

GEOTHERMAL TRAINING PROGRAMME Orkustofnun, Grensásvegur 9, IS-108 Reykjavík, Iceland Reports 2000 Number 15

BOREHOLE GEOLOGY AND HYDROTHERMAL ALTERATION OF WELL NJ-20, NESJAVELLIR HIGH-TEMPERATURE AREA, SW-ICELAND

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ABSTRACT

Well NJ-20, drilled in 1999, is located in the Nesjavellir high-temperature field in SW-Iceland. It was drilled as a discharge well to utilize high pressure for electric power generation. Directional drilling was performed to minimize environmental impacts and to gain closer access to the main upflow. The lithology consists predominantly of volcanic rocks. The upper part (from top to 730 m) is mostly composed of tuff, breccia, glass and glassy basalt, which are called hyaloclastites. Several basaltic intrusions have been intruded into the hyaloclastites. In the deeper part (730-1180 m) are predominantly basaltic lavas. According to the alteration mineral distribution, four alteration zones were found, smectite-zeolite zone (0-360 m), mixed layer clay zone (360-820 m), chlorite-epidote zone (820-940 and 1010-1180 m) and epidote-actinolite zone (940-1010 m). Their relevant temperature ranges are <200°C, 200-230°C, 230-280°C and >280°C, respectively. Alteration mineral study results indicate an increasing temperature regime from the top to 1010 m, but slightly decreased below there. According to the temperature log, heat increased below 1180 m. In this well, 15 aquifers were identified according to circulation loss or gain, pressure drops on pumps and temperature logs.

1. INTRODUCTION

1.1 Purpose of study

Drilling has an important role in both exploration and exploitation of geothermal fields. Borehole geologists can use cuttings and cores to determine subsurface lithology, hydrothermal alteration, and the location of probable aquifers. With such data, it is also possible to evaluate how the thermal evolution of a geothermal system has developed. In this paper, the author describes the borehole geology and alteration mineralogy of well NJ-20 which was drilled in 1999 in Nesjavellir high-temperature field in SW-Iceland. This report is mostly based on the study of available data from the time drilling occurred, and includes the study of the circulation fluid and drill cuttings. All obtainable relevant data was used, such as temperature, pressure and geophysical logs.



FIGURE 1: Stratigraphic and tectonic map of Iceland (Saemundsson, 1979)

1.2 General information

Iceland is located on the Mid-Atlantic Ridge where the American and Eurasian plates are drifting apart, at the average relative motion of 2 cm/year and where the main active volcanism takes place. Almost all the stratigraphical units are volcanic in origin. A stratigraphic and tectonic map of Iceland is shown in Figure 1. The oldest part of the geology of Iceland is of Tertiary age (3.1-16 m.y.). It is seen in the west and east fiords and is mainly composed of basaltic lavas, which dip smoothly towards the active volcanic zone. The younger part is composed of alternating sequences of lavas and hyaloclastites that belong to Plio-Pliestocene age (0.01-3.1 m.y.). The main difference between these two units is the volcanic environment. The lavas were formed during interglacial periods whereas the hyaloclastites were formed during the glacial periods.

The youngest formation is positioned in an active volcanic zone and is of Holocene age (younger than 10,000 years). In fact, this unit is located in a rift zone, in which fissure swarms predominate (Saemundsson, 1979). Fissure swarms showing en echelon features characterize the rifting zone, where central volcanoes develop. For example Krafla and Hengill volcanoes were formed in this manner. The geothermal areas in Iceland form a regular pattern and are divided into two main groups by their base temperature, low-temperature and high-temperature areas (Pálmason et al., 1979). Low-temperature areas are related to Tertiary and Quaternary volcanism and high-temperature areas are related to active volcanoes inside the rifting zone. The conventional definition for high-temperature and low-temperature areas is finding temperatures of $\geq 200^{\circ}$ C or $\leq 150^{\circ}$ C, respectively, at a depth of 1000 m or shallower.

1.3 Geology of the Hengill area

The Nesjavellir high-temperature field is located in SW-Iceland, about 30 km east of Reykjavik on the northern perimeter of the Hengill geothermal area. Its location and thermal manifestations are shown in Figure 2.

Hengill is one of the largest hightemperature areas in Iceland extending over some 50 km². Due to structural activity in the area, a tensional stress system has developed in the zone of the active Hengill volcanic system. The tensional stress has opened northeast trending vertical fractures, which provide high-permeability conditions for fluid flow (Björnsson et al., 1986). The fracture network is occasionally activated and provides conduits for the episodic eruption of basalt and the emplacement of dikes. Magma moves into the shallow crust at temperatures on the order of 1200°C and supplies heat to the hydrothermal system (Bödvarsson et al., 1990).

A simplified geological map of the Hengill volcano and Thingvallavatn lake is shown in Figure 3. The Hengill area is almost entirely built up of volcanic rocks of late Quaternary and postglacial age (Árnason et al., 1967). There are mostly basalt flows and hyaloclastites but small amounts of intermediate rocks and rhyolithes

occur as well. Hyaloclastites have formed ridge-shaped mountains, which are the product of subglacial fissure eruptions. Hengill itself is a hyaloclastite mountain with basalt flows on top, known as tuya or a table mountain. It was probably formed as a result of a monogenetic central eruption, which succeeded in breaking through the ice cap. The Nesjavellir field features a graben structure about 10 km broad, which runs NE-SW parallel to the hyaloclastite ridges. This graben is part of a greater structure, which accompanies the Reykjanes-Langjökull volcanic zone. The western part of



FIGURE 2: Location and thermal manifestations of the Hengill geothemal area

FIGURE 3: Simplified geological map of the Hengill volcano and Lake Thingvallavatn (Árnason et al., 1967)

the Hengill volcano is split up by numerous sub parallel normal faults. These constitute a 5 km broad inner graben amounting to a maximum of some 250 m in the outcrops of lavas belonging to the shield volcanoes surrounding lake Thingvallavatn (Árnason et al., 1967). During postglacial times, six fissure eruptions have occurred in this inner graben, four south of Hengill and two north of the mountain.

1.4 The Nesjavellir well field

Exploration at Nesjavellir well field has been carried out since 1964. In the beginning, the exploration was a part of a general exploration programme for the whole Hengill area. All the wells are located within the graben zone northeastward of the mountain Hengill. An enlarged map of the Nesjavellir well field and the location of borehole NJ-20 is shown

in Figure 4. The first wells were located near surface geothermal manifestations in the valley at low elevation, whereas later wells spread out more generally as the extent of the area was determined by resistivity and borehole geology. A resistivity profile through the Nesjavellir well field with temperature distribution is shown in Figure 5.

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The well field covers a land area of 3.5 km^2 . So far in the Nesjavellir geothermal field 22 deep (1-2 km) wells have been drilled and all of them have penetrated the geothermal reservoir. Some general information about wells 5-7 and 9-20 is shown in Table 1.

Thirteen of these wells are commercial producers, with an average thermal output of 59 MWt per well

The main objective of drilling now is to expand the production area and to evaluate the feasibility of increasing production from the field (Steingrímsson et al., 2000). In this field, there is a three dimensional variation in the reservoir, especially in the distribution o f temperature and pressure. Pressures at the feed zones in some the wells of in Nesjavellir field are shown in Figure 6.

or 8.5 MWe per well.

Well	Depth	Total flow	Enthalpy	Steam	Steam	Thermal
no.	(m)	(kg/s)	(kJ/kg)	at 7 bar-g	at 7 bar-g	power
				(kg/s)	(MWe)	(MWt)
NG-5	1804	10	1800	5	2.5	18
NG-6	1144	22	2480	19	9.5	55
NG-7	2001	36	1320	11	5.5	48
NG-9	1055	28	2200	20	10	62
NG-10	1798	52	1350	16	8	70
NJ-11	2265	37	2520	33	16,5	93
NJ-12	1856	57	1320	17	8,5	75
NJ-13	1609	36	2500	31	15,5	90
NJ-14	1304	28	1330	9	4,5	37
NJ-15	1746	47	1450	17	8,5	68
NJ-16	2025	27	2300	21	10,5	62
NJ-17	2100	45	950	6	3	43
NJ-18	2136	35	950	4	2	33
NJ-19	1700	36	2300	29	14,5	82
NJ-20	1800	32	1430	12	6	46
Total	26343	528		250	125	882
Average	1756	35		17	8.5	59

TABLE 1:Some characteristics of geothermal wells in Nesjavellir field
(Gunnarsson et al., 1992; Gíslason, G., pers. comm.)

