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CHANGES IN THE CHEMISTRY OF WATER AND STEAM DISCHARGED
FROM WELLS IN THE NÁMAFJALL GEOTHERMAL FIELD, ICELAND,
DURING THE PERIOD 1970-76.

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ABSTRACT

The chemical composition of borehole fluids in the Námafjall geothermal field, northern Iceland, has changed significantly during the exploitation period 1970-1976. Withdrawal of fluid by discharging production wells has produced a pressure drop in the reservoir and extended the zone of flashing. The chemical changes have resulted from the increased flashing in the reservoir. These changes include lowering of the concentrations of silica by as much as 40%, lowering of sodium and potassium by 0-30% and 5-50% respectively, and the lowering of total gas concentrations by 0-45%. The lowering of the silica concentrations is considered to be due to the precipitation of quartz from the flashing water in the aquifers feeding the wells. The flashed water, which flows from the major upflow zone, tends to leach sodium from the rock. The observed decrease in the concentrations of this element is explained by progressively less effective leaching during the exploitation period caused by accelerated replacement of the flashed water by unreacted water from below. The water temperatures derived from the NaKCa-geothermometer have decreased to about the same extent as the quartz equilibrium temperatures. This indicates that re-equilibration upon cooling between the solution on one ~~the~~ hand and quartz and the respective K₂Ca-silicate on the other is about equally fast, at least for the temperatures and water compositions in question. The lowering of the gas content of some of the well discharges can be explained by increased loss of steam underground from the aquifers feeding the respective wells. From the observed variation in the chemical composition of the well discharges, it is deduced that the main upflow zone is near well 7 or to the east of that well. Flashed water flows from the upflow zone in a westerly direction and the wells withdraw water and steam from this body of fluid.

INTRODUCTION

The Námafjall geothermal field is located in northern Iceland about 5 kilometers east of Lake Myvatn. Surface thermal manifestations cover some 5 square kilometers, being most intense on the low hyaloclastite ridge of Námafjall and just east of it. So far 10 wells have been drilled into the Námafjall geothermal reservoir. They are all located west of Námafjall and near the western margin of the field as deduced from surface thermal manifestations (fig. 1). Their depth varies from 340 to 1800 meters.

The present paper describes changes in the chemistry of water and steam discharged from 6 of the wells (nos. 4 to 9) that have been revealed by repeated sampling during the period 1970-1976. The other wells were not included in the study because they were not productive or had so low discharge rates that they were not exploitable. The deepest well, no 10, was drilled at the end of 1975, and is therefore not included in this study.

Fig. 1

The depth of the wells studied ranges from 637 to 1312 meters. The highest downhole temperature, 289°C, has been measured at 1100 meters depth in well 7. Downhole temperatures and aquifer locations (recorded by loss of circulation fluid during the drilling) for all the wells are presented in fig. 2.

Fig. 2

Only basaltic rocks are exposed in the immediate vicinity of the geothermal area. They include basalt lava flows, pillow lavas, and hyaloclastites. Other rock types have not been encountered in the drillholes. Rock alteration in the drillholes has been described by Gíslason (1973).

Exploitation of the Námafjall geothermal field started in 1967 and reached the present production in 1970. The wells have been producing continuously over the study period apart from minor stops during maintenance periods. The total discharge rate of wells 4 to 9 is of the order of 200 kg/sec with an average discharge enthalpy of some 270 kcal/kg. An account of the development of the geothermal field and its exploitation has been given by Ragnars et al. (1970).

WATER CHEMISTRY

Introduction

When the deep, hot reservoir water flashes in the drill-holes and in the aquifers feeding them, the volatiles are mostly transferred to the steam that forms. At the same time the pH of the remaining water increases as well as its content of non-volatile constituents. The gas content of steam samples depends on the original gas content of the reservoir water, the enthalpy of this water, possible loss/gain of steam during flashing underground, and the sampling pressure. The content of non-volatile constituents in samples of flashed water is determined by the same factors. It is therefore clear, even if the total discharge enthalpy had remained the same, that the analytical concentrations of the collected water and steam samples cannot be used to detect chemical changes in the well discharges that may occur with time, because the sampling pressures for individual wells varied from time to time.

If the enthalpy of the total discharge was known, the ratio of water to steam at any sampling pressure can be calculated easily (see Arnórsson et al., 1977), which in turn allows evaluation of the total discharge composition from analyses of water and steam samples collected separately on the wellhead at a known pressure. In the present work the only means of estimating the enthalpy of individual well discharges was from the silica content of the water assuming equilibrium with quartz. As pointed out by Arnórsson et al. (1977), this method may yield low values, when flashing occurs in the aquifer, except at the initiation of the discharge period. This is so because cooling, which accompanies the flashing, leads to precipitation of silica. Lower silica concentrations yield lower quartz equilibrium temperatures. Flashing in the aquifer may also cause the well discharge enthalpy to increase

during production, if some separation of the two phases occurs and the steam moves preferentially to the well. In the present study the enthalpy of the total discharge of individual wells is always referred to the initial quartz equilibrium temperature. The quartz solubility data used in this study are those of Morey et al. (1962) and Kennedy (1950).

