PROCEEDINGS, Fifteenth Workshop on Geothermal Reservoir Engineering
Stanford University, Stanford, California, January 23-25, 1990
SGP-TR-130

EVIDENCE OF A SUPERCRITICAL FLUID AT DEPTH IN THE NESJAVELLIR FIELD

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ABSTRACT

The Nesjavellir geothermal field is located in the active volcanic zone in southwest Iceland. The field is under development for district heating for Reykjavík. During the last 25 years, eighteen exploration/production wells have been drilled into the field. The deepest well, NJ-11, was drilled in 1985 to a depth of 2265 m. The well intersected several aquifers connected to at least four aquifer systems of different pressure potentials. Immediately after the drilling was completed an interaquifer cross flow was observed and possible blow-out conditions prevailed. Temperature surveys showed that a fluid with temperatures in excess of 380°C entered the well near the bottom and flowed up the well to the main feed zone at 1226 m depth. Return circulation with water could not reverse the flow indicating that the deep aquifer pressure was in excess of 220 bars. Considerable time was spent in order to quench the bottom aquifer but without success. Finally the well was filled with gravel at a depth between 1700-1900 m before it was completed with a slotted liner. The lithology section below 2 km depth in well NJ-11 consists near entirely of intrusive rocks. The low alteration intensity of the intrusive rocks suggests a young age and/or low permeability. The alteration assemblage belongs to the amphibolite facies mineralogy. Well NJ-11 has been discharged continously since it was completed. The discharge rate has been of the order of 35 kg/s and fluid enthalpy close to 2600 kJ/kg or almost dry steam enthalpy. The bottom aquifer is believed to be permanently sealed off, which is supported by fluid chemistry data.

INTRODUCTION

The Nesjavellir geothermal field in southwest Iceland is a part of the Hengill geothermal area, which is estimated to be one of the largest high-temperature areas in Iceland (Bjornsson et al., 1986). The exploration of Nesjavellir began several decades ago, but drilling started in the field in 1965 and up to the end of 1986 eighteen wells have been completed. The field is now under development for district heating in Reykjavík. The two-phase geothermal fluid produced at Nesjavellir will be used to heat up fresh water, which will subsequently be piped 27 km to Reykjavík. This paper deals with the exploration results obtained during and after the drilling of well NJ-11, the deepest well at Nesjavellir. The well was drilled in 1985 and encountered a super high-temperature aquifer below 2 km depth.

THE NESJAVELLIR FIELD

The Nesjavellir field has been described in several publications (Stefansson, 1985; Franzson et al., 1986; Árnason et al., 1986 and 1987; Bodvarsson et al., 1988 and Franzson, 1988). The discussion here will therefore be limited to the main features of the field.

The Nesjavellir field is situated at the northern perimeter of the central volcano Hengill, within the SW-NE trending fracture zone that intersects the volcano (Fig. 1). The surface is densely faulted with the primary fault direction

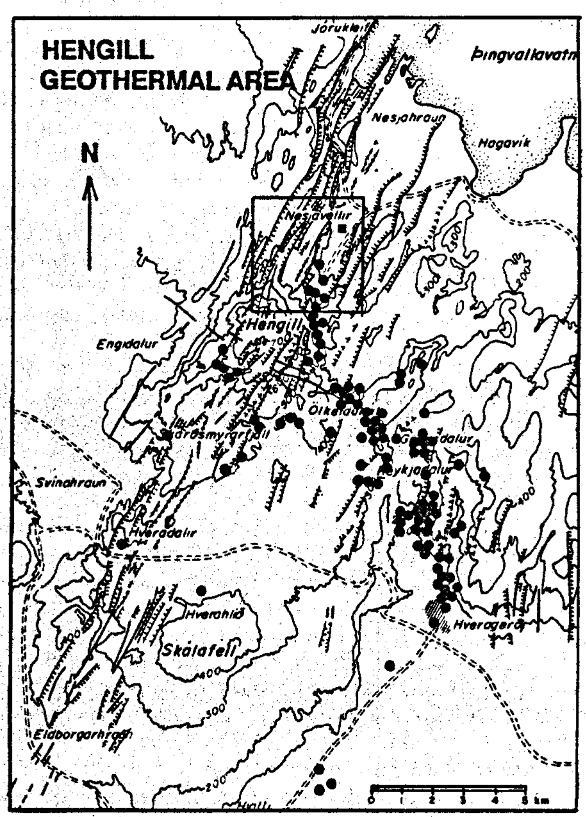

Figure 1. A tectonic map of the Hengill geothermal area. Location of fumaroles are shown as black dots. The Nesjavellir wellfield is within the square (c.f. Fig.5) (after Bjornsson et al., 1986).