FIGURE 6: Pressure conditions at feed zones in some wells in Nesjavellir field (Steingrímsson et al., 1990)

Several aquifers of different pressure potential have been identified. The interior of the reservoir is a two-phase boiling system, surrounded by a liquiddominated system. The two-phase system is mainly found in the southern parts of the reservoir (Gunnarsson et al., 1992).

At present, the Nesjavellir field provides 60 MW electric power and 200 MW thermal energy. Electric power is generated at Nesjavellir geothermal power plant. A portion of the separated hot water in the power plant is used for heating fresh groundwater in heat exchangers to supply hot water for the Reykjavík heating system. This hot water (83°C) is piped through a 27 km pipeline to Reykjavík.

2. BOREHOLE GEOLOGY OF WELL NJ-20

2.1 Introduction

Well NJ-20 is, as the number implies, the 20th well in the Nesjavellir field. It is located in the northeast slopes of Mt. Hengill 46 m to west of well NJ-14 and was directionally drilled. The coordinates (Lambert-system) for the well are: X = 659582,38, Y = 402735,94 and Z = 365 m. The goal was to increase high enthalpy fluid for electricity generation at the Nesjavellir power plant (Gudmundsson et al., 1999a; 1999b; 1999c)

In accordance with the topography and in order to minimize environmental impact, it was decided to locate well NJ-20 close to NJ-14, combining some of the surface manifestations.

The drilling project was divided up into four stages and performed by The Icelandic Drilling Company. Initially the well was predrilled down to 78 m in December 1998 by using a 22" bit and cased with 18%" surface casing. In March 1999 a bigger rig was installed over the well to continue and finish it. It started drilling for a 13%" anchor casing down to 300 m depth by using a $17\frac{1}{2}$ " bit. The third stage was drilled to 773 m depth and cased with 9%" production casing. The casings in the first three stages were cemented by using special quality cement for high temperatures. The last stage was drilling the production part down to 1800 m depth which was cased off by using a slotted liner. A mud motor was used from 78 m depth until the well was completed.

The penetration rate, as well as the weight on the bit and the pumping pressure, were monitored continuously by a geolograph. Special attention was paid to the circulation fluid throughout the drilling time by measuring regularly the temperature in the standpipe and in the flowline, the flow rate and the pressure on pumps. The kick-off point was at 334 m depth where the deviation from vertical started with the building rate at average $2^{\circ}/30$ m until 30° was exceeded. The direction was 220° +/-15°. During drilling the inclination and direction were measured regularly by using MWD-tools (measure while

drilling) placed in the collar close above the bit. It is based on magnetism. The main disadvantage of using this method in a volcanic environment is due to the disturbances that can be caused by the iron-rich minerals in the rock. Therefore, drilling was stopped once in a while to run a gyro device to verify MWD-readings. The 30° inclination was exceeded at 850 m depth. From 1200 m depth, drilling was blind, i.e. with total circulation loss. When the circulation loss appeared to be total, it was decided to pull out the string and remove the MWD-equipment and continue drilling with a locked string (one extra stabilizer was added). A specialist from the international company Halliburton supervised the directional drilling all the time.

Both inclination and direction versus depth are shown in Figure 7. The final drilled depth was 1800 m, the real depth 1640 m and the displacement from vertical was 655 m close to the direction of 210° from the wellhead.

In Figure 8 some information about the drilling of well NJ-20 is shown. Rock cuttings were taken regularly at 2 m interval in the well during drilling, and collected in 125 cc plastic boxes and

FIGURE 7: Inclination and direction of drilling of well NJ-20 vs. depth

Legend:

🔆 Large

FIGURE 8: Lithology and some drilling monitoring data of the well NJ-20, the main explanations apply to all figures showing lithology and alteration

labelled properly. The sampling method of collecting drill cuttings every 2 m in the well was based on the fact that lithology, alteration and fault/fracture intensity in geothermal systems can be very complex and can change abruptly over small distances. Therefore, it has a great value to achieve the best possible representative samples of the intervals.

After drilling completion, all data at the drillsite was moved to the database at Orkustofnun. The database of cuttings is divided into three main categories:

- 1. Original samples dried and archived;
- 2. Washed samples, archived in 30 ml boxes;
- 3. Cuttings are mounted on chipboard in an appropriate scale to allow observation of subtle downhole changes that might otherwise escape detection.

Every sample was analyzed to determine the rock type and to identify the secondary minerals. For further study, 23 thin sections were prepared for investigation using a petrographic microscope and 33 samples to be run through X-ray diffraction (XRD).

By studying of all cuttings, thin sections and geophysical logs and using binocular and petrographic microscopes and X-ray diffractometry methods, stratigraphy, alteration mineralogy, permeable zones, alteration zonation and aquifers were determined. In fact by studying all available evidence, it is possible to define the geological characteristics of the well and also find how these properties can affect the hydrothermal fluid flow through the aquifers in the well.

2.2 Stratigraphy

Iceland has been constructed by volcanic rocks mainly basalts. These basalts are divided into two major groups, the first one is olivine tholeitic with ophitic texture, and is generally associated with lava shields and individual lavas called pahoehoe lavas; the second type is tholeitic basalt, which is fine-grained and has sub-ophitic texture. These types of basalts are produced fissure eruptions, producing rough lavas, often called aa lavas.

Another volcanic unit is hyaloclastite, which forms under water in different environments. Its most common appearance is under glaciers where magma penetrates the roots of the glacier and melts part of it with enormous heat generation. It can result in an eruption through a very well defined lake in the glacier. A good example is the 1996 eruption in Vatnajökull. Similar processes happen under seawater, as was seen in the Surtsey eruption in 1963-1967 which formed a new island south of the coast of Iceland. Generally the volcanic products in hyaloclastite formation include

- Tuff, which is made up of volcanic glass;
- Breccia that consists of glass and partially crystallized basalt;
- Basaltic breccia, which mainly consists of partially crystallized basalt with a less volume of glass;
- Pillow lavas, which generally form in the roots of hyaloclastites depending on the composition of the magma and hydrostatic pressure.

Subglacial fissure eruptions form ridge-shaped hyaloclastite mountains (Saemundsson, 1979). In most cases, intrusive rocks are also seen, but they are coarser-grained than the lavas of the same composition, due to slower cooling.

Younger intrusive basalts are fresher than extrusive basalts because of their age, lower porosity and permeability. Simplified lithology and monitoring information about some parameters (such as circulation loss, etc.) of well NJ-20 are shown in Figure 8. The stratigraphic and alteration explanations in Figure 8 apply also to Figures 9, 10, and 14. It should be mentioned that from the top to 78 m depth, no cuttings were available. Geophysical logs were used including caliper, neutron-neutron, natural gamma, temperature, pressure and resistivity logs to determine lithological characteristics of the well.

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2.2.1 Extrusive rocks

Extrusive rocks of the well consist mostly of hyaloclastites and basaltic lavas. In shallower parts of the well hyaloclastites are predominant and in deeper parts basaltic lavas are more abundant. The extrusive rocks of the whole well are divided into 8 main units. The units are listed below.

Hyaloclastite unit I (78-108 m) consists of

78-92 m - tuff; 92-108 m - glass. The rocks are vesicular and contain alot of glass particles. Thin clay layers, calcite and Fe-oxides mostly fill all vesicles. There are many plagioclase phenocrysts in the tuffs. In deeper parts of the unit, vesicles are filled by zeolites. In the glassy sub-unit there are some pillow lava grains, which are differentially crystallized.

Basaltic lavas I (108-160 m) consists of	
108-124 m - basalt (fine- to medium-grained);	124-125 m - tuff;
125-128 m - basalt;	128-130 m - tuff;
130-136 m - basalt;	136-145 m - glassy basalt;
145-150 m - basalt (fine- to medium-grained);	150-160 m - glassy basalt.
The basalts are fine-grained, vesicular with sub-oph	itic texture. Clay layers (smectite

The basalts are fine-grained, vesicular with sub-ophitic texture. Clay layers (smectite) and calcite fill the vesicles. There are some pyroxene, olivine and plagioclase phenocrysts in the basalts. Alteration could be seen in both vesicles and groundmass.

