

Report 11, 1992

CALCITE DEPOSITION RELATED TO TEMPERATURE AND BOILING IN SOME ICELANDIC GEOTHERMAL WELLS

Pingtsoe Wangyal,
UNU Geothermal Training Programme,
Orkustofnun - National Energy Authority,
Grensasvegur 9,
108 Reykjavik,
ICELAND

Permanent address:
Science and Technology Office,
Bureau of Geology and Mineral Resources, Tibet,
Lhasa Beijing Road 132,
Tibet 850000,
P.R. CHINA

ABSTRACT

Calcite is a prominent secondary mineral in rocks. Calcite deposition is known to be troublesome for the exploitation of many geothermal fields in the world. This study is based on chemical data from selected wells in some Icelandic fields. The state of calcite saturation for a range of temperatures has been calculated for fluids from several geothermal wells in Iceland using the programme WATCH. Equilibrium calculations based on the WATCH computer programme have been used to estimate whether the fluid is saturated and whether supersaturation occurs upon boiling. Calculated and measured pressure and temperature profiles in several wells each with a single, dominant feedzone have been analyzed using the borehole simulator HOLA. In such cases HOLA is a useful tool to determine whether boiling takes place and if it does at what depth. Such simulations confirmed results for calculated supersaturation after boiling in wells. The borehole simulator was also used to study the effect of varying wellhead pressure on the depth of boiling in wells where calcite supersaturation was observed. Flashing depths which generally correspond to observed calcite deposition depths were found using the programme, and they were found to vary inversely with wellhead pressure. The two most important ways of combatting calcite deposition are drilling out and the addition of inhibitors. The cost of both increases with increased calcite deposition depth. The results of calculations on the variation of flashing depth with wellhead pressure are an aid in choosing the optimum wellhead pressure during production where the variation of flow with wellhead pressure shown by the characteristic curve must also be taken into account.

TABLE OF CONTENTS

	Page
ABSTRACT	3
TABLE OF CONTENTS	4
LIST OF FIGURES	5
LIST OF TABLES	5
1. INTRODUCTION	6
2. METHODS	9
2.1 Methods of analysis	9
2.2 Methods of calculation	9
3. CALCITE DEPOSITION WITH TEMPERATURE	11
3.1 Equilibrium constant	11
3.2 Calcite supersaturation relative to temperature	11
4. TEMPERATURE - DEPTH PROFILES AND BOILING DEPTH USING THE PROGRAMME HOLA	14
4.1 Temperature - depth profiles in Icelandic geothermal wells	14
4.2 Boiling depth using the programme HOLA	17
4.2.1 General	17
4.2.2 Calculated and measured downhole profiles in some Icelandic geothermal wells	17
5. RELATIONSHIP OF CALCITE DEPOSITION TO BOILING	24
6. OBSERVATION OF DEPOSITS IN THE WELLS	25
6.1 Methods of observation	25
6.2 Svartsengi	25
6.3 Nesjavellir	26
6.4 Hveragerdi - Olfusdalur	26
6.5 Krafla	27
7. CONCLUSIONS	30
ACKNOWLEDGEMENTS	31
REFERENCES	32

LIST OF FIGURES

	Page
1. The main geological features of Iceland and the location of areas studied	6
2. Calcite solubility with temperature in Olfusdalur well 6	12
3. Calcite solubility with temperature in Hveragerdi well 8	12
4. Calcite solubility with temperature in Nesjavellir well 18	12
5. Calcite solubility with temperature in Svartsengi well 7	12
6. Calcite solubility with temperature in Reykjavik well H-16	13
7. Calcite solubility with temperature in Krafla well KJ-9	13
8. Results of temperature measurements in some Icelandic wells	15
9. The high temperature geothermal field in Hveragerdi, Iceland	14
10. Hveragerdi, temperature distribution in cross section A-A'	16
11. Results of temperature measurements in Krafla well KJ-9 and Reykjavik well H-16	16
12. Calculated downhole temperature profiles in Olfusdalur well 6	18
13. Calculated and measured temperature profiles in Hveragerdi well 8	19
14. Calculated and measured temperature profiles in Nesjavellir well 18	20
15. Calculated and measured temperature profiles in Svartsengi well 7	21
16. Calculated and measured temperature profiles in Krafla well KJ-9	22
17. Calculated flashing depth with varying wellhead pressure in five Icelandic geothermal wells	23
18. The depth interval at which deposits form, and calculated depth of boiling level versus time in Svartsengi well 7	27
19. Scaling of liner and casing in Krafla well KJ-9	28
20. Enthalpy state of Krafla well KJ-9, 1977-1982	28
21. Time of undisturbed flow after removal of deposits from Krafla wells KJ-9 a and b	29

LIST OF TABLES

1. The chemical composition of selected samples from wells in Iceland	9
2. Basket caliper logs in Svartsengi wells	25
3. Cleaning workouts in Svartsengi	26
4. Decrease in depth of some Svartsengi wells	26

1. INTRODUCTION

Iceland is an island that is situated in the North Atlantic Ocean, at latitude 65°N, just South of the Arctic circle. Geologically it is a part of the Mid-Atlantic Ridge and has been built up entirely by volcanic rocks. About 10% of the area of 103,000 km² is covered by lava flows younger than about 10,000 yr. The geological processes of crustal spreading and the associated volcanism are responsible for the occurrence of geothermal fields providing the heat source and the necessary aquifer permeability to keep geothermal systems going.

The Icelandic population of about 260,000 is mostly concentrated in coastal areas. About one half lives in the southwestern part of the country. The climate is tempered by the Gulf Stream, precipitation varies with location from 400 to 4000 mm/yr. The average annual temperature in Reykjavik is 5°C. House heating is required all year around. Iceland is among the countries with the highest per capita consumption of energy in the world, about 417×10^9 joules per year per capita. About 50% of the electric power goes to energy intensive industries. Hydroelectricity is now the most important source of energy and geothermal energy is a close second contributing more to the primary energy supply than oil, which has to be imported. Hydropower provides 40% of the gross energy consumption in Iceland, geothermal energy 30%, imported oil 25% and imported coal 3%. The main use of geothermal energy in Iceland is for space heating. About 85% of all houses in the country are heated with geothermal energy and hot water and steam are used in many novel ways in industry but on a small scale. The total installed geothermal capacity for direct use in Iceland is about 800 MW_t. Due to the cold climate of the country, heating is needed most of the year so the load factor of direct use geothermal energy is very high (Palmason, 1992).

Figure 1 shows the main geological features of Iceland. Geothermal areas are found in all regions

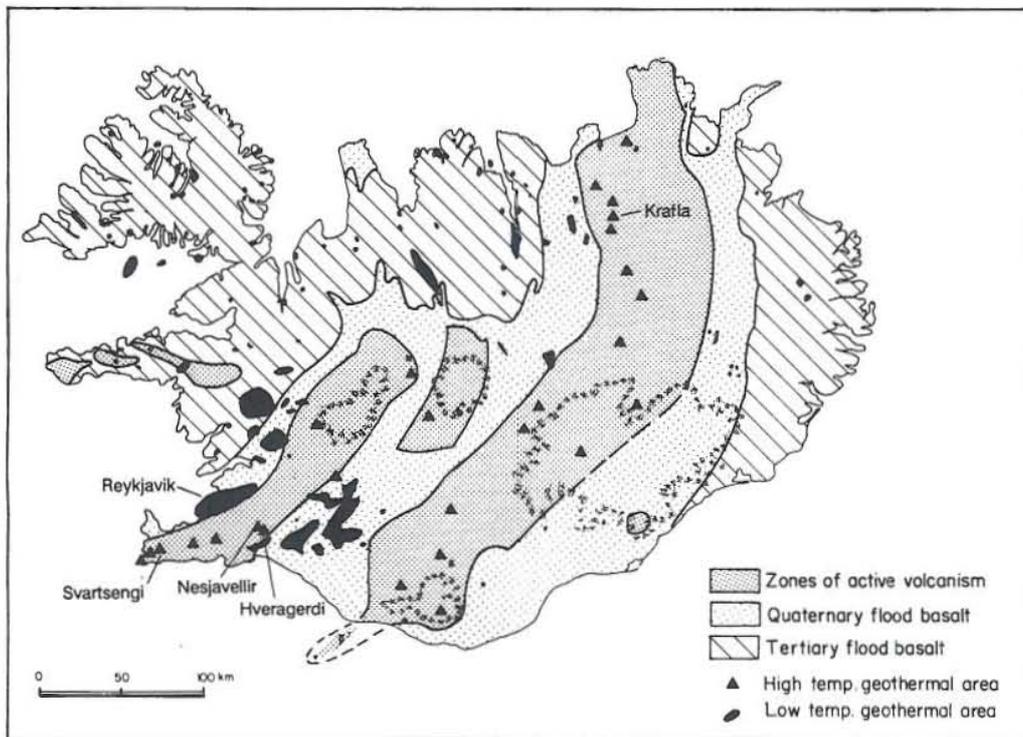


FIGURE 1: The main geological features and geothermal areas of Iceland, and the location of areas studied (after Flovenz et al., 1985)

of Iceland and are divided into high temperature areas where the temperature above 1000 m depth is more than 200°C and low temperature areas where it is usually less than 150°C. The geological structure in Iceland is entirely of igneous origin (basaltic) and the rock is highly fractured. Most of the major low temperature areas are found just outside the neovolcanic zone in rocks of Quaternary age but minor areas are found almost all over the country. The low temperature geothermal water is mainly used for space heating or greenhouses and today 85% of the population of Iceland is provided with geothermal space heating (Palmason, 1992). The low temperature areas are in Plio-pleistocene and Tertiary volcanics. The high temperature areas occur in the active zone of rifting and volcanism. They are associated with active volcanotectonics. Volcanic activity is controlled by movement along the active zones. The Tertiary areas include the classical plateau basalt series typical of the fjord landscapes of eastern Iceland and much of northern and western Iceland. Altogether Tertiary rocks cover about 50,000 km² or about 1/2 of the total area of Iceland (Fridleifsson, 1979). The following Icelandic geothermal fields have been selected for study.

- 1) Hveragerdi (See Figure 1 and 9) lies in the Hengill volcanic system in SW-Iceland. The Hengill system consists of three central volcanoes: Hveragerdi, which is the oldest one, active 300,000 to 700,000 years ago; Hromundartindur to which activity was subsequently transferred and whose rock formations are observed to be less than 115,000 years old and Hengill which is presently active (Saemundsson et al., 1990). Utilization in the Hveragerdi village started in 1928 when a milk processing plant utilizing geothermal steam from hot springs started production. In 1929, the Fagrihvammur Greenhouse centre was founded and in the 1930s, several more greenhouse farms were put into operation. All made use of springs and it is not until just after 1940 that drilling commenced. By 1944, 15 wells had been drilled, the deepest one 70 m. Hveragerdi Heating Services (hitaveita) have drilled several wells in the village (Saemundsson, 1970). The flowrate in well 8, which was selected for this study, is relatively large (40-50 kg/s total flow) but the general shape of the back pressure curve is typical of one phase liquid inflow. The major utilization problem in Hveragerdi has been calcite scaling. During the years 1958-1961, 8 wells were drilled in the Olfusdalur valley to the north of Hveragerdi village. They were intended to provide steam for a geothermal power plant. The best production wells, 3, 6, 7 and 8, draw water at 210-226°C from 250-700 m depth. Well 6, considered here, has been extensively tested (Einarsson, 1961; Ragnars et al., 1979; Steingrimsson, 1991).
- 2) The Nesjavellir high temperature field is connected to the Hengill central volcano and has been developed by the Reykjavik District Heating Utility. The capital's energy requirement for heating is now equivalent to 600 MW_t but the district heating utility installed capacity was only 500 MW_t before mid 1990. Estimates suggest that at present the Nesjavellir geothermal system can supply 300 MW_t equivalent to heat for 30 years, plus the option of up to 75 MW_t of steam generated electricity with a likely cost effectiveness unmatched anywhere else in the Icelandic electricity network (Gunnarsson et al., 1991). Most of the wells are very high enthalpy wells, but wells 14 and 18, studied here, are relatively cool compared to others in the area, being on the outskirts of the field, 18 being the coolest. The fluid is dilute (Bodvarsson et al., 1990).
- 3) The Svartsengi high temperature area in Iceland is on the Reykjanes peninsula in Iceland. The geothermal system is permeable and the fluid saline (Franzson, 1983). The Svartsengi field is produced by the Sudurnes Regional Heating Company. The company operates a power plant in the Svartsengi field that provides district heating water to several communities on the Reykjanes Peninsula, also called the Sudurnes Region. The capacity of the power plant is 125 MW_t for space heating and 8 MW_t of electric power.

Well 7, considered here, is 1352 m deep, with a total flow of 57 kg/s and enthalpy of 1040 kJ/kg (Bjornsson and Steingrimsson, 1992).