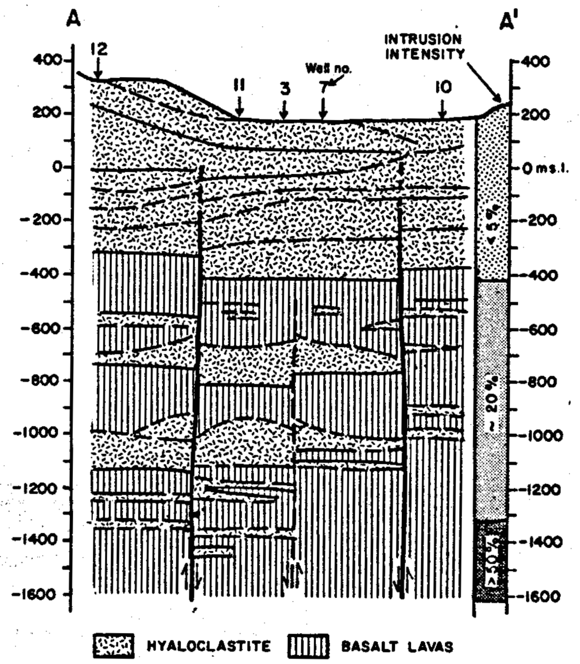

Figure 2. An E-W geological cross section through the Nesjavellir field (after Franzson et al., 1986)

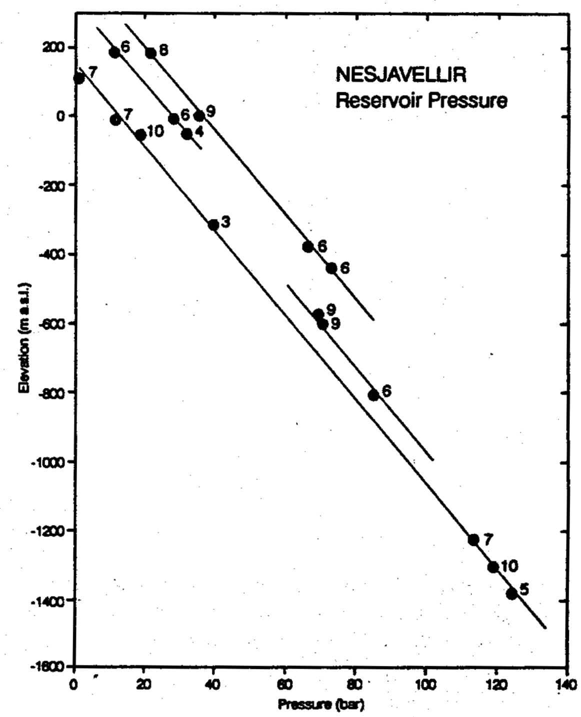

Figure 3. Pressure at feed zones in some of the wells at Nesjavellir (after Stefansson, 1985).

along the fracture zone and there is a clear correlation between geothermal surface manifestations and the fault pattern of the area. The subsurface formations encountered in the wellfield consists primarily of hyaloclastites and basalt lavas (Fig. 2). The hyaloclastites are dominant in the top 600 m but basaltic lava flows dominates the deeper regions of the system. Intrusive rocks are scarce above 800 m depth, but below that their frequency increases and exceeds 50% below 1500 m depth.

The Nesjavellir reservoir is highly complex and shows strong spatial variations in thermodynamic conditions. A part of the system in the uppermost 2 kilometers is two-phase with the remainder of the system in liquid dominated condition. The dominant aquifers have vastly different pressure potentials especially above 1000 m depth indicating limited vertical permeability in that part of the system (Fig. 3). Field data suggests that the system is fed by an upflow zone located southwest of the present wellfield underneath the Hengill volcano (Fig. 1). The upflow rate has been estimated from numerical simulation studies to be 65 kg/s of a two-phase fluid at an enthalpy of 1850 kJ/kg (Bodvarsson et al., 1988). The natural recharge from the upflow zone spreads laterally along the fault/fracture pattern through the geothermal system. Temperature and pressure data from the wells suggests that the main conduit of fluids from the upflow zone are SW-NE fractures along Kýrdalshryggur. This is demonstrated on figure 4 where well temperatures and alteration pattern are compared on a E-W cross section through the wellfield. The highest temperatures are found in the Kýrdalshryggur region. Good correlation is found between the measured temperatures and the alteration at the Kýrdalshryggur fracture zone and east of it. On the west side, however, especially above 1000 m, the alteration

