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A plan for a 5 km-deep borehole at Reykjanes, Iceland, into the root zone of a black smoker on land

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Abstract. A summary workshop report describing the progress made so far by the Iceland Deep Drilling Project (IDDP) is presented below. The report provides recommendations concerning technical aspects related to deep drilling, and invites international participation in both the engineering and the scientific activities of the next phase of the IDDP. No issues were identified at the workshop that should rule out attempting the drilling, sampling and testing of the proposed IDDP-2 well. Although technically challenging, the consensus of the workshop was that the drilling of such a hot deep well, and producing potentially hostile fluids, is possible but requires careful contingency planning. The future well will be explored for supercritical fluid and/or superheated steam beneath the current production zone of the Reykjanes geothermal field in SW Iceland. This deep borehole will provide the first opportunity worldwide to directly investigate the root zone of a magma-hydrothermal system which is likely to be similar to those beneath the black smokers on the world-encircling mid-ocean rift systems.

1 Introduction

Ninety-four engineers and scientists attended a workshop on the Iceland Deep Drilling Project (IDDP) from 3 to 5 September 2012, at Svartsengi, SW Iceland to discuss (i) the lessons learned from the first IDDP-1 exploratory borehole, in 2009 at the Krafla Volcano in NE Iceland, and (ii) plans to drill and study a new 4–5 km-deep borehole, IDDP-2, at Reykjanes, which is planned to be drilled in 2014–2015 at the SW tip of the island where the Reykjanes Ridge emerges from the Atlantic ocean (Fig. 1).

The workshop was funded by the International Continental Scientific Drilling Program and by the IDDP. The participants were from Iceland, Canada, France, Germany, Japan, Italy, Netherlands, New Zealand, Norway, Switzerland, UK, and USA, including several students and young researchers who presented their ongoing work relevant to the IDDP.

Since 2000 the Iceland Deep Drilling Project has planned to drill three 4–5 km-deep holes into the roots of three different high-enthalpy geothermal systems in Iceland. The workshop in September 2012 was the ninth in a series of IDDP workshops since 2002. An early key outcome was the IDDP Feasibility Report (2003, http://www.iddp.is), reporting on (1) geosciences, (2) drilling techniques, and (3) fluid handling and evaluation. One of the chief conclusions of that report was that a well that produces supercritical fluids should have a greatly enhanced power output relative to conventional high-temperature geothermal wells. This initial study identified three locations: Krafla, Hengill (Nesjavellir) and Reykjanes, (see Fig. 1) as being suitable locations to site deep wells to produce supercritical geothermal fluids. The concept was that at each site the geothermal industry would drill and case a 3 or 3.5 km-deep well that would then be deepened by the IDDP consortium to investigate the system below and explore for supercritical fluids. A short paper on the concept of the IDDP itself (Friðleifsson et al., 2013) is included in a special issue of Geothermics which we expect will be published this year.

In common with most high-temperature geothermal systems in Iceland, the systems at Krafla and Hengill contain

Figure 1. The slow spreading ($2\,cm\,a^{-1}$) Mid-Atlantic Ridge (MAR) connects with central neovolcanic rift systems of Iceland (dark blue). Black circles are high-temperature geothermal systems. RVZ = Reykjanes Volcanic Zone; EVZ = Eastern Volcanic Zone; NVZ = Northern Volcanic Zone. The SSZ = Southern Seismic Zone and TFZ = Tjorness Fracture Zone. The white areas are glaciers.

Figure 2. Oblique aerial view looking NE of the Reykjanes Peninsula showing the location of the Reykjanes Geothermal Field (steam plume in center) and the Svartsengi Geothermal Field in the far distance (upper right). Note the ridges of hyaloclastites surrounded by Holocene basaltic lava flows.