Hyaloclastite II (160-256 m) consists of

160-169 m - tuff;	169-170 m - basalt (fine- to medium-grained);
170-192 m - tuff;	192-230 m - breccia;
230-240 m - glassy basalt;	240-256 m - breccia.
Glass grains are highly vesicular and breecia	ted Vesicles are mostly filled by zeolites such a

Glass grains are highly vesicular and brecciated. Vesicles are mostly filled by zeolites such as scolecite and mesolite, clay and calcite. There are some very small plagioclase phenocrysts in glass grains. Thus, tuff units may be defined as porphyritic. In deeper parts basalt grains are fine-grained, vesicular with subophitic texture. They have been altered both in groundmass and vesicles. Vesicles are filled by clay, calcite, stilbite, scolecite and mesolite. In lower parts of the unit, glass grains are very altered.

Hyaloclastite III (256-488 m) consists of

256-272 m - basalt;		272-313 m - tuff;
313-320 m - breccia;		320-325 m - tuff;
325-333 m - glassy basalt;		333-488 m - tuff.

In upper parts of the unit, tuffs are vesicular and highly altered with plagioclase and olivine phenocrysts which they have altered to clay minerals. In deeper parts, tuff grains are also vesicular with plagioclase phenocrysts (labradorite). Glass grains are vesicular and partly to totally altered. Plagioclase crystals are fluid inclusion bearing. Basalts are very fine grained and porphyritic. In the middle part of the unit most of the vesicles are filled by stilbite, calcite and clay. Tuffs are also porphyritic and altered. Tuffs are very vesicular with large vesicles, which are filled by calcite and quartz or chalcedony. Also, they are porphyritic with a lot of plagioclase phenocrysts. In deeper parts they change to breccia and still they are vesicular and altered. Vesicles are filled with chalcedony and calcite. Basalt grains in the glassy basalt sub-unit are very fine-grained, non-vesicular with sub-ophitic texture, and moderately altered. In the last tuff sub-unit, plagioclase phenocrysts have partly changed to albite. In the last tuff unit, there are some basaltic intrusive bodies, which have intersected tuff layers.

Hyaloclastite IV (488-596 m) consists of

488-497 m - glassy basalt;	497-510 m - tuff;
510-523 m - glassy basalt;	523-540 m - breccia;
540-547 m - tuff;	547-553 m - breccia;
553-567 m - tuff;	567-570 m - basalt;
570-596 m - tuff.	

Glass grains are vesicular, highly altered, containing plagioclase phenocrysts. Generally they show different crystallization grade. Basalt grains could be found from poorly crystallized (very-fine-grained)

to well crystallized (medium-grained) with sub-ophitic texture and pyroxene phenocrysts. Glass vesicles are filled by quartz and wairakite. Tuffs are also plagioclase bearing, vesicular and highly altered. In some parts of the last tuff sub-unit, they change to breccia. Their vesicles have been filled by quartz and calcite.

Basaltic lavas II (596-734 m) consists of

596-649 m - glassy basalt;	649-658 m - tuff;
658-665 m - basalt;	665-669 m - glassy basalt;
669-677 m - tuff;	677-691 m - glassy basalt;
691-697 m - tuff;	697-724 m - glassy basalt;
724-734 m - breccia.	

Tuffs have a lot of plagioclase phenocrysts, some of them very large, and have been altered partly or completely to albite and clay minerals. In the middle part of the unit, basalts are altered and relatively large-grained with obvious pyroxene crystals, which are fresh and unaltered. Alteration in basalts could be seen in both groundmass and vesicles. In deeper parts, some basalt grains are very-fine-grained with very small pyroxene and Fe-oxide minerals. They have sub-ophitic texture and clay minerals (mixed layers clay) have been distributed inside them.

Basaltic lavas III (734-915 m)

This unit consists of 22 fine-medium grained basalt lavas with an average thickness of 7 m. Also 10 intrusions are seen. In shallower parts of the unit basalt grains are divided into two groups according to the grain size, fine- to medium-grained, which show different crystallization grade. All of them have sub-ophitic texture and are slightly altered. In the middle parts, fine-grained and vesicular basalts predominate. Vesicles are filled by mixed layer clays, calcite and quartz. Basalt grains have a lot of plagioclase phenocrysts, some of them very large. These phenocrysts have been altered to albite. In deeper parts, basalts still are fine-grained with sub-ophitic texture. They show different alteration grade from low to medium.

Basaltic lavas IV (915-1092 m)

This unit consists of 15 basalt lavas with an average thickness of 9.5 m; some of them are medium- to coarse-grained. In the upper parts of the unit basalt grains are fine- to medium-grained in size, slightly vesicular. Vesicles are filled by prehnite and chlorite. Chlorite could be found in groundmass also. Some fine-grained basalt is very highly altered. In these grains chlorite has covered all the grain groundmass. This condition continues to the middle parts of the unit. Here, medium-grained basalts are more abundant and their vesicles are filled by wairakite. In this unit there are some dark grains and it seems that they have been crystallized before. Probably they are related to surface contact between intrusive and parent rocks.

Basaltic lavas V (1092-1196 m)

It is difficult to distinguish between individual lavas below 1092 m depth, because of mixing due to high circulation loss. Basalt grains are non-vesicular and fine- to medium-grained, but fine-grained ones are more abundant. They have sub-ophitic textures, and the pyroxene crystals are fresh and unaltered. There are lots of Fe-oxide minerals inside the basalt grains. Plagioclase phenocrysts have been altered to albite and epidote. Basalts have been altered to green coloured clay (chlorite), which is visible in their groundmass. In deeper parts of the unit medium-grained basalts are more abundant and more altered than in the upper parts. But the fine-grained ones are highly altered. The small grains do not show vesicular condition but there might be some large fractures or vesicles due to some large crystals of epidote/wairakite.

2.2.2 Intrusive rocks

Intrusive rocks are distributed at different depths in the well. All of them are of basaltic composition, and are unaltered and very fresh. These characteristics define them easily. Below 1196 m depth, it is assumed that there are some acidic intrusive bodies, because of observation of some high peaks in gamma-ray logs

(Stefánsson et al., 2000). Lithological and geophysical logs of well NJ-20 are shown in Figure 9. This subject is described in the discussion part of this report. Intrusive rocks of well NJ-20 are shown in Table 2.

Depth	Thickness Composition		Extrusive unit	
(m)	(m)			
353	5	Basaltic	Hyaloclastite III	
366	6	"	"	
394	2	"	"	
400	5	"	"	
408	5	"	"	
433	1	"	"	
472	1	"	"	
503	3	٠٠	Hyaloclastite IV	
718	1	"	Basaltic lavas II	
781	6	"	Basaltic lavas III	
788	1	"	"	
790	1	"	"	
825	1	"	"	
830	1	٠٠	دد	
867	1	٠٠	"	
890	3	٠٠	"	
905	1	٠٠	"	
926	1	٠٠	Basaltic lavas IV	
1005	7	٠٠	"	
1013	9	"	"	
1029	1	"	"	
1045	1	"	"	
1062	1	"	"	
1080	1	دد	"	

TABLE 2: Distribution of intrusive rocks in well NJ-20

2.2.3 Comparison with geophysical logs

The main objective of geophysical logging is to obtain more information about the subsurface than can be obtained from conventional drilling, sampling, and testing. Although drilling a well is an expensive procedure, it provides access to the subsurface for geophysical probes from which many different kinds of data can be acquired for a cost usually much less than coring and making laboratory analyses of water and rock samples. Logs may be interpreted in terms of lithology, thickness, and continuity of aquifers and confining beds, permeability, porosity, temperature, pressure, resistivity and the integrity of the well construction (Keys, 1997).