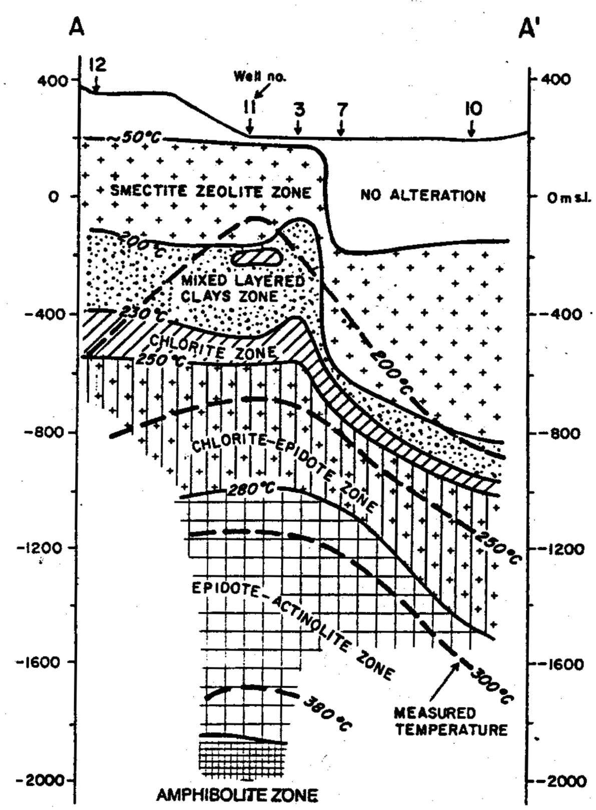

Figure 4. An E-W cross section through the Nesjavellir field showing alteration pattern and temperature distribution (after Franzson et al., 1986)

indicates much higher temperatures than measured in the wells. The explanation offered to this discrepancy is that the geothermal activity in the western part of the well field is presently retreating whereas at the fracture zone and further to east the activity is still at its maximum or even increasing.

The high permeability of the Kýrdalshryggur region is not surprising. Several volcanic eruption have occured there and off the three volcanic events which have occured at Nesjavellir during postglacial times (the last 10.000 years), two have been along eruptive fissures in Kýrdalshryggur. The last eruption took place some 2000 years ago.

DRILLING OF WELL NJ-11

Surface thermal alteration and minor geothermal activity is found along the eastern margin of the Kýrdalshryggur eruptive fissure zone. Early shallow drilling in the field (wells 3 and 4) proved the exsistence of an overpressurized high-temperature aquifer above 800 m depth close to the fracture zone. This aquifer has a limited areal extent and was not found in the deep exploration wells (wells 5 and 7) few hundred meters to the east of the fractures (Fig. 5).

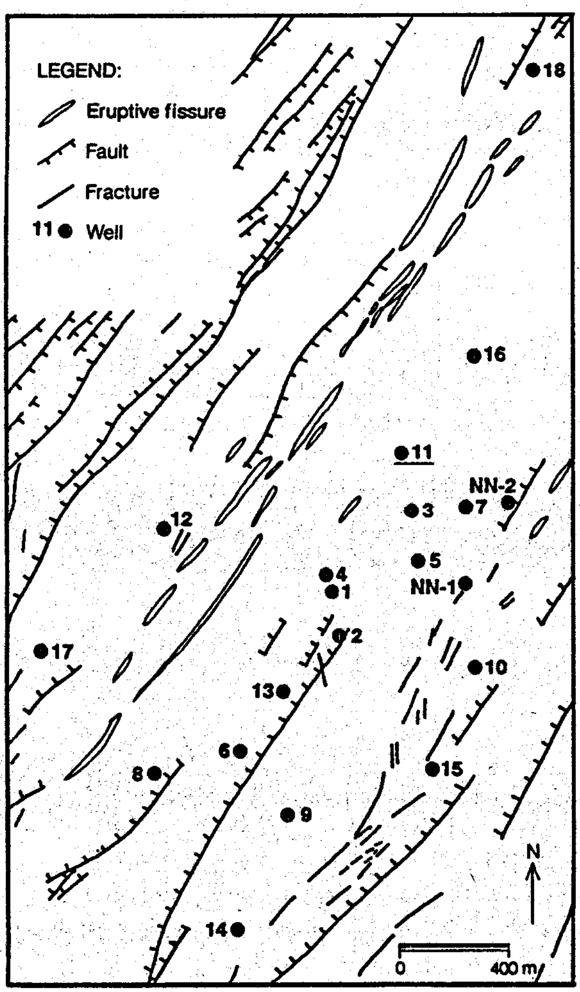

Figure 5. A tectonic map of the Nesjavellir wellfield, (adopted from Arnason et al., 1986).

Well NJ-11 was sited north of wells 3 and 4 to investigate further the shallow aquifer and the deeper parts of the geothermal system close to the volcanic fissure system (Steingrímsson et al., 1986). It was drilled in the spring of 1985 to a depth of 2265 m. A 13 3/8" anchor casing was cemented down to 183 m and a 9 5/8" production casing to 566 m depth. A total circulation loss occured at 115 m depth. This warm ground water aquifer had a static water table at 70 m depth and is sealed behind the anchor casing. Feed zones connected to the shallow geothermal aquifer were intersected at 414 and 508 m depth. The feed zones were overpressurized compared to the cold circulating water column. When circulation was stopped a wellhead pressure of 5-6 bar was observed and during drilling a circulation gain of some 35 l/s was measured. The estimated temperature of the two feed zones was 220 and 245°C, respectively.

