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DEEP GEOTHERMAL DRILLING ON THE REYKJANES RIDGE OPPORTUNITY FOR INTERNATIONAL COLLABORATION

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ABSTRACT

The Icelandic geothermal community is planning to join in a deep geothermal drilling research project on the Reykjanes peninsula - the landward extension of the Reykjanes-Ridge. The principal aim is to bring supercritical hydrous fluid (400-600°C) up to the surface under high pressure, through a 4 km deep drillhole, into a research pilot plant where the thermal energy of the fluid is separated and the chemicals extracted.

The consortium for this project will consist of Hitaveita Sudurnesja, Orkuveita Reykjavikur, Landsvirkjun, Federation of Icelandic Energy and Water Works, Iceland Drilling Company Ltd., Orkustofnun, University of Iceland and leading consulting engineering companies in Iceland. Leading equipment suppliers have already shown interest in the project. International participation is welcomed to this challenging and advanced project, which has a high potential payoff.

1. INTRODUCTION

Unintentional drilling into hydrous fluid zones at supercritical conditions has ment problems in conventional drilling in hydrothermal systems. In most cases such supercritical fluids have been sealed off from the exploitation wells, by cement plugs or gravel packs, like in well NJ-11 at Nesjavellir, Iceland (Steingrimsson et al. 1990). In this paper we bring forward the idea of drilling intentionally for hydrous fluid at supercritical condition. Tentatively, we have selected a drillsite in a saline hydrothermal system at the tip of the Reykjanes peninsula, the landward extension of the mid-Atlantic ridge (Fig. 1). The site-selection is made in order to mimic conditions in the ocean floor "black smokers" which are natural geothermal systems at supercritical conditions. A pilot plant needs to be designed and build at drillsite, into which the fluid is brought at supercritical conditions and its energy and chemicals separated at very high pressure (P) and temperature (T). While this technical challenge might possibly show the black smokers to be exploitable, our future vision is to continue the deep fluid research and exploitation in the metoric high-temperature systems further inland in Iceland, like at Nesjavellir and Krafla (Fig 1). Practical and environmental reasons will call for increasingly deeper drilling in exploiting the conventional high-T fields during the 21st century. Thus we more often will have to face fluids at supercritical conditions, and new advanced technology is needed. If successful, the technical gain from our deep drilling and research could have a global impact in geothermal utitlization.

Reykjanes can be considered a natural drilling platform above a mid-ocean-ridge high-temperature system. Its seawater

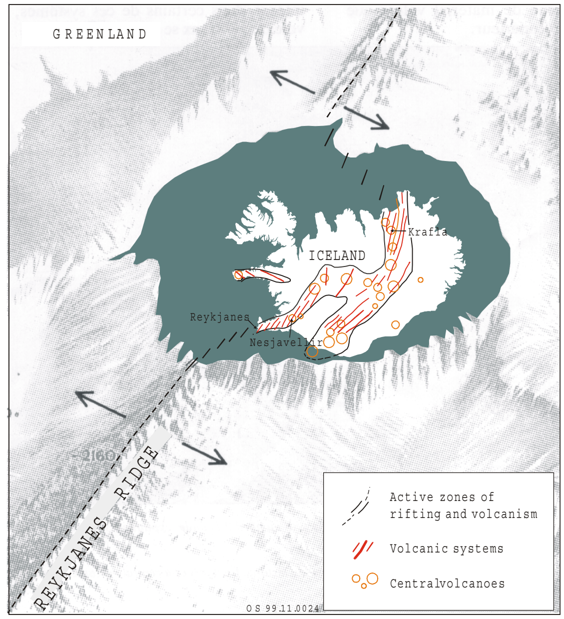

FIGURE 1 Iceland and its mid-ocean ridge. The location of Reykjanes, Nesjavellir and Krafla are shown