dilute geothermal fluids, only slightly modified by water/rock reactions and the possible admixture of some magmatic gas. In contrast, and in keeping with its location on a narrow peninsula surrounded on three sides by the Atlantic Ocean, the Reykjanes system contains hydrothermally modified seawater. The economic motivation behind the Iceland Deep Drilling Project (IDDP) is that deeper geothermal wells that penetrate higher enthalpy resources, capable of producing supercritical fluid, have the potential to greatly enhance the power output of geothermal fields without enlarging their size and environmental footprints (Friðleifsson and Elders, 2005). The first IDDP well, the IDDP-1, was drilled in the Krafla – a caldera in NE Iceland. It was intended to explore for supercritical geothermal resources at 4.5 km depth, but had to be terminated at only 2.1 km depth when it encountered molten rhyolite magma (Elders et al., 2011). The well was controlled by circulating cold water as drilling mud. It was completed as a production well, with an inner sacrificial casing cemented inside a production casing, and with a perforated liner to the bottom of the well. It was cooled extensively for about 2 months, and after many months of thermal recovery it was flow tested for more than 2 yr. It soon became clear that we were dealing with the world's hottest geothermal well, with wellhead temperatures up to 450 °C and wellhead pressure about 145 bar. The superheated steam produced from the well is sufficient to generate some 35 MW_e.

Because the Reykjanes peninsula (Fig. 2) is the landward extension of the Mid-Atlantic Ridge there is widespread interest within the scientific community in this drilling project. As the geothermal fluid at Reykjanes is modified seawater, this deep borehole will provide the first opportunity worldwide to directly investigate the root zone of a magma-hydrothermal system which is likely to be similar to those beneath the black smokers on the world-encircling mid-ocean rift systems. A complete ICDP-IDDP Workshop Report 2012 is provided at http://www.iddp.is.

2 Well IDDP-1 at Krafla

In 2006, the operator of the Krafla Geothermal Field offered to drill a deep borehole, called the IDDP-1, that was designed to reach supercritical conditions. Krafla lies near the northern end of the central rift zone of Iceland, within a volcanic caldera, where a 60 MW_e geothermal electric plant is currently operating (Fig. 1). Eruptions of the Krafla volcano are episodic occurring at 250 to 1000 yr intervals, with each episode lasting 10–20 yr, the most recent one took place from 1975–1984. The presence of a magma chamber beneath the caldera at 3–7 km depth was inferred from S wave attenuation during the 1975–1984 eruptive episodes. More recently this was confirmed by an MT-TEM survey. Basaltic rocks in the main reservoir are altered to epidote-actinolite mineral assemblages, and temperatures can reach 340 °C at depths as shallow as 2 km. Produced geothermal fluids are dilute solutions of meteoric origin modified by reaction with hot basalts.

In 2009 the borehole IDDP-1 was drilled near the center of the Krafla caldera, a site chosen because supercritical conditions were thought to be likely at 4 km depth. The IDDP-1 well was situated above what was interpreted to be a depression between two shallow lobes of low resistivity in an MT-TEM model, where the depth to a brittle-ductile boundary was estimated to be close to 4.5 km depth (Friðleifsson et al., 2013). In the spring of 2009 drilling had progressed without problems to 2 km depth, where the deepest rocks recovered were mostly unaltered basalt dikes and irregular lenses of felsite. In the next 100 m multiple acute drilling problems occurred. The drill bit got stuck twice, was cut loose and the well side-tracked two times before the reason for the drilling difficulties became apparent in June 2009. At 2104 m depth the drill bit penetrated molten rhyolite magma, which flowed into the well. In the third attempt the drillers were prepared and decided not to attempt retrieving the drill string but remained in magma with full circulation (~ 70 L s^{-1} of cold water) for some 28 h. Once retrieval was attempted the drill string was loose but the lowest 9 m of the open borehole was filled with chilled volcanic glass. Drilling was terminated and the hole was completed as a production well, cased down to 2072 m (Fig. 3) and cooled for over a month. Evidently the resolution of earlier geophysical studies was not sufficient to identify the magma intrusion that the IDDP-1 penetrated.

Extensive studies of this rhyolite indicate that the estimated temperature of the magma is approximately 900 °C, with a volatile saturation pressure of about 40 MPa, a value between hydrostatic and lithostatic. The very low value of δD in the rhyolitic glass (−121 ± 2 ‰) is remarkably similar to that of hydrothermal epidotes from Krafla geothermal wells and could neither be produced from hydration by local geothermal waters nor by mantle-derived waters; instead the source of its hydrogen is apparently derived entirely from hydrothermal alteration minerals. Thus this rhyolite magma formed in a basaltic volcano by partial melting of hydrothermally altered basalts (Elders et al., 2011; Zierenberg et al., 2013).