The production part of the well was drilled with a 8 1/2" bit. Feed zones connected to the shallow aquifer were intersected in the depth interval 600-950 m. Wellhead pressure of 2.5 bar was measured and when circulation was stopped the immediate flow from the well was 6 l/s. Circulation loss was first measured when the well was about 1130 m deep and at 1226 m a total loss occurred (>40 l/s). Drilling continued with a variable loss of 10-40 l/s. The drillstring was tripped out when the well was 1750 m deep for changing drillbit. Two temperature surveys were done at this point while 27-28 l/s of cold water was pumped on wellhead. The logs (Fig. 6) showed, as expected, a cross flow in the well from the high pressure feed zones above 950 m to the deeper feed zones. Drilling was resumed with a new bit and continued to a

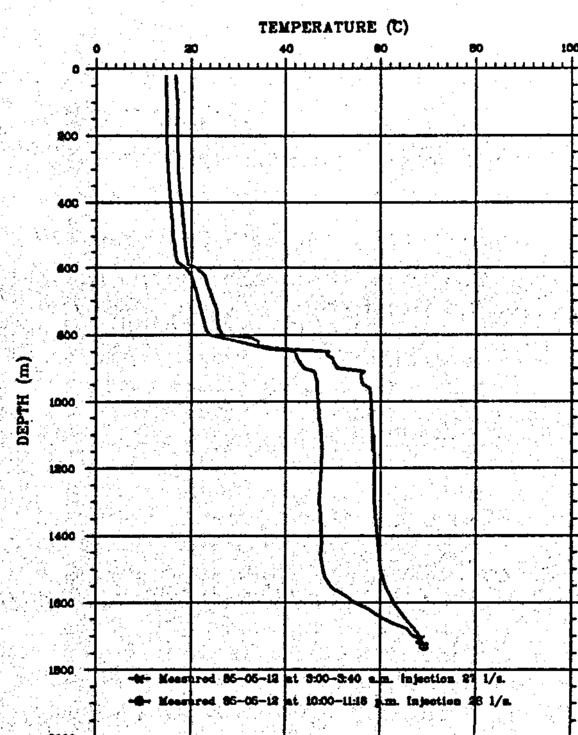

Figure 6. Temperature logs of well NJ-11 when it had reached 1750 m depth.

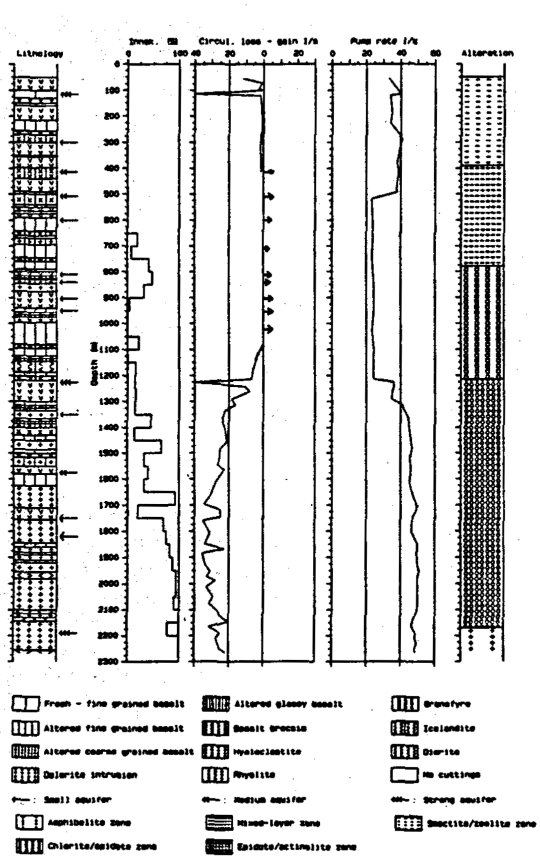

Figure 7. Well NJ-11. A simplified lithology section. Circulation during drilling and alteration zonation.

total depth at 2265 m. The data on circulation gains or losses collected during drilling of NJ-11 is summarized on figure 7 together with a simplified sections of the lithology and the alteration pattern for the well.

INTER-AQUIFER FLOW DURING COMPLETION

The drilling of well NJ-11 to 2265 m depth was completed in 42 days. Ahead was a completion program which was expected to take about five days. The first part of the program was circulation through the string with the drillbit still at bottom to clean out drill cuttings from the well. The circulation lasted a few hours with a circulation loss about 20 l/s. Circulation was then stopped and water injected into the casing-drillstring annulus and temperature logging prepared before pulling the drillstring out of the well. Shortly after the water injection had started it was observed by the drillers that no water entered the well. Instead there was flow of water up the annulus, initially some 10 l/s but increased in few minutes to 30 l/s. The BOP-valves were closed immediately to prevent a blow-out and circulation resumed. The well was easily quenched and a fluid loss of 30 l/s was measured.

During the next four days the well was pumped continously with 40-80 l/s of cold water either through drillstring (circulation) or into the annulus, or both. The water pumping was switched several times from circulation to injection only, but always with the same result; after few minutes injection either a wellhead pressure developed (up to 10 bar) or, if the BOP-valves were open, the well started to flow.

