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The Geological Significance of Two IDDP-ICDP Spot Cores from the Reykjanes Geothermal Field, Iceland

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ABSTRACT

Only two drill cores are available from the Reykjanes high-temperature field in SW-Iceland, on the Reykjanes Peninsula, which is a direct continuation of the Mid-Atlantic Ridge on land. The coring activity was funded by the International Scientific Continental Drilling Program (ICDP) in conjunction with the Iceland Deep Drilling Project (IDDP). The spot core from RN-19 was drilled at 2245-2248 m (2.97 m) in 2005. The spot core from RN-17 was drilled in a side tracked well (RN-17B) at 35° angle at depth of 2798.5-2807.5 m (9.3 m) in 2008. The true vertical depth from the surface above the RN-17B core is approximately at 2560-2570 m.

This paper describes the depositional environment of these deep drill cores. The RN-19 core is composed of a homogeneous coarse-grained dolerite that is relatively unaltered, and is interpreted to come from a sheeted dyke complex. Only narrow chlorite-acinolite veins are present in that core. On the other hand, the RN-17B core is composed of a shallow marine volcanoclastic/hyaloclastite breccia containing lenses of fine-grained tuffaceous sediment, which appears to contain remnants of shallow marine fossils (shell fragments). However, lower greenschist facies hydrothermal alteration and rock replacement by secondary minerals is almost complete, preventing study of the apparent fossil remains in the core. In spite of the great depth of the core in this well, the abundant vesicles in the volcanoclastic rock, as well as the extent of pillow lava formations suggest a relatively shallow marine depositional environment.

Based on the depth of these shallow marine sedimentary sequences, we estimate that rocks of the Reykjanes geothermal field have been subsiding at a rate of some 6 mm/year over the last 500.000 years, yielding a ratio of 1/3 subsidence/spreading rate on this part of the landward extension of the Mid-Atlantic Ridge.

1. INTRODUCTION

The purpose of the present paper is to describe preliminary results of our lithological interpretation and alteration study of the Reykjanes geology, with respect to shallow marine sediments in particular in two IDDP-ICDP spot cores (Figures 1 and 2). A drillcore from well RN-17B at Reykjanes, was cored at 2800 m depth in a 35° inclined hole late November 2008. The reason for that coring was to carry out a test of a new spot coring equipment, funded by ICDP, that was especially designed by the IDDP drilling engineering team for the extremely high-temperatures expected to be encountered in the Iceland Deep Drilling Project. This coring equipment has the main advantage over conventional spot coring equipment in that it allows some 40 l/s of circulating cooling water during coring, to effectively cool the bottom hole assembly at high temperatures and great depths. The very successful coring test was first described at the IDDP website: http://www.iddp.is and in more detail at this WGC-2010 conference (Skinner et al. 2010).

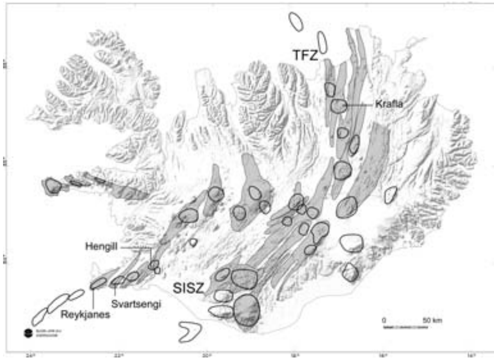

Figure 1: The geological setting of the high-temperature geothermal field at Reykjanes in SW-Iceland, the landward extension of the slowly spreading Mid-Atlantic Ridge