For description of the sampling procedure and the methods of calculation of the reservoir water chemistry, the reader is referred to Arnórsson et al. (1977).

Chemical characteristics

The reservoir water at Námafjall is very low in total dissolved solids, the low chlorine concentrations being most noteworthy. The major dissolved ions include bisulphide and sodium. The chemistry of the various well discharges is similar, but significant differences occur in the silica and the total gas concentrations. These differences can be related to the temperature and depth of the aquifers feeding individual wells.

It is believed ^what the chlorine in the water is derived from the rock by leaching. The data of Sigvaldason and Óskarsson (1976) indicate that the Icelandic basalts are low in chlorine. The low chlorine content of ^{tey}Námafjall waters is thus considered to be due to its limited supply in the rock. It is this supply of chlorine that is most important in determining the total dissolved solids content of the water. The concentration and distribution of other major ionic constituents are determined by this supply and various solute/solute

and mineral/solute temperature dependent chemical equilibria (Arnórsson et al., 1977).

Representative analyses of each of the well discharges at Námafjall are presented in tables 1 and 2. The calculated distribution of chemical species in the reservoir water for the same samples as in table 1 are shown in table 3.

Tables 1, 2, and 3

CHANGES IN THE CHEMISTRY OF THE WELL DISCHARGES WITH TIME

Factors affecting the chemical changes

Changes in the chemistry of well discharges tapping hot-water reservoirs may occur as a result of pressure drop in the reservoir, caused by withdrawal of fluid by the discharging wells. Increased flashing in the reservoir, leads to cooling of the reservoir water and thus upsets temperature dependent solute/solute and mineral/solute chemical equilibria that govern the water composition. Increased flashing in the reservoir may cause depletion in the volatile content of the well discharges and change the ratios of individual volatile constituents, if that part of the reservoir where the flashing occurs, acts as an open system. Withdrawal of fluid in excess of the natural recharge rate will upset the balance between the extent of the steam ~~and~~ ^{and} the formation/renewal of hot water from below, and can in this way change the dissolved solids content of the water feeding the wells. Invasion of the surrounding cold ground water into the geothermal system would have the same effect.

The following discussion will only include those chemical constituents, which have clearly shown changes in their concentrations during the observation period from 1970 to 1976.

Silica

A substantial lowering of the silica concentration of some of the well discharges has occurred during the

6 year observation period. Other well discharges have retained practically constant silica contents. The lowering of silica is strongest for wells 5 and 7. These wells are fed by aquifers, which had measured temperatures prior to exploitation nearest to the boiling point curve (see fig. 2). The decrease of silica in wells 5 and 7 corresponds to a lowering of the quartz equilibrium temperature by about 45° and 30° respectively over the period 1970-1975 (fig. 3). This is attributed to the precipitation of quartz in the aquifers outside the wells, where the water cools by flashing. It appears that the flashing zone has expanded progressively with time as a result of the pressure drop in the reservoir caused by the discharging wells. Local permeability will influence the pressure drop in the vicinity of individual wells and therefore influence the extent of the quartz precipitation. The lack of correlation between the lowering of the silica and sodium concentrations of individual well discharges, discussed below indicates that mixing of the geothermal water with surrounding cold ground water was not responsible for the decline in the silica content of some of the well discharges.

Fig. 3

For the total discharge rate of 40 kg/sec for each of wells 5 and 7, roughly 720 and 680 tons of quartz have been precipitated respectively in the aquifers around the two wells during the 6 years observation period. For a density of 2.6 this mass of quartz corresponds to 270 m^3 for each well, which is sufficient to seal completely a rock with 10% porosity of 2700 m^3 . This volume of rock corresponds to a 10 meter thick layer extending 9.3 meters in all directions from the well. It is thus evident that precipitation of silica in the

aquifers feeding discharging wells may reduce their exploitable life time significantly, particularly, if extensive flashing occurs in the aquifer. For the reservoir as a whole, such a precipitation is, however, insignificant.