It took the IDDP-1 well over 6 months to heat up to ambient temperature before flow testing. The well proved to be highly productive. It became the world's hottest producing geothermal well, with wellhead temperatures of up to 450 °C, shut-in pressure of ~ 145 bars, and enthalpy approaching 3200 kJ kg^{-1}. Production tests at different wellhead pressures indicate that the well would be capable of producing up to 36 MW_e, depending on the design of the turbine system. Unfortunately, however, after two years of flow testing, the well had to be shut down in July 2012 to repair some of the wellhead equipment and to replace the wellhead master valves. At this time it is not clear if this well will be allowed to flow again for power production, or be used for re-injection.

3 Plans for drilling well IDDP-2 at Reykjanes

Planning for the second deep well, IDDP-2 to ~ 3.5 km, to be drilled in the Reykjanes Geothermal Field in SW Iceland is now underway. According to a consensus arrived at in 2006 by the three energy companies, the plan is now that the field operator at Reykjanes, HS Orka hf, is now considering funding and drilling a "well of opportunity", IDDP-2 to ~ 3.5 km.

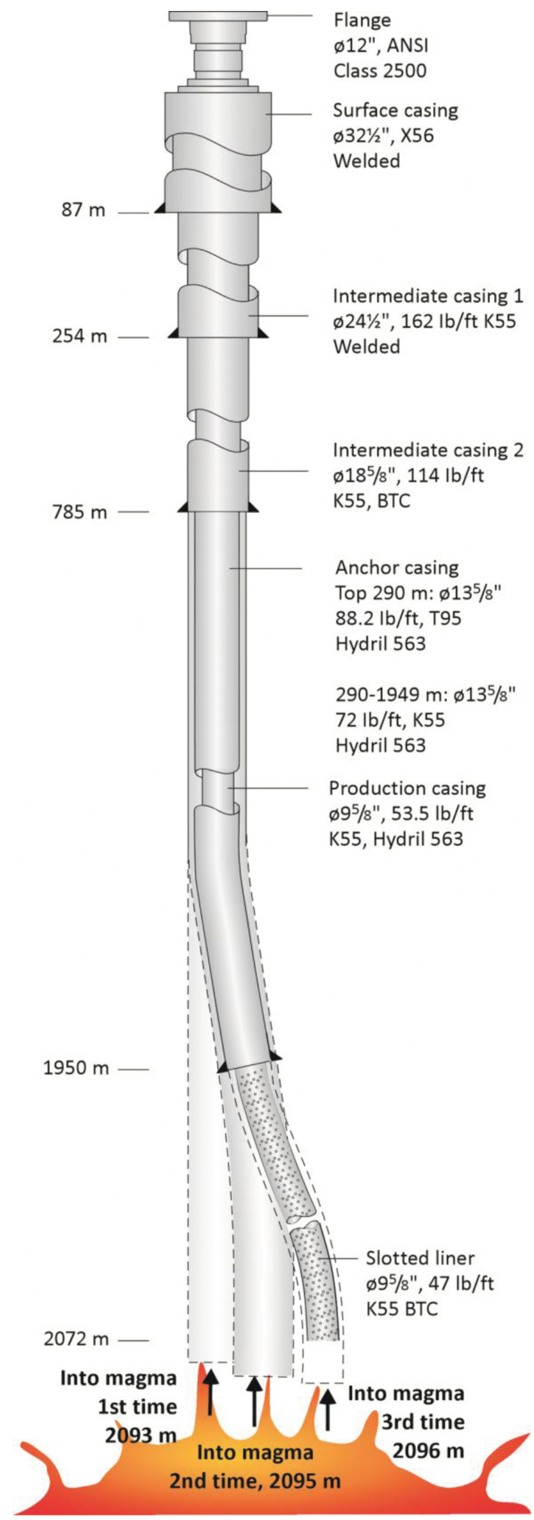

Figure 3. Well IDDP-1 at Krafla as completed.

