemical methods are extensively used and play a major role in geothermal exploration and exploitation!

Geothermal exploration and development

- At the onset of a geothermal exploration project it is uncertain whether or not the results will be economically, technically and environmentally feasible.
- Geothermal exploration and development, therefore, invariably necessitate risk money.
- Because of the uncertainty involved it has become common practice to divide the preparatory work into several phases in order to minimize cost and maximize information for each phase.

Geothermal project strategy

The main phases are
(in a simplified way) :

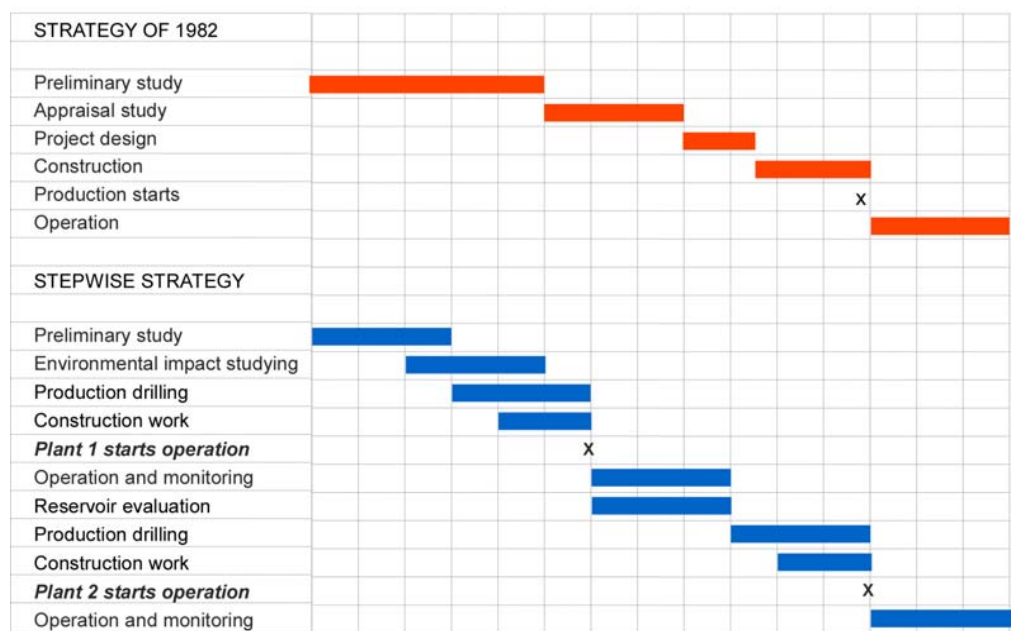
- Surface exploration
- Exploration drilling
- Production drilling
- Preliminary power plant design
- Financing, additional production drilling, construction
- Operation, monitoring



In a more sophisticated way we can divide each phase into several phases and we can put a time scale on the project!



Year 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15



Geochemistry and geochemical methods are extensively applied in all phases of geothermal exploration and development !



The basic philosophy behind using geochemical methods in geothermal exploration is that fluids on the surface (aqueous solutions or gas mixtures) reflect physico-chemical and thermal conditions in the geothermal reservoir at depth !

Geochemical studies of geothermal fluids essentially involve three steps:

- Sampling
- Analysis
- Data interpretation

Obtaining representative samples of geothermal fluids require specific sampling techniques and containers

In the exploratory phase the task of geochemistry is mainly to >

- Estimate subsurface temperatures by using chemical and isotope geothermometers as well as mixing models
- Identify the origin of the geothermal fluid, mainly with isotopic techniques
- Define chemical properties of the fluid with respect to environmental issues, scaling
- Provide data to a conceptual model of the geothermal system

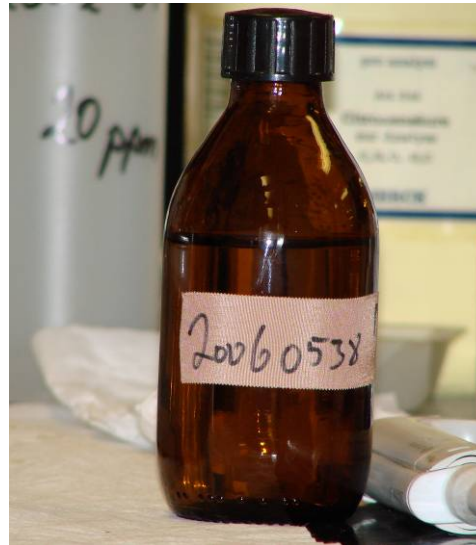
In the phase of exploration drilling the main task of geochemistry is to >

- Provide information on water to steam ratio in the reservoir
- Assess the quality of the geothermal fluid with respect to the intended use
- Assess the quality of the geothermal fluid with respect to the environment
- Provide information on scaling tendencies of the fluid in production as well as injection wells and surface equipment
- Provide additional information to a conceptual model of the geothermal reservoir

In the phase of production drilling and operation of a power plant the main task of geochemistry is to >

- Identify recharge into the reservoir of shallow groundwater or deeper hot water
- Assess boiling processes in production aquifers
- Identify changes in the chemistry of the geothermal fluid
- Quantify changes in scaling and corrosion tendencies
- Monitor the quality of the geothermal fluid with respect to the environment

