Paper Number
T23B - 0538

a 5 km Deep Drillhole Underway to Investigate Deep Geothermal Resources on the Mid-Atlantic Ridge

The Iceland Deep Drilling Project

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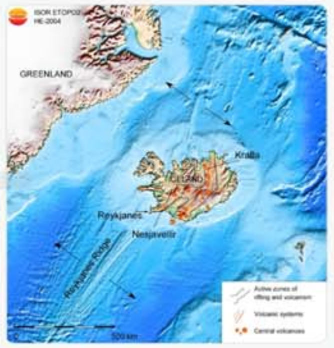


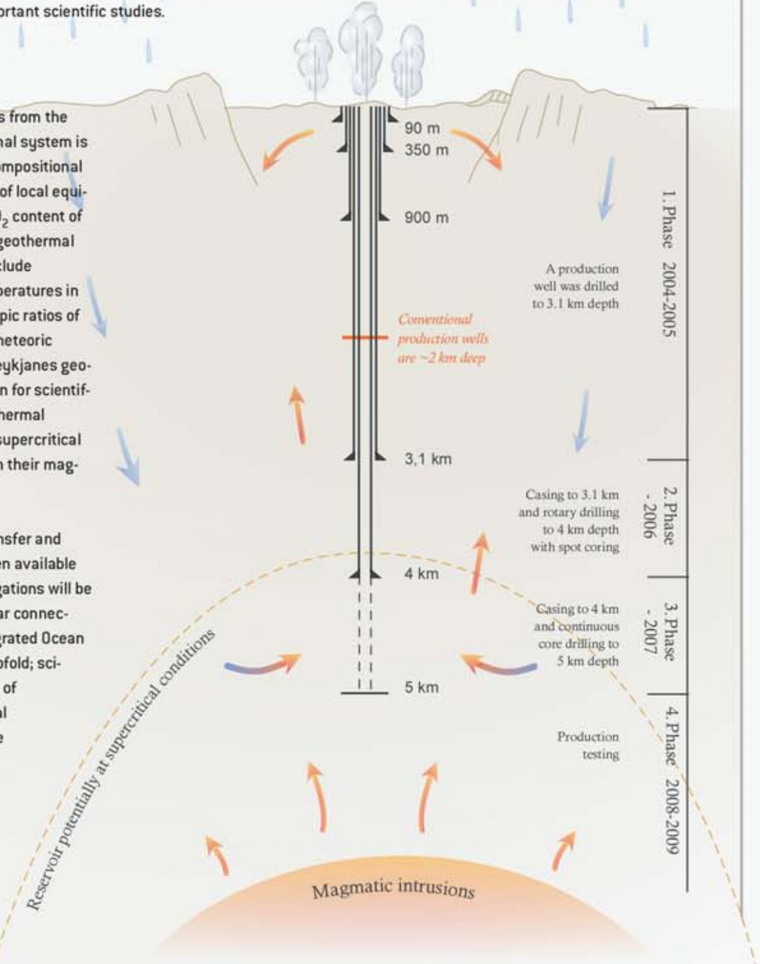
Abstract

The Iceland Deep Drilling Project (IDDP) is a long term study of high-temperature hydrothermal systems on the Reykjanes Peninsula, where the Mid-Atlantic Ridge emerges on to the SW tip of Iceland. The IDDP is a collaborative effort, by a consortium of Icelandic power companies and the Icelandic government, formed to investigate if utilizing supercritical geothermal fluids would improve the economics of power production from geothermal fields.

Over the next decade this will involve drilling a series of wells >4 km deep, to reach temperatures of >450°C. The deepest of these wells so far was completed at 3.1 km in February 2005. The rocks penetrated consist of Holocene basaltic lavas, subglacial hyaloclastites, marine sediments, submarine pillow basalts, and diabase dikes. In 2006, the IDDP will rotary drill and spot core this, or another candidate well, to 4.0 km, and in 2007, the IDDP will deepen the borehole from 4.0 km to 5.0 km, using continuous wireline coring. Such deep, hot wells present both technical challenges and opportunities for important scientific studies.

For example, preliminary analyses of rock samples and fluids from the existing geothermal wells indicate that the shallow geothermal system is complex, as indicated by paragenetic relations and strong compositional zoning in calc-silicate minerals, such as epidote. Calculation of local equilibria between calc-silicates and calcite suggests that the CO_2 content of the geothermal fluids increased during the evolution of this geothermal system. Zoned hydrothermal amphiboles at 3.1 km depth include tschermakitic hornblende (>13 wt. % Al_2O_3), suggesting temperatures in the upper 300°C range. Similarly, analyses of hydrogen isotopic ratios of epidotes and amphiboles currently underway indicate that meteoric water has mixed with seawater during the evolution of the Reykjanes geothermal system. The Reykjanes Peninsula is a superb location for scientific investigations of the deeper levels of a high enthalpy geothermal resource. Coring below 4.0 km is designed to penetrate into supercritical fluids which couple black smoker hydrothermal systems with their magmatic heat sources.

Supercritical fluids have greatly enhanced rates of mass transfer and chemical reaction. Such environments have never before been available for comprehensive direct study and sampling. These investigations will be a very important contribution to global science and have clear connections to the studies of ridge-hotspot interactions by the Integrated Ocean Drilling Program. The broader implications of the IDDP are twofold; scientifically it will permit a quantum leap in our understanding of active hydrothermal processes that are important on a global scale, and secondly, if the industrial aims are successful, the resulting technology could have a major impact on improving the economics of high-temperature geothermal resources worldwide. The IDDP has welcomed participation by an international group of scientists that will investigate and test models of the coupling of hydrothermal and magmatic processes.