Temperature surveys run in the well during one of the circulation stops is shown on figure 8. The upper part of the temperature log was measured with a thermo-electric tool while 44 l/s of cold water was being pumped in the annulus at a 6.8 bar wellhead pressure. Due to high temperatures the logging was stopped just above 1200 m depth and the deeper parts of the well had to be logged with an Amerada gauge. Temperature readings were taken at four levels in the well. At 1300 and 1600 m depth the measured temperature was 324 and 333°C, respectively, but at 1900 and 2200 the gauge showed full deflection, indicating that the temperatures at these depths exceeded 381°C, the full deflection temperature of the tool used. The temperature log on figure 8 shows a counterflow in the well. The water injected on wellhead flows down the well, some of it is probably lost into the feed zones at 600-950 m depth, but most of it reaches the feed at 1226 m where it meets an upflow originating at the bottom region of the well. The inflow temperature of the deep aquifer is at least 380°C but the temperature in the upflow drops due to additional inflow between 1600-1900 m depth and boiling above 1600 m.

It should be noted that the transition zone between up- and downflow is according to the temperature log on figure 8 well above 1226 m. The explanation to this is that the high temperatures at the bottom had damaged the float valve in the drillstring and a fluid leakage was on the lubricator used on top for the measuring wireline.

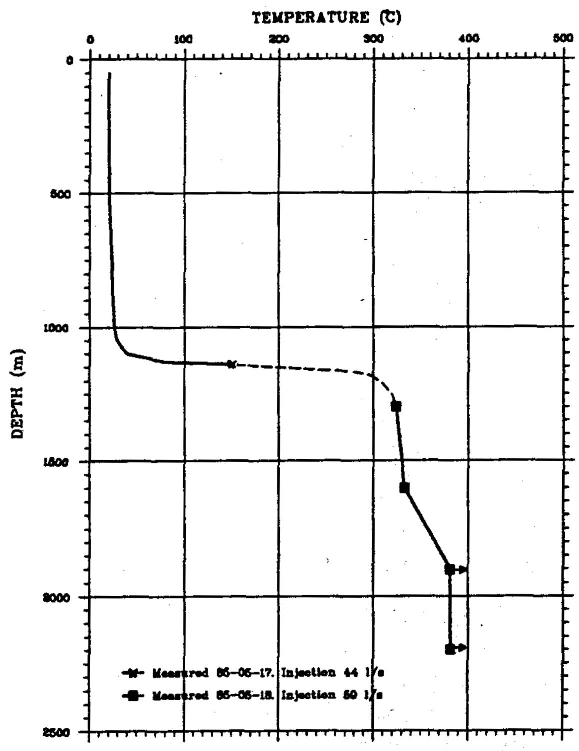

Figure 8. Temperature logs of well NJ-11 during the completion program. Water injected on wellhead.

It was obvious after the four days that the upflow from the bottom regions of the well could not be quenched with cold water. It was therefore decided to pull the drillstring out. A slow and hasardous process, which took another four days. To get the last drillcollars and the drillbit through the BOP-valves it was necessary to stop water injection and close the master valve for 45 minutes. When it was reopened the wellhead pressure was about 40 bar suggesting that the upflow in the well had reached the aquifers above 950 m depth. This wellhead pressure was not easily quenched. Neither injection for several hours of 40 or 50 l/s of cold water was sufficient, and it was not until the injection had been increased to 60 l/s that the wellhead pressure dropped to a few bars.

It is not possible to run a slotted liner into a pressurized high-temperature well. It was therefore decided to plug the bottom part of the well with gravel (grain size 0.6-3 cm). Several loads of gravel were sunk into the well and their position checked afterwards with a sinker bar. It was not until gravel corresponding to a 160 m depth interval had been accumulated in the well that the pressure on wellhead dropped to zero and the well swallowed all water available for injection (60 l/s). Few loads of gravel were added to secure the plugging of the deeper part of the well. The total amount of gravel used corresponds to nearly 200 m interval in the well. The sinker bar surveying showed that the gravel did not fall to the bottom of the well but occupied the depth interval from 1585 m to about 1800 m depth.

The final part of the completion program for well NJ-11 was traditional. A geophysical logging program was executed, the well cased with a slotted liner down to the top of the gravel plug and an injection test was carried out. The drilling and completion of the well NJ-11 took 59 days.

All information on well NJ-11 since drilling was completed indicates that the bottom aquifer is permanently sealed off (Steingrímsson et al., 1986). Temperature logging during heating-up after drilling did not reveal any upflow through the gravel plug. The well is a good producer with a production rate of about 35 kg/s at an enthalpy of about 2600 kJ/kg. The chemistry of the discharged fluids is in no way different from other high enthalpy wells at Nesjavellir as demonstrated in table 1.