Sodium and potassium

As the silica concentrations of the well discharges decrease, their ratio of Na/K increase. The water temperatures calculated from the NaK- and NaKCa-geothermometers (see Truesdell, 1975) parallels the quartz equilibrium temperature as demonstrated for wells 5 and 7 in fig. 3, although the former tend to be ^s somewhat higher for well 5. This suggests that the rate of re-equilibration between solution and quartz on one hand and the relevant NaKCa-silicat^ea on the other, is similar for the temperatures and water compositions in question. The erratic and low NaKCa-temperatures for well 7 result from the variable calcium content of the discharge. The calcium content of all the wells is somewhat erratic but without any observable trends with time. This may be due to dissolution of fine calcite crystals upon storage of the samples prior to analysis. The flashing in the aquifers and in the wells leads to calcite precipitation and a fraction of the precipitate could well be brought to the surface with the rapidly ascending steam-water ~~be brought to the surface with the rapidly ascending steam-water~~ mixture.

At the beginning of the exploitation period well 7 contained the lowest sodium concentrations or about 105 ppm as compared with 140-150 ppm in the other wells. It is observed that the initial sodium content of individual well discharges increases with distance from well 7. Well 7 has the highest temperature and the highest contents of volatiles. For these reasons this well is assumed to

be fed by the least evolved reservoir water, while the other wells are fed by water which has undergone more flashing and degassing. The difference in the sodium concentrations of these well discharges with that of well 7 cannot, however, be accounted for by steam loss. To increase the sodium concentration from 105 to 140 ppm the reservoir water must lose about 25% of steam. For flashing by one step adiabatic cooling this steam loss corresponds to a temperature drop of the order of 100°C. The temperature difference of the aquifer feeding well 7 and the aquifers feeding the other wells is in the range of 15-40°C. Such cooling by one step adiabatic flashing corresponds to a steam loss of 6-11%.

It is thought that the relatively higher sodium concentrations in the more evolved waters has resulted from leaching of sodium from the rock by the flashed water. This leaching is favored by a reaction towards an ionic exchange equilibrium between the major dissolved cations (Na^+ , K^+ and Ca^{++}) and protons, and a hydrothermal mineral, possibly smectite. Arnórsson et al. (1977) present data on water compositions for many geothermal areas in Iceland which support the existence of such an equilibrium. As water temperatures decrease the ratios of individual cation/proton ratios increase. Re-equilibration upon cooling would therefore involve a combination of loss of protons from solution and leaching of the major cations from the rock.

With the exception of well 7 the sodium content of all the well discharges has decreased during the exploitation period. This decrease amounts to 13-30% over a six year period (table 4, fig. 3). The potassium concentrations have decreased to conform with the decrease in the concentrations of sodium and the lowering of the water temperatures in the aquifers. This decrease amounts to 7-51% for different wells (table 4).

Table 4

The sodium and potassium values shown in table 4 have been obtained by using the well discharge enthalpies reported in that table. Flashing in the reservoir and some separation of the water and steam phases would cause individual well discharges to become depleted or enriched in steam. An error in the value of the discharge enthalpies will affect the sodium and potassium results. If the actual discharge enthalpies were lower than reported in table 4, higher concentration values would have been obtained for both elements. If individual well discharge enthalpies had decreased during the observation period the corresponding lowering of the sodium and potassium concentrations would be less. In the extreme case for well 5 the decrease for sodium would be 17% as compared to 30%. This refers to a enthalpy value of 203 kcal/kg (200°C) as compared to 262 kcal/kg and a sampling pressure of 10 bars absolute. If individual well discharges had increased with time, the decrease in the sodium and potassium concentration would be somewhat greater than reported, but in every case only to an insignificant extent.

The decrease in the sodium and potassium concentrations of the well discharges cannot be explained by diffusion of the geothermal water with cold water from above. If dilution was taking place there should exist a correlation between changes in silica and sodium concentration. This is not the case. For example well 4 has retained constant silica content but sodium and potassium have decreased by 24% and 20% respectively. It is thought that less effective leaching ^{of} sodium and potassium from the rock by the flashed geothermal water is the cause of the progressive decrease in the concentrations of these elements in the well discharges. The exploitation is expected to have

accelerated the replacement of the shallow flashed water by less reacted water from below. In this way less time has become available for the flashed water to leach sodium and potassium from the rock. Precipitation of quartz and calcite may also have decreased the effective leaching by reducing the contact area between water and rock. If the water feeding well 7 represents the unevolved reservoir water, one would expect the sodium concentrations in the other well discharges to approach gradually the sodium level in well 7 and stabilize there, or at a higher level depending on the steam loss in aquifers where flashing occurs.