- 4) The Krafla high-temperature geothermal area lies in the northern part of the neovolcanic zone in Iceland. It is located within the caldera of the Krafla central volcano, which was formed about 100 thousand years ago (Saemundsson 1983). A 50 km fissure swarm associated with the central volcano intersects the caldera. Volcanic activity is extensive and there have been several eruptive periods during the last few thousand years. The most recent one started late in 1975, and nine eruptions have already taken place in Krafla during this period, the last one in September, 1984 (Bjornsson, 1985). The first geothermal wells in the area were drilled in 1974, and a decision was made to build a 60 MW power station concurrent with the drilling for steam. Up to now, only one of the two 30 MW turbines has been installed. The area consists of at least four fields, Leirhnukur, Leirbotnar, Hvitholar and Sudurhlidar fields. The latter three have been drilled into, revealing a complex geothermal system; Leirbotnar has a relatively cool liquid-dominated upper zone (190-220°C), and a hot two-phase lower zone (300-350°C); Hvitholar has a relatively hot two-phase upper part (260°C at 600 m depth) and a cooler liquid lower part (180°C at 1200 m depth, gradually increasing to 240-250°C at 1800 m depth); Sudurhlidar has a two-phase system following the boiling temperature-pressure curve reasonably closely at depth. Isotope and gas composition suggests that the fluid is relatively local in origin. The area was affected by magmatic activity in the late seventies and early eighties (Armannsson et al., 1987). Well KJ-9, considered in this study, is in the Leirbotnar field and taps fluid from the border of the upper and lower zones and the results of enthalpy measurements suggest that the inflow is liquid-dominated and that flashing takes place in the well.
- 5) The Laugarnes low temperature field is in Reykjavik. Well H-16, considered here, is located in the westernmost part of the field. A general description of the thermal area is given by Tomasson et al. (1975).

The major chemical problems associated with geothermal exploitation are deposition, corrosion and possible pollution. The most common deposits encountered are silica, sulphides and calcite. Calcite scales are probably the most common and are known in Iceland as well as Tibet. In this report the occurrence of calcite scales in the above areas will be examined.

2. METHODS

2.1 Methods of analysis

The research is based on chemical data from selected wells in some Icelandic fields. The collection of representative samples from high temperature drillholes is a complex procedure. It is done using a separator placed at the wellhead or at the discharge (Olafsson, 1988)(see Tole et al., 1993 for methods of chemical analysis employed at Orkustofnun and the University of Iceland). After collection, the samples are analyzed in the laboratory.

Analytical results for total composition of the well fluids are given in Table 1.

TABLE 1: The chemical composition of selected samples (in ppm) from wells in Iceland

Constituent	Hveragerdi well 8	Nesjavellir well 18	Olfusdalur well 6	Svartsengi well 7	Krafla well KJ-9	Reykjavik well H-16
pH	8.98	9.67	9.31	6.18	9.26	9.34
/Temp. (°C)	21.4	23.0	23.0	21.9	22	22.3
SiO ₂	281	407.3	376	520.2	493	53.57
Na	152	164.5	177	6986.3	198.27	79.92
K	12.35	18.4	18.2	1272.7	24.78	1.93
Ca	2.51	0.90	2.3	1086.21	2.89	4.94
Mg	0.064	0.001	0	0.73	0.003	1.18
CO ₂ (total)	2986.8	1222.3	336.9	4793.99	4303	40.9
SO ₄	41.7	35.9	33.7	29.75	199.39	27.8
H ₂ S (total)	335.2	231.91	152.1	108.26	530.6	0
Cl	131.3	61.5	185.2	13810	27.7	68
F	1.917	1.09	1.04	0.173	0.949	0.54
Diss. solids	736.2		927	23790	1147.7	275.6
Ref.tem.(°C)	193.7	203.2	202.7	245.1	245	100

Calcite is a prominent secondary mineral in rocks, which dissociates into Ca²⁺ and CO₃²⁻ in the water. Analyses of water samples generally yield concentrations. Here we will assume that free ions, or ion pairs and other complexes really exist and try to calculate their activities in the water.

2.2 Methods of calculation

The WATCH programmes (Arnorrsson et al., 1982) were used to calculate from the results of chemical analysis, the deep water composition, chemical speciation, activity coefficients, H⁺ activity, redox potential, gas partial pressure and mineral solubilities. Two programmes were used: WATCH1 and WATCH3. The WATCH1 programme deals with the chemistry of fluid from wet-steam wells. WATCH3 is suitable for water from low-temperature fields and cold water. We input the analytical data into the computer. The analytical data required for the programme calculations are the following (Svavarsson, 1983):

CHEMICAL DATA

Water samples: pH/°C*, SiO₂, B, Na, K, Ca, Mg, Fe, Al, NH₃, ΣCO₂, SO₄, ΣH₂S, Cl, F, dissolved solids**, electrical conductance.

Steam samples: (only for wet-steam wells) CO_2 , H_2S , NH_3 , N_2 , O_2 , H_2 , CH_4 , and Na or Cl to check dryness of steam.

PHYSICAL DATA

Wet-steam wells: Sampling pressure, enthalpy of well discharge.

Hot springs and hot water wells: Discharge temperature.

DATA WHICH ARE DESIRABLE

Downhole temperature of wells.

Aquifer inflows of wells.

Discharge rates of wells and hot springs.

* Temperature at which the pH is measured

** These data are not necessary for the programme calculations

The WATCH1 programme can be used to study chemical changes accompanying boiling, variable degassing and cooling and how these changes disturb solution mineral equilibria. The water analysis must include a record of the temperature at which the pH is measured. Total carbonate and total sulphide are expressed as ΣCO_2 and $\Sigma \text{H}_2\text{S}$ respectively. If enthalpy data for wet-steam well discharges are not available, it is assumed that the enthalpy corresponds to that of water saturated with steam at the reference temperature selected for the calculation. If some components, like iron and aluminium, are not included in the analytical data, the respective mass balances and dissociational equilibria are automatically omitted. Analysis of silica, carbonate, and sulphide must, however, be included. These components relate to the calculation of the deep water pH. The term deep water is somewhat loosely defined here as the water existing in the geothermal reservoir at a saturated steam pressure corresponding to the selected reference temperature. The programme is specifically suited to handle geothermal data from wet-steam wells, hot-water wells and boiling hot springs. Solubility data for selected geothermal minerals are incorporated to facilitate the study of solution / mineral equilibria. All calculations can be carried out at any specified temperature in the interval 0 - 370°C. The initial temperature may be measured, obtained by a geothermometer or be arbitrary, and boiling and cooling studied at any temperature below that. In this report the quartz equilibrium temperature is generally the initial temperature and the effects of boiling considered at 25°C intervals down to 100°C. The activity of each species can be calculated from the relevant equilibrium constants, the temperature of the water (because the values of the equilibrium constants are temperature dependent), the ionic strength of the solution, and the concentrations of the various chemical components involved.

3. CALCITE DEPOSITION WITH TEMPERATURE

3.1 Equilibrium constant

The deposition of calcium carbonate is controlled primarily by equilibrium in the reaction.



Calcite is the most common form in reservoir rock, but in wells other forms may predominate. Benoit (1989) describes the scale in wells in the Dixie valley, Nevada as aragonite with a density of 2.67 g/cm^3 . In Icelandic wells, however, calcite is the most common form, although some aragonite has been detected too. The dissolution or precipitation of the CaCO_3 phases calcite or aragonite can be written as Chemical Reaction 1. Aqueous CO_2 will be in equilibrium with CO_2 vapour if a gas phase is present. A movement of CO_2 from the liquid to the gas phase will result in decreasing the concentration of aqueous CO_2 and will drive Reaction 1 to the left. CO_2 loss from solution, therefore, results in the precipitation of CaCO_3 . A concurrent reaction is:



Loss of aqueous CO_2 to the gas phase will drive Reaction 2 to the left, and the pH of the solution will rise. The species in Reaction 1 are related by an equilibrium constant that is dependent on temperature and pressure:

$$K = \frac{\alpha[\text{Ca}^{2+}] (\alpha[\text{HCO}_3^-])^2}{\alpha[\text{CaCO}_3] \alpha[\text{CO}_2] \alpha[\text{H}_2\text{O}]} \quad (3)$$

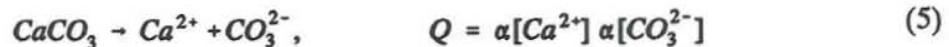
The symbol α represents the activity of the species in brackets, and the activity is related to the concentration by the equation:

$$\alpha[\text{Ca}^{2+}] = m[\text{Ca}^{2+}] \gamma[\text{Ca}^{2+}] \quad (4)$$

The symbol m is the molal concentration, and γ is the activity coefficient of the species. By convention, the activity of the crystalline solid is set equal to one, and the equilibrium constant then becomes a function of the activities of the aqueous species and water. The tendency for mineral precipitation or dissolution is indicated by comparison of K , the equilibrium constant, to the function Q , the quotient of activities of species in solution substituted into Equation 3.

3.2 Calcite supersaturation relative to temperature

Let us look at the following reaction:



If the dissolving calcite is pure then

$$\Delta G_r = -RT \ln K + RT \ln Q \quad (6)$$

K is theoretical, and Q is calculated. If $Q = K$, it means equilibrium. If $Q > K$, the solution is supersaturated with respect to calcite. If $Q < K$, it is undersaturated. How do we know whether

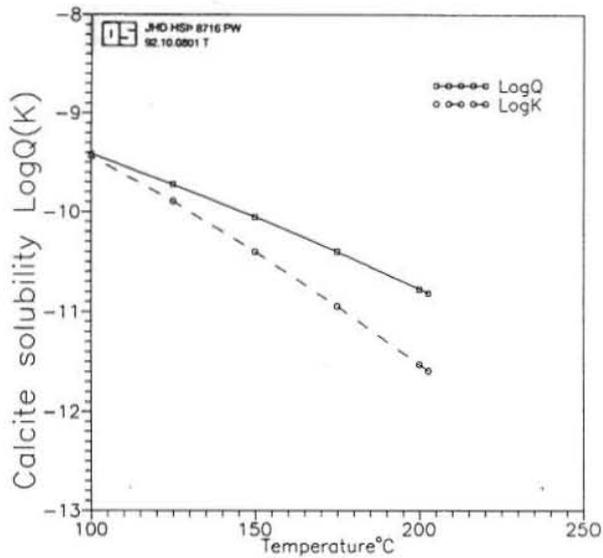


FIGURE 2: Calcite solubility with temperature in Olfusdalur well 6 fluid

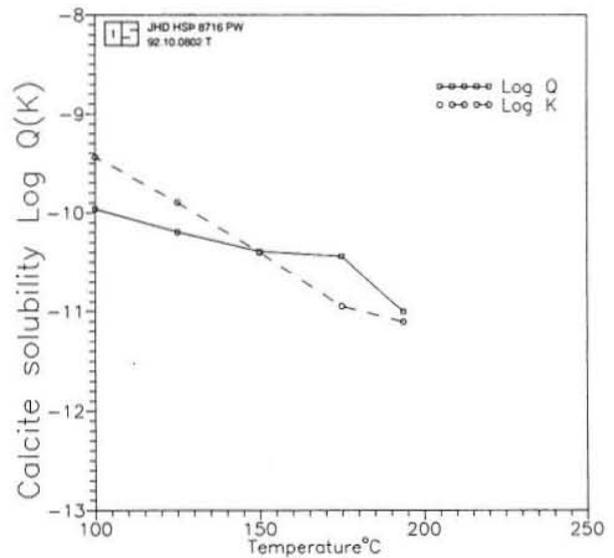


FIGURE 3: Calcite solubility with temperature in Hveragerdi well 8 fluid

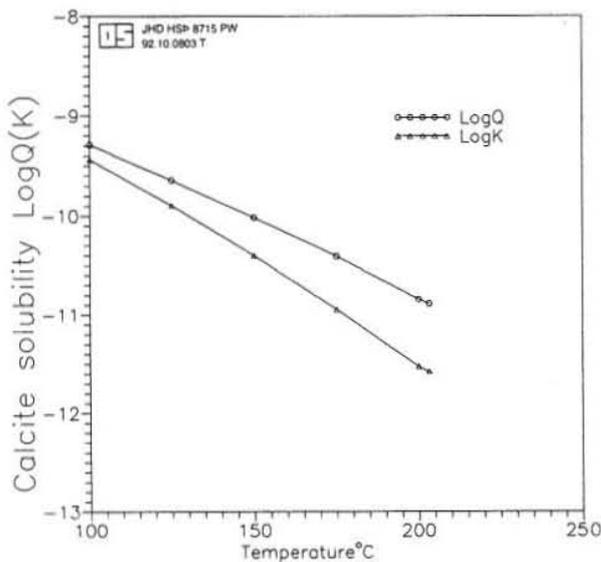


FIGURE 4: Calcite solubility with temperature in Nesjavellir well 18 fluid

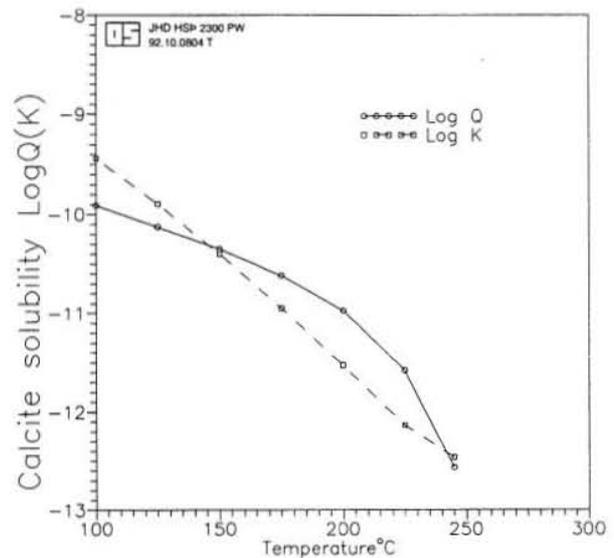


FIGURE 5: Calcite solubility with temperature in Svartsengi well 7 fluid

water is saturated, undersaturated, or supersaturated with respect to calcite? Geothermal reservoir waters in Iceland are generally calcite saturated (Arnorsson, 1989). We find supersaturation in some wells (Figures 2-7). The solubility of calcite decreases with (increasing) temperature. The magnitude of supersaturation is largely controlled by the initial temperature. The Hveragerdi Olfusdalur well 6 fluid is supersaturated at the initial temperature (202°C) and down to 100°C. The Hveragerdi well 8 fluid is supersaturated from the initial temperature (182°C) down to approximately 150°C, but undersaturated from 150°C to 100°C. For Nesjavellir well 18, we observe supersaturation over the whole temperature interval of 203°C to 100°C. In Svartsengi well 7, the fluids are undersaturated from 145 to 100°C, but supersaturation is observed from 245 to 145°C. Calcite deposition takes place at the first level of boiling in the well where the fluid tends to become supersaturated with respect to calcite. Reykjavik well H-16 is a non-boiling well whose quartz temperature is 90°C but its fluid is supersaturated with respect to calcite during cooling from 100°C to 50°C. For Krafla well KJ-9 fluid supersaturation with respect to calcite is observed in the temperature interval 245°C to 100°C.