Table 1 Chemical composition of deep fluids from Nesjavellir. Concentrations in mg/kg

Well	NJ-11	NJ-13	NJ-16
enthalpy	2585	2483	2010
ref.temp.	300	300	290
SiO_2	702.7	709.0	540.7
Na	103.3	71.7	100.5
K	16.7	17.9	21.7
Ca	0.42	0.07	0.59
Mg	0.101	0.023	0.001
SO_4	22.6	9.48	21.9
Cl	6.03	55.2	12.8
F	0.97	0.93	0.91
CO_2(w)	53.4	53.7	56.2
H_2S(w)	158.7	135.4	175.5
CO_2(g)	1884	2150	2413
H_2S(g)	1405	1434	1863
H_2(g)	119.7	109.3	218.3
CH_4(g)	3.53	5.13	11.75
N_2(g)	44.8	73.7	255

SUB-SURFACE GEOLOGY AND ALTERATION

The main lithological units at Nesjavellir are shown schematically in the cross section in figure 2. Hyaloclastite formations characterize the uppermost 600 m, which are either abundant or without plagioclase phenocrysts. There below is a basaltic lavapile interbedded by hyaloclastite units. The majority of the rock is of olivine-tholeiite and tholeiite composition. Less than 10% belong to the felsic rock series, mainly diorite intrusives. Chemical analyses of the rock types reveal rather primitive basaltic composition. The SiO_2 content of three basaltic lavas are 45-47% and the content of MgO is just above 7%. A greater chemical variance was measured in the main components of the hyaloclastites. One analysis of a diorite intrusion shows SiO_2 and MgO content to be 58% and 2%, respectively.

Figure 7 shows a simplified lithological section of well NJ-11. The proportion of intrusions, excluding the 650-900 m depth interval, shows a progressive downwards increase where 100% intensity is approached below about 1900 m depth. As discussed previously an overpressure was experienced during drilling from 400 to about 1100 m depth but circulation losses below that depth. A definite colour change was observed in the return circulation at 2190 m depth coinciding with an increase in gas smell. This suggests that the well intersects there the anomalous aquifer. Figure 7 also shows the prograde alteration; from a smectite-zeolite zone (<200°C) down to a zone which has been termed amphibolite zone (>340°C).

Figure 9 shows a detailed lithological column of well NJ-11 from 2000 m down to the bottom at 2265 m based on cutting analysis. Coarse grained to doleritic basaltic intrusions dominate with subordinate amount of more evolved intrusions. Minute remnants of the accumulative sequence, largely tuffaceous rock were positively identified at four levels, the lowermost one at 2180-2190 m depth.

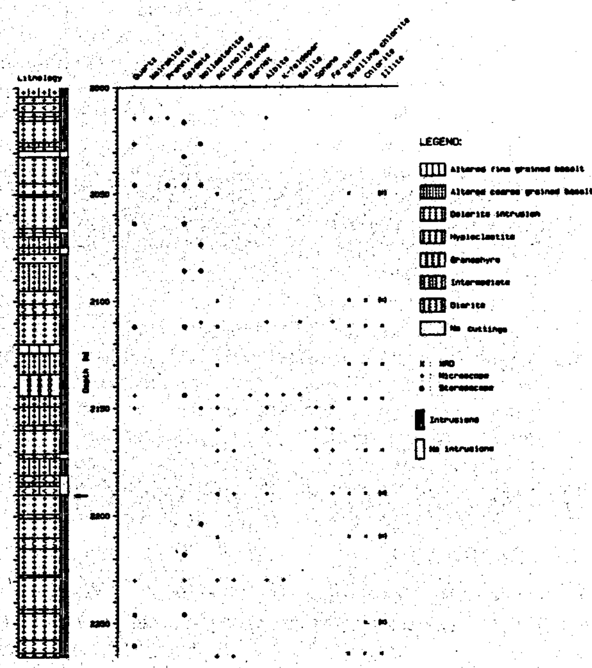

Figure 9. A detailed geological section below 2 km depth in well NJ-11 and observed alteration minerals.

The alteration intensity is relatively low in this part of the succession, where the intrusions are generally rather fresh in the centre but more altered at the finer grained margins. The alteration (as indicated in figure 9) shows a minimum of 16 minerals as analyzed by binocular, petrographic and XRD-methods. The plagioclase is preferentially altered into albite and chlorite and the pyroxens into amphiboles and chlorite. There appears to be a change in amphibole type at around 2170 m depth with an actinolitic type dominating in the pyroxene breakdown above but to hornblende below. Olivine appears to be mostly altered to illitic clays rimmed by ore mineral. Prehnite and wairakite are not found below 2015 m. Quartz is near solely confined to the evolved rocks. A striking alteration difference in rocks in the main hydrothermal system above and that below 2000 m is the rarity of mineral veins as an indicator hydrothermal activity in the latter. A noteable exception is the tuffaceous rock between 2180 and 2190 m depth where the appearance of the circulation fluid changedas mentioned above. There the rock is very heavily fractured and vesicles and veins filled by deposition. There the deposition minerals are dominantly actinolite, feldspar and ore.