During and after the drilling of well NJ-20, 4 types of geophysical logs, i.e. caliper, gamma ray, neutronneutron and resistivity, were used. All geophysical logs of well NJ-20 are shown in Figure 9. Due to greater diameter of the well in its upper part, it is difficult to correlate the lithological logs and the lithology, but in deeper parts where the well diameter is less, proper correlation can be done. The main advantages of the geophysical logs provided in well NJ-20 are described below:

Caliper log provides a continuous record of borehole diameter. Caliper logs are essential to guide the interpretation of other logs, because most types of logs are affected by changes in well diameter. They are also useful in providing information on well construction and lithology. In well NJ-20 at the 394, 506

FIGURE 9: Simplified lithological and geophysical logs of well NJ-20 (explanations, see Figure 8)

and 934 m depths, there are some changes in well diameter due to different consolidation of rocks. For example at 394 m depth, there is a fresh basaltic intrusive body that decreased well diameter, due to its density.

Neutron-neutron log is very useful for determining the porosity of rocks. This method measures the hydrogen (H) content in the rock and gives indirect information on the water content that may be interpreted as porosity. Higher values show dense rock with low water content. In this well at 716, 954, 1244, 1344, 1636 and 1666 m depths, there are some high values in the N-N log that represent denser rock

in relevant depths. According to the lithological logs, the first and second anomalies are related to intrusive bodies.

Natural gamma ray indirectly provides information on the chemical composition of volcanic rocks. The most common use of this log is for identification of lithological units and for stratigraphic correlation. In Iceland it is used for finding evolved to acidic rocks. In upper parts of well NJ-20 there was no natural gamma log from the surface to 280 m depth. But at 1036 and 1216 m depths, there are some anomalies in natural gamma values. Also below 1260 m depth, there are many anomalies in natural gamma ray values.

Resistivity log is one of the electrical log and useful for determining temperature of fluid, rock porosity and salinity. Higher values of resistivity show less porosity and vice versa. Due to the large diameter of the well, there was no resistivity log in the shallower part of the borehole. There were some definite negative resistivity anomalies at 946, 1250, 1480 and 1610 m depth.

3. HYDROTHERMAL ALTERATION

The hydrothermal alteration is a product of water-rock interaction. The factors, which can affect the formation of hydrothermal minerals, are temperature, pressure, parent rock type, reservoir permeability, fluid composition and duration of activity (Browne, 1978). These factors vary from field to field, and some of them are so intimately related that it is often impossible to separate one from another.

The hydrothermal mineral assemblages can be useful as geothermometers, in determining depth design of production casing, in estimating fluid pH and other chemical parameters, in predicting scaling and corrosion tendencies of fluids, in measuring permeability and possible cold-water influx, and as a guide to hydrology (Reyes, 1990).

3.1 Analytical methods

For studying hydrothermal alteration in well NJ-20, three main methods were used, namely:

- 1. The binocular microscope;
- 2. The petrographic microscope;
- 3. The X-ray diffractometer.

The binocular microscope is an important analytical instrument especially in cutting analysis during drilling. A number of hydrothermal minerals have been found to indicate particular formation temperatures in Iceland. The present work included studying the cuttings in great detail with this method.

The petrographic microscope is a useful instrument in the study of drill cuttings in thin section. Microscopic study of drill cuttings is a part of the geological and mineralogical research which aims towards a more throrough geological understanding of geothermal reservoirs. The essential use of this microscope relates to the small size of the primary and secondary minerals in the cuttings. The petrographic microscope may be used to:

- 1. Determine the rock type in more detail;
- 2. Identify minerals with optical methods;
- 3. Study the type of replacement mineralogy;
- 4. Study the sequence of secondary mineral evolution especially in veins and vesicles:
- 5. Study textural features like the displacement of early secondary minerals by later minerals.

Polarized thin-sections were not used for this study, but reflected light was used to distinguish between iron oxides and iron sulfides. In the present study 23 thin sections from borehole NJ-20 were studied.

The X-ray diffractometer is mostly used for identifying clay minerals and for crosschecking observations made under both the polarized and binocular microscope, especially where zeolites and other minerals could not be identified individually. In this study, 23 samples of zeolites and other alteration minerals were selected and run. The method is very useful for the study of clay minerals because only a fair picture of the different clay minerals can be obtained from both the binocular and polarizing microscopes, especially on the basis of colour and relative grain size. A more reliable identification and classification of them is possible with the help of the X-ray diffractometer. In this study, 33 runs of clay minerals were completed and identified. The standard methods of sample preparation, both for zeolites and clay minerals treated under the XRD are discussed in Appendix I.

The result of XRD analysis is most important for interpretation of rock formation temperature when referring to mineral alteration. It also provides fundamental data for the construction of alteration zones.

3.2 Rock alteration

The most common volcanic rock in Iceland is basalt. The primary mineral composition of basaltic rocks in Iceland is relatively uniform, comprising calcium plagioclase, clinopyroxene, olivine and magnetiteilmenit ore. If the basaltic magma cools rapidly, quenched volcanic glass results. Hyaloclastite tuff may be composed of volcanic glass only, while the breccias and the lavas range in glass content from alot, to little or no glass. Under the influence of hydrothermal fluids, primary minerals alter to similar and/or different alteration minerals as follows:

- 1. Glass alters mostly to clays, sphene (titanite), epidote, calcite, zeolite and quartz;
- 2. Olivine alters to iddingsite or clays, sphene, calcite or sulphides;
- 3. Pyroxene is relatively resistant to hydrothermal alteration but mainly alters to clays;
- 4. Plagioclase is also relatively resistant to alteration but it starts to alter to clay minerals and in accordance with increasing temperature it alters to albite, calcite, sphene, chlorite, epidote and adularia. Wairakite is a common replacement mineral of plagioclase phenocrysts;
- 5. Iron ore minerals alter to sphene and sulfides, usually pyrite and pyrrohtite.

In general, the order of decreasing susceptibility to alteration is glass, olivine, plagioclase and pyroxene. Due to more extensive alteration in deeper parts of well, deeper cuttings are light coloured while shallower cuttings are darker and the quantity is in direct proportion of the water/rock ratio.

In borehole NJ-20, plagioclase phenocrysts, which mostly are labradorite or andesine, have been altered to clay at shallower depths (118 m), but in deeper parts of the well they have been altered to calcite (480 m). At 480 m depth they also were changed slightly to albite. But at 698 m depth to the bottom of the well, this change is very obvious and common. At 942 m depth, the first appearance of epidote inside the plagioclase phenocrysts was seen.

Olivine was altered to clay minerals at shallow depths. For example, at 170 m depth they were changed to clay minerals (probably iddingsite). This trend was stable continuously to the bottom of the well. They were very small grained and mostly altered to clay minerals. Pyroxenes are very stable and alteration resistant. At 942 m depth they were altered slightly to clay minerals. Glass grains are very sensitive to alteration and even at shallow depths (118 and 170 m) they were altered to clay minerals. This trend continued to the bottom of the well and in the deeper parts they were totally altered to clay minerals. In the case where the glass was vesicular, it was more sensitive to alteration according to increasing water/rock interaction. Opaque minerals were altered to sphene and some Fe-oxide minerals.

3.3 Distribution of hydrothermal alteration minerals

The distribution of hydrothermal minerals along with the simplified stratigraphy of borehole NJ-20 is shown in Figure 10. They were mostly distinguished by drill cutting analysis, and petrographic thinsection study. Some of these minerals are very abundant in the borehole such as pyrite, quartz, calcite, clays and zeolite. A brief description of each mineral is outlined below.

Calcite is the most common mineral in geothermal systems. In this well, it was found from top to bottom. Calcite disappears

when temperature is higher than 280-300°C and its absence is a useful evidence for finding the boiling In cuttings it zones. can be distinguished by HCl acid and in thinsections by good cleavage, relief varies with direction but high relief is most common and strong interference colours can distinguish it. In most cases they were found in vesicles but in some cases, for example at 360 m depth, plagioclase phenocrysts had been replaced by calcite. Generally, calcite has a very wide temperature range (100-300°C).

Chalcedony is semicrystallized silica and is very abundant in 336-342 m depth. It does not show any crystal surface. Generally, it could be found from 360 m to 514 m depth. In deeper parts of the well, quartz was seen, which is more stable at higher temperatures. Chal-cedony could be formed in vesicles with before quartz or crystals.