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Preliminary Results from Phase 1

Reykjanes is the landward extension of the Mid-Atlantic Ridge. The geothermal system is hosted in an active ophiolite-like environment

Figure 1: Back scattered electron photomicrograph showing complex oscillatory zoned epidote with Fe-rich cores and Al-rich rims from 1430 m depth in well RN-10 at Reykjanes.

Figure 3. Back scattered electron photomicrograph showing altered diabase from 2350m depth in well RN-17.

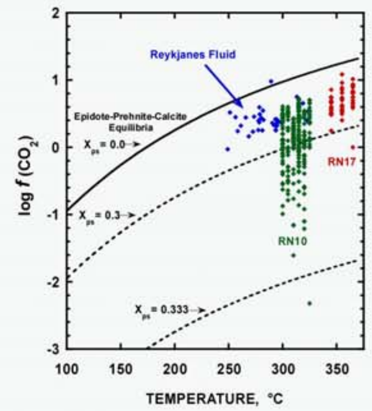

Figure 2. Calculated fugacity of CO_2 as a function of temperature, showing isopleths of epidote compositions for epidote-prehnite-calcite equilibria. Blue symbols are measured fluid compositions, Green symbols are calculated CO_2 based on zoned epidotes from well RN-10, Red symbols are calculated CO_2 based on epidotes from well RN-17.

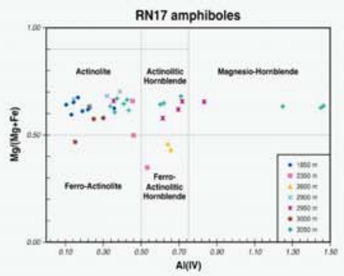

Figure 4. Amphiboles in RN-17 range in composition from actinolite through magnesio-hornblende, although the latter compositions have only been identified at depths below 2950 meters. Strong compositional zoning has been identified in some samples, e.g., in vein amphiboles from 2350 meters (BSE image), which have cores of ferro-actinolitc hornblende and rims of actinolite. By analogy with studies done on cuttings from wells in the Nesjavellir geothermal system (Hreggvidsdottir, 1987), the presence of hornblendic amphiboles implies that temperatures have exceeded 350°C at depths below 2950 meters in RN-17. This conclusion is consistent with data from fluid inclusion studies currently underway.

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Some comments on epidote zoning and predicted CO_2 fugacities in two geothermal wells at Reykjanes

(Text and figures presented represent a portion of Adam Freedman's Senior Honors Thesis at Stanford University)

In order to predict the evolution of CO_2 in Reykjanes geothermal fluids based on the Epidote - Prehnite-Calcite-Quartz buffer (proposed by Stefansson and Arnorsson 2001), zoned epidotes from drillhole RN10 (between 1 and 2 km depth) and drillhole RN17 (between 2 and 3 km depth) were analyzed by electron microprobe. Epidotes between 1 and 2 km depth in RN10 are strongly zoned with Fe^{3+}-rich cores and Al-rich rims (Figure 1). The earliest formed epidotes have values of the mole fraction of the Fe^{3+} component (Xps) as high as 0.48. Compositions range from Xps of 0.18 to 0.48. In contrast, epidotes from 2 to 3 km depth in RN17 do not have the extremely Fe^{3+}-rich cores; compositions range for Xps 0.18 to 0.3, however the zoning is similar in that the latest formed epidotes are Al-rich.

Assuming ideal site mixing for epidote solid solutions, the fugacity of CO_2 in equilibrum with these epidotes and the minerals prehnite-calcite-quartz are computed from the equilibrium constant for the reaction

$$2\ \text{Al-Epidote (clinozoisite)} + 2\ \text{Calcite} + 2\ H_2O = 3\ \text{Prehnite} + 2\ CO_2$$

Results are shown in Figure 2 as a function of temperature (approximated from the boiling point curve for water).

The following relations are apparent:

1. At depths between 1 to 2 km in drillhole RN10 the early Fe^{3+}-rich cores of epidote crystals formed from fluids with CO_2 fugacities of < 1, values much less than present day geothermal fluids.
2. The content of CO_2 in geothermal fluids increased during the evolution of the geothermal system near drillhole RN10. Here Al-rich rims of epidotes formed from CO_2-rich solutions that are similar to present day geothermal fluids.
3. Low-CO_2 fluids, and related Fe^{3+}-rich epidotes (Xps > 0.3), were never present in the deep portions of the geothermal system near drillhole RN17. Predicted CO_2 contents of fluids in drillhole RN17 between 2 and 3 km are in accord with present day measured values."

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RN-17 flow tested November 28, 2005

The flow test lasted for 100 minutes before the wellbore became blocked at 376 m depth. It is not clear if this blockage was caused by rock debris, casing damage, or for some other reason. A large quantity of rock debris, roughly estimated to be 300-500 kg, was ejected during the test. The highest wellhead pressures reached were 59 bar-g, and the highest flow rate about was 130 kg/s. The reservoir engineers estimate that in order to reach such high pressure, even only for few minutes, the downhole temperatures must above 320°C, indicating an input pulse from 2-3 km depth . For some time before that, the wellhead pressure was only about 20 bar-g, corresponding the well temperatures down to 2 km of about 265°C. The blockage will be investigated further before attempting to remove it with a drill rig.

Acknowledgments:

Our thanks to Hitaveita Sudurnesja, Landsvirkjun, Orkuveita Reykjavikur and the Icelandic Government for financing the IDDP and encouraging international cooperation, and to the ICDP and the NSF for supporting the scientific program.