salinity, its high metal content and its open fracture system on the spreading Reykjanes ridge, seems to be an ideal setting for a high P-T pilot plant to harness similar fluids as thrive within the black smokers. Nevertheless, in selecting a suitable drillsite for research on supercritical fluids in Iceland, several options will and need to be discussed by a research group, yet to be established. Here we only introduce the better studied high-temperature systems, i.e. the Krafla-, Nesjavellir-, Svartsengi- and the Reykjanes geothermal systems. The first three are already utilized, producing electricity in steam and/or binary cycle turbines, and the latter two also by heat exchangers producing hot water for domestic use. Of these three systems, the Svartsengi system on the Reykjanes peninsula will not be discussed further, as it is probably the least suitible for deep research drilling for supercritical fluids. The Reykjanes system on the other hand is much hotter and not exploited at present, except on a limitied scale where high-quality salts are extracted from the high-T geothermal brine. Partly for that reason the Reykjanes system seems feasible for a joint research progamme, financed by the main energy producers in Iceland, possibly with participation of an international consortium of researchers and equipment manufactures. Our discussion thus focusses on the Reykjanes system while both Nesjavellir and

Krafla are introduced as potential sites for deep fluid research.

As yet a consortium for this research project has not been established, but will involve the main energy producers and research groups in Iceland. An international participation is welcomed and the form of the research cooperation is open for discussion. It could be similar to the Japanese Deep-seated Geothermal Resources Survey Project (Uchida et al. 1997, Muraoka et al. 1998), or similar to the international Iceland Research Drilling Project in eastern Iceland (Fridleifsson et al. 1982). A link with the international Ocean Drilling Program and its effective research methods could be established, as Reykjanes is simply a drilling platform on the mid-Atlantic ridge with the advantages of blowout preventers and casings. Whatever research form we choose to opperate, we will need advanced technology in both subsurface and production thechnology.

2. SUPERCRITICAL CONDITIONS

The critical point for pure water is at 221.2 bar and 374.15°C, and slightly higher in saline water. If a natural hydrostatic hydrothermal system was at boiling point from the surface down to the critical point (CP), maximum pressure and temperature at each depth would be determined by the boiling point depth curve (BPD-curve), and the CP-point would be reached at about 3.5 km depth. Below that depth the hydrous fluid would be at supercritical conditions, a hydrous gas, and there would be no phase change in the fluid upon further temperature increase at constant or rising pressure. While the hydrostatic BPD-curve controls the maximum P-T in most hydrothermal systems, temporal exceptions thrive within the systems, some examples of which are discussed below.

A boiling water column has much lower density than a cold water column. The CP-pressure in a cold water column would thus be reached at about 2.3 km depth, instead of 3.5 km in a water column at boiling point. That is the reason why 400-600°C hot hydrous fluids can be expelled directly into the oceans in the black smokers without any phase transition occurring, such as boiling.

Some modern-day power plants utilize the benefits of dealing with clean supercritical hydrous gas for electricity production in high-pressure gas turbines. This is done by heating water to supercritical temperatures by external heat sources at pressures above supercritical.

3. THE REYKJANES RIFT ZONE

The geology and surface distribution of the high-temperature geothermal system at Reykjanes is shown in Fig. 2, and an aerial view in Fig. 3. The surface is almost entirely covered by subaerial lavas of Holocene age, whereas hyaloclastite ridges of late Pleistocene age poke the lava fields, with the same strike as the volcanic crater rows, faults and fissures. Parts of the hyaloclastite ridges and the lava fields are hydrothermally altered, centred within manifestations of fumaroles, mud pools and hot springs. Also shown on the map in Fig. 2 is an isopath map of a high-resistivity body below a low resistivity anomaly (Karlsdottir, 1997). This high resistivity body roughly delineates a 250°C isothermal surface within the high-T system. This change in the resistivity character is related to the transformation of low-T smectitic clay minerals to high-T chloritic clays, roughly set at 250°C (e.g. Arnason and Flovenz, 1992). The shallowest