Hreggviðsdóttir (1987) has also studied the mineralogy and chemical composition of the alteration assemblage in NJ-11. Her study confirms the data of this study and finds furthermore pyroxene of salitic composition and plagioclase of andesine-oligoclase composition which apparently equilibrate at temperatures from 350°C to above 380°C. She postulates that an amphibolite facies is reached below 2170 m depth. Her classification is adopted here and the boundary with the epidote-actinolite zone above set at about 2170 m where hornblende is first observed.

A search was made of hydrothermal fluid inclusions within primary and secondary minerals below 2150 m depth. Vein and vug minerals are, as previously mentioned, relatively scarce. Fluid inclusions were mainly found within the diorites. These were mostly very small. In a petrographic microscope with a higher magnification than possible in fluid inclusion work these were seen as being dominantly empty, in a few cases though a thin rim of fluid was observed around the edges of the inclusions. Only in two instances, both within the diorite at 2150 m depth, was fluid found in inclusions. These homogenized at 340-350°C. A repeat of the heating was impossible probably due to the excape of the fluid from the inclusion. These rough values fall near the boiling point curve at that depth. No inclusions with an observable fluid phase were found below that depth. These observations seem to eliminate a water-dominated system, but could conform to a vapour dominated, super critical or a gas-rich condition.

DISCUSSION

Well NJ-11 intersected several aquifers connected to at least four aquifer systems with different initial pressure potential. The thermodynamic conditions of the aquifer systems are summarized on figure 10 and 11. In the uppermost first kilometer a warm (< 100°C) ground water system overlies an over pressurized liquid dominated

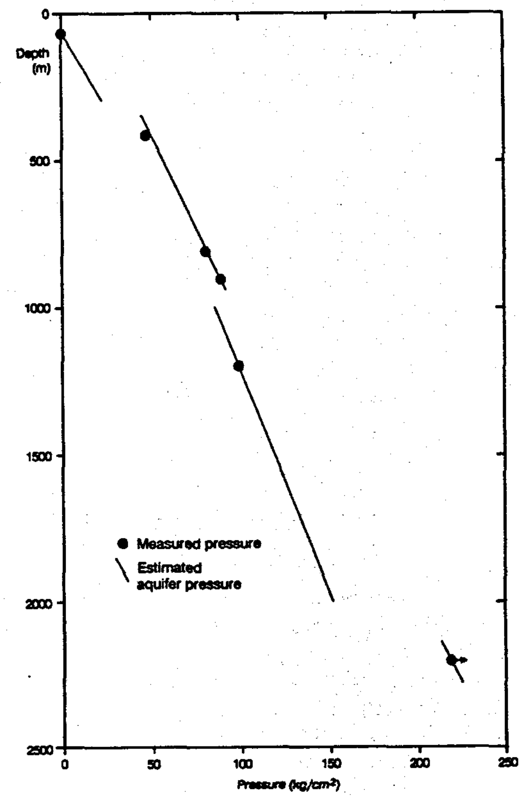

Figure 10. Aquifer pressures in well NJ-11.

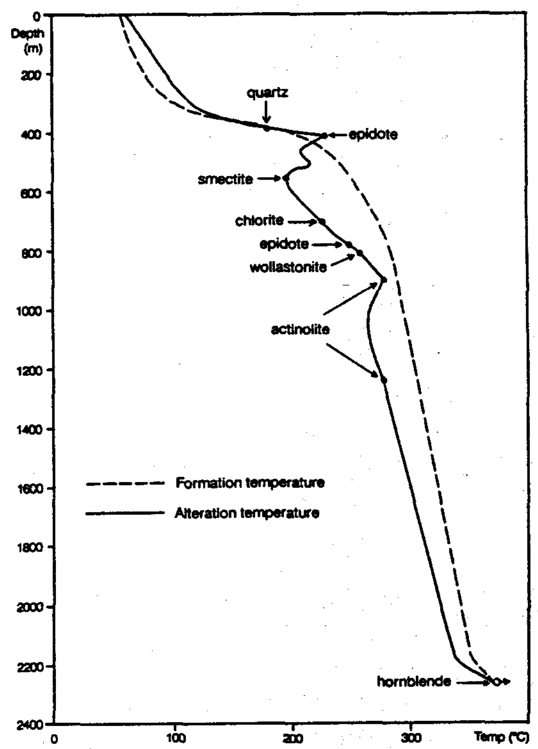

Figure 11. Estimated formation temperatures in well NJ-11.

aquifer at 200-280°C, the boundaries between the two being at 300-350 m depth. The main geothermal reservoir resides at 1-2 km depth. It is two-phase liquid dominated with temperature and pressure increasing with depth along the boiling point depth curve.

The aquifer system near the bottom of the well could not be quenched with circulation of cold water suggesting initial aquifer pressures in excess of 220 bar. It was not possible to measure the exact temperature of that aquifer but Amerada temperature surveys showed a minimum of 380°C at the bottom of the well. No samples were obtained of the aquifer fluid but for dilute fluids such as the reservoir fluids at Nesjavellir the temperature and the pressure of the bottom aquifer of well NJ-11 would correspond to a supercritical fluid state in the aquifer.