- Chemical and isotopic analyses are expensive and tedious and all is wasted if the sampling is incorrect
- Chemical data interpretation becomes meaningless or even worse, misleading, if the sampling is incorrect



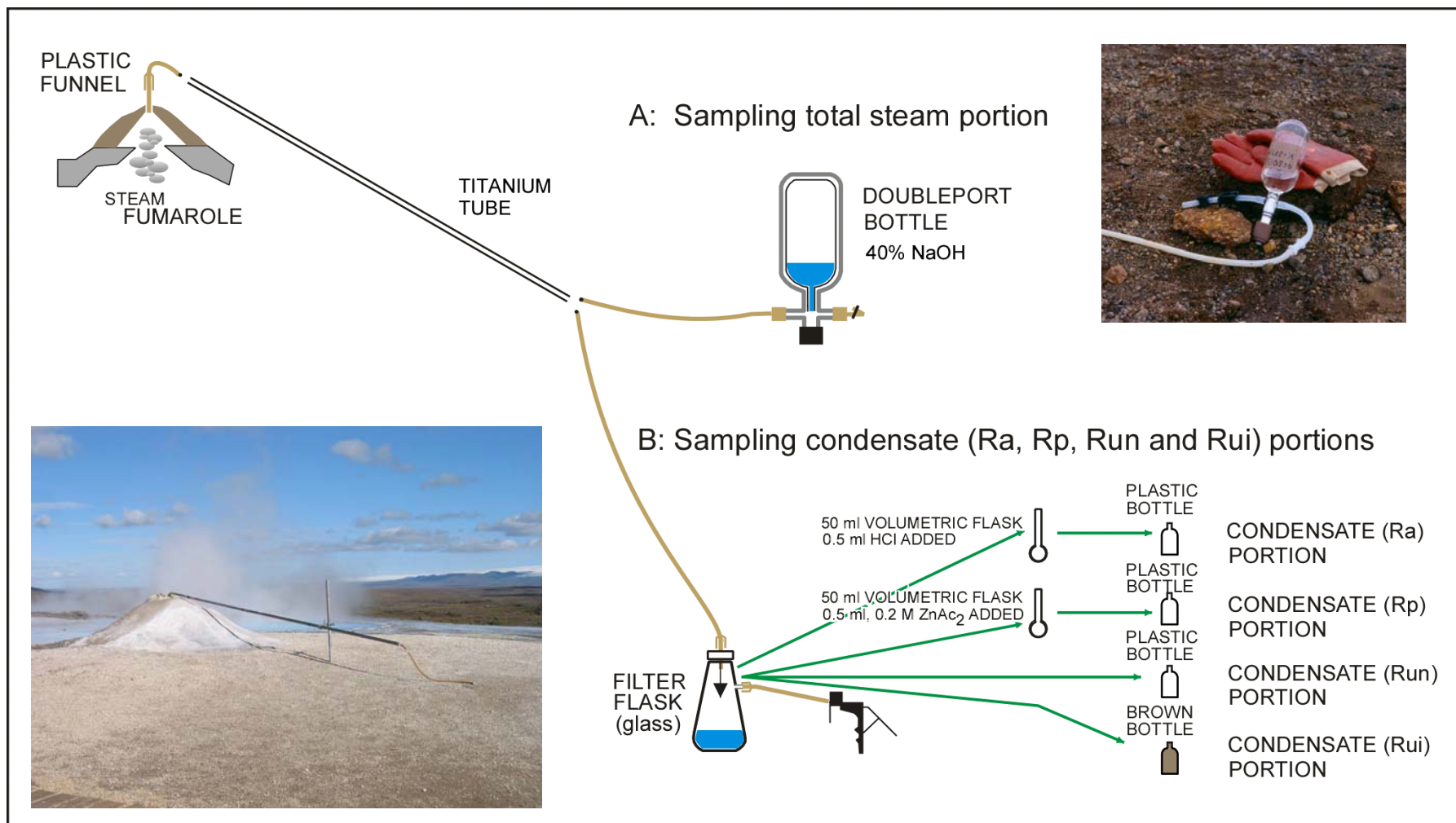
Important to emphasise the need of careful sampling

- Sampling in a high temperature field
- Safety first
- Selection of suitable sites
- Fumaroles
- Hot springs
- Sample thermal and non-thermal fluids