Initially, it was the IDDP intention to continuously core drill the deeper part of the first IDDP well of opportunity at Reykjanes (see review in Friðleifsson et al., 2010). After some 5 years of preparation, IDDP intended to accept an offer from Hitaveita Suðurnesja hf., one of the consortium members, to deepen a 3082 m deep production well at the Reykjanes high-temperature system in SW-Iceland. These plans and drilling of the well RN-17 have been described at length (Friðleifsson et al., 2005, A, B, C) The goal was to drill for 400–600°C supercritical fluid, in order to significantly increase the power output of geothermal wells. Funding to deepen this well and flow test it was secured by the IDDP energy consortium, and funds for obtaining drill cores for scientific study had already been awarded jointly by the International Continental Scientific Drilling Program (ICDP) and the United States National Science Foundation (NSF). The 3082 m deep well, however, became blocked during a production test in November 2005 and had to be abandoned few months later when attempts to recondition it failed. Prior to that, the PI's for the ICDP funds (G.Ó. Friðleifsson and W.A. Elders), had been pre-funded by ICDP to collect one spot core from well RN-17. However, as there was no supporting liner in the 3082 m deep well, it was considered too risky at that time to attempt a spot coring test in the open hole. Therefore, the spot coring test was moved to a production well RN-19, which was drilled shortly after the RN-17 well. There, an almost 3 m long spot core was drilled and retrieved from 2245-2248 m depth, below a hanging 9 5/8" perforated liner in the vertical RN-19 production well. That operation was described in the RN-17 well report (Friðleifsson et al., 2005 C) as well as being repeated in the RN-19 well report (Mortensen et al., 2005).

The lithological information from both these wells, as well as from well RN-17B (Helgadóttir et al., 2009), are referred to and used in the present paper. Additionally, we refer to our observation in well RN-10 with respect to shallow marine fossils in particular (Friðleifsson et al. 1999, Franzson et al. 1999, Franzson et. al 2002, Franzson, 2004).

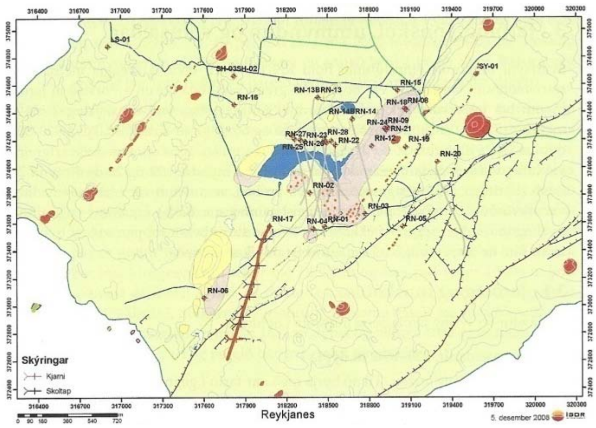

Figure 2: The RN-17B was drilled towards the SSW and ends some 800 m south of the wellhead. Well RN-19 is in the NE part of the drill field and RN-10 in the west side of the main drill field

Several science studies in relation to the RN-17 well at Reykjanes are already published, in press, or submitted to international journals (Freedman et al., 2009, 2010; Olsen et al., 2010, Marks et al. 2009, 2010; Pope et al. 2009 A,B, 2010, Raffone et al. 2008, 2009A,B; Elders and Friðleifsson 2009, 2010). Publications from French and Russian IDDP teams are also to be expected. The new spot core from RN-17B is being studied more extensively by the IDDP science teams.

2. THE REYKJANES DRILL FIELD

The lithology of the Reykjanes high-temperature drill field is relatively simple. The surface is characterized by a large number of NE-trending eruptive fissures, faults and fractures and several Holocene lava flows (Sæmundsson, 1978), while the uppermost 1 km is characterized by subaquatic/subglacial hyaloclastite formations interbedded with shallow marine sediments. At greater depths pillow basalts and intrusive rocks characterize the lithology (Björnsson et al. 1971, Friðleifsson et al., 1999, Franzson et al., 1999, 2002). In Figure 3, we outline two potential interglacial intervals, at about 600 m depth and at about 1200 m depth. The intrusive rock intensity increases with increasing depth and has been estimated as high as 50 to 60% at around 2 km depth (Franzson, 2004), but varies from well to well. The geothermal fluid at Reykjanes is a modified sea-water, and the hydrothermal alteration pattern is characterized by typical greenschist facies mineral assemblage. It differs, however, from the meteoric recharged high-temperature hydrothermal systems in Iceland in showing much greater abundance of base metals (Zn, Cu), and an abundance of anhydrite ($CaSO_4$) at relatively shallow depths. The abundant anhydrite formation results from mixing of cold recharging seawater with the hydrothermal brine, which results in a self-sealing process that caps the geothermal system.