Major gas constituents

The gas phase of the well discharges at Námafjall consists 80-90% of hydrogen, hydrogen sulphide, and carbon dioxide, the remainder being mostly nitrogen and methane (table 2). The analytical results for the major gas constituents are rather erratic, which makes it difficult to observe any trends in the gas content of individual well discharges with time. Yet it is certain that the gas content of the total discharge of wells 6, 7, and 8 has declined with time during the period 1970-1976. For well 7 this decline is estimated to be 10%, but 45% for wells 6 and 8. During the same period no changes could be observed for wells 4 and 5. Well 9 is not included here. Insufficient data are available from this well in this respect. As the gas content of well 6, 7, and 8 has declined, an apparent lowering of the $\text{CO}_2/\text{H}_2\text{S}$ and $\text{H}_2/\text{H}_2\text{S}$ ratios has occurred, but changes in the same ratios cannot be detected for wells 4 and 5. The erratic results for carbon dioxide and hydrogen sulphide make this statement somewhat uncertain. The analytical results for hydrogen are presented in fig. 4. They

give an impression of the erratic nature of the data. The results for hydrogen sulphide and carbon dioxide are more erratic.

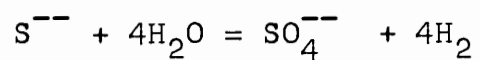
Fig. 4

The gas content of individual well discharges varies much more than the observed time variations just discussed (fig. 5A). The hottest aquifer, which feeds well 7, contains the highest gas concentrations, whereas the coldest aquifer, which feeds well 5, is lowest in gas. Degassing by flashing of the reservoir water does not explain the relation of the ratios of $\text{CO}_2/\text{H}_2\text{S}$ and $\text{H}_2/\text{H}_2\text{S}$ to the total gas content. There is no relationship between the total gas content and the $\text{CO}_2/\text{H}_2\text{S}$ ratio although progressive decrease with falling temperature is observed for the $\text{H}_2/\text{H}_2\text{S}$ ratio (fig. 5B).

Fig. 5

Flashing, which leads to increased pH of the water, causes precipitation of calcite (Arnórsson, 1977) and *pyrite and pyrrhotite*. ~~(It is though that sulphide always precipitates from solution as pyrrhotite, which later recrystallizes into pyrite.)~~ The removal of carbon dioxide and hydrogen sulphide from solution by such precipitation will lower the total gas content of the steam-water mixture. Conductive cooling will also lead to *pyrrhotite and pyrite* precipitation but not to calcite precipitation because the solubility of *pyrrhotite and pyrite* decreases with falling temperature but that of calcite increases. It seems possible that the relatively high $\text{CO}_2/\text{H}_2\text{S}$ ratios in the cooler and more gas deficient waters, has resulted from removal of sulphide from solution by *pyrrhotite and pyrite* precipitation during conductive cooling. At the same time the hydrogen concentrations would decrease though the foll-

owing reaction:



Oxidation of hydrogen sulphide would have the same effect as pyrrhotite precipitation. Which of these two processes is the most important cannot be deduced from the available data.

DISCUSSION

The variable gas content of the well discharges at Námafjall can be explained by the following model: The major upflow zone underlies the Námafjall hyaloclastite ridge and sideways movement of water to the west supplies the wells. Steam formation in the upflow zone, and during the lateral movement of the water from that zone, causes degassing of the water. When the water cools, as a result of the flashing, sulphide is lost from solution and hydrogen decreases simulatanously by virtue of its participation in a chemical equilibrium between sulphide, sulphate, and water. These reactions explain the lowest hydrogen and hydrogen sulphide concentrations in ~~the lowest hydrogen and hydrogen sulphide concentrations in~~ the shallowest aquifers and in the wells, which are farthest away from the assumed upflow zone.

Withdrawal of fluid by the discharging wells has produced a pressure drop in the reservoir with the effect of extending the zone of flashing. Only hot water existed in the aquifers penetrated by the wells while the reservoir was undisturbed, but when the wells were put into production, the pressure drop became sufficient to initiate boiling in the aquifers. Some of the steam, which has formed by flashing in the feeding aquifers, has escaped from the steam-water mixture entering some of the wells with the effect that the total gas content of their discharge has decreased. This effect of degassing will obviously be most pronounced farthest away from the upflow zone and where pressure drop is strongest in unconfined aquifers. The discharges of wells 6 and 8 have shown the largest decrease in the total gas content, and accordingly, these wells are either farthest away from the upflow zone or they are fed by the least confined aquifers.

On the basis of aquifer temperature and total gas content, wells 4 and 5 are farther away from the upflow zone than well 7. One might therefore have expected a decline in the gas content of these two first mentioned wells during the exploitation period, but this has not been observed. It may be that wells 4 and 5 are fed by confined aquifers so steam separation does not occur underground in the immediate vicinity of the wells.