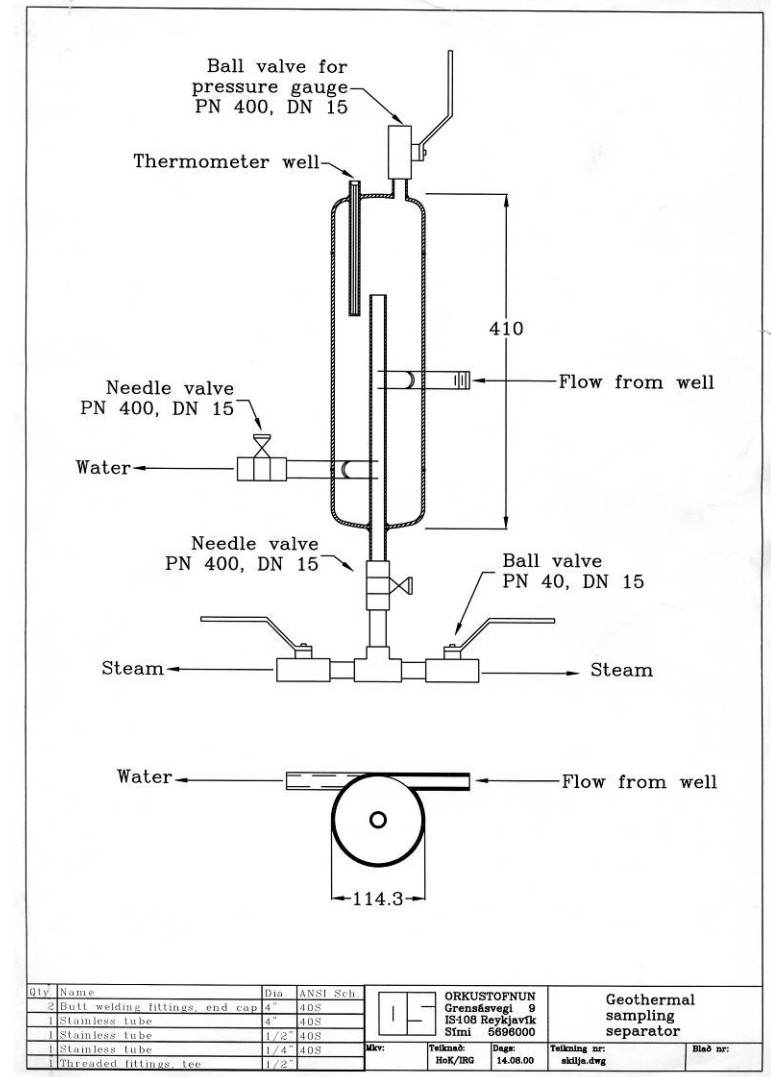
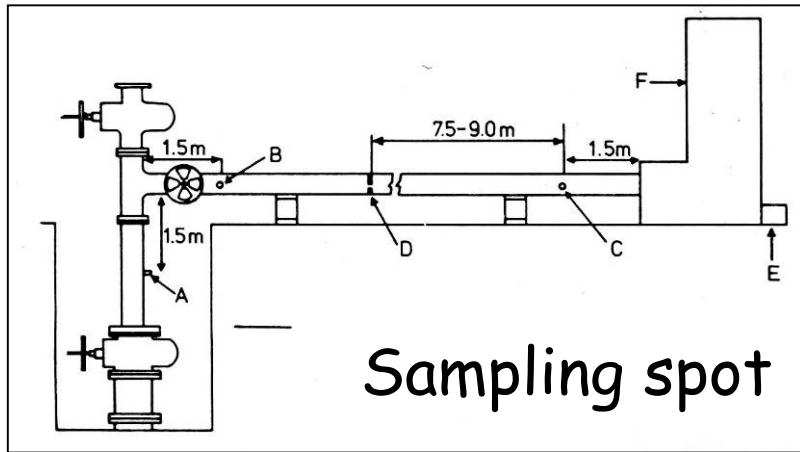


Collection of sample from a fumarole



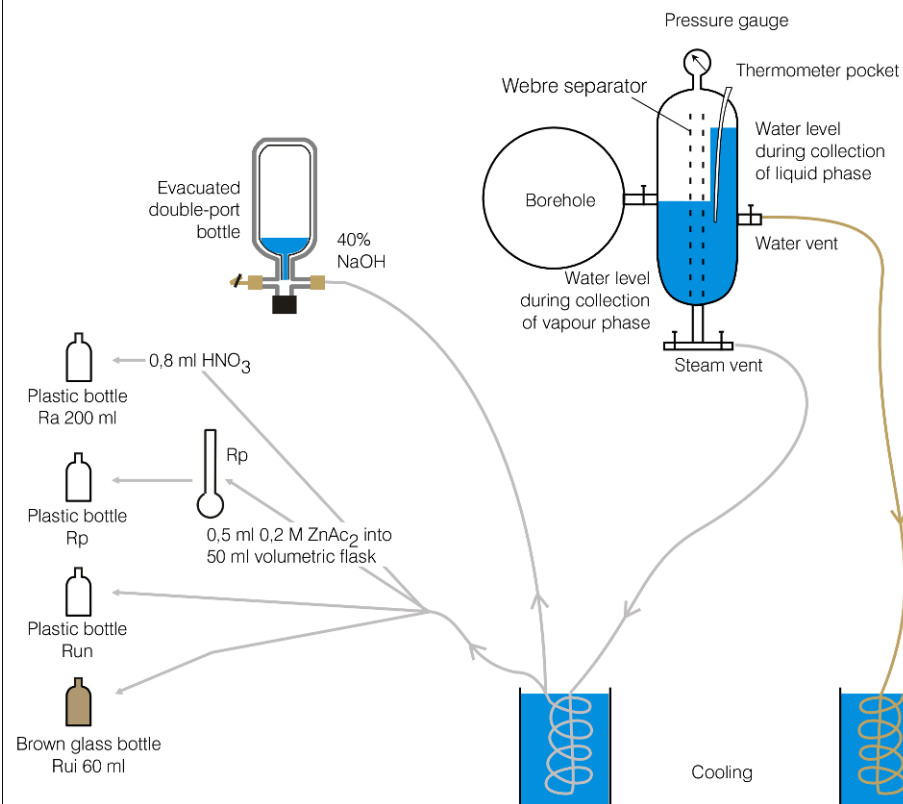
Sampling from :
Exploration wells
Production wells
Power stations