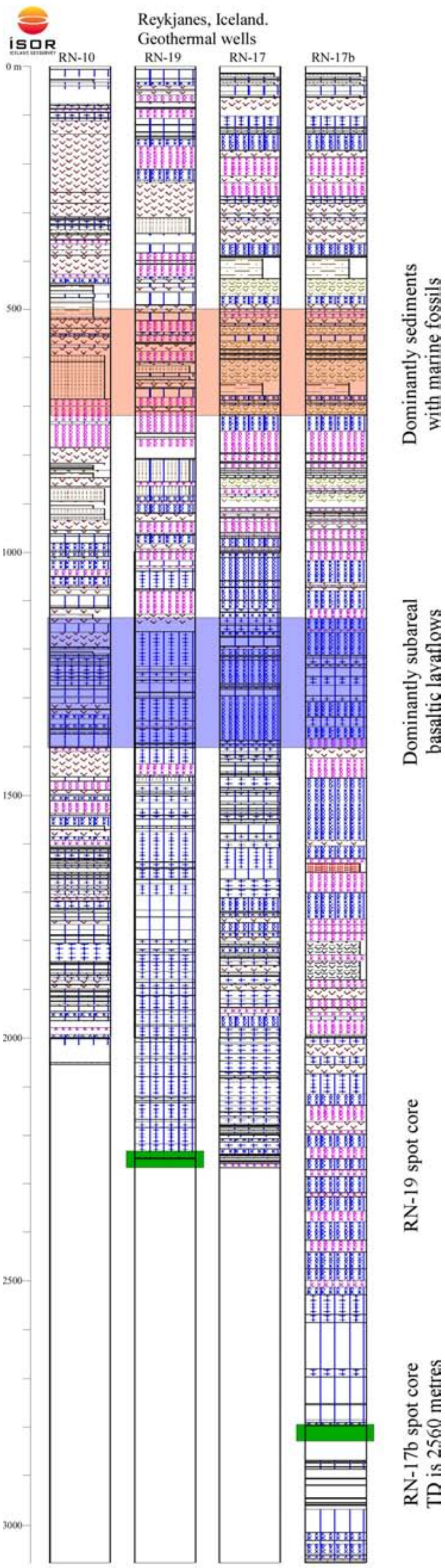

Figure 3: To the right are detailed lithological logs from selected wells at Reykjanes. The blue pattern in these logs indicates crystalline to glassy basaltic units. Red and brown indicate hyaloclastite units and green indicates sedimentary units. The orange and blue boxes highlight units believed to be formed during interglacial periods. Green boxes show where the cores were collected

Late Weichselian/Early Holocene marine fossils have been observed and studied at several places on the Reykjanes peninsula, both at the surface and in boreholes. The elevations of these findings seem to range between 50 meters above sea level down to 50 meters below sea level. Norðdahl and Pétursson (2005) present a model of relative sea level changes in the western and southwestern part of Iceland in the Late Glacial and early Holecene times. Their model indicates that during the period of 12000 to 9000 years BP the relative sea level changes lie between the aforementioned range of +/- 50 meters. Therefore, within this 3000 years period of deglaciation, the real subsidence rate within the active rift area is obliterated by the noise of the relative sealevel changes. Another factor, also playing a role, is the difficulty in assigning the marine fossils found in the boreholes to a specific environment, i.e. if they are *in situ* or being washed ashore. Due to these factors, evaluation of the subsidence rate based on marine fossils is inconclusive without detailed age determinations, not available at present. Therefore, we have approached the problem in estimating the subsidence rate by accepting an error bar of some +/- 50 meters.