As was pointed out in the previous chapter, the sodium content was lowest in well 7 at the initiation of the exploitation period, but this well contains the highest gas concentrations and for that reason it is fed by water that has lost less steam than the waters feeding other wells. The higher sodium concentrations of the other well discharges could not be accounted for by steam loss. Leaching of this constituent from the rock by the cooler flashed water was offered as a possible explanation. The withdrawal of fluid from the geothermal reservoir by the discharging wells has increased the rate of recharge from below. As a result less time has been available for leaching of sodium from the rock by the flashed waters explaining why the sodium concentrations in the flashed water have decreased with time. This explanation fits the model drawn up earlier from interpretation of the gas content of the well discharges. This model also fits the distribution of the surface thermal manifestations in the area (fig. 1).

On the basis of the reservoir model drawn up here, it is recommended that further wells in the Námafjall field should be located in an easterly and southeasterly direction from well 7. To improve modelling of the reservoir water chemistry it is essential to obtain data on discharge enthalpies of individual wells.

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Table 1. The concentrations^x (in ppm) of the major chemical components in the total discharge of wells at Námafjall.

Component	Well no./Year and month of sampling					
	4 73.07	5 74.03	6 74.03	7 73.07	8 73.11	9 74.03
SiO ₂	543	356	501	511	465	528
Na	133	128	132	122	124	119
K	23.2	19.4	23.1	22.6	21.7	22.2
Ca	1.3	2.2	0.7	0.7	1.3	0.9
Mg	0.09	0.04	0.04	0.11	0.03	0.03
CO ₂ ^{***}	110	113	158	257	131	184
SO ₄	101	59	60	74	56	63
H ₂ S ^{***}	168	110	205	326	163	198
Cl	16	23	25	19	22	18
F	1.5	0.8	0.8	1.5	1.0	0.9
H ₂	3.8	0.8	5.2	13.1	3.4	5.2
Diss.solids	990	719	931	974	861	913
t _{qtz} ^{oC}	255	218	248	251	241	254

^x These concentrations have been calculated from analyses of water and steam samples collected on the wellhead by assuming that the enthalpy of the total discharge corresponds to that of water at the quartz equilibrium temperature (t_{qtz}) given above.

^{***} total carbonate.

^{***} total sulphide.

Table 2. The concentrations (in millimoles/kg) of volatile constituents in the steam fraction of selected samples from wells at Námafjall

well	4	5	6	7	8	9
year/month of sampling	74.03	73.05	73.05	73.05	73.05	74.03
sampling pressure bars abs	12.8	11.2	11.2	12.0	10.9	6.9
CO ₂	13.3	13.1	21.4	31.8	27.5	18.1
H ₂ S	20.0	12.2	25.0	40.8	18.9	19.1
H ₂	14.7	4.2	23.1	41.4	18.6	13.2
O ₂	0.00	0.00	0.00	0.00	0.00	0.00
N ₂	3.3	3.6	3.6	1.0	4.7	2.3
CH ₄	0.18	0.55	0.73	0.30	0.82	0.19
Ar	0.10	0.10	0.12	0.05	0.12	0.08
discharge enthalpy kcal/kg*	267	262	276	298	256	265

* corresponds with the initial quartz equilibrium temperature of the well discharges.

Table 3. The distribution (in ppm) of chemical species in the unflushed reservoir water feeding the wells at Námafjall. The same samples were selected as in table 1. The computation methods applied to obtain the chemical speciation are those of Arnórsson et al. (1977). They refer to the quartz equilibrium temperature (t_{qtz}) reported below.

Chemical species	Well no./Year and month of sampling					
	4	5	6	7	8	9
	73.07	74.03	74.03	73.07	73.11	74.03
pH	7.47	7.34	7.35	7.02	7.30	7.25
Na ⁺	123.6	123.8	126.4	115.6	119.8	113.4
K ⁺	21.7	18.9	22.2	21.4	20.9	21.2
Ca ⁺⁺	0.42	1.21	0.32	0.27	0.62	0.37
Mg ⁺⁺	0.001	0.002	0.001	0.002	0.001	0.0006
H ₄ SiO ₄	844.5	551.3	783.2	808.0	727.4	829.6
H ₃ SiO ₄ ⁻	23.9	17.5	18.8	8.6	16.6	14.5
H ₂ CO ₃	97.7	64.8	139.2	290.2	110.6	187.4
HCO ₃ ⁻	56.6	93.2	82.0	70.8	72.5	70.2
CO ₃ ⁻²	0.006	0.04	0.01	0.004	0.01	0.005
H ₂ S	73.2	35.3	94.1	215.8	73.8	109.3
HS ⁻	91.8	72.8	107.8	106.7	86.4	86.2
S ⁻²	0.001	0.0004	0.0009	0.0004	0.0006	0.0006
HSO ₄ ⁻	0.29	0.07	0.18	0.55	0.16	0.30
SO ₄ ⁻²	56.6	40.1	35.1	43.8	34.4	36.5
HF	0.02	0.006	0.01	0.06	0.01	0.02
F ⁻	1.45	0.80	0.84	1.47	1.01	0.85
Cl ⁻	15.4	23.3	24.4	19.2	21.4	17.9
NaCl ⁰	0.20	0.15	0.28	0.21	0.20	0.21
KCl ⁰	0.01		0.02	0.01	0.01	0.01
NaSO ₄ ⁻	46.4	19.1	26.3	31.7	22.6	27.6
KSO ₄ ⁻	5.4	1.9	3.1	3.9	2.6	3.4
CaSO ₄ ⁰	3.0	3.2	1.2	1.4	2.2	1.7
MgSO ₄ ⁰	0.48	0.20	0.20	0.58	0.16	0.15
CaCO ₃ ⁰	0.02	0.19	0.02	0.008	0.04	0.01
MgCO ₃ ⁰	0.0001	0.0005	0.0001	0.00009	0.0001	0.00004
Ionic strength	0.00639	0.00613	0.00654	0.00626	0.00593	0.00574
t_{qtz}	255	218	248	251	241	254