FIGURE 10: Distribution of hydrothermal alteration minerals in well NJ-20 (explanations, see Figure 8)

Quartz grains were identified in thin-sections from 360 m to the bottom of the well. They have different features. In some cases, they are very fine-grained while in some vesicles they have euhedral crystals. At many depths, some former structures are transparent, when quartz replaced other minerals; it was also identified by the XRD method. Quartz appears at temperatures above 180°C.

Prehnite is present above 250°C in Nesjavellir field (Browne, 1978). It is found at about 550, 680 and 900-1000 m depths. It is found in vesicles with epidote crystals. In thin-sections it can easily be distinguished by its bow-tie texture, high relief and strong interference colours. It was defined at 1016 m depth by the XRD method.

Zeolites are white or colourless hydrous sodium calcium aluminum silicates, which are analogous in composition to feldspars with sodium, calcium and potassium. This group consists of minerals such as stilbite, huelandite, mesolite, scolecite, mordenite, laumontite, analcime and wairakite. Except for laumontite and wairakite, most of them indicate temperatures of less than 120°C. In well NJ-20 they were found from about 90 to 400 m depth. But wairakite is determined from 400 to 1172 m depth.

Stilbite in cuttings is transparent and was found with huelandite in pores as a filling. It was determined from about 130 to 360 m depth. Stilbite indicates temperatures of 80-120°C.

Huelandite is seen with stilbite in vesicles. Its crystal form resembles stilbite but has a better cleavage. Most often it is found in very small crystal grains. Its temperature range is similar to the stilbite range.

Mordenite shows an irregular very tiny fibrous form under the petrographic microscope. It is found at 674 and 920 m depths by petrographic microscope. The presence of mordenite at these depths is unusual. Probably in those parts of the well, permeability is lower than in adjacent areas. Thus, due to lower waterrock interaction this mineral could be found in the hotter parts of the well. The temperature range of mordenite is 80-150°C.

Scolecite can easily be distinguished by its radial crystal form, in both cuttings and thin sections. It is found from shallower parts of the well up to about 360 m depth. Its temperature range is 60-90°C. This mineral was determined in vesicles. At higher temperatures it converts to quartz and calcite.

Mesolite is found with scolecite. Its location and temperature range is very similar to scolecite and was not found lower than at 360 m depth. It was found in higher temperature minerals such as calcite and quartz as psuedomorphism.

Laumontite is the most heat resistant mineral in the zeolite group if wairakite is excluded (Gudmundsson, pers. com.). It will disappear at temperatures up to 180°C. In borehole NJ-20 it was found at 410 m in thin sections and also at 802 and 804 m depth by XRD method. In cuttings it can be distinguished by its special crystal structure, which has white coloured and parallel needles.

Analcime can be distinguished by its isotropic character in thin-sections and was determined at 674 and 872 m depths. This mineral has a very low temperature range ($< 100^{\circ}$ C). The unusual existence of analcime at these depths may be explained by lower permeability in some defined parts of the well.

Wairakite, the calcium analogue of analcime, is sometimes classified as a zeolite (200-330°C). It could be identified in cuttings by its cloudy appearance due to the high abundance of fluid inclusions. In thinsections, a dull colour and the characteristic cross-thatched twinning identify it. It is also found by the XRD method at 600, 710, 782 and 1016 m depth. This mineral extends from 480 m to the bottom of the well.

Epidote is an index mineral in high-temperature geothermal systems and shows at temperature conditions higher than 250°C. It can easily be identified in cuttings by its yellowish colour. In thin-sections it shows high relief and high interference colours. This mineral is seen with prehnite, wollastonite and quartz in

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vesicles. In this borehole, the first epidote minerals were found at 802 m depth, although more commonly at lower than 920 m depth.

Wollastonite is a calcium silicate which is identified in cuttings by its fibrous structure or very tiny white needles. It is also found in thin-sections at 802, 920, 1006 m depth. Its temperature range is >270°C. In well NJ-20 it is distinguished at 1016 m depth by the XRD method. It is mostly found with quartz and epidote in vesicles.

Garnet is found in thin-sections at 1006 and 1172 m depths. This mineral was not very common in well NJ-20. It is found as a very small and isotropic crystal inside vesicles with quartz and epidote. Garnet is usually seen as contact alteration mineral and indicates high-temperature conditions.

Anhydrite is an anhydrous calcium sulfate, which is found in cuttings (804 m) and thin sections (410 and 430 m depth). In cuttings it is white coloured and in thin-sections represents high interference colours. It is also found by the XRD method at 608 m depth.

Pyrite is a very common iron sulfide present from top to bottom of the well. In most cases it was seen with quartz and calcite. It is believed that hydrogen sulfide reacts with iron in the rock and forms iron sulfide. Pyrite forms above 100°C and is abundant in permeable zones. Therefore, it is a good indicator for aquifers (Gudmundsson, pers. com.). For example, pyrite crystals are very abundant at 506 m depth, where there is contact between intrusive and parent rocks in the well.

Iron oxides are common in geothermal systems, formed from 698 to 1006 m depth. Their existence may be explained as a consequence of invasion of oxygen-rich water (colder water) in the geothermal system.

Albite is the alteration product of Ca-rich plagioclase in basaltic rocks. At lower temperatures and in the upper parts of the well, plagioclase crystals can be replaced by clay minerals but at higher temperatures (>200°C) albitization is commonly seen. In thin-sections, albite can be distinguished within the plagioclase crystals by their lower refractometry index and extinction angle. The first appearance of albite was at 480 m depth and extends to the bottom the well.

Clay minerals are the most common alteration minerals in geothermal systems. Clay minerals are formed by the alteration of glass, olivine, plagioclase and rarely pyroxenes. They were studied by the X-ray diffractometery method. In borehole NJ-20, 33 clay samples were examined. Their results are shown in Table 1 in the Appendix I. Smectite is the most common clay in the upper part, then with depth and temperature it changes to mixed layer clays, corrensite and finally to chlorite. The colour also changes from yellowish brown (shallower parts) to green (deeper parts). In the upper sections of the well, clay crystals are very fine-grained while in lower parts they are relatively coarse-grained in thin-sections. Most often they were formed in vesicles and yeins as a thin internal layer, but in deeper parts of the well, they were also found in both vesicles and groundmass due to extensive alteration.

Smectite is the first clay which formed in well NJ-20. It extends from the top to 360 m depth. In thinsections it can be distinguished by its brownish colour. In X-ray diffractometry analysis it shows peaks at about 14 Å for untreated samples and 16 and 9.9 Å for glycolated and heated samples, respectively.

Mixed layer clay extends from 360 to 790 m depth. In thin-sections the colour is light green and shows coarser grains in comparison to smectite crystals. The layer is composed of interlayered smectite-chlorite. In XRD method results, peaks show at 30 and 14 Å for untreated, 30 and 15-17 Å for glycolated and 12 Å for heated samples.

Corrensite or swelling chlorite is another variety of smectite and chlorite mixing. This mineral could be defined by the XRD method only in one clay sample at 730 m depth. In this sample smectite and chlorite could also be defined. Corrensite could be distinguished from chlorite due to its expansion in glycolated treatment.

Chlorite is the highest temperature graded clay mineral found in borehole NJ-20, from 820 m to the bottom. In thin-sections it is coarse-grained and light green coloured in plane polarized light and gray-light green in polarized light. Its texture is like tiny green needles.

3.4 Alteration zones

The hydrothermal minerals are results of water-rock interactions. There are some factors which affect the hydrothermal alteration process, such as temperature, permeability, fluid composition, initial composition of rocks, duration of superimposed hydrothermal regimes and hydrology (Reyes, 1998).

The minerals commonly used as geothermometers are the clays, zeolites, epidote and amphiboles (Browne, 1984). According to Kristmannsdóttir (1979) in Icelandic hydrothermal areas, smectites, zeolites, calcium silicates, calcite, pyrite and quartz are formed at rock temperatures below 200°C. Smectites transform into mixed-layer clay minerals and swelling chlorites at 230-240°C. Chlorites become the dominant sheet-silicates when the rock temperature exceeds 240°C. Epidote and prehnite are formed at slightly higher temperatures. Actinolite appears at near 300°C. The clay minerals are quantitatively the most significant alteration minerals. They respond quickly to temperature changes in the geothermal system. An examination of the clay minerals is very useful for interpretation of the thermal history of a geothermal field (Kristmannsdóttir, 1979).