Then IDDP consortium would fund the deepening and testing of that well to 4.5–5 km. Once again the IDDP is inviting international scientific participation with the international science team again being responsible for obtaining funds for scientific sampling, data collection, and study, both on-site and in the laboratory.

Due to drilling problems encountered in IDDP-1, the cost of drilling of that well in Krafla was very high. The cost of drilling and testing together probably approached about USD 20 million. The HS Orka team is currently re-evaluating the drilling program and cost estimates for the IDDP-2 well at Reykjanes in order to optimize the drilling and testing while lowering the costs significantly. One option would be to scale down the drilling program by drilling and casing a smaller diameter well than the IDDP-1. This re-evaluation is expected to be completed in 2013. It is already quite clear that any expenditure of funds by the international science program will be highly leveraged by the very large contribution by the engineering program of HS Orka hf and the IDDP consortium. It is their funding that will create the opportunity for the science team to participate and the scientists will also benefit from the extensive practical experience and technical capability of the Icelandic geothermal industry.

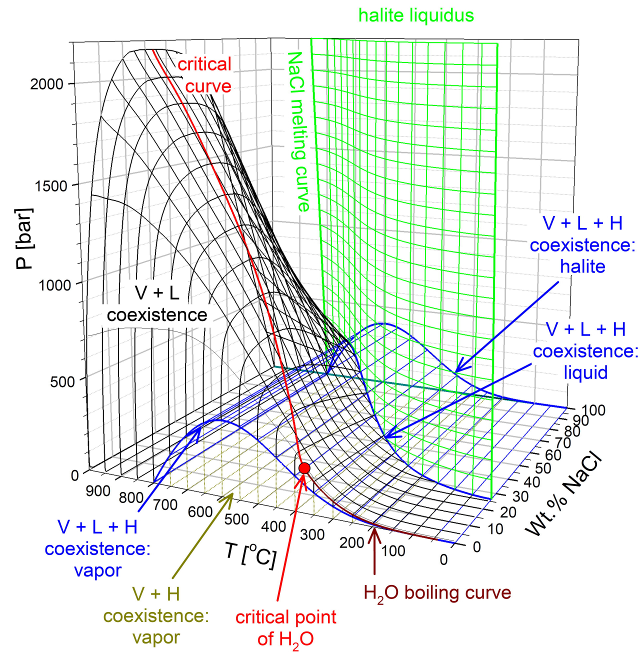

Figure 4. Phase diagram of the system H_2O-NaCl from ambient to magmatic conditions. From Driesner and Heinrich (2007).

4 Workshop results

The aims of the workshop were (1) to review the lessons learned from the IDDP-1, (2) to develop the criteria for optimizing the drilling of the IDDP-2, (3) to review the specifics of the site selection, (4) to define the drilling target better, (5) to broaden the scope of international participation and disciplinary range of the science program, (6) to coordinate the engineering and science programs, (7) to develop and coordinate strategies for funding both the IDDP-2 engineering and science activities, (8) to invite broader international and disciplinary participation, and (9) to prepare and distribute a report on the results of the workshop that documents its findings and recommendations, and publicizes the engineering, technical and scientific opportunities that the IDDP-2 offers.

After series of presentations dealing with (1), (2), (3) and (4) above, the workshop participants split up into three main subgroups (Geoscience, Fluid Handling and Drilling) to have more focused discussions about prioritizing the activities that should be performed before, during and after drilling the IDDP-2 deep hole at Reykjanes. By far the largest group was in Geosciences, so for practical reason two discipline-oriented subgroups were formed on diverse geosciences and hydrology. Each breakout group began with 5–10 min presentations relevant to the topic being discussed by the whole group or by subgroups. The following day the breakout groups continued with writing assignments to prepare reports to be submitted to the whole meeting. These reports are part of the SAGA report No. 9, available in full length at the http://www.iddp.is.