Table 4. The variation in the sodium and potassium concentrations of well discharges at Námafjall during the period 1970-1975. The reported values have been read from the best fit lines through the analytical points and refer to a reservoir water enthalpy, which corresponds to the initial quartz equilibrium temperature of individual well discharges.

Well	Reservoir water enthalpy Kcal/kg	sodium ppm		potassium ppm	
		01.1970-12.1975	% decrease	01.1970-12.1975	% decrease
4	267	154 - 117	24	25.5 - 20.3	20
5	262	139 - 97	30	27.6 - 13.6	51
6	276	142 - 124	13	22.9 - 21.2	7
7	298	104 - 110	- 5	22.0 - 18.8	15
8	256	146 - 115	21	28.3 - 18.8	34
9	265	152 - 115	24	30.2 - 19.2	36

CAPTION TO FIGURES

- Fig. 1 Location of drillholes in the Námafjall geothermal field (from Gudmundsson et al., 1971).
- Fig. 2 Measured downhole temperatures and aquifer locations in wells 4 to 9 at Námafjall. The profile for well 9 shows low temperatures. It was recorded shortly after completion of drilling and before the well had attained equilibrium after the cooling by the drilling fluid. Other profiles represent stabilized temperatures prior to the period of discharge. The figures in the bottom left corner indicate quartz equilibrium temperatures (t_{qtz}). If there has been a trend towards lowering of t_{qtz} with time the respective set of figures is joined with an arrow.
- Fig. 3 Variation in the quartz equilibrium temperature (t_{qtz}), the NaKCa-temperature (t_{NaKCa}) (see Fournier and Truesdell, 1973), and the Na and K Concentrations of the discharges of wells 5 and 7 during the period 1970-1976.
- Fig. 4 Changes in the hydrogen content of the discharges of wells 4 to 8 during the period 1970-1976. The hydrogen concentrations have been calculated from the reported enthalpy of the well discharges, which corresponds to the quartz equilibrium temperature at the initiation of the discharge period.
- Fig. 5 The relationship of gas concentrations (A) and gas ratios (B) with aquifer temperatures in wells 4 to 9. The plotted points are averages for samples collected during 1973-1974. In this period trends in the gas compositions were not observable.

The averages are believed to demonstrate better the relationship in question than individual analyses do, because they level out the erratic distribution of the former.

MYNDSKÝRINGAR

- Mynd 1. Staðsetning borhola á jarðhitasvæðinu við Námafjall.
- Mynd 2. Mælt hitastig og ^{lega} ~~staðsetning~~ vatnsæða í holum 4 til 9 við Námafjall. Hitaferillinn fyrir holu 9 sýnir lágt hitastig. Hann var tekinn skömmu eftir að þorun lauk og áður en holan hafði náð að hitna upp. Aðrir hitaferlar sýna ótruflað hitastig í holunum, áður en þeim var hleypt í stöðugan blástur. Tölurnar neðst til vinstri á myndinni sýna kísilhita fyrir einstakar holur. Ef kísilhitinn hefur farið lakkandi með tíma, er viðkomandi talnappar tengt með ör.
- Mynd 3. Breytingar á kísilhita, NaKCa-hita, og styrk natríums og kalís í holum 5 og 7 á tímabilinu 1970-1976.
- Mynd 4. Breytingar á vetnisinnihaldi í borholum 4 til 8 á tímabilinu 1970-1976. Styrkur vetnis hefur verið reiknaður út frá ofanskráðu entalpiúgildi. Svarar þetta gildi til kísilhitans við upphaf nýtingartímans.
- Mynd 5. Samband gasinnihalds (A) og gashlutfalla (B) við hitastig í vatnsæðum hola 4 til 9. Einstakir punktar á línuritunum samsvara meðaltali fyrir sýni, sem safnað var á tímabilinu 1973-1974. Á þessu tímabili voru ekki sjáanlegar breytingar á gasinnihaldi einstakra hola. Talið er, að meðaltölin sýni betur þau sambönd, sem um ræðir, en einstakar valdar efnagreiningar gerðu, þar sem þau jafna út óreglulegar sveiflur í gildum einstakra efnagreininga.