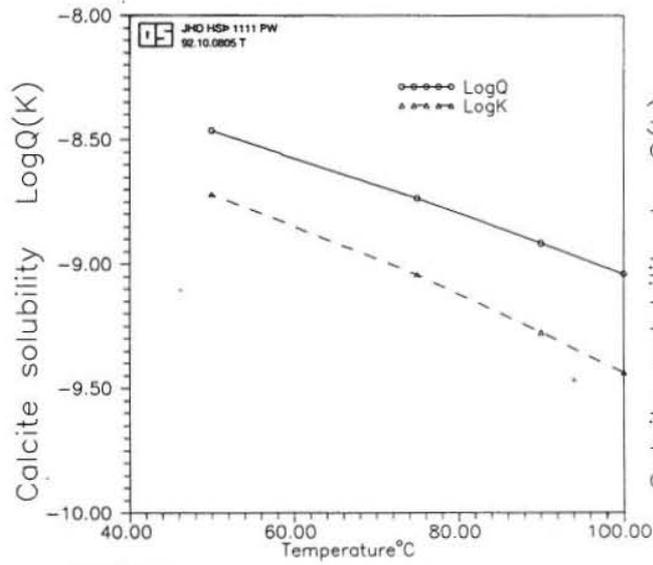


FIGURE 6: Calcite solubility with temperature in Reykjavik well H-16 fluid

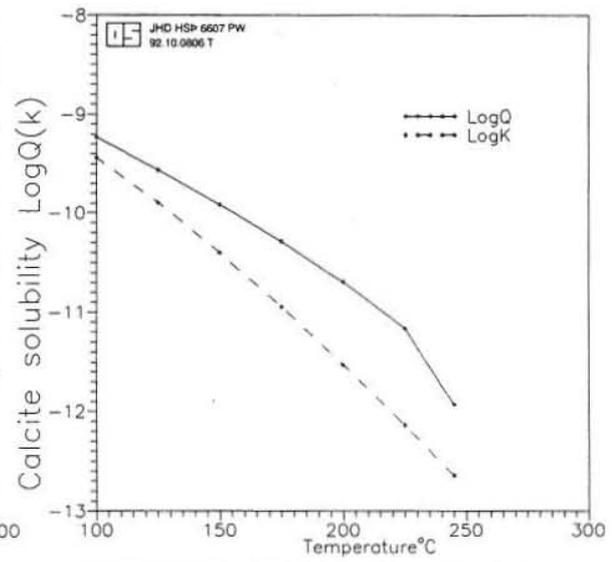


FIGURE 7: Calcite solubility with temperature in Krafla well KJ-9 fluid

4. TEMPERATURE-DEPTH PROFILES AND BOILING DEPTH SIMULATED BY HOLA

4.1 Temperature-depth profiles in Icelandic geothermal wells

Results of temperature measurements in Olfusdalur well 6, in Hveragerdi well 8, in Nesjavellir well 18 and in Svartsengi well 7 are shown in Figure 8, where various temperature profiles, obtained during and after discharge, are drawn. The boiling point of water is defined by two parameters, temperature and pressure. At atmospheric pressure water boils at the well known temperature of 100°C . If the pressure is higher a higher temperature is needed to reach the boiling point. The temperature from 400-660 m depths in Olfusdalur well 6 has always been found to be below 216°C . When there is no flow between aquifers, the temperature in the well will usually reach equilibrium with the surrounding rock. However, processes like boiling accompanied by one-dimensional convection can disturb the temperature profile in the well. For Hveragerdi well 8 and Nesjavellir well 18 profiles obtained both during discharge and closure are shown, but for Olfusdalur well 6 both profiles were obtained during closure and

for Svartsengi well 7 both during discharge. The Nesjavellir well 18 case shows well the difference between the two types of profiles. The one obtained during closure reflects the rock temperature with depth whereas boiling and convection are reflected in the one obtained during discharge. The boiling depth can be read from such profiles, being for instance about 700 m in Svartsengi well 7 at the conditions of the log whose results are shown in Figure 8. We can see in Figure 8 for Hveragerdi well 8, that the temperature from 100-150 m has reached 182°C , which is the maximum and the temperature decreases with depth in the deepest part of the well. This has been observed in high temperature as well as in low temperature geothermal fields. The negative gradient in wells can be used to determine the horizontal flow direction if there are several wells drilled in the field. In Figure 9 the locations of several wells in the Hveragerdi high temperature field in Iceland are shown and in Figure 10 a cross-section of the field from northwest to southeast is shown. In the cross-section, isothermal lines have been drawn. It can clearly be seen that the upflow is located in the northern part of the field and the hot water flows southwards at a fairly shallow level (100-200 m depth) (Stefansson and Steingrímsson, 1980). Results of closed well temperature measurements in Krafla well KJ-9 and Reykjavik well H-16 are shown in Figure

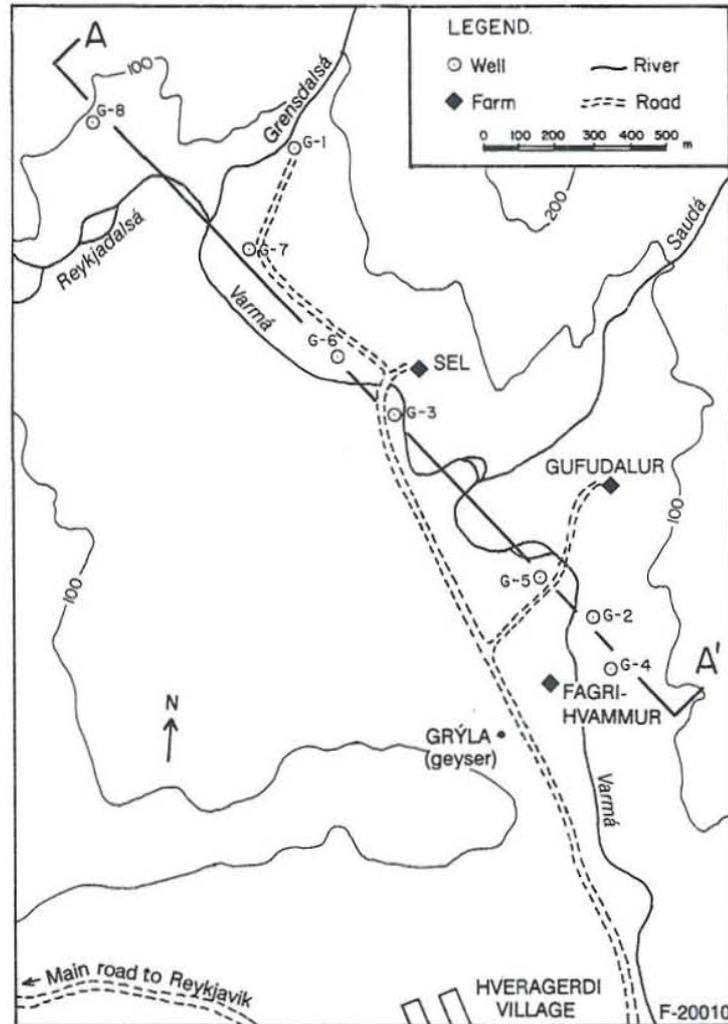
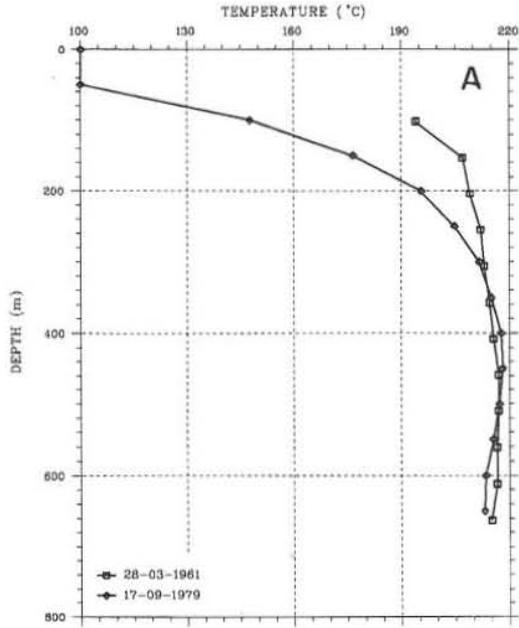


FIGURE 9: The Hveragerdi-Olfusdalur high temperature field, A-A' shows location of temperature cross-section in Figure 10 (after Zhou Xi-Xiang, 1980)

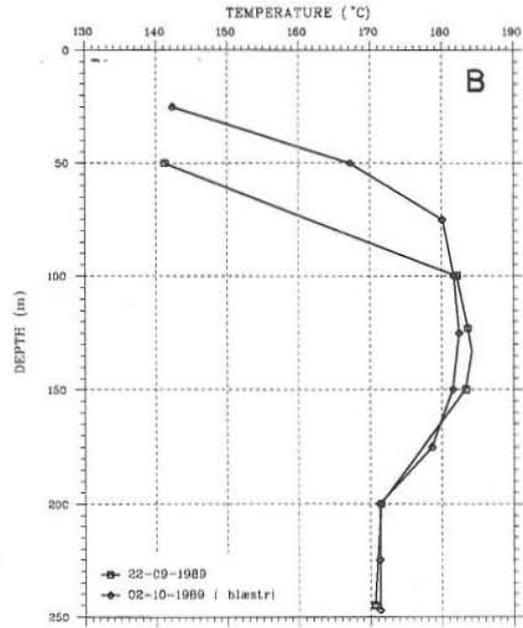
14 Oct 1992 das
L- 97327 Oracle

Ölfusdalur, well 6



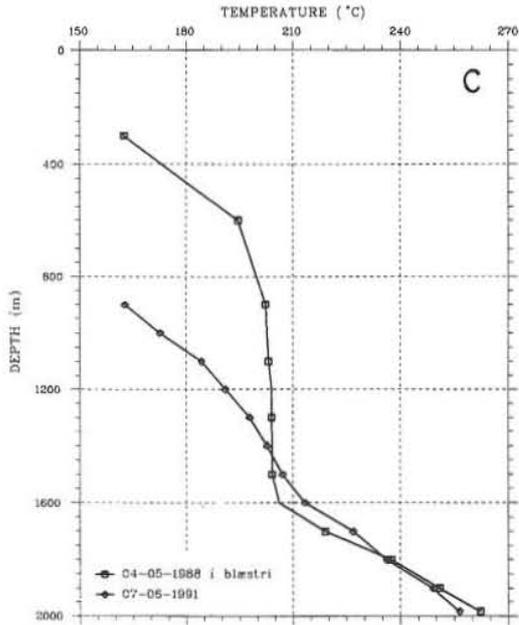
14 Oct 1992 das
L- 95808 Oracle

Hveragerði, well 8



14 Oct 1992 das
L- 95018 Oracle

Nesjavellir, well 18



14 Oct 1992 das
L- 16957 Oracle

Svartsengi, well 7

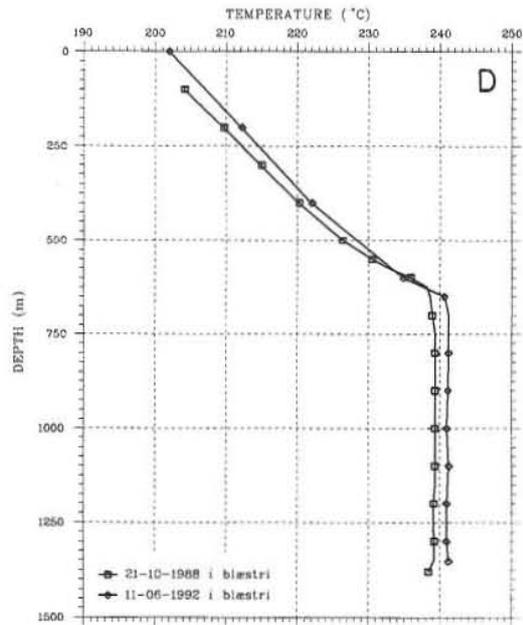


FIGURE 8: Results of temperature measurements in some Icelandic wells:
a) Ölfusdalur well 6; b) Hveragerði well 8; c) Nesjavellir well 18; d) Svartsengi well 7
(í blæstri = during discharge)