Each of the discipline groups concluded by listing (1) the essential, and (2) the recommended and/or desirable geoscience, hydrological, chemical, material, and drilling research and activities that should be undertaken in support of the proposed IDDP-2 well: pre-, during and postdrilling. The Geoscience group began by focusing on the past, recommending that as much information as possible should be obtained and interpreted in the next couple of years ahead of the drilling of IDDP-2 and make use of and gather information from new production/injection wells to refine existing conceptual model of the Reykjanes drill field. A series of recommendations for research and monitoring activities during and after drilling followed. The hydrology subgroups emphasized that the hydrology of saline geothermal systems is significantly more complicated than for dilute water systems. This is because the phase diagram for saline waters is more complex than that for dilute water. It shows a much wider temperature–pressure range between the coexistence of two phase vapor + liquid, and also shows regions of coexistence of vapor + salt and liquid + salt (Fig. 4). Preparation for the IDDP-2 drilling should consider the possible effects of this on achieving the project goals. The group felt that it is essential to develop a series of plausible conceptual models in which complex phase relations are taken into account. These models should cover possible scenarios for the deep parts of the system below the better known part of the reservoir that reaches down to about 2.5 km. Possible scenarios include (see Fig. 5) (i) a tight conductive deep zone below the reservoir formation down to the brittle-ductile transition;

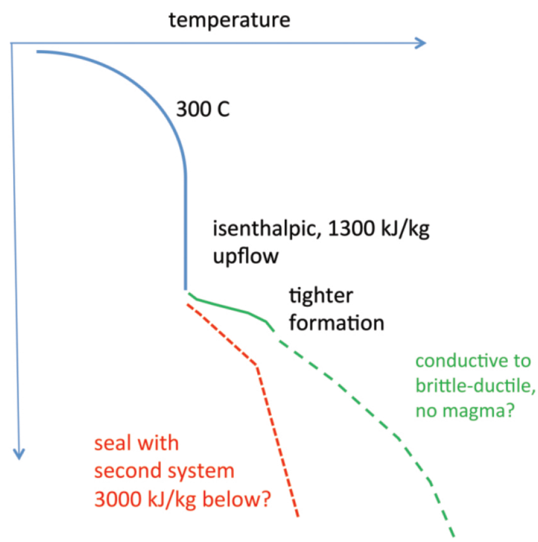

Figure 5. Thermal structure of the up-flow zone for different conceptual models of geothermal systems. Notice difference in thermal structure at depth.

(ii) a tight seal of finite thickness separating the currently exploited reservoir formation from a deeper, supercritical or superheated second reservoir; or (iii) alternative scenarios that need to be formulated based on all available geological and geophysical information. Such models should pay particular attention to the recharge system, the water balance, and the boundaries of system. Possible ways to better constrain these may be obtained from modeling the causes of subsidence patterns, observed trends in vapor fractions, and geophysical survey data.

This was followed by discussion on possible mineralogical and physical methods to better constrain model parameters like temperature and pressure during and after drilling. The hydrology group concluded by recommending that concepts, predictions, and interpretation of data on enthalpy–salinity–pressure relations should be based on phase diagrams for saline fluids (Figs. 4 and 6) rather than approximations based on pure water diagrams.

The fluid handling group began their discussion by emphasizing that they neither knew in advance how high the temperature and pressure will be in IDDP-2 below 4 km depth, nor the composition of the fluid that might be encountered. The wellhead equipment, however, would need to be designed to handle whatever is produced. The best guess on possible temperature–depth profiles need be drawn upon what is known about the overlying presently exploited Reykjanes hydrothermal system. The formation at depth might be *very tight* with a very steep conductive thermal gradient to account for the high rate of heat discharged at the surface. Alternatively, a *sealed zone* might be present, separating the upper convective hydrothermal system from a lower very high-temperature convective system where fluid pressure might be at or above the pressure exerted by a column of fluid extending upward to the surface, as shown in Fig. 5 above.