TÖFLUHEITI

- Tafla 1. Styrkur (í ppm) aðalefna í heildarrennsli borhola í Námafjalli.
- Tafla 2. Styrkur (í millimólum/~~kg~~) rokgjarnra efna í gufu frá holum við Námafjall.
- Tafla 3. Styrkur (í ppm) efnasambanda í ósoðnu vatni, sem streymir inn í borholur í Námafjalli. Sömu sýni voru valin og í töflu 1. Reikningsaðferðirnar, sem notaðar voru, ~~við spesiureikningana~~ voru fengnar frá Stefáni Arnórssyni o.fl. (1977). Þessir reikningar miða við kísilhitann, sem gefinn er upp neðst í töflunni.
- Tafla 4. Breytingar á styrk natriúms og kalís í holum við Námafjall. Gildin, sem sýnd eru, hafa verið lesin út úr beinni línu, sem fellur best í gegnum mælipunktana og miða við entalpíu, sem svarar til upphaflegs kísilhita einstakra borhola.

ÚRDRÁTTUR

Nýting jarðgufu á Námafjallssvæðinu hófst 1967. Hafa alls verið boraðar 10 holur niður í jarðhitageyminn og er dýpt þeirra á bilinu 340-1800 metrar. Hæstur hiti hefur mælst á um 1100 metra dýpi í holu 7, 289°C. Í þessari grein er fjallað um þær breytingar, sem orðið hafa á efnainnihaldi vatns og gufu úr borholum á tímabilinu 1970-1976. Þessar breytingar má allar rekja til þrýstifalls í jarðhigageyminum, sem skapast hefur við nýtingu svæðisins.

Djúpvatnið, sem streymir inn í borholurnar í Námafjalli, er tiltölulega snautt af uppleystum efnum. Er hinn lági styrkur klórs sér í lagi markverður. Klórið mun komið í vatnið við útskolun úr umlykjandi bergi. Guðmundur Sigvaldason og Niels Óskarsson hafa með athugunum sínum leitt í ljós, að basískt berg hérlandis er klórsnautt og gæti lágur styrkur þessa efnis í berginu verið ein meginorsök hins lága styrks þess í vatninu.

Þegar heita vatnið í jarðhitageyminum sýður í borholum og vatnsæðum, sem fæða þær, tapar það miklum hluta þeirra rokgjörnu efna (aðallega kolsýra, brennisteinsvetni og vetni), sem voru uppleyst í því, en þessi efni leita í gufuna, sem myndast við suðuna. Um leið vex sýrustig vatnsins (pH), svo og styrkur órokgjarnra efna vegna gufutapsins.

Breytingar á efnainnihaldi vatns og gufu úr borholum, sem orsakast af þrýstifalli í jarðhitageyminum, má rekja til aukinnar suðu í berginu. Við suðuna kólnar vatnið þegna gufumyndunarinnar og þessi kólnun raskar hitastigsháðum efnajafnvægjum milli uppleystra efna í vatninu og steinda í berginu. Suðan í berginu getur líka leitt til minnkandi gasmagns í borholurennslinu, ef hluti þeirrar gufu

(og með henni gas), sem myndast út í berginu, skilur sig frá þeirri vatns/gufublöndu, sem streymir inn í holurnar. Vinnsla úr svæðinu umfram upphaflegt náttúrulegt rennsli getur raskað jafnvægi milli uppgufunar og endurnýjunar vatns neðan frá og á þann hátt breytt heildarstyrk uppleystra efna í vatninu. Sömu áhrif hefði blöndun við kaldara grunnvatn, sem liggur utan með jarðhitageyminum, en þrýstifallið, sem nýting veldur, örvar hugsanlegt innstreymi utanaðliggjandi grunnvatns.