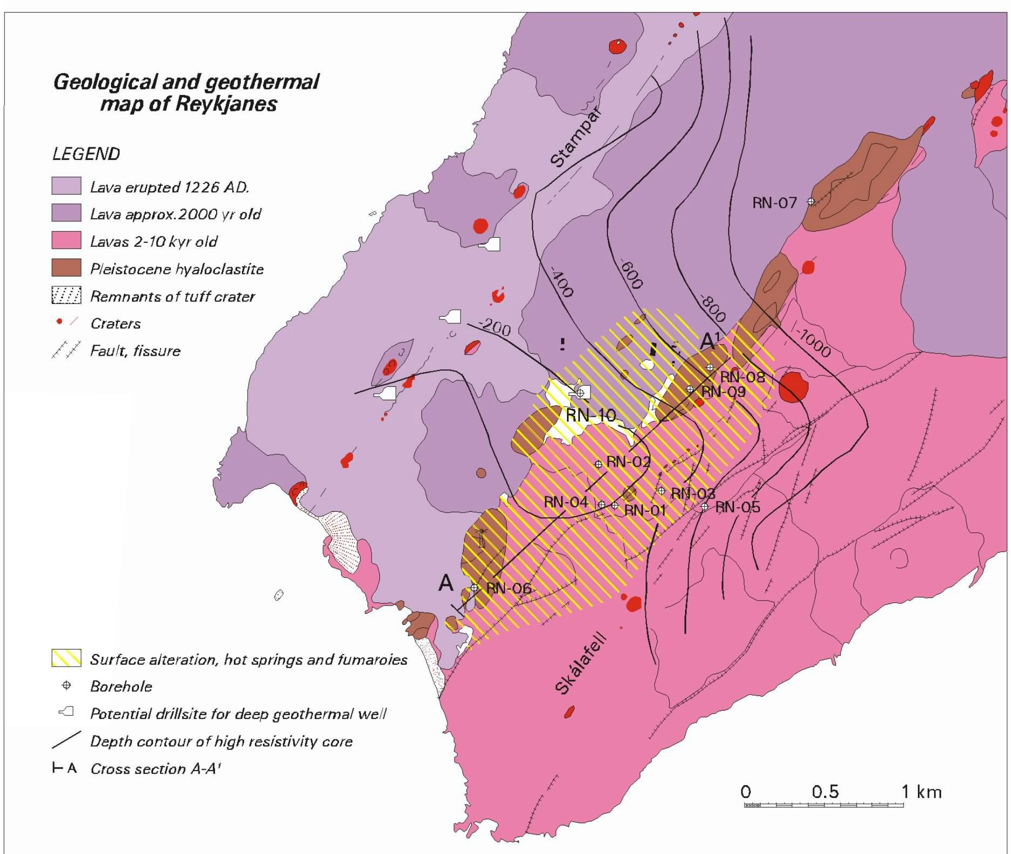

FIGURE 2
Geological map of Reykjanes (based on Saemundsson 1997) showing drillhole locations, potential drillsites for deep drilling, depth contours to high resistivity core and hydrothermal surface manifestations.

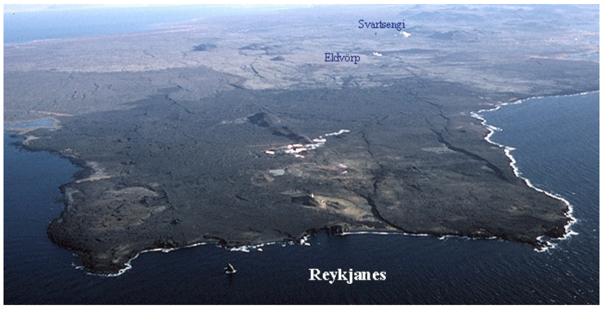

FIGURE 3 Reykjanes, the landward extension of the Reykjanes ridge. The drillfields at Reykjanes, Eldvörp and Svartsengi can be seen.

depth to the 250°C high-resistivity body is underlying the hydrothermal surface manifestations, falling steeply on the east-side of Reykjanes, but clearly above 400 m depth on the west-side.

The location of drilhole RN-10 (2046 m), drilled in early 1999, is also shown in Fig. 2, as are three other potential drillsites for a 4 km deep drillhole for supercritical fluids. They are targeted in between the youngest crater rows, within the active Stampar eruptive fissure zone on the NW-side of Reykjanes. The youngest fissure eruption dates back to 1226, while the 2nd youngest is about 2000 year old. In Holocene time, at least four volcanic eruptions have taken place within this fissure zone. An older eruptive fissure zone is on the SE-side of Reykjanes (the Skalafell fissure zone), mostly involving early-Holocene lava eruptions, while the faults have moved frequently in historic times, reactivating the hydrothermal surface manifestation, which are mostly located in between these two eruption zones. So are all the deep drilholes sunk into the Reykjanes field sofar.

