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Report of an IDDP-ICDP Workshop to Plan a 5 km deep borehole (IDDP-2) into the Root Zone of an Analog to a Black Smoker on Land at Reykjanes, Iceland.

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Executive Summary:

A workshop on the Iceland Deep Drilling Project (IDDP) was held in Iceland at the Eldborg Conference Centre, at Svartsengi, SW Iceland, from the 3rd to the 5th of September 2012. 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, or even high-pressure superheated steam, have the potential to greatly enhance the power output of geothermal fields, without enlarging their size and environmental footprints. The workshop was funded by the International Continental Drilling Program and by Deep Vision, the steering committee of the IDDP. It discussed the lessons learned from the first IDDP exploratory borehole, in 2009, at the Krafla Volcano in NE Iceland, intended to explore for supercritical geothermal resources at 4.5 km depth, that was terminated at only 2.1 km depth when molten rhyolite magma flowed into it, creating the world's hottest geothermal well (wellhead temperatures up to 450^{o}C).

This report has three purposes, firstly to inform Deep Vision of progress made so far, to advise on the way ahead from a technical perspective, and to invite international participation in both the engineering and the scientific activities of the next phase of the IDDP. This discussion is necessary to plan the drilling and study of a new 4 -5 km deep borehole, the IDDP-2, to be drilled in 2014-5. It will explore for supercritical water, and/or superheated steam, beneath the current production zone of the Reykjanes geothermal field in SW Iceland.

Deep Vision is inviting participation by the international community in the IDDP to maximize the scientific and technical impact of the project. Because the Reykjanes peninsula is the landward extension of the Mid-Atlantic Ridge there is widespread interest within the scientific community in this drilling project. Because 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. Zones of intensive water-rock reaction along rift systems are exceedingly important for the practical goals of the IDDP. It is predominantly there that fluids are heated and interact chemically with their host, where most of the geologically important heat transport and chemical alteration take place, and where high enthalpy superheated steam or supercritical water should be most easily accessible for power production and research.

Ninety-four engineers and scientists attended the workshop; about two-thirds were from Iceland and the rest from Canada, France, Germany, Japan, Italy, Netherlands, New Zealand, Norway, Switzerland, UK, and USA, including several students who were given the opportunity to present their work relevant to the IDDP. The workshop program, with a list of attendees giving their email addresses, is given in Appendix 1. Several presentations were made concerning similar ambitious projects in Japan and New Zealand that are concerned with drilling into deep, high-enthalpy, geothermal systems in those countries. Breakout sessions allowed smaller groups to discuss the topics of drilling, hydrology, geosciences, and fluid handling, and to prioritize activities that should be carried out before, during and after drilling, together with other activities that are complementary to the goals of the IDDP.

No issues were identified that should rule out attempting the drilling, sampling and testing of the proposed IDDP-2 well. The consensus of the workshop was that the drilling of such a hot, deep well, and producing from it, potentially hostile, supercritical or superheated fluids, although technically very challenging, are possible but require careful contingency planning. Another challenge will be building on the enthusiasm expressed at the workshop by participants of different nationalities, different areas of expertise, and different institutional affiliations. We anticipate that the outcome of the workshop will be much fruitful technical and scientific collaboration, if the momentum and coordination are maintained.

1.0 Background of the IDDP

1.1 High-enthalpy Geothermal Systems in Iceland.

In the next 2-3 years, as part of a long-term program, the Iceland Deep Drilling Project (IDDP) plans to drill a 4-5 km deep well in a high-temperature magma-hydrothermal system at Reykjanes, that lies on the landward extension of the Mid-Atlantic Ridge. The main motivation of the IDDP is to explore for new, very large, economic sources of high-enthalpy geothermal energy derived from magma-hydrothermal fluids at supercritical conditions. Such fluids are of interest to the IDDP, and to the international energy research community, because of their very high enthalpy and favorable flow characteristics. At, and above, the critical point there are orders of magnitude increases in the ratio of buoyancy forces to viscous forces that permit extremely high rates of mass and energy transport. This is accompanied by intense high temperature water/rock reaction and increased transport of dissolved components.

The IDDP was initiated in 2000 when a steering committee, Deep Vision, representing a consortium of the three principal energy companies in Iceland (HS Orka, Landsvirkjun and Orkuveita Reykjavikur, together with Orkustofnun, a government agency, and later joined by ALCOA, an international aluminum company) was established to plan and fund drilling for high-enthalpy geothermal resources in Iceland. IDDP welcomed participation by the international scientific community. In 2002 scientists and engineers from 12 countries attended two workshops funded by the ICDP; the first discussed the optimal strategy for drilling such deep hot wells and the second discussed the science program, and an international advisory committee SAGA (Science Applications Group of Advisors) was convened. The current workshop is the ninth in a series of IDDP workshops since 2002, which appear as SAGA reports on the website <www.iddp.is>.