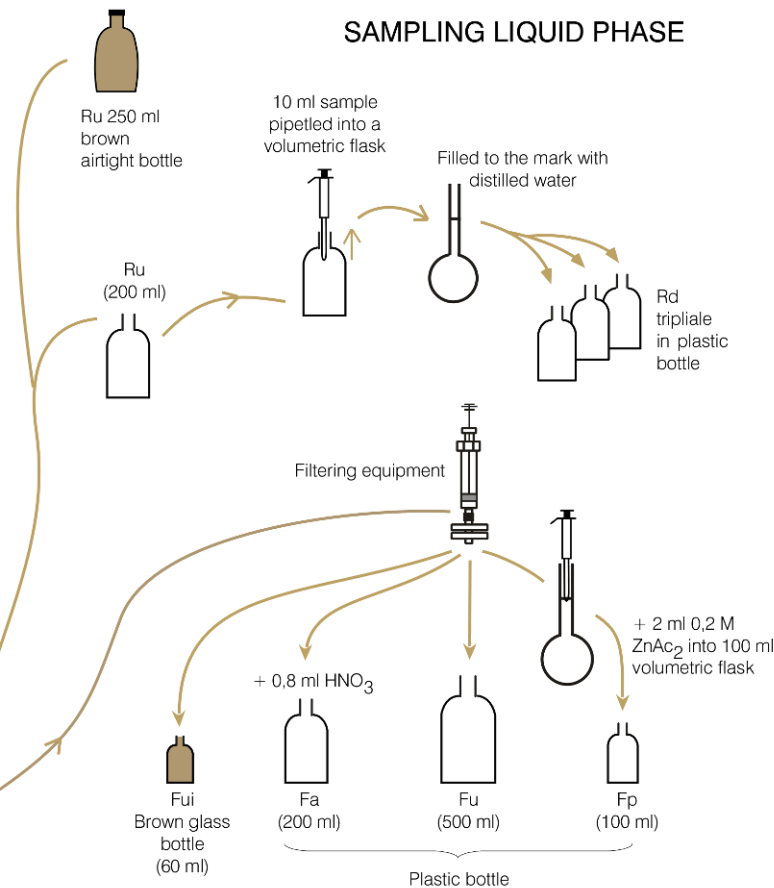


Webre separator

SAMPLING VAPOUR PHASE



SAMPLING LIQUID PHASE



Collection of sample from a two-phase geothermal well

Data Interpretation - Geothermometers

- Chemical and isotope geothermometers probably constitute the most important geochemical tool for the exploration and development of geothermal resources.
- They are used to :
 - Estimate subsurface temperatures of a geothermal reservoir
 - Monitor temperature changes of the reservoir during production
- Geothermometers have been classified into three groups:
 - Water or solute geothermometers
 - Steam or gas geothermometers
 - Isotope geothermometers

Water and steam geothermometers are generally referred to as chemical geothermometers

Water or solute geothermometers

- Mostly developed from mid-1960's to mid 1980' s
- The most important once are :
 - Silica
 - Na/K
 - Na-K-Ca

 - And less important are e.g.:
 - Na/Li, Li/Mg and Na-K-Mg

Silica geothermometer - a bit of history

- Suggested by Böðvarsson in 1960 and developed further by Böðvarsson & Pálmason 1961
- Fournier & Rowe, 1966, 120° - 330°C
- Arnórsson, 1975; Chalcedony
- Fournier, 1977. Silica-enthalpy mixing model
- Fournier & Potter 1982 - new equation 20° - 330°C and salinity accounted for