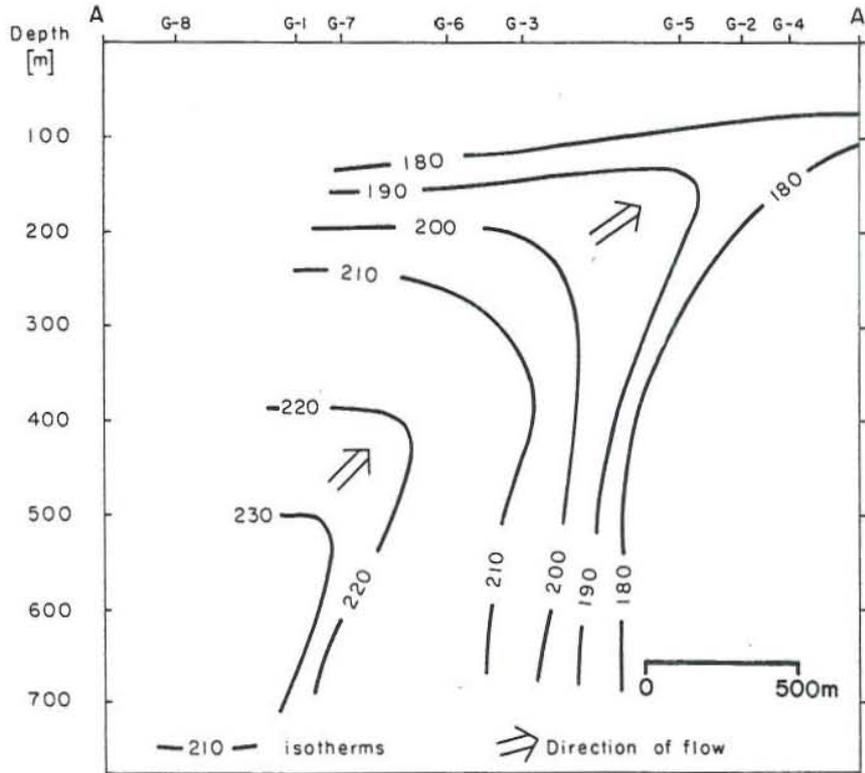
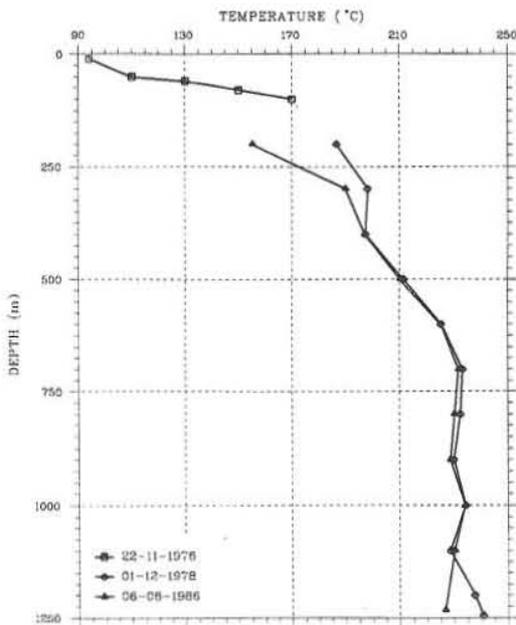


FIGURE 10: The Hveragerdi field, temperature distribution in cross-section A-A'; location is shown in Figure 9 (after Stefansson and Steingrímsson, 1980)

IS Oct 1992 dan
L 58009 Oraele

Krafla, KJ-9



IS Oct 1992 dan
L 6016 Oraele

Reykjavik Laugarn, H-16

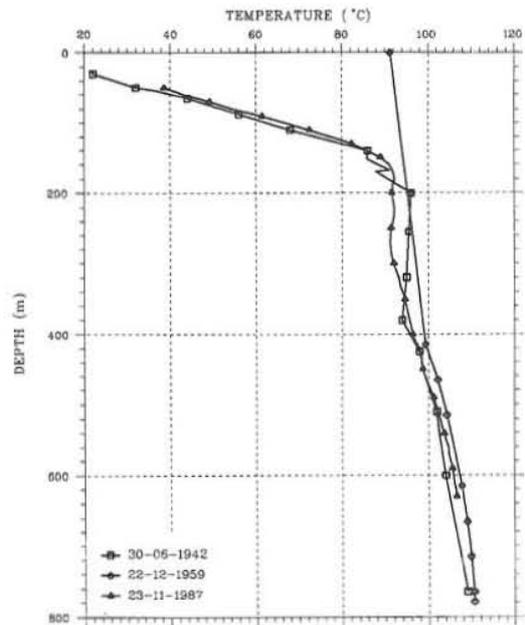


FIGURE 11: Results of temperature measurements in Krafla well KJ-9 and Reykjavik well H-16

Krafla well KJ-9 the temperature has reached about 230°C between 700 m to the bottom, where it is thought to be close to boiling. Reykjavik well H-16 is a low temperature well. The temperature increases with depth and has reached 110°C at the well bottom.

4.2 Boiling depths using the programme HOLA

4.2.1 General

The wellbore simulator HOLA (Bjornsson and Bodvarsson, 1987) solves numerically the differential equations that describe mass, momentum and energy flow in a vertical pipeline. The flow is assumed to be steady state. Calculations either start at the wellhead and continue downwards in a finite difference grid, or at the wellbottom and proceed upwards. The program HOLA allows for multiple feedzones, variable grid spacing and well radius. Feedzones are assumed to occur at single grid points in the well, apparently a reasonable assumption for wells in fractured geothermal reservoirs. Two-phase mixtures are always assumed to flow upwards whereas single-phase fluid can flow either up or down. The solution algorithm is explicit, giving one unique solution for each set of wellhead/wellbottom calculations, as long as there are no fluid sources/losses in the well.

4.2.2 Calculated and measured downhole profiles in some Icelandic geothermal wells

Calculated and measured pressure and temperature profiles in these wells each with a single, dominant feedzone are analyzed using the HOLA program. First, all the wellhead parameters are specified for HOLA and fed to the computer, according to the required wellhead conditions and the known properties of the feedzone. The only condition is that the input fluid enthalpy must be higher than the wellhead enthalpy. The calculated temperature and pressure with depth for different wellhead pressures in Olfusdalur well 16 are shown in Figure 12. The wellhead pressure was 6.5 bar-a when the sample listed in Table 1 was collected. Using values of 3, 10 and 15 bar-a with constant temperature, three distinct additional profiles were obtained. The phase change level is observable. The flashing depths are 450 m, 250 m and 100 m, respectively, for these three values, but 350 m for 6.5 bar-a. No temperature and pressure profiles have been obtained during discharge for well 6, Olfusdalur.

Measured and calculated pressure and temperature profiles for Hveragerdi well 8 are shown in Figure 13. The wellhead pressure was 7.2 bar-a when the sample listed in Table 1 was collected. Adding pressure values of 3, 10 and 15 bar-a, we can see increasing pressure with decreasing flashing depth. When the wellhead pressure is specified 3 bar-a, the flashing depth has reached the wellbottom. When the wellhead pressure is changed to 10 and 15 bar-a, flashing depths are 20 m and above the wellhead, respectively.

Measured and calculated pressure and temperature profiles for Nesjavellir well 18 are shown in Figure 14. When the sample considered in Table 1 was collected the wellhead pressure was 4.75 bar-a giving a flashing depth of 400 m. When the wellhead pressure is changed to 3, 10 and 15 bar-a, the flashing depths have reached 450, 200 and 60 m, respectively, i.e. increasing pressure with decreasing flashing depth.

Measured and calculated pressure and temperature profiles for Svartsengi well 7 are shown in Figure 15. A wellhead pressure of 17.10 bar-a gave a flashing depth of 400 m. Observed pressure and temperature are close to calculated pressure and temperature. When the wellhead pressure is changed to 3, 10 and 15 bar-a, we can see the flashing depths change to 1200 m, 750 m and 525 m, respectively.

Measured and calculated pressure and temperature profiles for Krafla well KJ-9 are shown in Figure 16. When the sample considered in Table 1 was collected the wellhead pressure was 9.5