The Deep Vision committee then funded a feasibility study that reported on (1) geosciences, (2) drilling techniques, and (3) fluid handling and evaluation (also available at http://www.iddp.is). One of the chief conclusions of the feasibility report was that a well that produces supercritical fluids should have a greatly enhanced power output relative to conventional high-temperature geothermal wells.

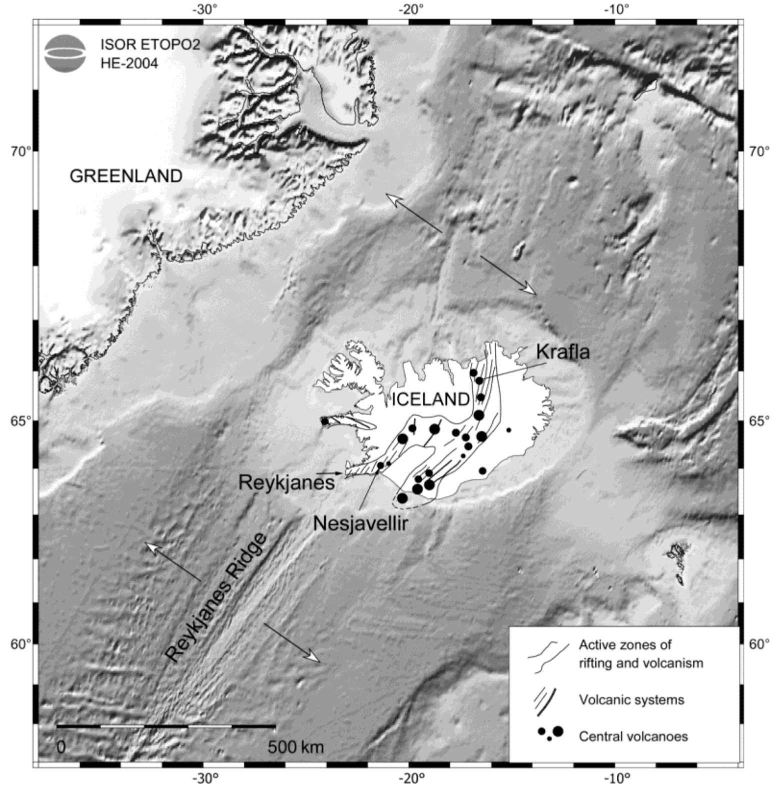


Figure 1: Map of Iceland and the North Atlantic ocean floor, showing the active zones of rifting and volcanism through Iceland, that are the landward extensions of the Mid-Atlantic Ridge, and the locations of the three high-temperature geothermal systems of Krafla, Hengill (Nesjavellir) and Reykjanes, selected as sites for deep drilling by the IDDP (Friðleifsson and Elders, 2005).

This initial study identified three locations, Krafla, Hengill (Nesjavellir) and Reykjanes, as being the best locations in Iceland to site a deep well to produce supercritical geothermal fluids (Figure 1). Deep Vision's concept was that at each site the field operator would drill and case a 3 or 3.5

km deep well that would be then be deepened by the IDDP consortium to investigate the deeper part of the system and explore for supercritical fluids.

These three high-temperature geothermal areas, which are already developed for conventional geothermal energy utilization, display different stages in the tectonic development of the mid-ocean ridge, and are therefore of great interest to the international scientific community. The Krafla high-temperature geothermal field is developed above a magma chamber in a mature, active, volcanic caldera where numerous wells have reached temperatures of more than 340^{o}C at depths as shallow as 2 km. The Hengill central volcano is the heat source for a large geothermal reservoir with temperatures of >300°C, including one exceptionally high temperature of ~380^{o}C at 2.2 km depth in well NJ-11 at Nesjavellir. The Reykjanes site represents an immature stage of rifting with a heat source that is probably an active sheeted dike swarm. In common with most high-temperature geothermal systems in Iceland, the systems at Hengill and Krafla contain 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.

1.2 IDDP-1 at Krafla

In 2006, Landsvirkjun, the operator of the Krafla Geothermal Field, offered to drill a deep borehole (to be called IDDP-1), 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 MWe geothermal electric plant is currently operating. This active volcano is cut by N-S trending fissure swarms that are part of the neovolcanic rift zone of Iceland. The Krafla volcano has a 300,000 year long history of predominately basaltic volcanic activity, most recently during 1975-1984. Eruptions of the Krafla volcano are episodic occurring at 250 to 1000 year intervals, with each episode lasting 10-20 years. The presence of a magma chamber beneath the caldera at 3-7 km depth was inferred from S-wave attenuation during the 1975-84 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. 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. In June 2009, the reason for the drilling difficulties became apparent. At 2104 m depth an intrusion of rhyolite magma flowed into and filled the lowest 9 m of the open borehole. Drilling was terminated and the hole was completed as a production well, cased to 2069 m. Evidently the resolution of earlier geophysical studies was not sufficient to identify the 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 not 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.

After months of cooling by injecting water, during and after drilling, the IDDP-1 well was allowed to heat and proved to be highly productive. It became the world's hottest producing geothermal well, with wellhead temperatures of up to 450°C, pressures of 140 bars, and enthalpy of 3150 kJ/kg. Production tests at different wellhead pressures indicate that the well would be capable of producing up to 36 MWe, 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.