Given these two contrasting temperature-depth models, different types of fluid could be produced. A reasonable starting point for designing the equipment that must handle the fluid that will be produced is to assume that it will be consistent with the composition of black smoker fluids, extrapolated to the temperature and pressure of the sub-sea reaction zone. These fluid compositions have been examined experimentally by basalt–seawater reaction at the anticipated (T, P). The expected pH's are approximately 4.0–5.5 which is near neutral at the in situ conditions. In contrast, there also is a possibility that highly saline brines might be present beneath the presently exploited hydrothermal system at the Reykjanes Peninsula, formed as a result of repeated subsurface injections of basaltic dikes into rocks bearing fluids initially of seawater composition. The brine produced by this mechanism would be very dense, and tend to migrate downward and accumulate above the transition zone from brittle to plastic conditions. The separated "steam" phase would migrate upward, possibly accumulating beneath an overlying self-sealed zone. Such a "steam" phase would carry some salt and a significant amount of silica. A discussion of how such a self-sealed zone might form and persist in an environment of regional extensional faulting is beyond the scope of the present discussion of the handling of fluids that might be produced from the IDDP-2. The important point is that if a relatively low density, salt-bearing and silica-rich "dry steam" phase is encountered and produced, that fluid is likely to carry a high concentration of non-reactive HCl°, formed by the hydrolysis reaction of salt with water at high temperature and a relatively low pressure. There will be silica precipitation and erosion problems, irrespective of whether black smoker-type brine is produced, or whether a very high enthalpy dry steam phase is produced. In conventional liquid-dominated hydrothermal systems, at temperatures below about 350 °C, low pH prevents polymerization and precipitation of silica. It is not known whether silica precipitation from black smoker-type brines at greater than 400 °C might be inhibited by the natural low pH of such fluids. In the event that dry steam is encountered at > 400 °C, the experience from IDDP-1 should provide insights about how to deal with silica precipitation in that environment. Furthermore, it appears that the most likely fluid that will be encountered in IDDP-2 will be very high-temperature black smoker-type brine. If so, scaling as a result of precipitation of various metal sulfides could be a major problem. If possible, production should be carried out at conditions that prevent metal sulfide scaling in the well, and so induce maximum scaling in a sacrificial portion of surface piping. But, without information regarding the actual composition of the fluid that will be encountered in IDDP-2, the importance of metal sulfide scaling is speculative. Nevertheless, because the likelihood of producing black smoker-type brines is high, computer modeling of the behavior of dissolved metals in such brine during

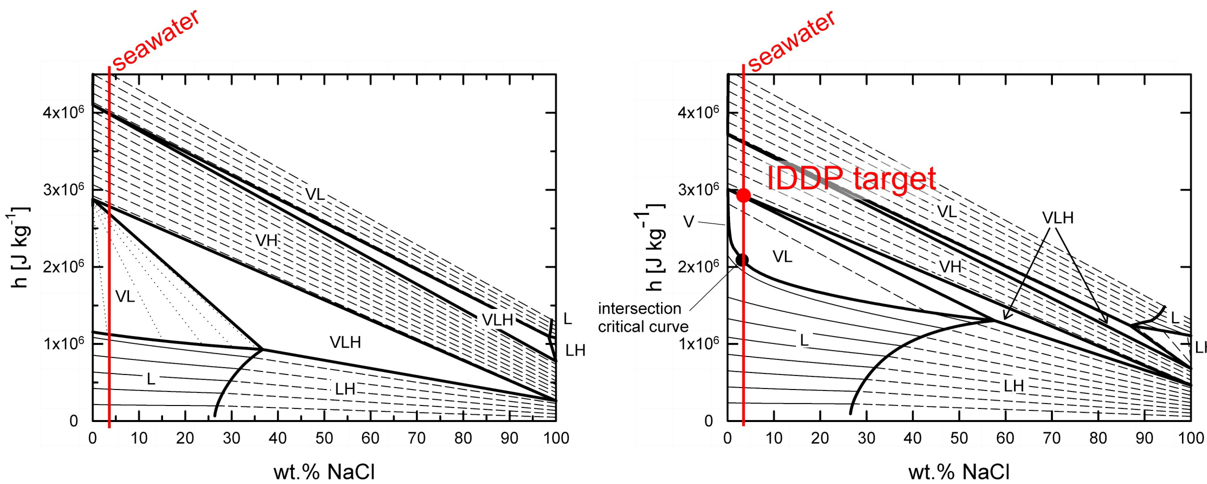

Figure 6. Enthalpy–salinity diagrams for geothermal conditions. Thin solid lines: isotherms in single-phase regions; dashed: isothermal tie lines in two phase regions. Based on Driesner (2007).

production should be undertaken soon, as a guide to methods of dealing with the problem of metal sulfide scaling. Finally, there is a potential for intercepting high levels of hydrogen sulfide, and fluids with high levels of toxic metals, so the hazards of fluid production and disposal need to be considered in advance of drilling. The fluid handling group concluded by emphasize a few items during the IDDP-2 operations such as (i) personnel safety, (ii) well integrity and (iii) that reservoir fluids uncontaminated by drilling fluids should be sampled. This was followed by listing up high priority items before, during and post drilling.