A correlation of alteration zones with rock temperature in active high-temperature areas in Iceland is shown in Figure 11. By using the X-ray diffractometry method for analyzing 33 clay samples, 4 alteration zones were defined. The results for the NJ-20 borehole clay samples are shown in Table 1 in Appendix I. The following is a description of the alteration zonation with temperature approximations.

Smectite-zeolite zone. This zone extends from the top of the well to about 360 m depth. It consists mostly of smectite group minerals. At 200 m depth, there were some weak peaks of some impurities such as zeolites. This zone indicates temperature conditions lower than 200°C.

Successive alteration zones in active geothermal areas	Index minerals	Regional metamorphic facies	Mineralogical changes	Approximate rock temperature °C
a Zone I b	Smectite — Zeolites	Z eolite Facies	 Smectite and low temperature zeolites form Low temperature zeolites disappear Laumontite forms' Smectite becomes interlayered Wairakite forms-laumontite disappear 	- 100 - 150
Zone II	Mixed— layer clay minerals		→ Smectite → mixed -layer clay minerals Mixed - layers → Chlorite	– żoo
Zone 🎹	Chlorite epidote	Greenschist	Epidote - continous occurrence Actinolite forms	- 250
Zone IV	Chlorite actinolite	Facies	Plagioclase commonly albitized	- 300

FIGURE 11: Comparison of calculated rock temperature to the alteration minerals temperature (Kristmannsdóttir, 1979)

Mixed layer clay zone. This zone extends from 360 to 820 m depth. It is made up of smectite and mixed layer clays. The latter includes smectite and chlorite. There was some indication of zeolites at 430 m depth. Also at 600 m depth, some weak evidence of mixed layer clays was shown. This zone shows a temperature range from 200 to 220-230°C.

Chlorite-epidote zone. This zone is made up of chlorite and epidote. It extends from 820 to 940 m and 1010 to 1118 m depths. In this zone chlorite shows 14.5 Å peaks for untreated, glycolated and heated samples, but for the 7.1 Å peak, there is no visible change in peaks for the heated sample. Thus, this type of chlorite is called unstable chlorite. Epidote was determined in thin sections and couldn't be detected by XRD analyzing method. The temperature range of this zone is 230- 280°C.

Epidote-actinolite zone. This zone extends from 942 to 1010 m depth. This zone was distinguished according to well-defined peaks in untreated, glycolated and heated clay samples at about 8.5 Å. This peak is well known as evidence of actinolite. The temperature range that forms the actinolite zone is $>280^{\circ}$ C.

3.5 Deposition sequences

By studying hydrothermal alteration minerals in drilling cuttings and especially thin sections, the thermal evolution in well NJ-20 was discovered. Most alteration minerals were found in vesicles and veins. It may be difficult to evaluate the final alteration product in vesicles and veins based on cutting analyses. But by comparison with available data from neighbouring wells, the alteration sequences were defined. Table 2 shows the thermal evolution of borehole NJ-20.

D 41			
Depth	Alteration minerals sequences (earlier to later)		
118	Smectite-calcite		
170	Smectite-scolecite-calcite		
230	Smectite-scolecite-calcite		
280	Smectite-stilbite-calcite		
330	Smectite-huelandite-calcite		
360	Smectite-chalcedony-calcite		
410	Scolecite-chalcedony		
438	Scolecite-chalcedony-quartz		
480	Scolecite-calcite-chalcedony-quartz		
514	Calcite-quartz		
574	Calcite-quartz		
650	Stilbite-quartz		
674	Calcite-wairakite-prehnite		
698	Calcite-quartz-prehnite		
764	Calcite-quartz-prehnite		
802	Calcite-quartz-prehnite		
827	Calcite-wairakite-quartz		
920	Wairakite-quartz-prehnite-wollastonite-epidote		
942	Calcite-quartz-prehnite-epidote		
1006	Wairakite-quartz-prehnite-epidote		
1080	Wairakite-quartz-epidote		
1150	Wairakite-quartz-prehnite-epidote		
1172	Calcite-wairakite-quartz-prehnite-epidote		

TABLE 2:	Alteration	minerals	sequences	in	borehole NJ-20	
	1 III allout	minuterals	bequeilees		0010101010 20	

Table 2 shows that at shallower depths, the main alteration mineral component is smectite, which extends to 400 m depth. In the smectite-zeolite zone, there are some other minerals such as scolecite, huelandite, and stilbite that show temperatures lower than 120°C.

In deeper parts, zeolites become unstable and calcite and quartz replace them. In this zone clay minerals convert to mixed layer clays. By increasing depth, alteration mineral assemblages change to higher temperature ones such as calcite, quartz, wairakite and prehnite. The sequences show a consistant trend as the well gets deeper and temperature increases. The minerals representing highest temperatures at each interval, are the final product. No overprinting due to reservoir cooling, was seen. At 1170 m depth, calcite could be defined in thin-section. As calcite disappears at temperatures higher than 300°C, then the temperature at this depth must be lower than 300°C.

Finally, it is obvious that with increasing depth, temperature increases too.

4. AQUIFERS

Aquifers are confined zones of permeable rocks or fracture zones, which can hold ground water, oil, gas, hot water or steam. In geothermal regions, they can be related to a single geological structure such as an intrusion, fault or stratigraphic boundary. Aquifers in the borehole were assessed based on circulation loss or gain, temperature logs during drilling, and alteration extensivity. Pressure drop on the drill rig pumps was the most effective way to locate aquifers after total circulation loss at 1200 m depth. There are some very week changes in the temperature logs at the 116, 180 and 260-270 m depth in borehole NJ-20. But in deeper parts of the well, many aquifers were found with more obvious evidence.

According to all data, 15 aquifers are found in borehole NJ-20. They are divided into two main groups. The first 5 aquifers in the shallower parts of the well are behind casings. The second are the aquifers, located in the production part of the well. Aquifers in well NJ-20 are shown in Figure 8.

4.1 Aquifers at shallow depths

These aquifers extended from the top to about 768 m depth. All of them are related to lithological borders. A brief description of each aquifer is given below:

Aquifer 1 is located at 360 m depth and is found according to changes in the temperature log as a weak inflow indicating an overpressure. This aquifer is very close to a border of fine-grained basalt intrusion.

Aquifer 2 is situated at 445 m depth and was found by changes in the temperature log with evidence of a weak inflow showing overpressure. In geophysical logs, there are two clear changes in neutron-neutron and resistivity logs. The neutron-neutron log shows increasing values and a dense basaltic intrusive body while the resistivity logs show decreasing values, which indicates aquifer conditions. At this depth there are many Fe-oxide minerals and the aquifer is close to the border of a basaltic intrusion and a tuff layer.

Aquifer 3 is a small aquifer at 525 m depth. It is seen in the temperature log with little circulation fluid loss. This aquifer is located very close to a border between basalt breccias and breccias.

Aquifer 4 is a small aquifer at 540 m depth. It is identified by the temperature log and small circulation fluid loss. This aquifer is also situated at the border between a breccia and a tuff layer inside a hyaloclastite formation.

Aquifer 5 is situated at 645 m depth and is seen in the temperature log. This aquifer is very close to a border between glassy basalt and a tuff layer.

4.2 Aquifers in the production part of the well

Many aquifers are located in the production part of the well that extends from 768 m to the bottom. They are divided into two sub-groups. The first includes those relevant to circulation fluid changes and cuttings and extends from 768 to 1172 m depth. The second sub-group includes those aquifers that were found according to drilling condition changes and temperature. This group of aquifers extends from 1172 to the bottom of the well (1800 m).

Aquifer 1 is located at 930 m depth. It was identified according to circulation fluid loss of about 12 l/s and also by a weak anomaly in the temperature log. This aquifer is related to a very thin breccia layer which is situated between fine-grained basalts on the top and coarse-grained basalts in the lower part.

Aquifer 2 extends from 1034 to 1165 m depth and is an aquifer zone. It includes many aquifers although it was not possible to locate them individually with certainty. At this depth circulation fluid loss increased in steps from 10 to 24 l/s. There were also some anomalies in the temperature logs. These aquifers are located in basaltic lavas, which are both coarse- and fine-grained. At 1098, 1153 and 1162 m depths, there are three thin breccia layers.