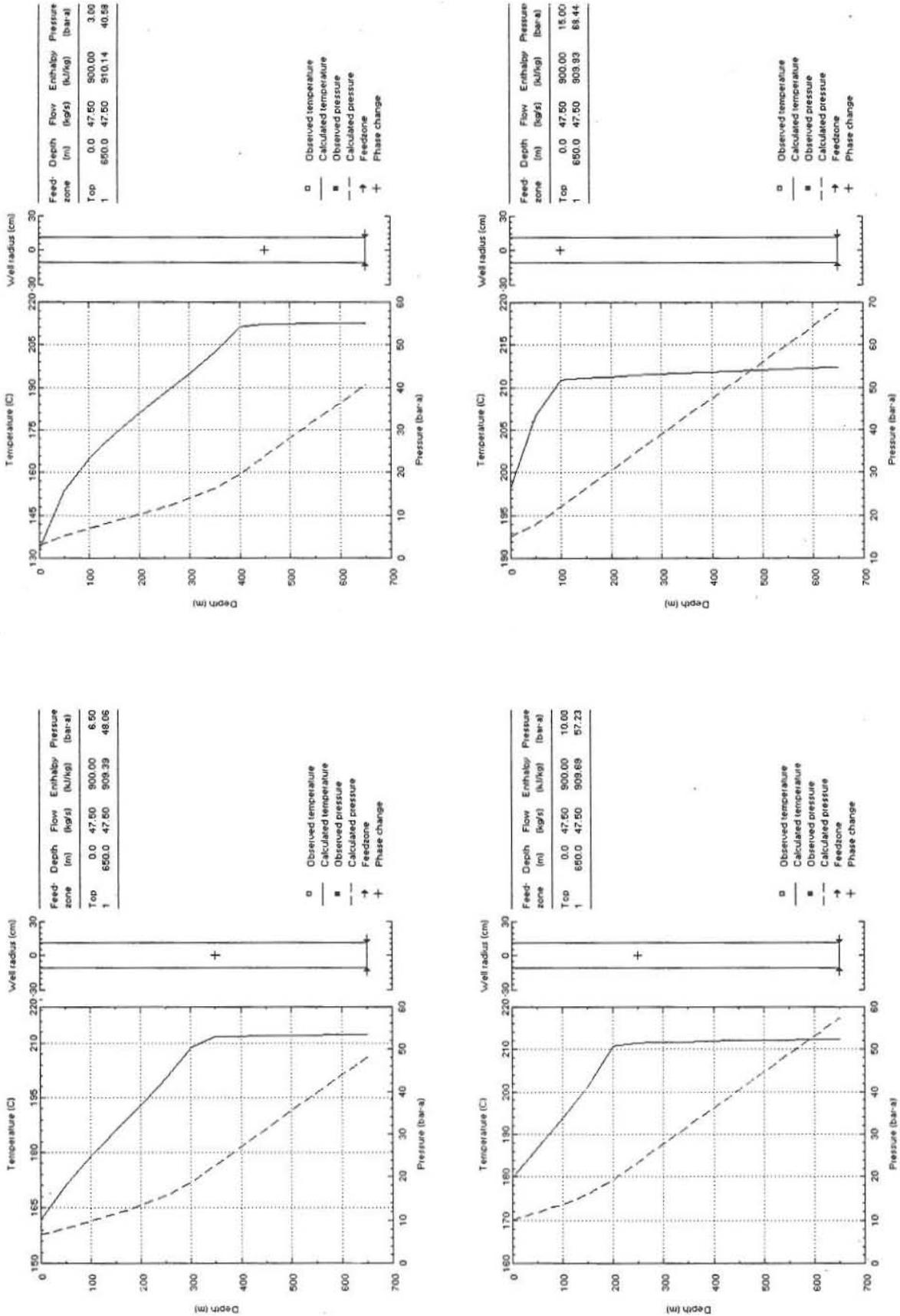


FIGURE 12: Calculated downhole profiles in Olfusdalur well 6

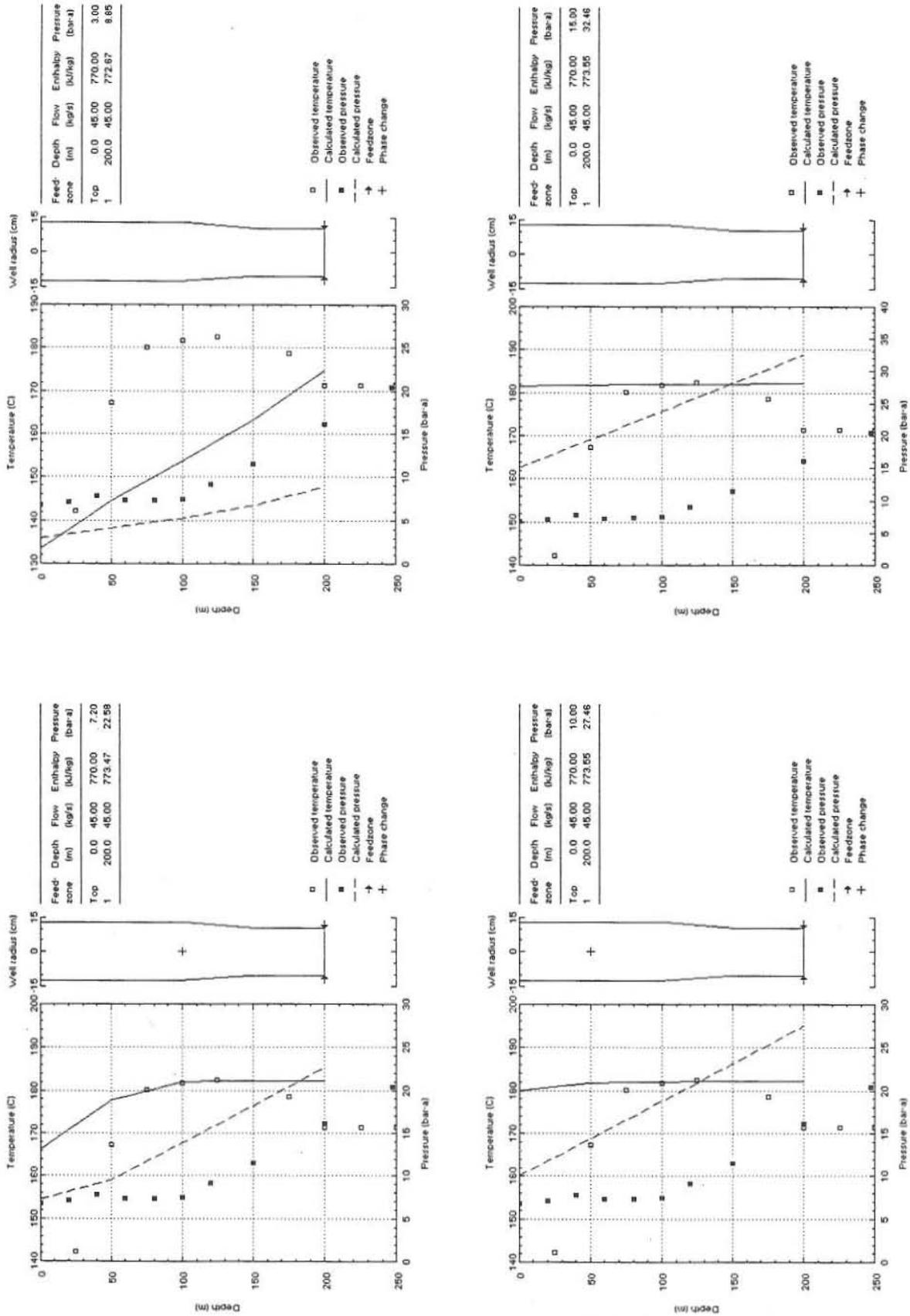


FIGURE 13: Calculated and measured profiles in Hveragerdi well 8

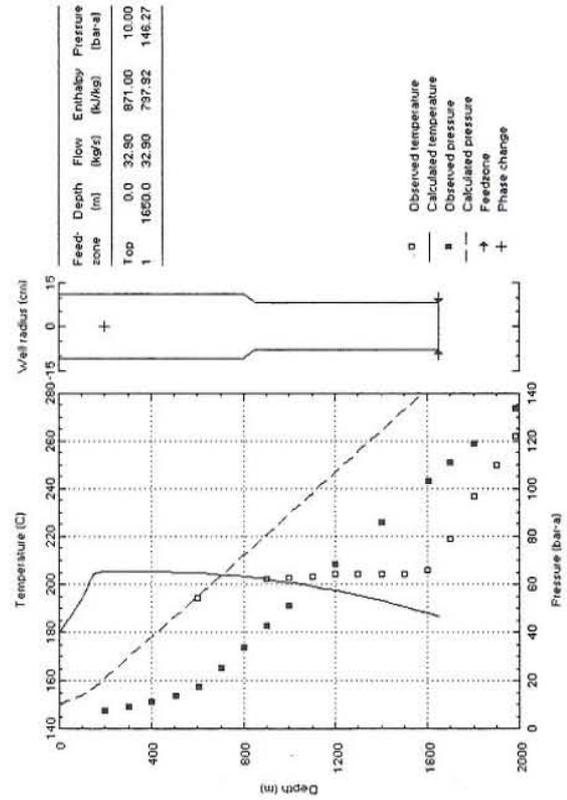
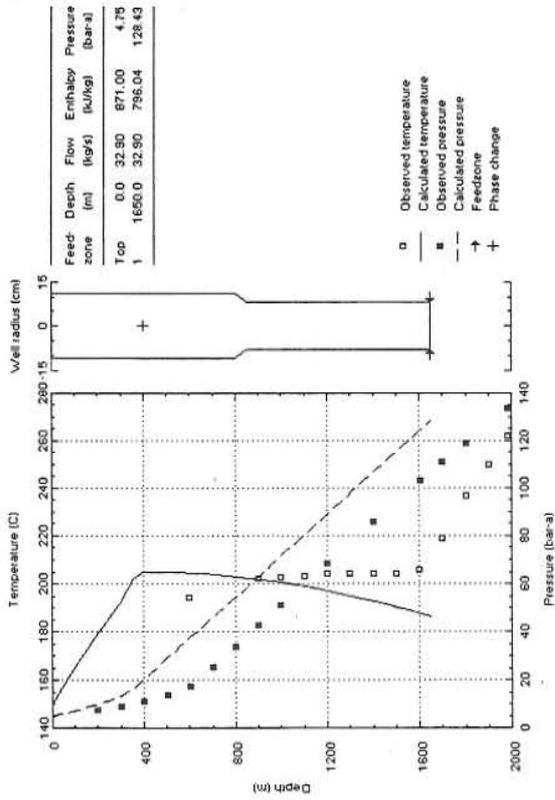
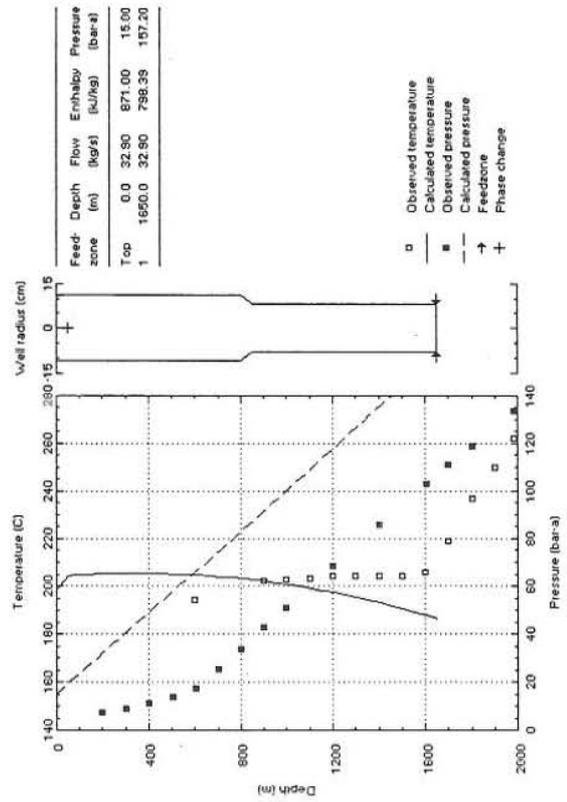
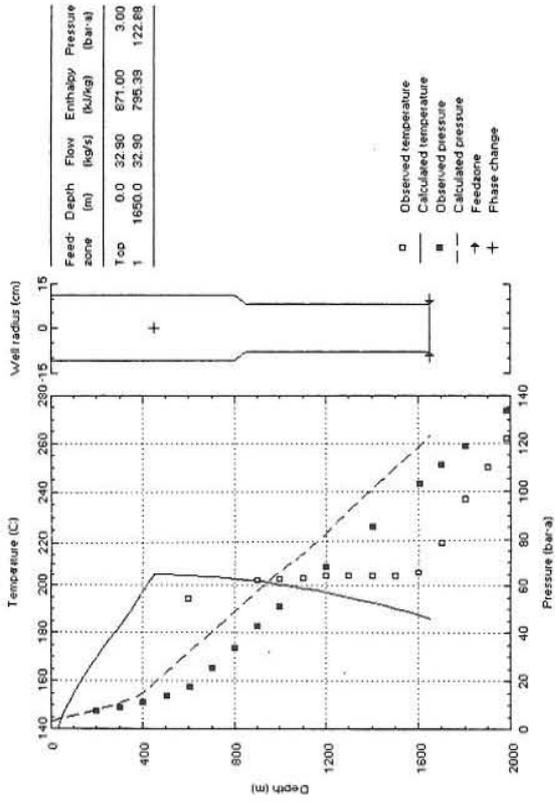


FIGURE 14: Calculated and measured profiles in Nesjavellir well 18

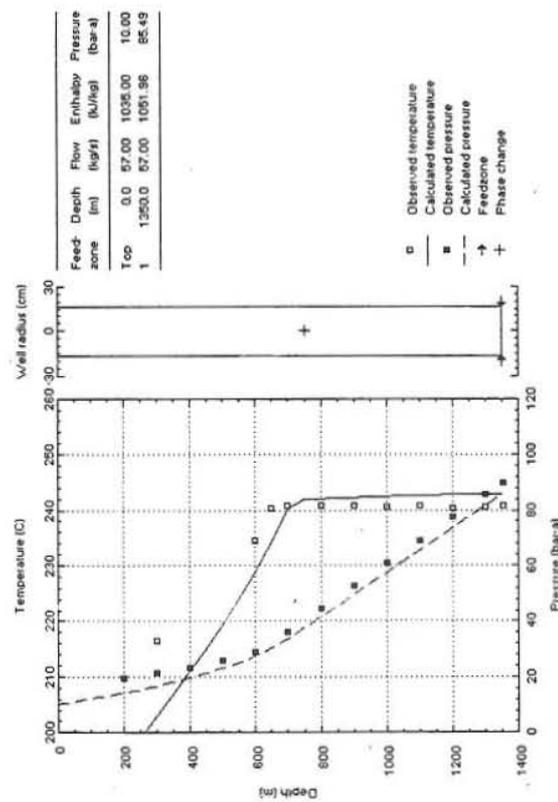
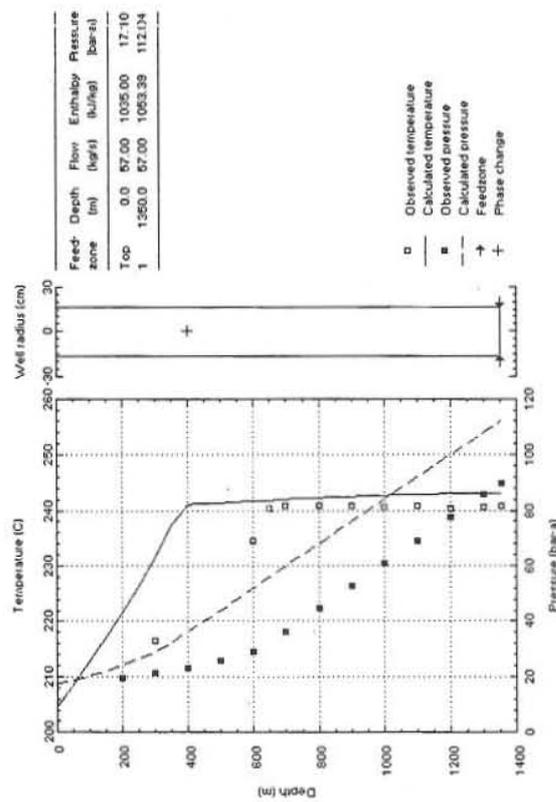
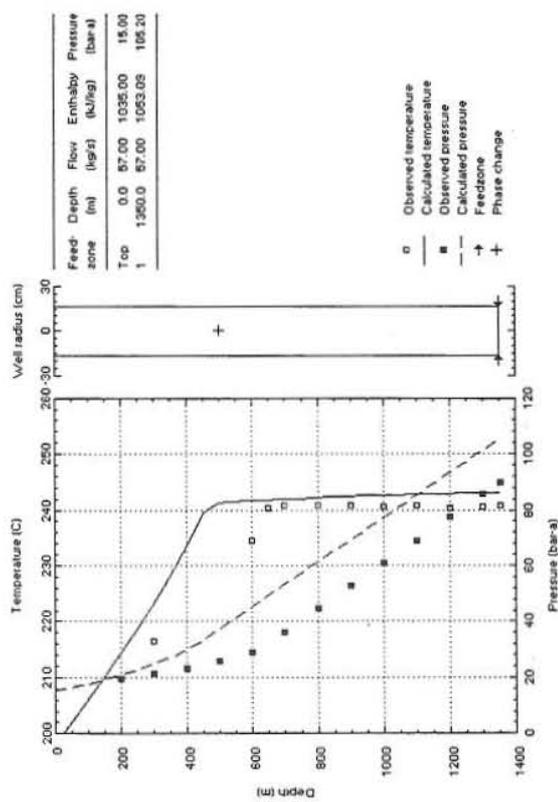
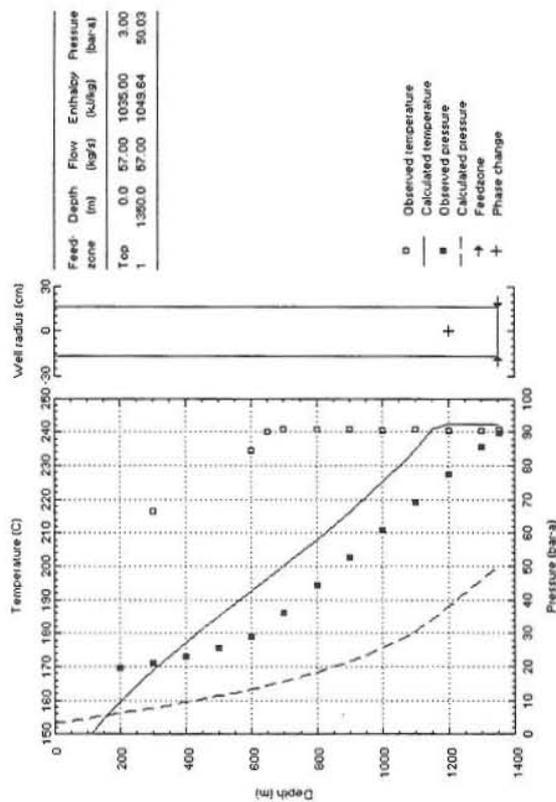