Drillhole RN-10 may also be considered as a potential drillsite for a 4 km deep well, simply by deepening. It has a 13 3/8" cemented production casing down to 692 m depth, and a slotted 9 5/8" liner to 2030 m within a 12 1/4" hole to 2046 m depth (Fridleifsson et al. 1999, Franzson et al. 1999). By deepening well RN-10, the hanging liner needs to be removed, the hole deepened by some 500-1000 m and a high-resistant cemented casing placed in. Drilling to the 4 km target depth could continue with 8 1/2" drillbit.

Well RN-10 is the deepest drillhole on Reykjanes. It penetrates several hundred metre thick succession of shallow-marine sediments, submarine tuffs and pillow lava formations interbedded with subaerial lava formations in the upper 1 km, and hyaloclastite formation in between thick lava sequences in the lower 2nd km. A total circulation loss of >60 l/s was met between 1900-2000 m depth in a wollastonite bearing vein system. The formation temperature judging from the secondary alteration may be well over 300°C.

Intrusive rocks in RN-10 are unexpectedly meagre at depths (< 5 %), compared to similar depths at Nesjavellir and Krafla drillfields (50-100%). Undouptedly this reflects the difference between a young volcanic rift at the Reykjanes ridge system and the more evolved rift systems involving central volcanic complexes like at Nesjavellir and Krafla further inland. Also the near vertical dykes at Reykjanes swarm into narrow fissure zones, like the two during Holocene (Fig. 2). Nevertheless, earlier evaluation on the crustal structure of Reykjanes (Björnsson et al 1972) suggested the depth to crustal layer 3 (6.5 km/s), mostly of intrusive nature, could be as little as 2.5-3 km. This data needs updating with more recent seismic surveys, and other geophysical data, in order to estimate the depth to a sheeted dyke complex. This will be dealt with during the preparation phase for the deep drilling project.

Fig. 4 shows a hydrothermal cross section along the rift axes in the centre of Reykjanes, the location of the profile is shown in Fig 2. The present-day thermal distribution and the hydrothermal alteration zonation are shown. Only a crude correlation is seen. The smectite-zeolite zone thrives up to 200°C, mixed layer clays up to 250°C, surpassed by the chlorite-epidote zone, and then by the epidote-actinolite zone at T approaching 300°C. The formation temperature in well RN-10 is above 300°C below 1000 m depth and close to 320°C at 2000 m depth when this is written.

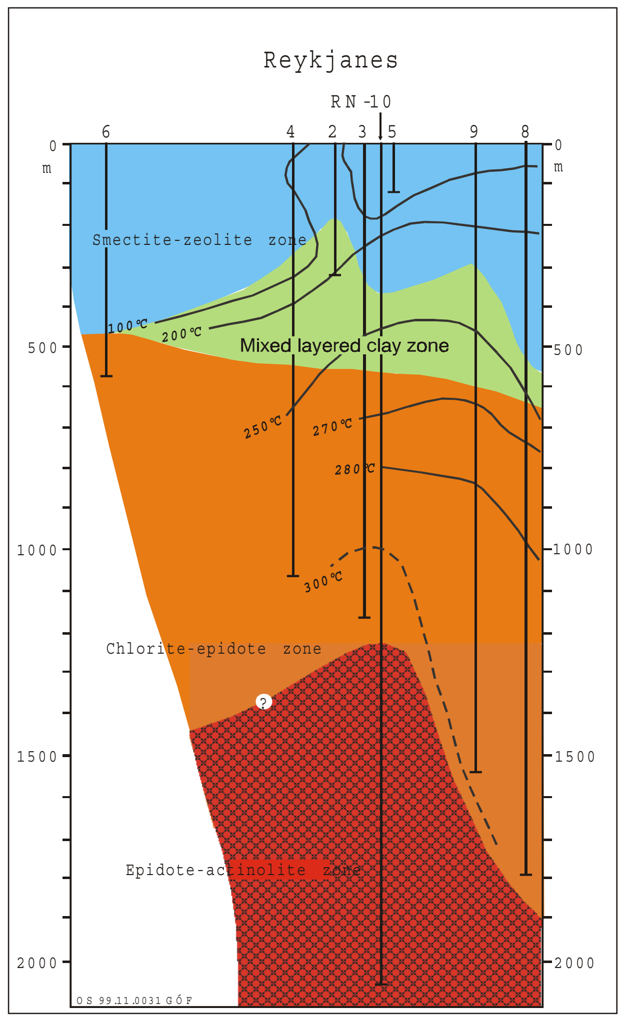

FIGURE 4. Hydrothermal section along the rift axes at Reykjanes, including all deep drillholes (based on Björnsson et al. 1972; Franzson et al. 1983, 1999; Mungania, 1993; Lonker et al. 1993; and a current study on well RN-10).