At approximately 500 metres depth in well RN-10, white calcite fragments were found and when inspected further, it was apparent that these were shell fragments. More fragments were found at 630 metres depth, strongly indicating marine sediments. The fragments (Figures 4 and 5) encountered were of several different species, amongst them barnacles, bryozoans, bivalves and sea urchins.

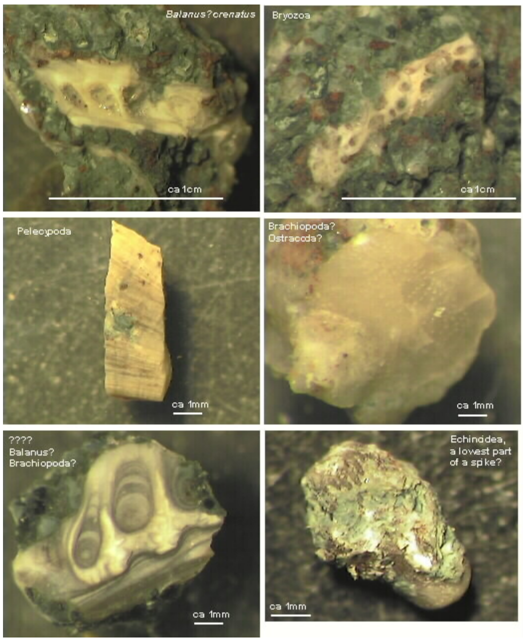

Figure 4: Shell-fragments from about 630 metres in well RN-10. The fragments are probably from barnacles, bryozoans, mollusks, brachiopods and sea urchins

This combination and types of marine life, as well as the overall low roundness of the grains in the sediments, indicate shallow environment and sediments which only have been transported short distances. A depth of less than 50-100 meters may be assumed.

A ^{14}C age determination of these fragments is probably not possible since the calcite in the shells has re-crystallized at temperatures around 200°C and above (Figure 5). While our described observations relate to well RN-10, these sedimentary sequences including fossils are found in most of the studied wells at Reykjanes, including RN-17 and RN-19. Due to extensive greenschist facies alteration within the Reykjanes high-temperature field, good preservation of fossils is not expected. However, a hole drilled a few hundred meters outside the geothermal field where subsurface temperatures are lower could be ideal for detailed chronostratigraphic research.

Lithologic logs of the wells at Reykjanes (e.g. see Figure 3), show that the wells have penetrated relatively thin hyaloclastite formation at shallow levels, that are interbedded with the marine sediments at around 500 meter depth and deeper. The tuff-rich hyaloclastite formations indicate shallow water depth, irrespective of its submarine or subglacial nature (e.g. Franzson 2004). The series of crystalline lava flows, however, could only form at subaerial conditions during an interglacial period. Looking at the stratigraphic profiles (Fig. 3), it appears that the top of the first thick pile of crystalline lava flows in wells RN-10, -17, -17B and -19, occur at about 1200 (± 50) metres depth, and formed either during the last interglacial (Eemian), from 115-130 Ka ago (Willerslev, 2007), or the second to last interglacial period (Saale) from 200-250 Ka ago (Lowe and Walker, 1998). Theses approximations give subsidence velocities of 10.4 and 6.0 mm/year respectively. The latter figure is close to the 6.5 mm/year subsidence rate estimated from satellite radar interferometry for the plate boundary in SW-Iceland (Vadon and Sigmundsson, 1997).

Further study of the species of the fossils from 630 metres, might reveal if they are arctic fauna or not. If they are from an interglacial period, it supports the idea that the lava series below 1200 m depth are from the second last interglacial period, Saale, which would support a mean subsidence velocity in the region of about 6 mm/year.