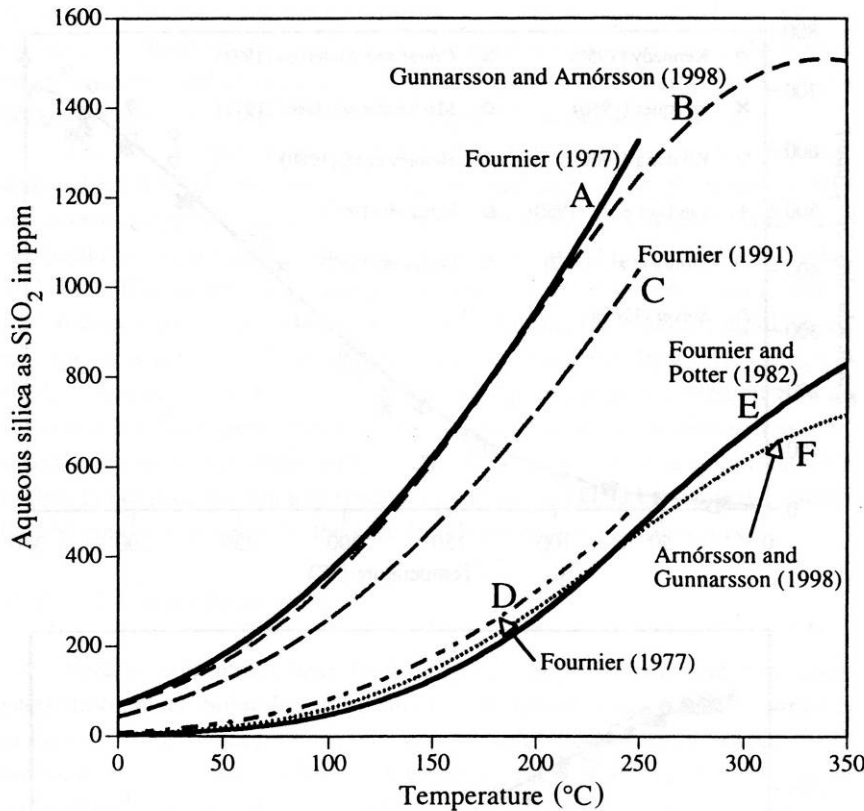
Silica geothermometer, cont'd

- Several known silica polymorphs in nature
- Quartz, amorphous silica, moganite, tridymite, cristobalite, coesite, stichovite.
- Chalcedony is a variety of quartz, composed of very fine quartz crystals, so fine that their surface energy contributes to their solubility and therefore explaining why chalcedony is more soluble than quartz.
- The Icelandic experience is that geothermal waters equilibrate with chalcedony below 180°C and with quartz at higher temperatures.

The solubility of quartz, chalcedony, opal and amorphous silica in water at 1 bar below 100°C and at the vapour pressure of the solution at higher temperatures.

Silica geothermometers, examples

S represents silica conc. as SiO₂ in mg/kg

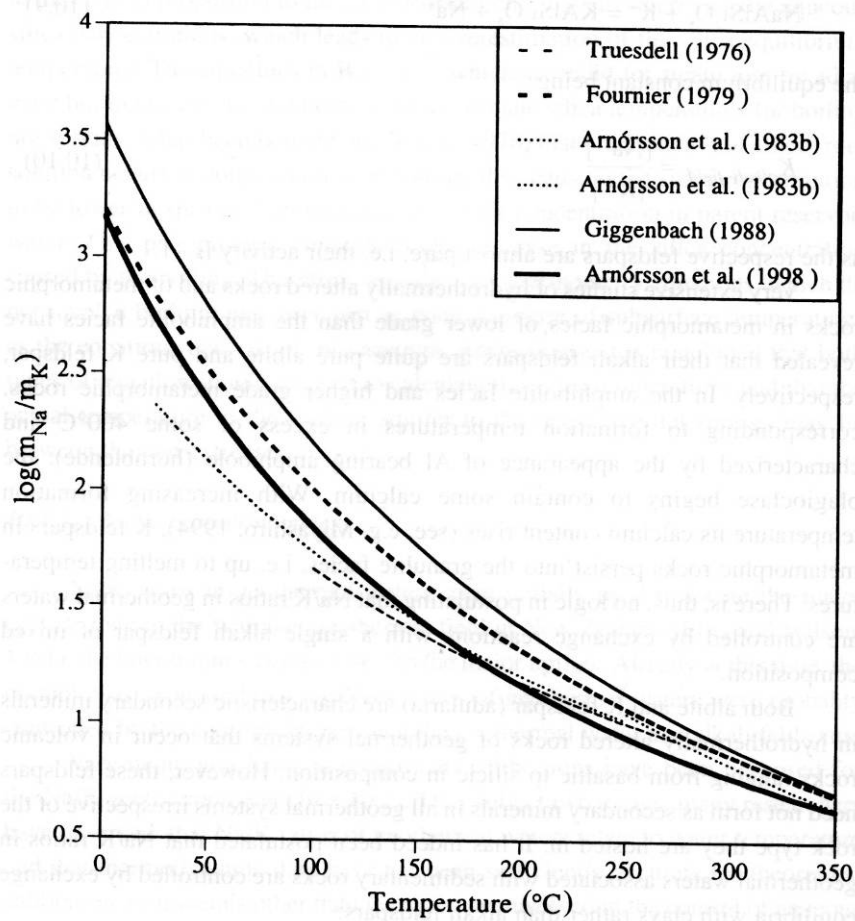


Geothermometer	Equation (t in °C)	Range (°C)	Source
Quartz	$\frac{1309}{5.19 - \log S} - 273.15$	25–250	Fournier (1977)
Quartz ^a	$\frac{1522}{5.75 - \log S} - 273.15$	25–250	Fournier (1977)
Quartz	$-42.2 + 0.28831S - 3.6686 \times 10^{-4}S^2 + 3.1665 \times 10^{-7}S^3 + 77.034 \log S$	25–900	Fournier and Potter (1982)
Quartz ^{a,b}	$-53.5 + 0.11236S - 0.5559 \times 10^{-4}S^2 + 0.1772 \times 10^{-7}S^3 + 88.390 \log S$		Fournier and Potter (1982)
Quartz	$-55.3 + 0.3659S - 5.3954 \times 10^{-4}S^2 + 5.5132 \times 10^{-7}S^3 + 74.360 \log S$	0–350	Arnórsson et al. (1988a)
Quartz ^a	$-66.9 + 0.1378S - 4.9727 \times 10^{-5}S^2 + 1.0468 \times 10^{-8}S^3 + 87.841 \log S$	0–350	Arnórsson et al. (1988a)
Chalcedony	$\frac{1032}{4.69 - \log S} - 273.15$	0–250	Fournier (1977)
Chalcedony	$\frac{1112}{4.91 - \log S} - 273.15$		Arnórsson et al. (1983b)
Moganite ^c	$-30.7 + 0.53113S + 1.2578 \times 10^{-4}S^2 - 5.9241 \times 10^{-7}S^3 + 19.576 \log S$	0–200	Gíslason et al. (1996)
α-Crisobalite	$\frac{1000}{4.78 - \log S} - 273.15$		Fournier (1977)