The correlation between the alteration data and the resistivity survey is not good, except in wells RN-8 and RN-9 (compare Fig 2 and Fig 4). In RN-10, the mixed layer clay-chlorite transition ought to take place at about 200 m depth according to the depth to the high resistivity core. However, the only well at Reykjanes including the high-T epidote-actinolite zone is well RN-10. That may possibly have some connection to the shape of the high-resistivity core.

While the correlation between the surface geology and geophysics, and the drillhole data need closer attention, a rise in the subsurface temperature and alteration towards the tentative deep drillsites within the Stampar eruptive fissure zone seems to emerge. A further support for a potential drillsite for deep drilling is sought to an analogue situation at Nesjavellir in well NJ-11 which was sunk close to a 2000 year old volcanic eruption fissure.

4. THE NESJAVELLIR HIGH-T FIELD

The location of Nesjavellir in shown in Fig.1 and a map of its drillfield in Fig. 5. The Nesjavellir field is a part of the active Hengill central volcanic complex. The surface and subsurface geology is characterized by subglacial volcanics formed during glacial periods, and lavas formed during interglacials and at present (e.g Franzson et al. 1986). A 2000 year old volcanic eruptive fissure is shown in Fig 5 in the western part of the drillfield.

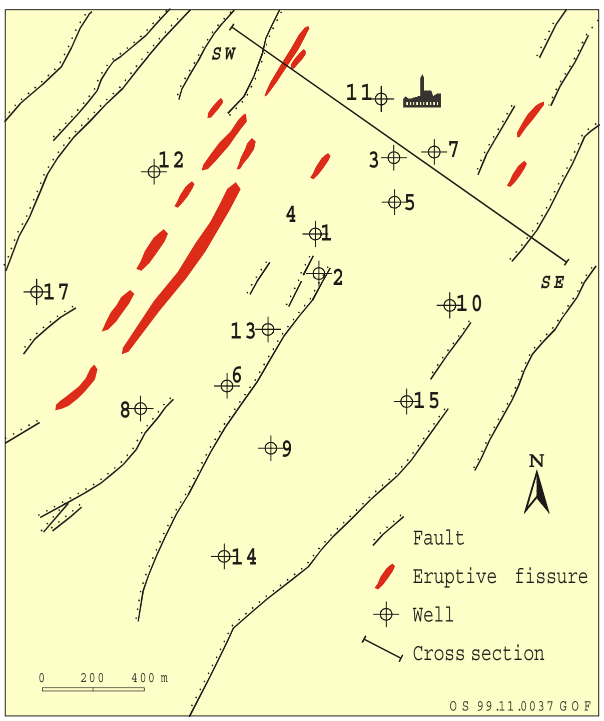

FIGURE 5 The Nesjavellir drillfield

Fig. 6 shows a hydrothermal NW-SE profile across the Nesjavellir drillfield, slightly modified from Franzson et al. 1986, made in a similar fashion as Fig 4 for Reykjanes. The correlation between the subsurface temperatures and the alteration zones is much better at Nesjavellir than at Reykjanes, and the base temperatures higher. An amphibolite zone is shown at the bottom of well NJ-11, which is 2265 m deep.

Unexpectedly supercritical conditions were met in well NJ-11 (Steingrimsson et al. 1990). Controling the well after drilling was exceptionally difficult. The pressure was deemed from the well's behaviour to have been well over 222 bars. A temperature profile could still be made inside the drillstring (Fig 7), the termometer only set for 380°C maximum. Therefore the bottom hole temperature was at least 380°C, but could have been much higher. The measured T-profile in

Fig. 7 shows the well in a state of underground blowout below a feed point at 1100 m depth. The feed point accepts all the 44-59 l/s of cold water injected. The BPD-curve is shown for reference.