If the same criterion is applied to the core from the RN-17B, the rocks collected from about 2560 meters TD, might be about 430,000 years old.

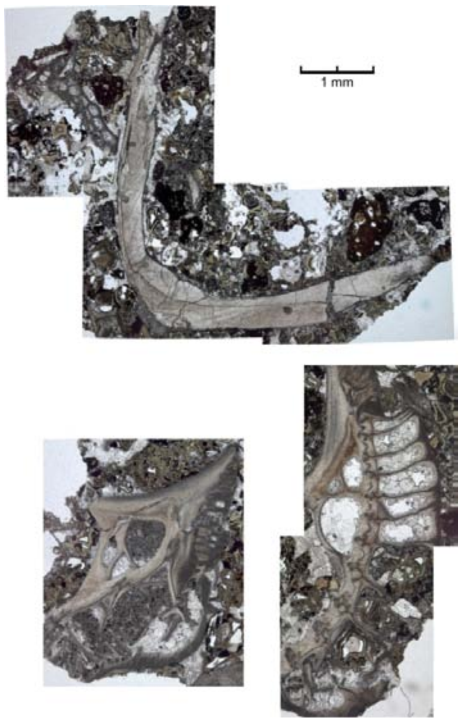

Figure 5: Microscopic images of shell fragments from 630 metres in well RN-10. The upper is probably a mollusk and the two lower barnacle fragments, which seem to be somewhat re-crystallized

3. THE SPOT CORES

The first spot coring was attempted in well RN-19 in April 2005 at 2045 m depth. That resulted in a 2.7 m long, 4" diameter drill core which consisted of a coarse grained dolerite intrusion. High angle fractures with dip angles of 70°-85°, lined with partially healed chlorite-actinolite veins, were probably the main reason for the splitting and jamming in the core barrel. Besides the high angle fractures, low angle (20-40°) set of actinolite veins were also observed.

In late November 2008 a very successful spot coring test was performed at 2800 m depth in the production well RN-17B at Reykjanes. Well RN-17B was being reconditioned by sidetracking it out of well RN-17 at 930 m depth, to become an inclined exploration/production well. The newly built ICDP core barrel and core bits proved just perfect for our IDDP purpose of coring in high temperature wells (Figure 6).

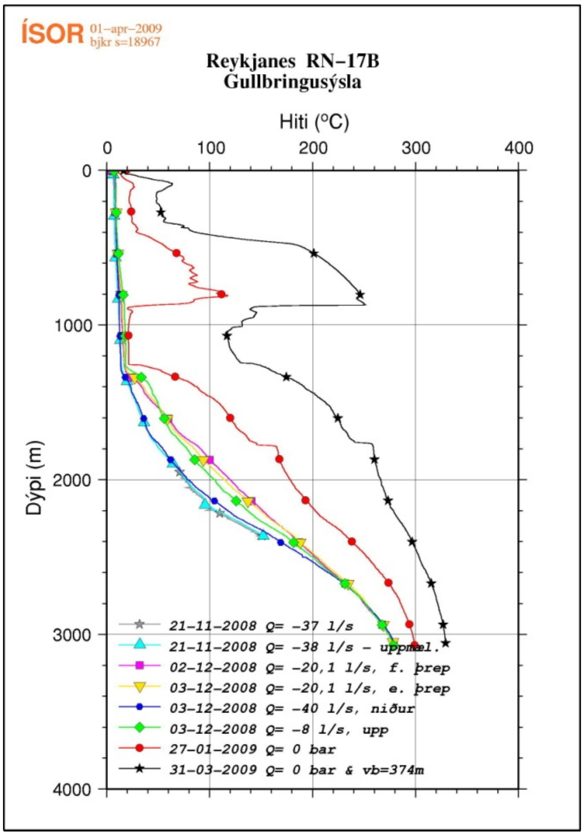

Figure 6: The last temperature log (from 31.03.2009) shows that the formation temperature during coring was at least 320°C in well RN-17B