Aquifer 3 is located at 1180 m depth and is found according to total circulation fluid loss.

Aquifer 4 is found at 1230 m depth. At this depth, circulation fluid reached the surface for the last time during drilling.

Aquifer 5 is defined at 1335 m depth according to a pressure drop at the pumps.

Aquifer 6 is defined at 1410 m depth by a pressure drop at the pumps.

Aquifer 7 is located at 1480 m depth according to a pressure drop at the pumps and is also seen in the temperature log.

Aquifer 8 is situated at 1580 m depth and is found by a pressure drop at the pumps.

Aquifer 9 is found at 1700 m depth according to a pressure drop at the pumps and is also seen in a temperature log.

Aquifer 10 is estimated at 1735 m depth by a pressure drop at the pumps and a temperature log.

A flowtest in well NJ-20 started on September 8, 1999. The well has flowed continuously since, and been very stable. Wellhead pressure was 10 bar-g, flowrate was 32 kg/s and enthalpy was 1430 kJ/kg. These figures rated the well as average at Nesjavellir.

The chemistry has shown little changes, except for decreasing of gases, which is normal; the gas content in steam at wellhead pressure is about 0.3% by mass. Geothermometers indicate aquifer temperature close to 270°C. At this temperature the wellhead enthalpy shows some excess steam at the inflow point (13%). Based on the Cl-content and enthalpy, boreholes at Nesjavellir are of two types, one of which is a high-enthalpy, low-Cl (boreholes in the western part of the area); the second with a high Cl content (140 ppm). Borehole NJ-20 (drilled south of the main field) belongs to the latter type (Steingrímsson, pers. comm.).

5. DISCUSSION

In well NJ-20 temperature has been assessed in two ways, first by investigation of hydrothermal alteration minerals during the drilling period, and second by calculations based on temperature logs during the warm-up period. The results of the two completely unrelated methods are revealed in Figure 12 with a temperature range for the alteration minerals. Each range is provided according to the relevant alteration

FIGURE 12: Comparison of calculated rock temperature to the alteration minerals temperature

mineral assemblages at every depth. Reservoir temperatures according to the first appearance of hydrothermal alteration minerals are shown in Figure 13. It is obvious that temperature has a progressive trend with increasing depth.

As shown in Figure 12 there is a reasonable conformity between these two temperature evaluation methods. But there appears to be some discrepancy at 400 and 802 m depths. At 400 m depth, there is evidence of low-temperature clay or smectite, which is accompanied by mixed layer clays. It seems that chlorite characterizes the Another case is clay. observed at 802 m depth, where calcite, quartz, laumontite, epidote and

wollastonite were all observed at the same depth. It seems that the temperature condition of the well at this depth accords to the mineral assemblage of epidote, wollastonite, calcite and quartz. It gives reliable temperatures above 250°C or even higher and also indicates that laumontite is not stable at this depth. Its existence here is due to a less permeable part of the reservoir, where the water/rock interactions have not been completed.

Laumontite was defined at 802 and 804 m depths. Mordenite was distinguished at 674 and 920 m depths. These zeolites are older than their adjacent minerals, and due to lower permeability condition, they can still be determined. Below these depths, there is no evidence of these zeolites.

In the XRD analysis of clay samples from 820 to 1080 m depth there were found no obvious peaks for chlorite. These types of chlorite are called unstable chlorite.

Due to a lack of zeolite minerals in the shallower parts of the well, there is no evidence for the present thermal condition of the well. Below 360 m depth calcite, quartz, and wairakite have replaced the zeolite minerals (except mordenite and laumontite).

There are some alteration minerals such as pyrite and Fe-oxides, which are not temperature dependent. Pyrite can be useful for indicating the extensivity of permeability in the reservoir (Gudmundsson, pers. comm.) and can provide evidence of fossil and present reservoir conditions. For example in cuttings at the 482 m depth, lots of pyrite minerals are seen, but there is no evidence of an active aquifer. At present, it indicates a fossil permeable zone, in which secondary minerals have filled most of the pores and vesicles.

Calcite has a very wide temperature range (100-300°C); in hotter environments it is not stable. Therefore, its absence can be a reliable sign for temperatures exceeding 300°C, which is very close to the boiling curve temperature at 1100-1200 m depths. In well NJ-20, calcite was distinguished in thin-section at 1172 m depth. Accordingly, temperature at this depth is <300°C.

In well NJ-20, there are some aquifers related to the lithological boundaries in the first 1200 m section of the well. For example at 360, 525, 540 and 930 m depths, all the aquifers are related to the stratigraphic borders. In some cases, these boundaries are between hyaloclastite and intrusive bodies (360 and 930 m) and for other aquifers they are between two different types of hyaloclastite formations. For example, at 525 m depth this boundary is between glassy basalts and breccia. At 540 m depth this border is between tuffs and breccia.

Below 1200 m depth, due to a lack of cuttings there was no direct lithological evidence and the only useful evidence for determining different lithological units was geophysical logs. For instance, by using the neutron-neutron log it is possible to locate the porous zones. Also, by using the gamma-ray log, composition of rock units could be identified. Resistivity logs give indications on porosity and fluid composition in pores. By combining all geophysical logs, well lithology can be defined.

In the deeper parts of the well (>1200 m) due to total circulation loss, all aquifers were determined by both temperature logs and pressure drops at the drilling pumps.

Well NJ-14 is very close to NJ-20 (about 40 m) and was drilled in 1985. Alteration zones in borehole NJ-14 are slightly different from NJ-20. A comparison of alteration zones and lithology in both NJ-14 and NJ-20 is shown in Figure 14. As shown in Figure 14, in NJ-14 a mixed layer clays zone starts at 240 m depth and extends to about 800 m depth (Steingrímsson et al., 1986). But, between 330 and 400 m depths, there is a thin layer of chlorite-epidote, which was not identified in NJ-20. It is also obvious that the mixed layer clays in NJ-14 start at a shallower depth (240 m); the layer in NJ-20 starts at 360 m depth. One probable reason for this difference may be related to some vertical upflow close to well NJ-14.

In the upper parts of the well all intrusive bodies are basaltic but in deeper parts it is assumed that some have acidic composition. In gamma ray logs from 1270 to 1445 and 1678 m depths there are some strong signs of high-silica content rocks. They are probably of rhyolithic composition, related to the silicic intrusive bodies. These types of intrusive bodies have been found at similar depths in other wells in the Nesjavellir geothermal field.

In the hydrothermal alteration zones from 940 to 1110 m depth, an actinolite zone has been determined. This zone indicates temperatures above 280°C. But below 1110 m depth there is chlorite zone and there is no evidence of actinolite. Due to increasing temperature by increasing depth, it is assumed that an actinolite zone exists in deeper parts of the well. But because of a lack of cuttings, it has not been observed in the well. The author believes that this actinolite indicates the lower limit of its temperature range because calcite was identified in these parts of the well, which shows temperatures lower than 300°C.

Well NJ-20 was directionally drilled to approach the main upflow zone as assumed by the conceptual model of the area. It is believed that hotter parts of the reservoir have more steam than hot water. By using the directional drilling method, it is possible to mine geothermal fluid of the big reservoir using only one well site. Because of lower environmental impacts such as less pipelines, expansion loops, access roads to drill site and so on, this method of drilling will be used more in the future. In this case, all reservoir fluid can be transferred to the consumption plants by one large pipe. This type of fluid exploitation is quite similar to offshore oil well drilling.

At the present time well NJ-20 is being discharged for testing some physical and chemical parameters like steam/water ratio. chemical components, flowrate, and pressure. This discharge well was connected to well NJ-20 by pipeline but is not currently used. It will be used in the near future, after completion of construction of the new part of the Nesjavellir power plant.

FIGURE 14: Comparison of alteration zones and lithology in wells NJ-20 and NJ-14

6. CONCLUSIONS

• The lithology of well NJ-20 consists predominantly of volcanic rocks. The upper part (from top to 730 m) mostly includes tuff, breccia and glassy basalt (pillow lava). Several basaltic intrusions have been intruded into the hyaloclastites. In the deeper parts of the well (730-1180 m) it consists of basaltic lavas. Below 1200 m depth no cuttings were available because of total circulation loss, but

geophysical logs give evidence of existence of some intrusions of basaltic and acidic rock composition. There is good correlation with previous studies in the field.