The Drilling Breakout Group emphasized that a comprehensive report on the drilling of IDDP-1 (Lesson Learned) was currently in progress by IDDP. That report should be comprehensive and the drilling group recommended its completion to aid in the planning of the IDDP-2. That report, and the analysis of the failure of the well-head valve on IDDP-1 should then supersede the discussions presented at the workshop. The group then listed several key items as follows:

i. *Safety*: as was demonstrated, the IDDP-encountered higher T and P than had been drilled previously. Also fluid with extreme corrosion and erosion potential could be met and dealt with. This would present drilling difficulties and challenges for standard materials, well designs and fluid handling protocols. On the other hand, these technical and safety challenges present opportunities for the improvement of materials and techniques that can then be applied to the exploration and commercial developments of the roots of geothermal systems worldwide.

ii. *Technical success*: IDDP-2 must be completed as a well that will be expected either to produce geothermal energy for 10 years or more, or to serve as an injection well. In addition, the well should be designed and built to collect the scientific samples and data required by the IDDP. The drilling group accepted the casing plan that had already been established for the IDDP-1 with significant redundancy. However, there are several areas where improvement of equipment and materials will be required for project success. Lessons learned from IDDP-1should be applied to the design of IDDP-2 and management of drilling operations to mitigate risk.

iii. *"The Lessons Learned report from the IDDP-1"* should be finished as soon as possible. When drilling into frontier environments, the drilling engineers are relying on the geologic models of temperature, pressure and fluid compositions. When unexpected conditions are encountered, the well design may not work as planned. In particular, careful analysis should be given to casing design, cementing procedures, the well head and selection of the appropriate materials. In addition, a clear management plan specifying roles and responsibilities should be established to streamline the decision process.

At the conclusion of the workshop conveners had a joint meeting of the SAGA committee and Deep Vision to discuss its outcome and implications. The most important outcome is that none of the wide ranging discussions of drilling, fluid handling, and geoscience identified "critical project issues" that should cause abandonment of the project. Producing much higher enthalpy geothermal fluids from the deeper, hotter, potentially supercritical zone, beneath the producing geothermal reservoirs in Iceland remains an attractive target. However drilling and testing these exploratory boreholes will be technically challenging and expensive. The experience gained from the IDDP-1 well reinforced the truism that drilling leads to surprises, requiring careful contingency planning. Better definition of the conditions in the target zone is a basic requirement for such planning. The discussions at the workshop and the activities suggested before drilling will reduce risk, and put plans for the IDDP-2 on a more confident footing.

The consensus of the geoscience and fluid handling groups is that at depth the Reykjanes system is most likely to be similar to the conditions underlying the high temperature hydrothermal vents (black smokers) on the Mid-Atlantic Ridge. Several vents at 5° S on the Mid-Atlantic Ridge produce supercritical fluids, more dilute than seawater, with temperatures measuring up to 464 °C. Many marine high-temperature hydrothermal vents on different mid-ocean ridges emit fluids with salinities either higher or lower than that of seawater, so that phase separation of supercritical dilute and hypersaline fluids must be an important process in fluid circulation beneath the worldwide mid-ocean ridges. However this does not guarantee that supercritical fluids will be reached by the IDDP-2 well. This depends not only on the fluids and temperature gradients encountered, but also on the nature of the permeability that controls fluid circulation. Fracture permeability is, in turn, affected by earthquake activity, by self-sealing, and by transitions to ductile behavior with depth.

The discussions and suggestions from both the engineering and scientific participants were very wide ranging and to implement all of them would have been unrealistic in terms of available time, resources, and personnel. In response to the workshop, a major challenge facing the IDDP is to form engineering and scientific planning groups to guide the way ahead, by prioritizing the essential activities necessary to advance.

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