3.1 The RN-19 Spot Core

The core drilling was conducted on Sunday, the 10th of April, and the core was retrieved on Monday, the 11th of April 2005. The core bit used was a Baker Hughes PDC core-bit type: BHC 606-8½" x 4" HT 30 treads (Figure 7). The coring operation went well for the first approximately 1.7 m, with a weight on bit at about 2-3 tonnes, a ROP around 10 m/hr, a rotation on bit at 50-60 RPM, and a torque around 1100 dNm. After coring approximately 1.7 m, a drop in torque was observed and drilling did not advance, which most probably indicated core jamming. In order to keep the core-bit going, the driller increased the weight on bit and managed to continue coring for another meter - before the torque decreased again, indicating core jamming for the second time during this core run.

The reason for the core jamming was related to subvertical fractures, which were filled with actinolite. The core recovery was good and the drilled core being in a generally good condition. The core-bit seemed to work quite well until the core jammed. The wear on the bit, however, seemed too severe and unsatisfactory.

Figure 7: A close-up picture of Baker Hughes PDC core-bit after the 1st spot coring operation in well RN-19. Some of the PCD's were chopped and one was damaged

Approximately 2.7 m of core were drilled and the core recovery was close to 100%. After the drilled core was laid out at surface, the total length of the core in the aluminum core barrel was measured at about 2.97 m due to the fracturing of the core. The first 2 m of core were in quite a good condition, fractured but continuous, whereas the last approximately 1 m of core was clearly more fractured, broken up and crushed towards the bottom (Figure 8).

Figure 8: The core cut into a dolerite intrusion with high angle actinolite veinsf that are quite visible in the box to the left. The top of the core is in the box to the right - bottom right corner of the image, looking downwards. The boxes are 1.6 m long and the aluminum liner is still around the bottom of the core

3.2. The RN-17B Spot Core

During the 25th of November 2008 a very successful spot coring test was performed at 2800 m depth in the production well RN-17B at Reykjanes. Well RN-17B was being reconditioned by side-tracking it out of well RN-17 at 930 m depth below the production casing. The core test was performed in an open hole at 35° inclination with newly built coring equipment, the well trajectory direction is shown in Fig. 2. A 9.3 m hydrothermally altered hyaloclastite breccia was cored with 100% core recovery. The core bit experienced up to 155-180°C for a short period during coring, while it remained close to 100°C during most of the core cutting operation, measured and digitally recorded with a memory tool within the core barrel. The entire operation with tripping in and out of the hole took some 33 hours rig time.

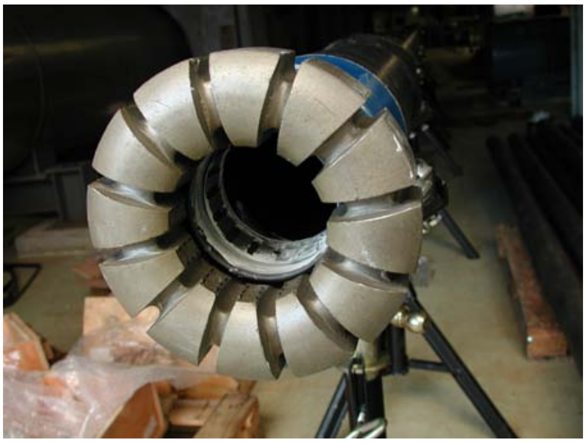

Figure 9: The ICDP core bit and core catchers

Originally, it was intended to perform the coring test after the 9 5/8“ perforated liner had been landed on the bottom of RN-17B. However, the HS company decided to deepen and side-track the well a bit further after 2798.5 m depth had been reached, in an attempt to improve the well - a deepening that might have excluded IDDP’s chance to perform the coring test. Therefore, after having considered the safety and the stability of the inclined well, it was decided to perform the coring test in an open hole close to 2800 m depth (about 2560 TD). The reservoir temperature at that depth was later confirmed to be approximately 320° C (see Figure 6). Accordingly the cooling efficiency of the coring equipment proved satisfactory.