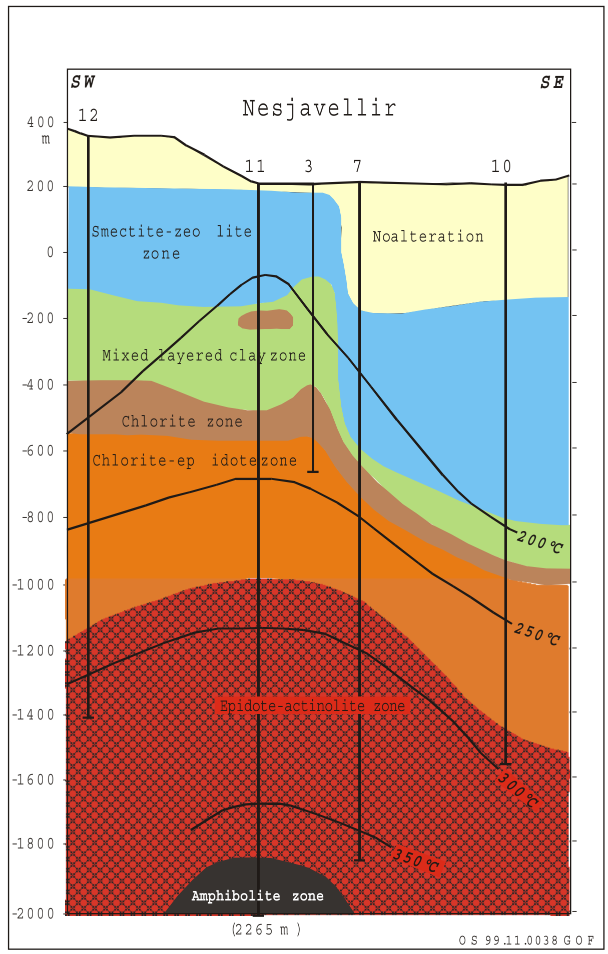

FIGURE 6 Hydrothermal cross section across the rift zone at Nesjavellir, including well NJ-11 (based on Franzson et al. 1986).

The NJ-11 example seems to show that supercritical coinditions can thrive in some form of isolated pockets within a conventional hydrothermal system. The boiling pressure is only about 140 bars at 2 km depth. Thus a pressure increase by at least 80 bars over 200 m interval needs explanation. The closest we get is to look to the 2000 year old volcanic fissure just west of well NJ-11. There is a sharp temperature decline on the west side of the fissure, judging from both wells 12 and 17, meaning there is a heavier water column on the western side of the volcanic fissure, but far from accounting for the pressure difference. Additional pressure barrier is needed, which we leave here with questions on inclined faults and dykes allowing for fluid layers at different PT-conditions within the reservoir. Evidently, deepening of a neighbouring well to NJ-11, to about 2.5 km, would give us an idea on the distribution of the supercritical fluid layer at Nesjavellir, and the amphibolite zone.

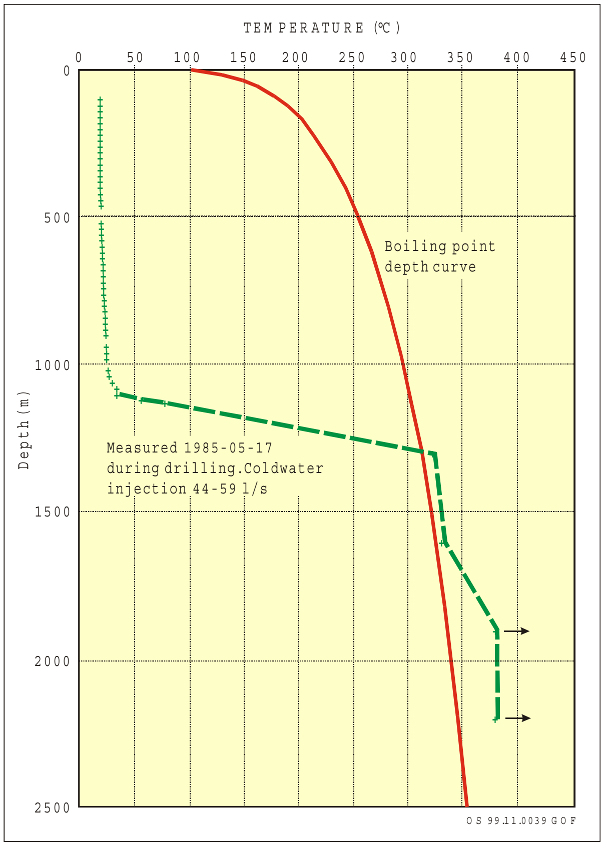

FIGURE 7 A temperature profile of well NJ-11 during drilling (from Steingrimsson et al 1990). The boiling point depth curve for pure water is shown for comparison.