FIGURE 15: Calculated and measured profiles in Svartsengi well 7

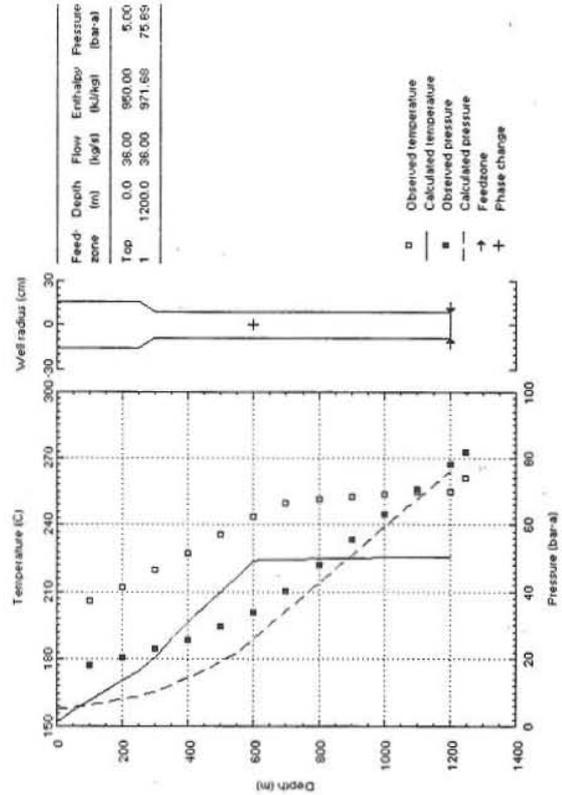
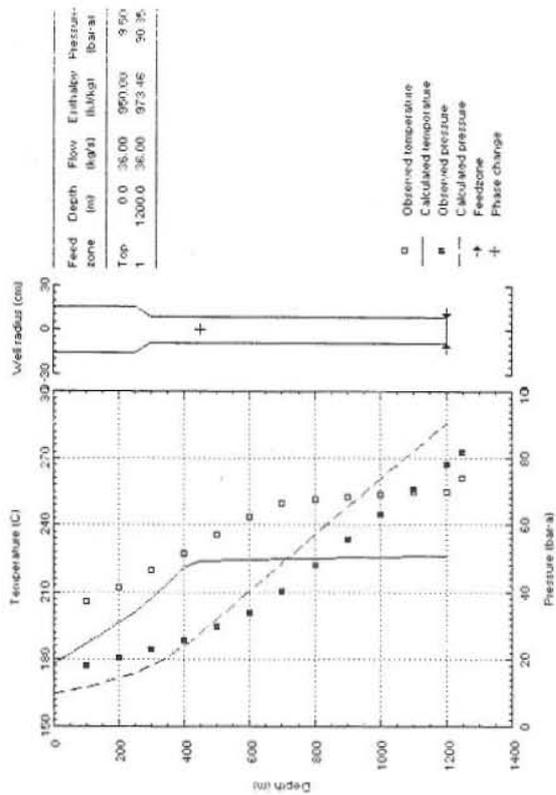
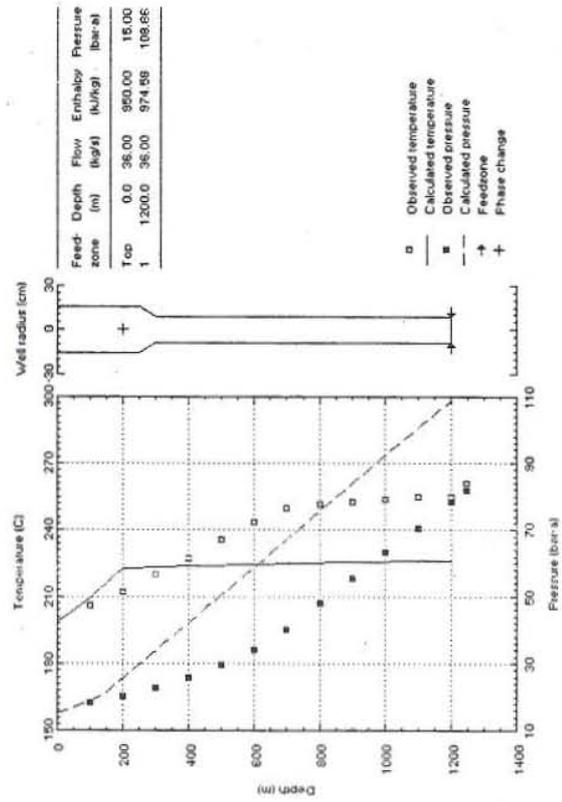
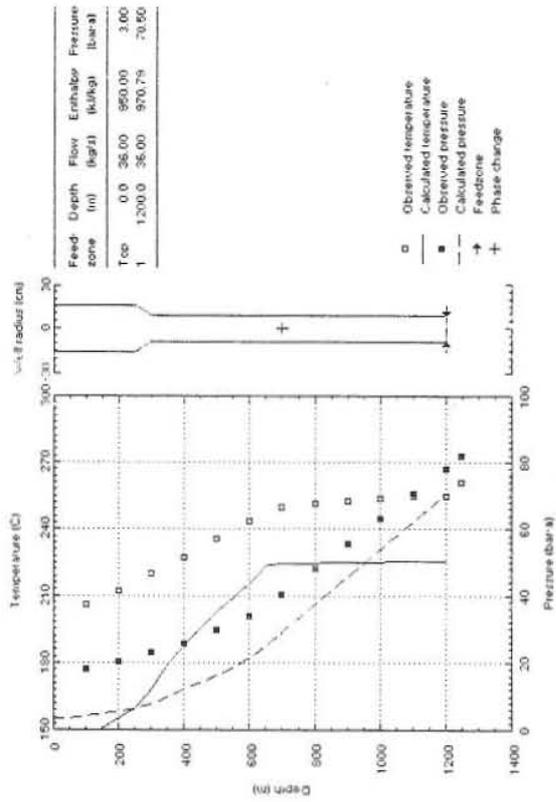


FIGURE 16: Calculated and measured profiles in Krafla well KJ-9

bar-a and the flashing depth 450 m. When the wellhead pressure is changed to 3, 5 and 15 bar-a, we can see the flashing depth change to 700, 600 and 200 m, respectively, i.e. increasing pressure with decreasing flashing depth.

The effect of changing the wellhead pressure by some bars on flashing depth is shown in Figure 17. We can see increasing wellhead pressure with decreasing flashing depth.

The two most important methods of combatting calcite scaling are drilling out and the use of inhibitors. Both methods are difficult to employ technically and more expensive the deeper the deposits lie. A bigger and more expensive drilling rig may be needed and problems with inhibitor injection pumps increase rapidly with depth. Therefore, a knowledge of the variation in deposition depth with wellhead pressure may prove useful practically because a wellhead pressure causing deposition at moderate depth may be chosen.

There are, however, constraints. Most wells can be discharged up to a certain wellhead pressure, the closing pressure. Moreover the backpressure curves will show that there is a decline in the flow from the well with increasing pressure. Taking Olfusdalur well 6 as an example, it is clear that by increasing wellhead pressure from 6.5 to 15 bar-a the boiling level would be moved from 350 m to 100 m which is a considerable achievement as far as raising boiling level goes. But if a backpressure curve for this well (Ragnars et al., 1979) is extrapolated, a closing pressure of 14 bar-a is obtained, so we cannot use this method to raise the boiling level to 100 m. At 10 bar-a, however, the well is in good shape but even so the steam flow is 5 kg/s compared with 10 kg/s at 6.5 bar-a. The boiling level is at 250 m depth so it becomes a difficult evaluation as to whether the cost in steam loss caused by increasing the pressure is worth the raising of the boiling level to reduce the cost of the calcite deposit prevention and depends, of course, very much on the availability and need for steam.

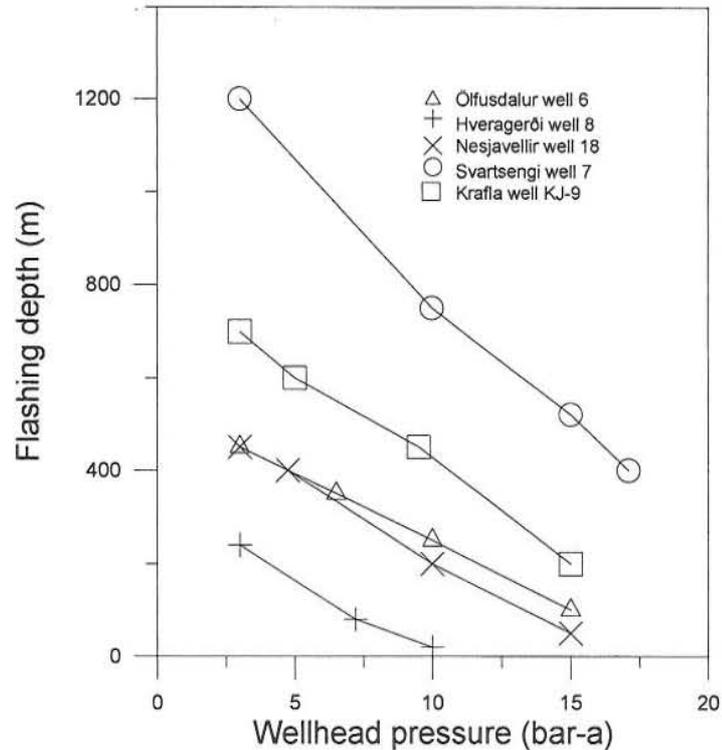


FIGURE 17: Calculated flashing depth with varying wellhead pressures in five Icelandic geothermal wells

5. RELATIONSHIP OF CALCITE DEPOSITION TO BOILING

The solubility of CaCO_3 in pure water decreases as the temperature rises. This is contrary to the behaviour of most salts, the general result of increasing temperature being to give higher solubility, but a number of carbonates and sulfates behave exceptionally. In addition to this effect, the solubility of CaCO_3 in natural water decreases at higher temperatures because CO_2 , like any other gas, is less soluble in hot water than cold water. In general, the solubility of carbonates is much more influenced by this change in solubility of CO_2 than by the temperature dependency of the solubility itself. As an illustration of temperature effects on CaCO_3 we can consider its behaviour in the ocean where it dissolves at great depths, where the water is perennially cold, but is deposited near the surface, especially in the tropics, where the water is warm (Krauskopf, 1967). In Figures 2-7 there are good examples of calcite supersaturation in Icelandic geothermal water in geothermal reservoirs which are not boiling under natural conditions but a pressure drop caused by discharging causes extensive boiling above the feedzone. The enthalpy of well fluids drawn from such reservoirs characteristically corresponds to that of a liquid phase at the start of discharge, but upon continued production the enthalpy may increase and some wells produce steam only, after a period of time. There are two processes that can lead to an increase in the enthalpy, i. e. the steam to water ratio, of well discharges. One is the separation or partial separation of the flowing water and steam due to their different flowing properties, the steam preferentially making it to the well. The other process involves enhanced evaporation of the flowing water by heat flow from the rock. Such a heat flow tends to occur where water cools by boiling. Calcite deposition (including some aragonite) is largely confined to wet-steam wells. However, some deposits have also been observed in hot water wells near the coast where seawater and dilute water of meteoric origin mix in the well. In wet-steam wells, deposits have mostly been troublesome at the first boiling level in the well. Deposition begins at this level where it is also most intense. Higher up it decreases and may disappear altogether below the wellhead or still be intense at the surface. Geothermal reservoir waters in Iceland are close to being calcite saturated (Arnorsson, 1989). Boiling causes a drastic decrease in CO_2 partial pressure which leads to calcite supersaturation and deposition. The supersaturation reaches maximum at this point and the water is almost quantitatively degassed. Further boiling which leads to cooling will cause successively less supersaturation as the solubility of calcite increases with decreasing temperature. In some cases the fluid eventually becomes undersaturated upon cooling. When extensive boiling starts in the feedzone of a discharging well, calcite precipitation has not been observed although it is expected to occur in the formation. The intensity of calcite deposition is a function of the temperature of the reservoir water, its salinity and the CO_2 partial pressure. Boiling leads to strong calcite supersaturation due to effective transfer of CO_2 into the steam phase that forms.

6. OBSERVATION OF DEPOSITS IN THE WELLS

6.1 Methods of observation

Calcite deposits are sometimes discovered during logging operations designed for different purposes, but direct observation is by means of caliper surveys. For sophisticated work, measuring sondes are used. The ordinary type is a three arm caliper, but tools with up to 60 arms are available. The arms are in all cases motorized, i.e. an electrical motor is present inside the caliper tool. The logging cable makes it possible to control this motor and close the arms at demand. The arms will centralize the tool in the well, and the position of the arms is sensed through a variable resistance. A caliper log is measured continuously from bottom to top. For everyday purpose caliper baskets or "go-devils" are adequate. They are in fact sinker bars of different diameters, and therefore show the maximum depth of each clearance in the well (Stefansson and Steingrímsson, 1980).

6.2 Svartsengi

Basket caliper logs that have been performed on Svartsengi wells are recorded in Table 2.