Figure 10: Six boxes, 1.65 m each, full of 4” drill core from RN-17B

The core consisted of hyaloclastite breccia, interbeded with finer grained sediments (silt) which contains white fragments that suggest the presence of fossil shell material. Preliminary thin section study was not conclusive of an organic origin, because if any original calcite had existed, it has completely been replaced by epidote.

In addition to the interbedded silt layers possibly containing fossils, the high vesicularity of the basaltic volcanoclasts in the hyaloclastite breccia is suggestive of relatively shallow water interaction.

4. SUBSIDENCE RATE AT THE SLOWLY SPREADING REYKJANES RIFT ZONE

Our rough estimation of subsidence rate at Reykjanes, as discussed above, based on the lithology of the drillfield, yields a rate of about 6 mm/year. This gives an age of some 430,000 years for the RN-17B hyaloclastite core at 2.5 km vertical depth. This seems to fit neatly into one of the structural models of Pálmason (1986) as shown below (Figure 11). Evidently the heat flow calculation of Pálmason (1986) is irrelevant to our convective high-temperature hydrothermal system at Reykjanes, while the subsidence rate fits neatly to this model for the middle of the rift zone.

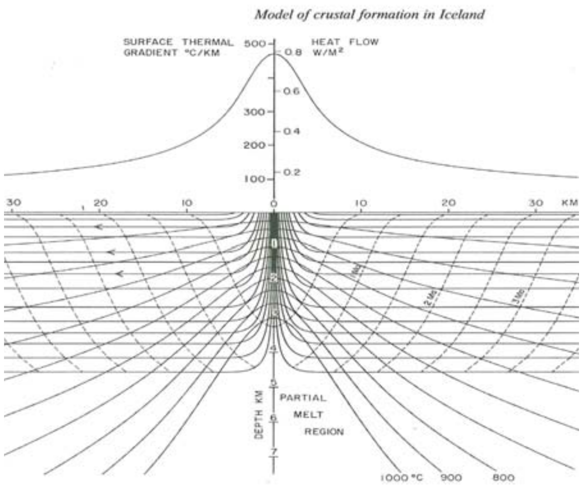

Figure 11: A structural model from Pálmason (1986), showing lava trajectories (arrows), lava isochrones (dashed), calculated isotherms as well as surface gradient and heat flow. The model parameters used are: spreading half rate, 1 cm/year, lava production rate $5x10^{-5}$ km^2/yr; standard deviations of crustal strain rate and lava deposition rate 2 km; and normal fault fraction of crustal strain, 0.5

CONCLUSION

Two spot cores have been collected at the sea-water recharged Reykjanes high temperature field in SW-Iceland, in connection to the Iceland Deep Drilling Project (IDDP). Both these spot cores have been funded by the International Scientific Continental Drilling Program (ICDP). The core in RN-19 was collected at 2245 m depth, while the spot core at RN-17B was collected at some 2560 m depth below the present surface.

Shallow marine fossils at great depths within the Reykjanes field strongly indicate a fairly continuous subsidence over the last few hundred thousand years at Reykjanes. This, in turn can be used to explain the occurrence of shallow water volcanoclastic hyaloclastite breccia at 2560 m depth in the RN-17B drill core. Our interpretation of the data indicates a subsidence rate of some 6 mm/year over the last 500,000 years or so. The slowly spreading Reykjanes ridge has an average spreading rate of some 19 mm/year (Sigmundsson and Sæmundsson 2008), which indicates that the ratio of subsidence/spreading could be close to 1/3 at the very landward extension of the Reykjanes ridge.

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