Cation geothermometers – a bit of history

- Na^+ , K^+ , Li^+ , Ca^{+2} , Mg^{+2} are mostly used
- The Na/K ratio in geothermal water were initially used to locate upflow zones in Wairakei by Ellis and Wilson 1961
- At that time it was already proposed that the Na/K ratios were probably controlled by equilibrium between geothermal water and alkali feldspars and depended on temperature
- Many empirical calibrations have been proposed
- Recently Arnórsson et al. have retrieved a new calibration based on experimental thermodynamic data

Proposed temperature curves for the Na-K geothermometer



Na-K geothermometers, examples

BOX 10.2. TEMPERATURE EQUATIONS FOR CATION GEOTHERMOMETERS

Concentrations are in ppm if not otherwise specified.

Geothermometer	Equation (t in °C)	Range (°C)	Source
Na-K	$\frac{856}{0.857 + \log(\text{Na/K})} - 273.15$	100–275	Truesdell (1976)
Na-K	$\frac{1217}{1.438 + \log(\text{Na/K})} - 273.15$		Fournier (1979)
Na-K	$\frac{833}{0.780 + \log(\text{Na/K})} - 273.15$		Tonani (1980)
Na-K	$\frac{933}{0.993 + \log(\text{Na/K})} - 273.15$	25–250	Arnórsson et al. (1983b)
Na-K	$\frac{1319}{1.699 + \log(\text{Na/K})} - 273.15$	250–350	Arnórsson et al. (1983b)
Na-K	$\frac{1178}{1.470 + \log(\text{Na/K})} - 273.15$		Nieva and Nieva (1987)
Na-K	$\frac{1390}{1.750 + \log(\text{Na/K})} - 273.15$		Giggenbach et al. (1988)
Na-K ^a	$733.6 - 770.551Y + 378.189Y^2 - 95.753Y^3 + 9.544Y^4$	0–350	Arnórsson et al. (1998)
K-Mg ^b	$\frac{2330}{7.35 + \log(\text{K}^2/\text{Mg})} - 273.15$		Fournier (1991)
K-Mg ^c	$\frac{1077}{4.033 + \log(\text{K}^2/\text{Mg})} - 273.15$		Fournier (1991)
K-Mg	$\frac{4410}{14.0 + \log(\text{K}^2/\text{Mg})} - 273.15$		Giggenbach (1988)



Steam (gas) geothermometers

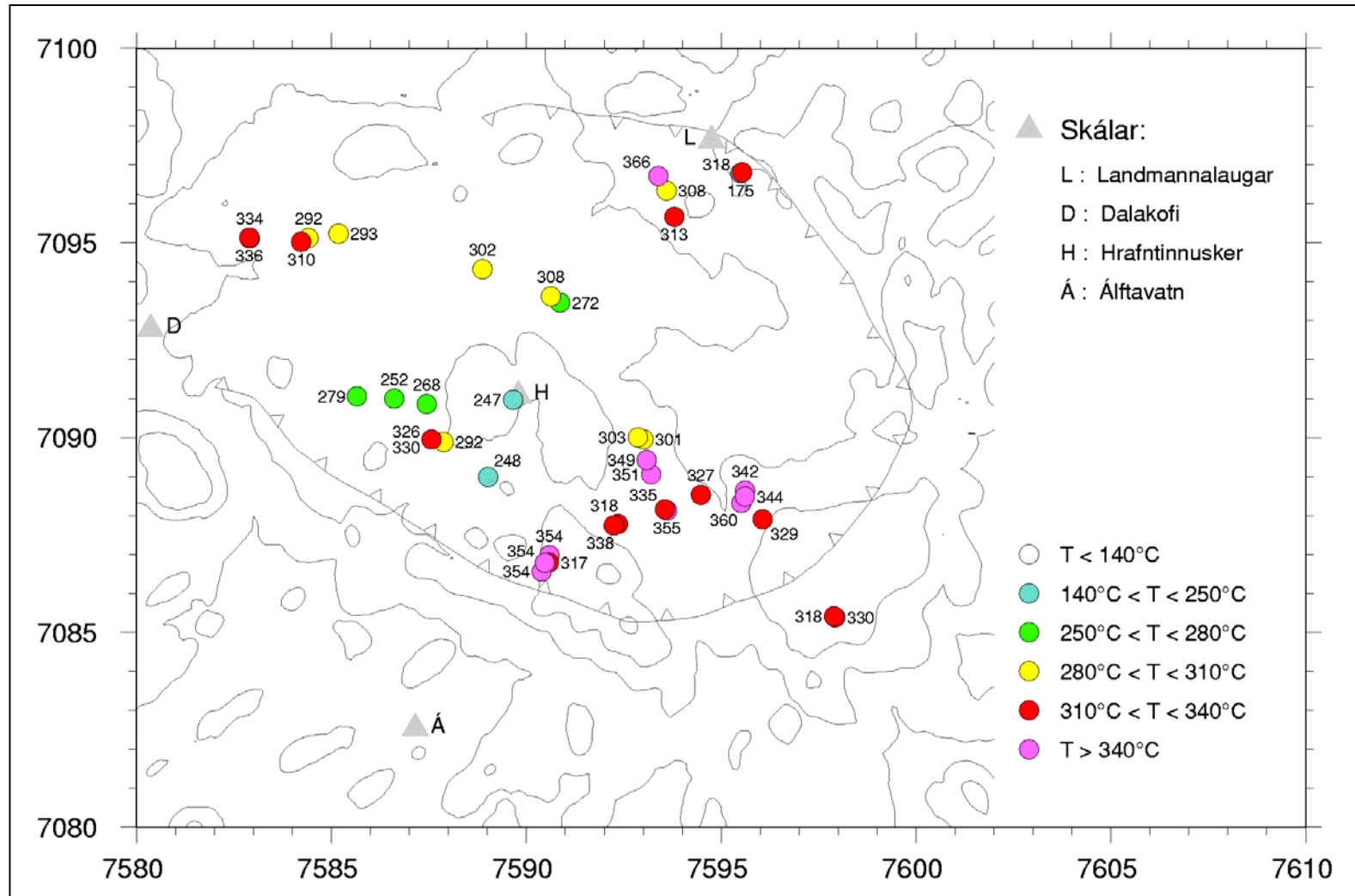
- The first gas geothermometer developed was that of D'Amore & Panichi (1980)
- Essentially three types of steam geothermometers
 - Gas - gas equilibria
 - Mineral - gas equilibria involving H_2S , H_2 and CH_4 and assuming CO_2 to be externally fixed
 - Mineral - gas equilibria