The intrusive rock sequence below 2000 m depth in NJ-11 shows a very limited alteration and vague indications of hydrothermal activity in terms of vein fillings. This suggests a relatively young age and/or very low permeability of the succession. The dominant alteration is monotonous with an assemblage of amphiboles, feldspars, iron ores, chlorite and illite which is the higest alteration assemblage so far found in an active geothermal field in Iceland.

A comparative alteration assemblage is found below 2100 m depth in well KJ-15 in the Krafla high-temperature field where actinolite and hornblende were identified along with chlorite, swelling chlorite, illite and quartz and the absence of epidote. Temperatures measured there surpassed 340°C.

The closest analog of the alteration sequence in well NJ-11 is, however, the aureole around the deeply eroded Geitafell gabbro in SE-Iceland (Fridleifsson 1983, 1984) where a supercritical condition is postulated to have prevailed. There a later and superimposing alteration is found, but the absence of such superimposition at the base of NJ-11 implies that the alteration there is contemporaneous with the present thermal condition.

The exsistence of a >380°C aquifer below 2 km depth in well NJ-11 suggests proximity of a magmatic heat source. The center of magmatic activity in the area is the Hengill central volcano south of the wellfield at Nesjavellir. The volcano-tectonic activity is episodic and is accompined by rifting and major faulting along the fissure swarm that intersects the central volcano as magma from the roots of Hengill is injected into the fissure swarm (Arnason et al., 1986). The last eruption in the Hengill area was about 2000 years ago along the volcanic fractures just west of well NJ-11 (see Fig. 5). A major rifting of the fissure swarm has occured since that time indicating magmatic activity at depth within the fissure swarm. Historic annals describe one such rifting event in the year 1789 (Arnason et al., 1986). During the last 2000 years the tectonic activity in the Hengill fissure swarm has been limited to the western part of the swarm and not where it intersects the present wellfield.

Exploration of the Hengill area does not reveal an extended magma chamber in the upper crust beneath the central volcano. Interpretation of magnetotelluric measurements (Bjornsson et al., 1986) show, however, that partially molten rocks are present at a depth of 7-8 km. Similar results have been obtained from seismic studies (Foulger, 1984).

The primary heat source for the Nesjavellir geothermal field is believed to be the hot partially molten rocks beneath the Hengill central volcano, causing there a major upflow zone of geothermal fluids. Secondary heat sources are the upper crustal intrusions found within the geothermal system. Analysis of microseismicity along the Kýrdalshryggur fracture zone show activity caused by thermal cracking at a depth of 2-6 km (Foulger, 1984). Intrusions dominate the lithology below 1500 m depth at Nesjavellir and geological and alteration studies show episodic intrusive activity in the past (Franzson, 1988). The anomalously high temperature at depth in well NJ-11 is probably related to a recent intrusive event. Not only do the upper crustal intrusions supply heat to the geothermal systems, but they also do enhance permeability of the reservoir. Several of the best feed zones of the Nesjavellir wells are located at the boundaries of intrusives (Franzson et al., 1986).

The >380°C at the bottom of well NJ-11 is the highest temperature measured in a geothermal well in Iceland but the thermodynamic conditions of the aquifer are not unique. Temperatures in excess of 400°C have also been measured in deep wells in the Tuscany geothermal areas and Phlegrean fields in Italy (Capetti et al., 1985 and Barberi et al., 1984) where highly saline and corrosive aquifers have been found.

MAIN CONCLUSIONS

The drilling of well NJ-11 to 2265 m depth revealed the existence of an anomalously high temperature and pressure aquifer deep in the Nesjavellir system. Information on the characteristics of the aquifer is, however, limited because the well had to be plugged below 1600 m depth due to technical problems in controlling it during the completion program. The main conclusion on the nature of this aquifer are as follows:

1) The aquifer resides within intrusive formations below 2 km depth. The exact location of well feeds is uncertain, but drilling data and geological studies indicate a feed zone at 2190 m depth in the well.

2) An aquifer pressure in excess of 220 bar is suggested and temperature higher than 380°C has been measured. This is a higher temperature than previously measured in a geothermal well in Iceland. The high temperature and pressure indicate supercritical fluid conditions in the aquifer.

3) The alteration assemblage at the bottom of the well conforms closely to amphibolite facies.

4) Well NJ-11 is located close to an eruptive fissure zone and the anomaliously high temperature aquifer at the bottom of the well is postulated to be related to a magmatic heat source, probably an intrusion.

ACKNOWLEDGEMENTS

Inspiring discussions with Gudmundur Ómar Fridleifsson and Valgardur Stefansson during the preparation of this work are acknowledged. The Reykjavik Municipal District heating Service is thanked for the permission to publish data from the Nesjavellir field.

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