The closest Icelandic analogue to the alteration seqeunce in NJ-11, is found within a gabbro contact aureole in an eroded Miocene central volcano in SE-Iceland where supercritical conditions are postulated to have prevailed at shallow depth for some length of time (Fridleifsson 1984).

While hydrous fluids at supercritical conditions may possibly thrive temporarily within onland hydrothermal systems at shallow depths, exploitable for research were found, we are all the more interested in knowing if supercritical fluids thrive in economic quantities deeper within the rift system at Nesjavellir and elsewhere.

5. THE KRAFLA HIGH-T FIELD

A large geothermal system exists within the Krafla central volcano (Fig 1). Hitherto, 35 deep drillholes have been sunk into the geothermal system, mostly into one large drillfield just north of a power plant. The installed 60 MW electric are produced from about half of the wells at present. The deepest well is 2222 m. Enlargement to 90 MW is being planned. The enlargement will involve deep exploration drilling in 2-3 new drillfields within the central volcano.

An active rifting episode took place in the Krafla volcano during 1975-1984, involving some 21 cycles of uplifting periods and shorter subsidence events, due to inflow of magma into a large magma chamber at 3-7 km depth within the volcanic centre (Björnson 1985). The rifting took place during the subsidence events, involving earthquakes and outflow of magma from the magma chamber into a fissure swarm, and in 9 cases up to the surface also in volcanic eruption. In one case the volcanic product on the surface came up through a 600 m deep borehole in a drillfield south of the Krafla centre (Larsen et al. 1979). The flaring tephra eruption lasted for several hours. Accumulative spreading during the 9 year rifting episode was about 8 metres. A comparable rifting episode took place in 1729-1741, starting with a huge explosion forming the crater Viti in the presently exploited drillfield in Krafla.

The volcanic episode during 1975-1984 severly affected the exploited drillfield in Krafla, mostly by increased CO_2 to the order of 10^5 (e.g. Armannsson et al. 1987), which made the most energetic part of the drillfield inexploitable for 10-15 years. The magmatic degassing has now diminished and the drillfield is probably better than before. The next volcanic rifting episode in Krafla is not expected untill 2225 or there about, the rifting episodes taking place at about 250 years interval.

Adjacent to the cooling magma chamber in Krafla a supercrital hydrous fluid layer is bound to exist, probably separated from the magma chamber by a narrow inner aureole of contact metamorphism. At present, a suitible drilling target in Krafla for supercritical fluids has not been set, but will be considered during our preparation phase

6. CONCLUSION

The foreseeable need for deep drilling for exploitable hydrothermal fluids in Iceland during the 21st century calls for research on supercritical hydrous fluids in nature. The high-temperature geothermal systems within the rift zones in Iceland provide several options in finding suitable targets for supercritical fluids. Tentatively, the active rift zone at Reykjanes, the landward extension of the Reykjanes Ridge, is selected here as a suitable target.

The selected drillsites at Reykjanes flank the surface geothermal manifestations, but are located within the high-temperature system at depth. Supercritical condition may be expected at these drillsites in Reykjanes, which area located in between a 2000 year old volcanic fissure and a volcanic fissure from historic times (1226 AD). While uncertainity exists on the supercritical conditions at Reykjanes above 4 km depth, a supporting analogue is sought to the time-temperature constraint at a 2000 year old volcanic fissure at Nesjavellir, where a supercritical hydrous fluid was met at 2265 m depth in well NJ-11. A 4 km deep well at Reykjanes will need to be cased off with high resistant steel casing to about 2.5 km depth, in order to control the well during drilling and to meet very hot and possibly corrosive fluids during exploitation. The fluid will be brought to the surface at supercritical condition into a pilot plant, where the energy and the chemicals will be separated and extracted.

A preparation for this deep drilling programme at Reykjanes will take 2-3 years. The drilling may be realized in 2003 and an operating pilot plant a year or two later.

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