TABLE 2: Basket caliper logs in wells in Svartsengi (Björnsson and Steingrímsson, 1991)

Day	Well	Depth (m)	Basket (")	Result	Day	Well	Depth (m)	Basket (")	Result
5/8'77	SG-4	1200	6	no resistance	10/7'86	SG-6	613	5¼	stops
10/11'77	H-3	49	6		27/4'87	SG-9	549	10	stops 549
10/11'77	H-3	375	5		27/4'87	SG-9	800	7	no resistance
10/11'77	H-3	375	3		29/4'87	SG-7	800	10	no resistance
18/8'81	SG-7	620	10	no resistance	29/4'87	SG-11	543	7	no resistance
18/8'81	SG-11	542	10	no resistance	29/4'87	SG-11	700	10	
18/8'81	SG-11	1130	8	no resistance	30/4'87	SG-8	700	7	no resistance
19/8'81	SG-9	555	10	stop liner	30/4'87	SG-8	531	10	stops
19/8'81	SG-9	962	8	start	7/5'87	SG-5	650	5½	no resistance
10/9'81	SG-8	1562	8	start	7/5'87	SG-6	624	5½	stops
10/9'81	SG-8	403	10	stops	7/5'87	SG-6	619	7	stops
9/11'82	SG-5	82	8	casing change	7/5'87	SG-6	630	4½	stops
9/11'82	SG-5	1225	6	no resistance	26/6'87	SG-12	1407	7½	stops 626 m, stuck 907 m
19/11'82	SG-12	1459	6	no resistance					
16/3'83	SG-8	421	10	stops	31/5'88	SG-5	650	6	no resistance
16/3'83	SG-8	650	3½	no resistance	13/7'88	SG-9	750	6	no resistance
16/3'83	SG-8	455	6	stops	13/7'88	SG-9	549	7½	stops
7/5'84	SG-6	770	5½	no resistance	15/4'89	SG-7	750	10	no resistance
7/5'84	SG-6	528	7½	stops 10 m	15/4'89	SG-8	577	6¼	stops
18/4'85	SG-9	510	7½	stops	15/4'89	SG-8	576	5½	stops
18/4'85	SG-9	501	10	stops	15/4'89	SG-8	545	7½	stops
22/4'85	SG-7	700	7½	stops	29/4'89	SG-9	750	6¼	no resistance
22/4'85	SG-7	497	10	stops	29/4'89	SG-9	545	7½	stops
23/4'85	SG-8	700	5½	no resistance	29/4'89	SG-11	703	7½	no resistance
23/4'85	SG-5	493	10	no resistance	29/4'89	SG-11	543	10	stops liner 547
23/4'85	SG-8	504	7½	stops	27/8'90	SG-8	583	10	stops liner 585
24/4'85	SG-11	532	7½	stops	27/8'90	SG-8	800	4½	no resistance
24/4'85	SG-11	504	10	stops	27/8'90	SG-8	603	8	stops
30/4'85	SG-6	624	4½	stops	27/8'90	SG-8	607	6	stops
30/4'85	SG-6	529	7½	stops	30/8'90	SG-6	641	1½	stops, stuck
30/4'85	SG-6	608	5½	stops	1/10'90	SG-12	422	10	resist. from 400
9/7'86	SG-5	600	6¼	no resistance	1/10'90	SG-12	471	8	resist. from 460
10/7'86	SG-6	750	4¼	no resistance	1/10'90	SG-12	700	6¼	difficulties 700m
10/7'86	SG-6	613	7	stops	15/11'90	SG-9	750	8	no resistance
10/7'86	SG-6	613	6¼	stops	15/11'90	SG-11	750	8	no resistance

TABLE 3: Cleaning workouts in Svartsengi (Bjornsson and Steingrímsson, 1991)

Time	Well	Depth of deposit (m)	Time	Well	Depth of deposit (m)	Time	Well	Depth of deposit (m)
Aug '77	SG-4	352-400	Feb '81	SG-5	410-470	Jun '85	SG-9	414-538
May '78	SG-4	363-405	Mar '81	SG-6	600-640	Jun '85	SG-11	482-535
Dec '78	SG-4	350-405	Feb '82	SG-5	427-492	Jun '85	SG-8	473-539
Jul '79	SG-4	355-417	Mar '83	SG-8	431-532	Jun '85	SG-7	482-546
Oct '79	SG-4	343-430	Apr '83	SG-7	408-498	Jul '85	SG-6	510-630
Nov '79	SG-5	376-415	Apr '83	SG-9	380-519	Jun '87	SG-6	618-651
Mar '80	SG-6	480-560	Apr '83	SG-11	408-504	May '89	SG-8	514-587
Apr '80	SG-5	419-456	Apr '83	SG-6	546-605	May '89	SG-9	520-564
Sep '80	SG-6	563-642	Dec '83	SG-9	450-522	Jun '89	SG-6	630-659

Deposits have been drilled out 27 times since 1976 from the 12 wells in the Svartsengi field (Table 3). The boiling level becomes deeper with drawdown which increases with time. The increased depth of deposit formation in well SG-7 with time is shown in Figure 18. Liners tend to be damaged with repeated cleaning operations and deposits will fall to the bottom and make the wells shallower (Table 4).

TABLE 4: Decrease in depth of some Svartsengi wells (Bjornsson and Steingrímsson, 1991)

Well	Decrease (m)	Well	Decrease (m)
SG-6	10	SG-9	35
SG-7	60	SG-11	30
SG-8	5	SG-12	60

A pressure drop is observed in the boreholes as deposits form but the effect on wellhead pressure is not great due to decreased flow rate and the boiling level will move up (Bjornsson and Steingrímsson, 1992). The deposits in Svartsengi well 7 (Figure 18) have been observed at the calculated flashing depths (Figure 15).

6.3 Nesjavellir

Nesjavellir well 18 discharged for about seven months at about 9 bar-a in 1986 and then closed. No direct caliper surveys have been made, but no signs of deposits have been observed during logging (Sigurdsson and Gunnlaugsson, 1989).

6.4 Hveragerdi - Olfusdalur

Calcite scales have been a recurring problem in earlier village wells and have been observed at depths ranging from 20 to 75 m. In Hveragerdi well 8, deposits were drilled out in 1991. Some resistance was observed at 12-18 m depth, but the major deposit turned out to be at 45-62 m depth, a small resistance was found down to 84 m, but none below that (Jardboranir, 1991). This is in agreement with my calculation results (see Figure 13). Well 6 in Olfusdalur discharged for a total of about 10 months in 1961-1963 at 3-11 bar-a and for nearly 2 years (1979-1981) at 8-12 bar-a. No decrease in flow that could be connected to deposits was observed, but logging information indicates that calcite is present and that it needs drilling out (Steingrímsson, 1991).

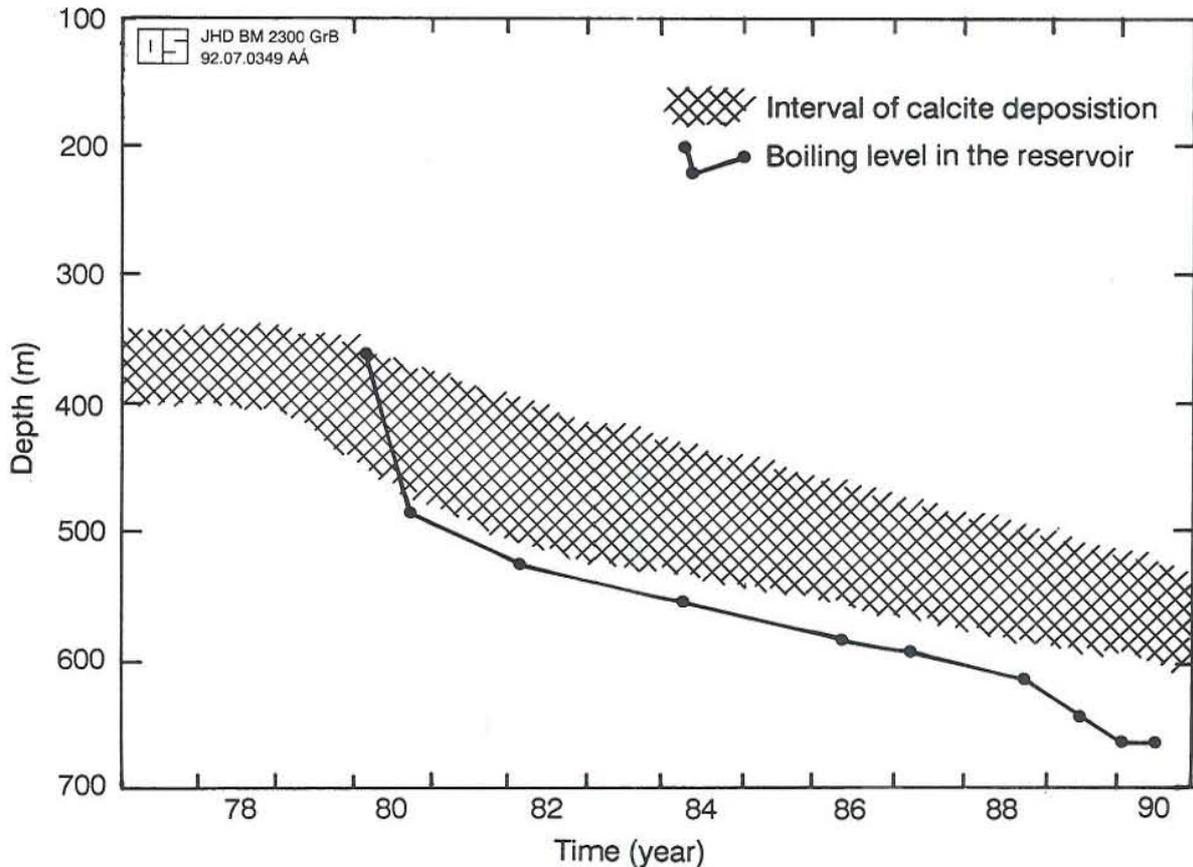


FIGURE 18: The depth interval at which calcite deposits form, and calculated depth of boiling level versus time in Svartsengi well 7 (Bjornsson and Steingrimsso, 1992)

6.5 Krafla

For Krafla well KJ-9 fluid, the results of calculations show supersaturation from 245 to 100°C (Figure 7) suggesting that calcite deposition should take place in the well. Calculated and measured temperatures and pressures with depth are shown in Figure 16. The calculated flashing depth is in the range of 750 to 200 m at wellhead pressures of 3-15 bar-a. The observed depths for the deposits are up to a maximum of 730 m, in agreement with the calculated values. Deposits have formed quite regularly since 1976 and been drilled out 1-2 times per year from 1977, when it was deepened, to 1982, when it was redrilled, and from 1982 to 1991, when it was closed. There is a record of calcite deposits in well KJ-9. The results of the flashing depth calculations are discussed above (Chapter 4). The Krafla well KJ-9 was selected for observation by Armannsson (1989). His discussion with reference to Figures 19, 20 and 21 follows.

According to the above calculation 850 m depth is below flashing, even after the formation of deposits. The concentrations calculated from the wellhead samples agree reasonably well with those measured in a deep water sample from 850 m depth, except for the all-important pH, and of course calcium and magnesium, which are known to have been precipitated. The carbon dioxide concentration calculated from the wellhead composition is slightly lower than expected from deposition only. Solubility calculations based on both wellhead and deep water concentrations reveal a considerably greater extent of supersaturation for the former in spite of lower measured concentrations of calcium and total carbonate, demonstrating the importance of the pH. Well KJ-9 flowed at an average rate of 16 kg/s, at 5 bar pressure for 180 days. At the end of that period the liner was pulled out, the thickness of calcite scale measured, and a caliper log run on the casing (Figure 19). Results of analyses suggest that the scale consists essentially of calcium

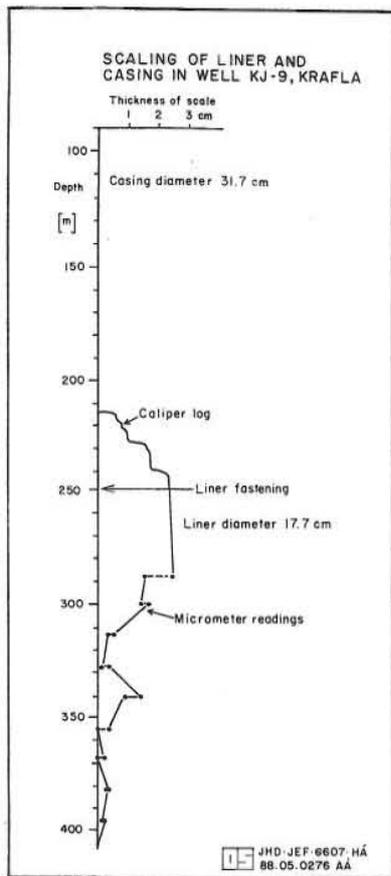


FIGURE 19: Scaling of liner and casing in Krafla well KJ-9 (Armannsson, 1989)

carbonate with a trace of magnesium carbonate. Assuming a density of 2500 kg/m^3 for this material, the extent of the scale was calculated using the difference between the observed wellhead and deep water calcium concentrations with flow and flow time data. The result is compared with that of the caliper log and the scale thickness measurement in the liner, and a good agreement is found. When ideas on quantity formed and the depth interval of formation have been obtained, predictions on time of formation may be made. Experience shows that flow tends to be relatively constant from a well until it is virtually blocked, when it will decrease dramatically.

As has been suggested, the enthalpy and the saturation state affect deposition greatly. Well KJ-9a was boiling intermittently during its first two years, and the extent of this, presented as the difference between the measured fluid enthalpy and enthalpy calculated from the quartz geothermometer temperature, is shown in Figure 20. It took the well about 2 years to become blocked by calcite deposits at this time, which was significantly longer than experienced later. While conditions were stable, the blocking times of wells KJ-9a and b, were relatively constant, but with decreasing flow, they increase somewhat, although not drastically (Figure 21).