Kísilinnihald í sumum borholanna hefur minnkað mikið á tímabilinu 1970-1976, mest í borholum 5 og 7. Minnkunin svarar til 30-45°C lækkunar á kísilhita. Þessi lækkun kísils er talin stafa af útfellingu kvars í berginu umhverfis holurnar, þar sem suða hefur átt sér stað. Á nefndu 6 ára tímabili hafa um 700 tonn kísils (sem kvars) fallið út í æðunum, sem fæða holur 5 og 7 hvora fyrir sig. Þessi útfelling er talin munu hafa áhrif á nýtingartíma borholanna, en ekki á vatnsleiðni jarðhitakerfisins í heild. Vatnsleiðni umhverfis einstakar holur ræður miklu um það þrýstifall, sem blásandi borholur valda, í æðunum, og þar með magni kísilútfellinga.

Í upphafi nýtingartímabilsins var natríum innihald lægst í vatni frá borholu 7, eða um 110 ppm, samanborið við 140-150 ppm frá hinum holunum. Hefur natríum innihaldið ekki breyst í holu 7, en farið lækkandi í hinum holunum. Nemur lækkunin 13-30% á tímabilinu 1970-1975. Inn í holu 7 streymir vatn, sem hefur soðið minna, en það sem streymir inn í hinar holurnar. Talið er, að soðna vatnið hafi skolað natríum út úr berginu og sé það ástæðan fyrir hærri upphaflegum styrk þess í hinum holunum. Gufutap vegna suðu veldur einhverri aukningu í styrk natríum, en sú aukning getur ekki valdið meiru en 10% mun á holu 7 og köldustu holunni, nr. 5, og því mun minnu en svarar til þess mismunar, sem til staðar er.

Suðan og kælingin, sem er henni samfara, raska jónaskipta-
jafnvægjum, sem ákvarða hlutföll í styrk vetnisjóna og
annarra aðalkatjóna í vatninu. Útskolun natríums er talin
ráðast af efnabreytingum í átt til jónaskiptajafnvægis.
Með nýtingu svæðisins hefur heita vatnið í efri hluta
jarðhitageymisins endurnýjast hraðar en áður var með ó-
soðnu vatni neðan frá og því ekki gefist jafnlangur tími
fyrir útskolun á natríum og raunin var, áður en nýting
hófst. Skýrir þetta aukna rennsli soðna vatnsins þá lækun
á styrk natríums, sem orðið hefur í sumum holunum.

Styrkur kalís hefur minnkað í samræmi við styrk natríums
og að auki nokkuð vegna þeirrar kælingar, sem suðan í
vatnasæðunum umhverfis borholurnar hefur valdið, en sem
kunnugt er, er Na/K hlutfallið í heitu vatni háð hita-
stigi. Með vaxandi hitastigi lækkar þetta hlutfall.
Hitastig reiknað út frá Na/K hlutfallinu í vatninu hefur
minnkað hliðstætt við kísilhitann. Þessi fylgni bendir
til þess, að svipaðan tíma tekur fyrir kísil annars vegar
og natríum og kalí hins vegar að ná efnajafnvægi á ný
við steindir í berginu eftir kælingu jarðhitavatns, a.m.k.
fyrir það hitastig og heildarefnasamsetningu vatns, sem
hér um ræðir.

Innihald gass er mjög breytilegt í einstökum borholum.
Er mest gas í heitustu holunum, en minnst í þeim köldustu.
Ekki er unnt að skýra hið breytilega gasmagn með afgösun
samfara gufumyndun. Slík afgösun hefði í för með sér
lækun á hlutfallinu $\text{CO}_2/\text{H}_2\text{S}$, en sú er ekki raunin.
Einhver afgösun og frekari minnkun á H_2S við útfellingu
járnsúlfíða í berginu gæti skýrt hið breytilega gasmagn
í borholunum.

Eftir að nýting hófst hefur gasmagn minnkað í sumum holanna.
Minnkunin er lítil í holu 7 (10% á 6 árum), en mest í
holum 6 og 8 (45% á 6 árum). Þessi minnkun er talin stafa

af nokkru tapi gufu úr vatnsæðum umhverfis borholurnar, en gufan myndast þar við suðu. Með þrýstifallinu í jarðhitageyminum samfara nýtingu svæðisins, hefur suða farið vaxandi í æðunum. Engar mælanlegar breytingar hafa orðið á gasinnihaldi í holum 4 og 5. Þetta má skýra með því, að þessar holur fái vatn og gufu úr lokuðum æðum, þannig að ekkert gufu-og gastap geti átt sér stað, heldur skili öll sú gufa sér inn í holurnar, sem myndast við suðu í æðum.

Á grundvelli túlkunar á efnainnihaldi vatns og gufu í borholunum, er talið, að aðaluppstreymissvæðið sé í nágrenni holu 7 eða þar fyrir austan. Soðið vatn streymir síðan frá uppstreymistappanum til vesturs og fá hinar holurnar vatn sitt og gufu úr þeim straumi. Á grundvelli þessa líkans væri rétt að staðsetja næstu borholur austan holu 7.

Fig. 2