The first two groups require only data on the relative abundance of gaseous components in the gas phase

The third group calls for information on gas concentration in steam

Torfajökull, Iceland

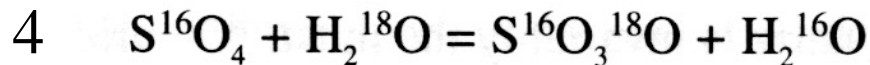
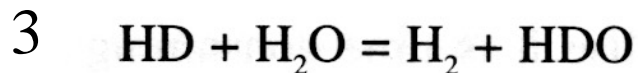
CO₂ / N₂ - gas geothermometer



Isotope geothermometers

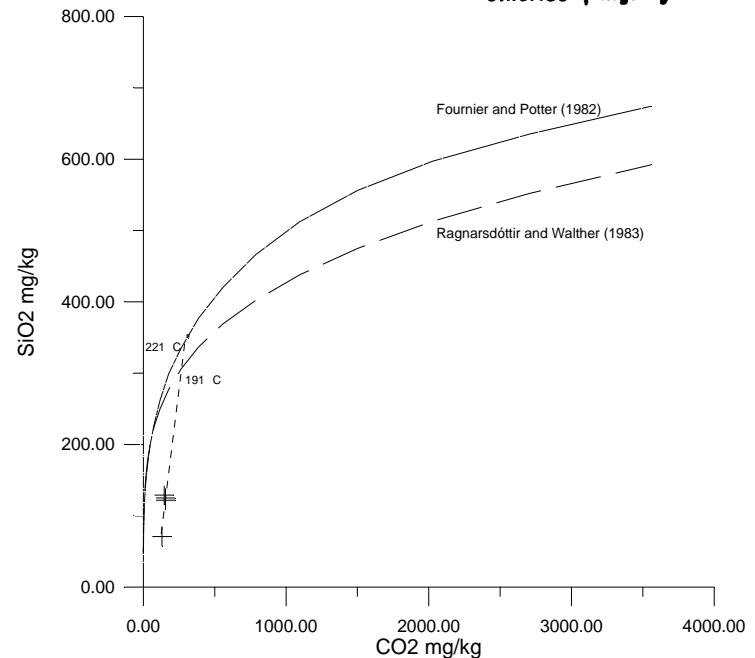
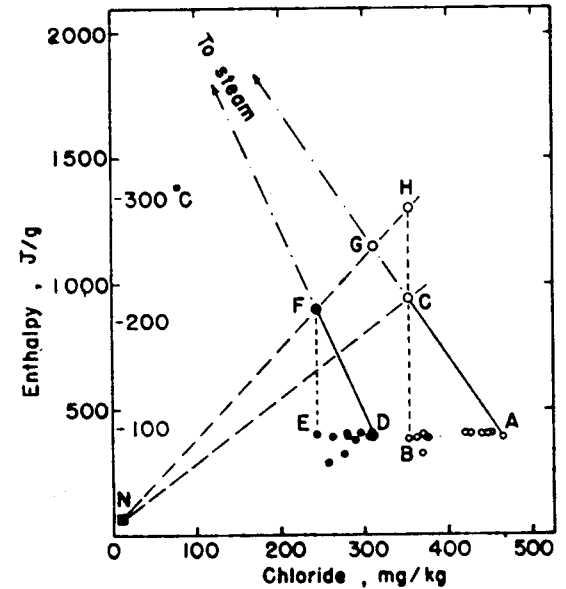
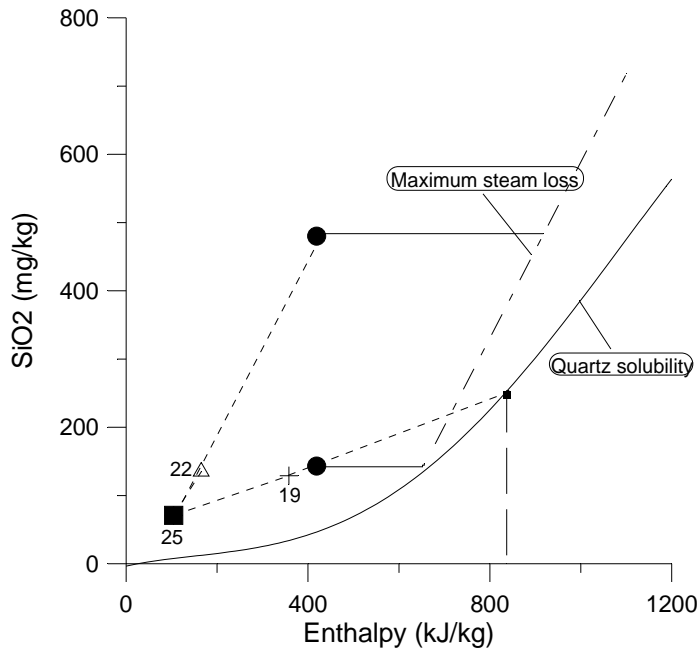
- Fractionation of isotopes of the light elements is quite significant and temperature dependent
- Possible to use the distribution of the stable isotopes of H, C and O between aqueous and gaseous compounds as geothermometers
- Several isotopic geothermometers have been developed and are quite extensively used