- According to the distribution of alteration minerals, four alteration zones were found, smectite-zeolite zone (from the top to 360 m), mixed layer zone clay (360-820 m), chlorite-epidote zone (820-940 and 1010-1180 m) and epidote-actinolite zone (940-1010 m). Their relevant temperature ranges are < 200°C, 200-230°C, 230-280°C and >280°C, respectively. The chlorite-epidote zone is separated into two parts by an epidote-actinolite zone at 940-1010 m depth.
- According to circulation loss or gain, temperature logs, pressure drops at the pumps and the study of cuttings, 15 aquifers were identified in the well NJ-20.
- By studying the hydrothermal alteration minerals, it was found that temperature rises with increasing depth. The alteration minerals from top to bottom are smectite, zeolite, quartz, wairakite, prehnite, wollastonite and epidote. A small disturbance is seen at 940-1010 m depth, where actinolite appears, indicating a heat anomaly in a short interval.
- Most of the aquifers are very close to lithological boundaries, especially in the first 700 m part of the well. For example, all aquifers at 360, 445, 525, 540 and 645 m depths are related to stratigraphic borders. These borders are divided into two main types. The first is related to basaltic intrusions and in the second, borders are positioned inside the hyaloclastite formation.
- In comparison, directional drilling is more environmentally sound. Because drillers can use one platform for the drilling of many wells, it decreases all possible environmental impacts of geothermal drilling. Here, for example each geothermal field can have one or two individual well sites. Then all geothermal fluid (steam or hot water) can be transmitted by major pipeline to a power plant with the least impact on nature and the surroundings.

ACKNOWLEDGEMENTS

I would like to express my thanks to Dr. Ingvar B. Fridleifsson, Mr. Lúdvik S. Georgsson and Mrs. Gudrún Bjarnadóttir for their best assistance during the training course. Thanks also to all staff members at Orkustofnun, especially my supervisors, Mr. Ásgrímur Gudmundsson and Dr. Hjalti Franzson for their excellent guidance for the completion of my project and report. Also thanks to Mr. Sigurdur Sveinn Jónsson for his kind help in the preparation of clay samples for XRD analysis.

Thanks to my wife's parents for their help during my absence. My deepest thanks to my wife, Zahra Mottian Rad and my daughter, Sara for bearing all the inconveniences of having me away for six long months.

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APPENDIX I: Preparation of sample minerals for analysis by the XRD technique and results of XRD analysis of clay minerals in well NJ-20

Preparation of sample minerals for analysis by the XRD technique

Procedure 1: For zeolite and other hydrothermal mineral analysis

- 1. Under the binocular microscope, hand pick grains filling either vesicles or veins from the cuttings contained in the rectangular plastic box. The sampling depth is dependent on the worker's purpose and objectives. There is no strict rule on the sampling methodology. The amount of samples should be more than enough to fill up the sample window used in XRD.
- 2. Crush the sample in an agate bowl to a grain size of 5-10 microns. Acetone is added to prevent loss of sample while powdering.
- 3. Fill the sample window slot with an appropriate amount of powdered sample, then press a glass slide against the sample in a slot to make it firm, flat and level.
- 4. Run the sample from 4 to 56 on XRD.

Procedure 2: For clay mineral analysis

- 1. Place approximately two teaspoons of drill cuttings into a test tube, wash out dust with distilled water. Fill the tube 2/3 with distilled water and plug with rubber stopper. Place the tube in a mechanical shaker for 4-8 hours, depending on the alteration grade of the samples.
- 2. Remove the tube from the shaker and allow to settle for 1-2 hours, until particles finer than approximately 4 microns are left in suspension. Pipette a few mm from the tube, below the level of the sample, and place about ten drops on a labeled glass slide. Avoid having the samples thick. Make a duplicate for each sample and let dry at room temperature overnight.
- 3. Place one set of samples in the desiccator containing Glycole $(C_2H_6O_2)$ solution and the other set in a desiccator containing CaCl₂2H₂O. Store at room temperature for at least 24 hours. Thick samples will need a longer time in the desiccator, at least 48 hours.
- 4. Run both sets of samples from 2-14° on the XRD.
- 5. Place one set of samples (normally the glycolated one) on an asbestos plate and heat in a preheated oven at 500-550°C. The exact location of individual samples on the asbestos plate must be known before heating because labeling will disappear during the heating process. Cool the samples sufficiently before further treatment.
- 6. Run the samples from $2-14^{\circ}$ on the XRD.

Depth	Untreated	Glycolated	Heated	Results
(m)	d (Å)	d (Å)	d (Å)	
90	14.98, 13.1	16.8	9.98	Smectite
120	14.15	17	9.87	Smectite
150	15.26	16.83	9.99	Smectite
200	12.96	15.54	9.94	Smectite
250	14.99, 12.87	15.24	9.91	Smectite
260-270	14.97, 12.77	15.66	9.9	Smectite
300	15.18, 12.85	15.18	9.85	Smectite
330	15.18, 12.87	15.18	9.85	Smectite
360	14.77, 12.87, 7.1	15.15, 7.23	9.9	Smectite, MLC
				(smectite, chlorite)
400	29.85, 14.9, 12.94, 7.26	16.46, 15.34	9.98	Smectite, MLC
				(smectite, chlorite)
430	30.34, 14.59, 7.23	16.49, 15.01	12.49, 9.14	MLC (smectite)
460	30.34, 14.71, 12.75, 7.22	16.92, 15.27, 8.33	12.4, 9.83, 9.14	MLC (smectite)
500	30.09, 14.71, 7.66, 7.24	30.09, 14.71, 7.66, 7.24	12.62, 8.16	MLC
550	30.48, 14.68, 7.66, 7.24	30.48, 14.68, 7.66, 7.24	12.62, 8.14	MLC
600	15.12, 12.98	30.48, 16.92, 15.21, 8.44	9.98	Smectite
650	29.92, 14.81, 12.86	31.49, 16.84, 15.25,	12.64, 9.29	Smectite, MLC
		8.44, 7.22		
700	29.8, 15.09, 12.82	31.08, 16.84, 15.25, 8.39	12.32, 9.88	Smectite, MLC
730	30.23, 14.59, 7.21	30.23, 14.59, 7.21	10	MLC, Smectite
760	30.1, 14.62, 7.2	30.1, 14.62, 7.2	10.01, 9.07	MLC
790	30.35, 14.74, 7.22	30.35, 14.75, 7.22	9.33	MLC
820	14.45, 12.85, 7.68, 7.14	14.45, 7.68, 7.14	14.71, 9.97	Unstable chlorite
850	14.51, 7.17	14.51, 7.71	14.56, 9.14	Unstable chlorite
880	30.51, 14.55, 7.18	30.51, 14.55, 7.18	14.38, 9.15	Unstable chlorite
910	30.85, 14.86, 7.19	30.35, 14.86, 7.19	14.68, 9.9	Unstable chlorite
940	30.1, 14.59, 7.2	30.1, 14.59, 7.2	19.33, 8.52	Unstable chlorite
970	30.23, 14.56, 7.17	30.23, 14.56, 7.17	14.56, 10.41	Unstable chlorite,
				MLC, actinolite
1000	30.23, 14.59, 7.21	30.23, 14.59, 7.21	8.98, 8.58	Unstable chlorite, actinolite
1006	14.42, 8.49, 7.16	14.42, 8.49, 7.16	8.98, 8.49	Unstable chlorite, actinolite
1050	14.56, 7.17	14.56, 7.17	14.56, 12.78, 8.49	Unstable chlorite, actinolite
1080	14.48, 7.15	14.48, 7.15	14.83, 8.92, 8.44	Chlorite, actinolite
1110	14.43, 7.14	14.43, 7.14	14.43, 7.33	Chlorite
1140	14.45, 7.15	14.45, 7.15	14.45, 7.31	Chlorite
1180	14.45, 7.15	14.45, 7.15	14.83, 7.33	Chlorite

 TABLE 1:
 Results of the XRD analysis of clay minerals in well NJ-20