Comparing the analytical results for calcium in deep water samples (before boiling) and wellhead samples (after boiling) and relating the difference to the flow and flow period is an effective way to estimate the extent of calcite deposition.

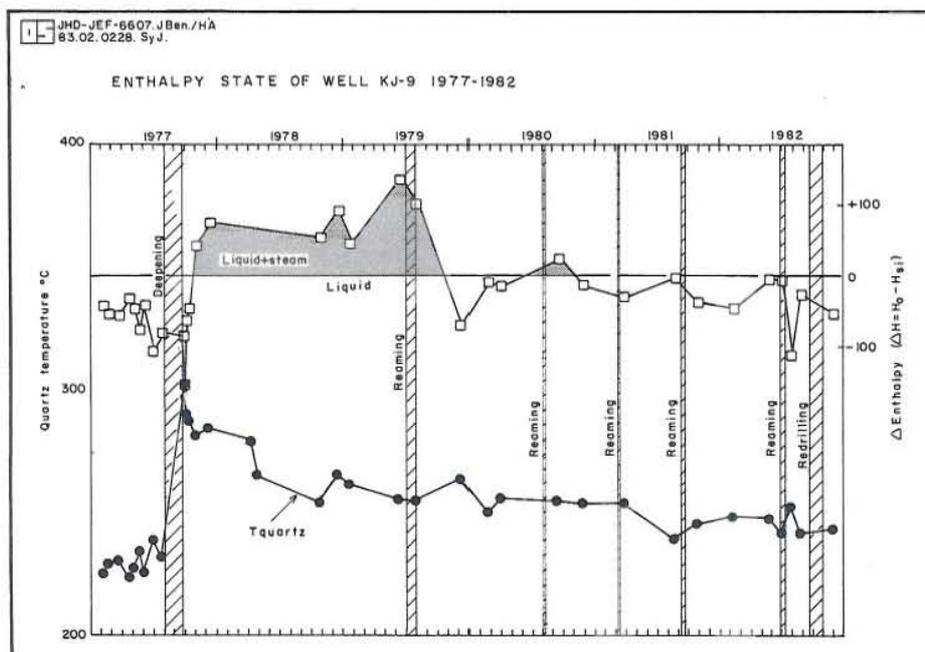


FIGURE 20: Enthalpy state of Krafla well KJ-9, 1977-1982 (Armannsson, 1989)

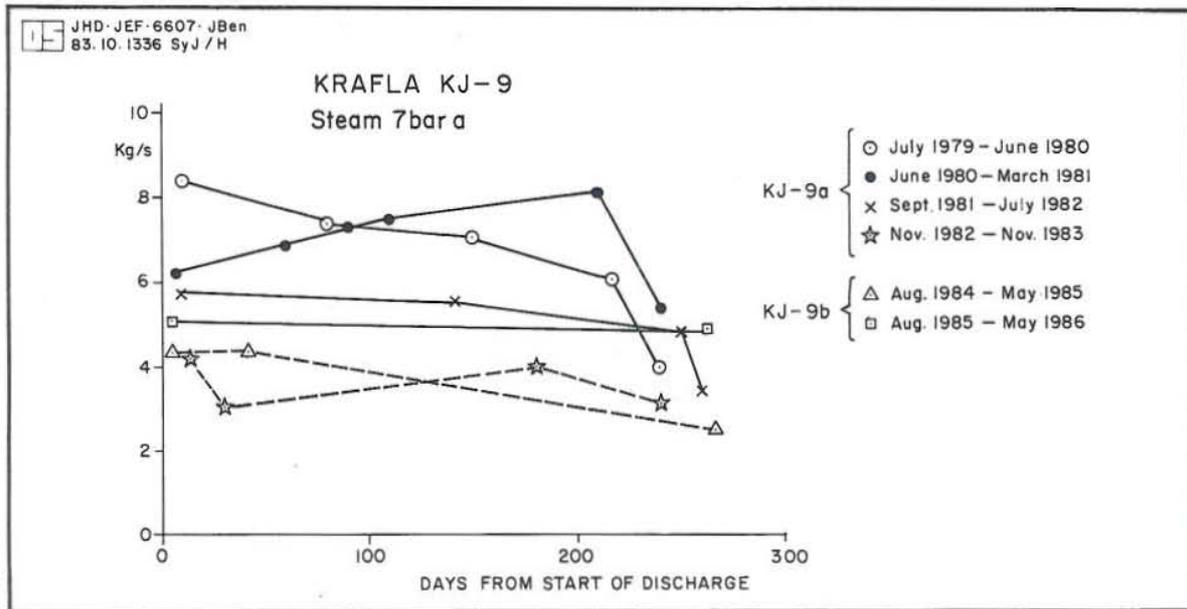


FIGURE 21: Time of undisturbed flow after removal of deposits from Krafla wells KJ-9a and b (Armannsson, 1989)

7. CONCLUSIONS

The state of calcite saturation for a range of temperatures has been calculated for fluids from several geothermal wells in Iceland using the programme WATCH. Some are found to be close to saturation, some are undersaturated and some are supersaturated. Most are close to saturation near the inflow but tend to become supersaturated if boiling occurs on the way to the surface.

Temperature profiles taken during discharge give valuable information on whether a phase change such as boiling takes place in the well and, if it does, at which depth. Where these are available they confirm that calcite supersaturation occurs after boiling in the well. Temperature profiles taken during discharge are not available for all wells. In such cases a borehole simulator such as HOLA is a useful tool to study whether boiling takes place and if it does at what depth. Such simulations confirmed results on supersaturation after boiling in wells where temperature profiles had not been obtained during discharge. The simulator was, furthermore, used to study the effect of varying wellhead pressure on the depth of boiling in wells where calcite supersaturation was observed. As expected, the boiling depth was found to vary inversely with wellhead pressure and, in some cases, it was found that it could be moved to a relatively shallow depth by increasing wellhead pressure.

The most common methods for combatting calcite deposition are drilling out and the use of inhibitors. For both, a shallow depth of operation is a considerable technical and economic advantage. But wellhead pressure increase is constrained by the properties of the well, notably the closing pressure. Characteristic curves for wells tend to show a marked decrease in flow with increasing pressure, so a compromise may have to be reached on how much steam loss can be suffered for moving the deposition depth up to a certain level.

ACKNOWLEDGEMENTS

I would like to thank the Icelandic government and the UNU for giving me this chance to study geothermal resources. I would like to thank Orkustofnun - Icelandic National Energy Authority and, Hitaveita Reykjavíkur - Reykjavik Municipal Heating Service, for providing the data used in this report. Special thanks to Halldor Armannsson for giving all the guidance and providing information and advice in writing the report. I am greatly indebted for his very helpful suggestions and his overall supervision and support.

Special thanks to Dr. Ingvar B. Fridleifsson, director of the Geothermal Training Programme, for his selection of myself to attend this course and providing conditions of hospitality and comfort. Special thanks to Ludvik S. Georgsson for his help; his care makes one feel at home during the whole course. Thanks to Prof. Stefan Arnorsson for giving useful lectures at the University. Thanks to Dr. Jon Orn Bjarnason and Mr. Magnus Olafsson for their help, and to the staff of the chemical laboratory for their help in analytical work. The following people are gratefully acknowledged: Benedikt Steingrimsson, Grimur Bjornsson, Pordur Arason, Gudrun Sverrisdottir, Kristjan Hrafn Sigurdsson.

Thank you UNU fellows in 1992 for your help during this course. Extend a lot of the thanks to the Icelandic people. Thank you very much.

Finally I would like to thank my office for their support and also Mr. Zhang Zhenguo.

REFERENCES

- Armannsson, H., 1989: Predicting calcite deposition in Krafla boreholes. *Geothermics*, 18, 25-32.
- Armannsson, H., Gudmundsson, A., and Steingrímsson, B.S., 1987: Exploration and development of the Krafla geothermal area. *Jokull*, 37, 13-30.
- Arnorsson, S., 1989: Deposition of calcium carbonate minerals from geothermal water - theoretical considerations. *Geothermics*, 18, 33-39.
- Arnorsson, S., Sigurdsson, S., and Svavarsson, H., 1982: The chemistry of geothermal waters in Iceland. I. Calculation of aqueous speciation from 0°C to 370°C. *Geochem. Cosmochim. Acta*, 46, 1513-1532.
- Benoit, W.R., 1989: Carbonate scaling characteristics in Dixie Valley, Nevada geothermal wellbores. *Geothermics*, 18, 41-48.
- Bjornsson, A., 1985: Dynamics of crustal rifting in NE Iceland. *J. Geophys.*, 90, 151-162.
- Bjornsson, G., and Bodvarsson, G.S., 1987: A multi-feedzone wellbore simulator. *Geoth. Res. Council Trans.*, 11, 503-507.
- Bjornsson, G., and Steingrímsson, B., 1991: Temperature and pressure in the Svartsengi geothermal system. Initial state and changes due to production. *Orkustofnun, Iceland, report OS-91016/JHD-04* (in Icelandic), 69 pp.
- Bjornsson, G., and Steingrímsson, B., 1992: Fifteen years of temperature and pressure monitoring in the Svartsengi high-temperature geothermal field in SW-Iceland. *Geoth. Res. Council Trans.*, 16, 627-634.
- Bodvarsson, G.S., Bjornsson, S., Gunnarsson, A., Gunnlaugsson, E., Stefansson, V., and Steingrímsson, B., 1990: The Nesjavellir geothermal field, Iceland. *Geotherm. Sci. Tech.*, 2(3), 189-228.
- Einarsson, S.S., 1961: Proposed 15-Megawatt power station at Hveragerdi, Iceland. *Proc. UN Conf. on New Sources of Energy, Rome*, 354-364.
- Flovenz, O.G., Georgsson, L.S., and Arnason, K., 1985: Resistivity structure of the upper crust in Iceland. *J. Geophys. Res.*, 90, B12, 10136-10150.
- Franzson, H., 1983: The Svartsengi high-temperature field, Iceland. Subsurface geology and alteration. *Geothermal Resources Council Trans.*, 7, 141-145.
- Fridleifsson, I.B., 1979: Geothermal activity in Iceland. *Jokull*, 29, 47-56.
- Gunnarsson, A., Steingrímsson, B., Maack, R., Gunnlaugsson, E., and Magnusson, J., 1991: Nesjavellir. Geothermal co-generation power plant. *Hitaveita Reykjavíkur, Iceland*, 17 pp.
- Jardboranir, 1991: Drilling reports.
- Krauskopf, K. B., 1967: Introduction to geochemistry. McGraw and Hill, New York, 721 pp.
- Olafsson, M., 1988: Sampling methods for geothermal fluids and gases. *Orkustofnun, Iceland, report OS-88041/JHD-06*, 17 pp.

- Palmason, G., 1992: Geothermal energy in Iceland; electricity production and direct heat uses. Transactions of HYDRENEW meeting, Pisa, 1992, 11 pp.
- Ragnars, K., Armannsson, H., and Steingrímsson, B., 1979: Olfusdalur. Investigations of wells G-3, G-6 and G-7. Progress report. Orkustofnun, Iceland, report OS-79053/JHD-25 (in Icelandic), 51 pp.
- Saemundsson, K., 1970: Geothermal heat in the southern lowlands and its utilization. Sudri (in Icelandic), 101-160.
- Saemundsson, K., 1983: Fractures in the Krafla area. In "Ravens' congregation" on the status of the Krafla geothermal power station, 2nd and 3rd March 1983, Krafla power station, Iceland, (in Icelandic), 4-8.
- Saemundsson, K., Snorrason, S.P., and Fridleifsson, G.O., 1990. Geological map of the southern part of the Hengill area between Hengladalur and Krossfjoll. Orkustofnun, Iceland, report OS-90008/JHD-02 B (in Icelandic), 15 pp.
- Sigurðsson, O. and Gunnlaugsson, E., 1989: Nesjavellir. Well NJ-18. 4th stage. Warming up, start of discharge, discharge and the equalization of pressure after discharge. Orkustofnun, Iceland, report OS-89011/JHD-05 B (in Icelandic), 47 pp.
- Stefansson, V., and Steingrímsson, B., 1980: Geothermal Logging 1 (An introduction to techniques and interpretation). Orkustofnun, report OS-800017/JHD-09, 117 pp.
- Steingrímsson, B., 1991: Boreholes in Olfusdalur. Conditions, temperature and flow. Orkustofnun, Iceland, internal report BS-91/01 (in Icelandic), 15 pp.
- Svavarsson, H., 1983: "The WATCH1" and the "WATCH3" programs, - vehicles for interpreting chemical analyses of geothermal water. A guide for users. Translated by Leo Kanner Assoc., Los Alamos Nat. Lab., University of California, U.S.A., 13 pp.
- Tole, M.F., Armannsson, H., Pang Zhong-he, and Arnórsson, S., 1993: Fluid/mineral equilibria for geothermal fluids and chemical geothermometry. Geothermics (in press).
- Tomasson, V., Fridleifsson, I.B., and Stefansson, V., 1975: A hydrological model for the flow of thermal water in SW-Iceland with a special reference to the Reykir and Reykjavik thermal areas. Proc. 2nd United Nations symposium on the Development and Use of Geothermal Resources, San Francisco, USA, 643-648.
- Zhou Xi-Xiang, 1980: Interpretation of air surface temperature measurements in the Mosfellssveit and Olfusdalur geothermal areas, SW-Iceland. UNO G.T.P., Iceland, report 7, 101 pp.