Examples of isotope geothermometers (SA, 2000)

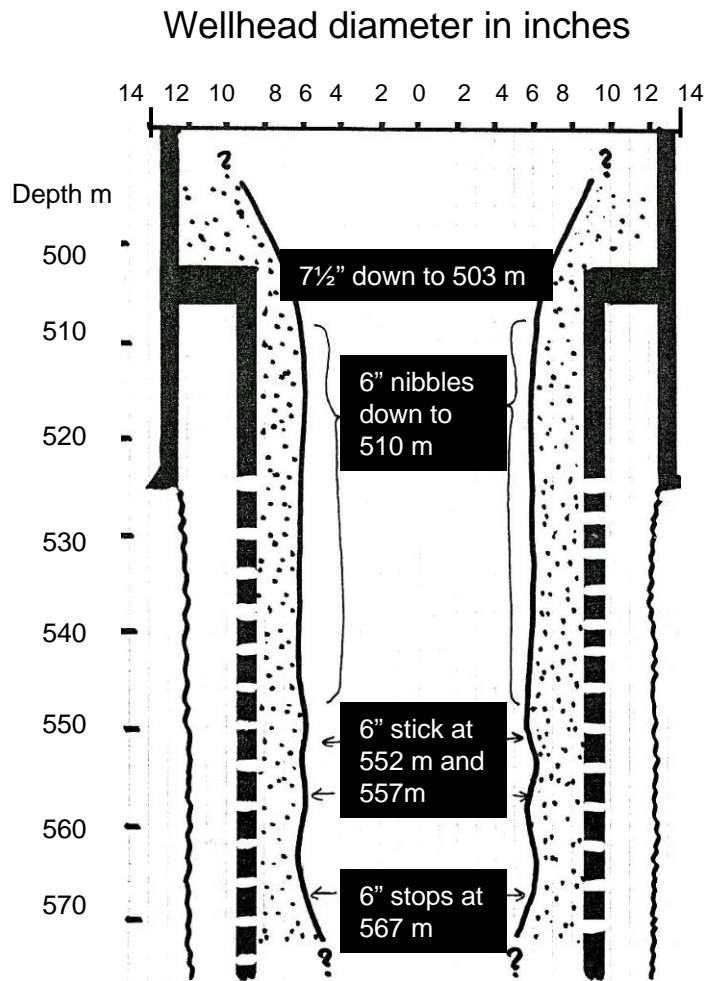


Thus, the first geothermometer is based on $\delta^{13}\text{C}$ values in CO_2 and CH_4 , the second and third on $\delta^2\text{H}$ in CH_4 and steam and in H_2 and steam, respectively. The fourth geothermometer uses $\delta^{18}\text{O}$ in aqueous SO_4 and liquid water.

Mixing models are used to estimate temperatures in geothermal reservoirs



Scaling, corrosion



RN-9

Some future geochemical tasks associated with e.g. UGR or IDDP (dealing with super critical fluids), EGS, CO₂ capture and storage, etc

- Many unsolved chemical problems may be associated with mining geothermal fluids from very deep and very hot reservoirs, IDDP-project, UGR, EGS etc.
 - Hostile fluid - super critical fluids!
 - Precipitation, scaling, corrosion etc.
 - Geochemical methods are heavily involved in a present project involved in capturing and geological storage of CO₂ at Hellisheiði, SW-Iceland
 - New methods and new technologies might be needed
 - It is necessary to strengthen the thermodynamic database for computer programmes used for data evaluation and modelling
-
- Geochemical methods will be involved in many future geothermal projects



Thank you !