Although the IDDP-1 did not reach depths at which supercritical pressures exist, it was a success both scientifically and from an engineering standpoint. A special issue of the Journal Geothermics with 15 papers on the IDDP-1 (and IDDP-2) will be published shortly. Perhaps in the future, such accessible magmas will be used as sources of very high enthalpy geothermal energy in Iceland, and elsewhere, wherever suitable young volcanic rocks occur.

1.3 Plans for drilling IDDP-2 at Reykjanes:

The IDDP-1 experience did not cause the project to lose sight of its original goal of exploring for supercritical geothermal fluids. Planning for the second deep well, IDDP-2, to be drilled in the Reykjanes Geothermal Field in SW Iceland is now underway. Once more the plan is that the field operator (in this case HS Orka) will fund and drill the well to ~3.5 km, and that the IDDP consortium will then fund deepening and testing of the deepened well. 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 onsite and in the laboratory.

HS Orka is now in the final stages of negotiating for a major expansion of the geothermal power plant at Reykjanes. Some 20 production or injection wells exist in the field, so that a great deal is known about the upper 2.8 km of the geothermal system. This expansion will require drilling at least six new production and injection wells in the Reykjanes field and the last one in that series could be the IDDP-2. This timetable will allow the planning and drilling the IDDP-2 to benefit from the new information and the experience gained from drilling the new wells.

Because of the drilling problems encountered, the cost of drilling of the IDDP-1 at Krafla was very high. The cost of drilling and testing together probably approached about 20 million USD. 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, if this can be done without jeopardizing safety or the economic goal of exploring and producing the Reykjanes geothermal system from between 3 - 5 km depth. This re-evaluation is expected to be completed in 2013. Nevertheless, it is 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 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.

2.0 The Workshop

2.1 Overall Aims of the Workshop

The aims of the conveners 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.

2.2 The Agenda

2.2.1 Day 1

The full agenda of the workshop appears in the Appendix. After a welcome by Júlíus J. Jónsson CEO of HS Orka, G.Ó. Friðleifsson reviewed the aims and achievements of the IDDP to date, and W.A. Elders reminded the attendees of the purpose of the workshop.

B. Pálsson et al., then reviewed the problems in drilling the IDDP–1. The main problems in drilling were that two twist offs that required sidetracking occurred when the bottom hole assembly became stuck as magma congealed around the drill bit, although this was not recognized at the time. On the third occasion that magma was penetrated, circulation was maintained allowing some quenched magma to be sampled and the drill head assembly to be freed. In retrospect, drilling into the magma might have been recognized by the sudden rapid increase in rate of penetration, accompanied by large increases in torque, and reduction in the weight on bit. For example, at 2104 m depth on the third leg (after the second sidetrack), the ROP doubled from 2 to 4 m/hr, the torque increased dramatically, and hook load decreased by 40 to 50 tons, but in this case circulation was maintained and increased to 70 l/s. Prior to encountering the magma, fluid circulation had been totally lost but for some 2 hours, drilling fluid reached surface so that abundant cuttings of quenched glassy rhyolite where returned to the surface for some 2 hours before circulation was lost again. Landsvirkjun, the field operator at Krafla and the IDDP Drilling Technique Group, are preparing a detailed report on the lessons learned in drilling the IDDP-1 well. Meanwhile articles on drilling and flow testing the IDDP-1 will appear in the special issue of Geothermics mentioned above.

S.H. Markússon, et al., then described in detail the experience of the flow tests of the IDDP-1 that produced dry superheated steam at 450^{O}C at 138 bars, with an enthalpy of 3200 kJ/kg flowing, and showed no signs of cooling down. The steam had a low gas content of 0.1-0.2%, including 80-100 ppm of HCl, but transported corrosion products and erosive particles of silica when flowing at pressures less than 80 bars. The condensed steam had a pH of 2.5-3.0. Data from experiments on wet scrubbing and corrosion testing are still being evaluated. Unfortunately the well had to be shut down in July 2012 to repair some of the wellhead equipment and the wellhead master valves were found to have failed. The cause of the valve failures and the damage to the well casing due to the rapid quenching are now being evaluated. K. Ingason et al., reviewed the design and operational experience of the IDDP-1 wellhead and above ground installations. There were five phases of testing, from initial restricted flow through a 4 inch orifice to full flow through 10 inch valves and pilot testing of wet scrubbing, corrosion and scaling.

G.Ó. Friðleifsson then turned attention to site selection for the IDDP-2 at Reykjanes. The range of possible choices is more limited than at Krafla and Hengill due to the relatively smaller size of the area permitted for drilling, the existing infrastructure, and the large amount of information from the existing wells which are relatively closely spaced. This issue was later discussed both in the Geosciences and Drilling workshop breakout groups and more information will be found in the special issue of Geothermics referred to above. The next presentation by K. Árnason et al., was also related to site selection. It concerned newly completed modeling of the 3D MT data from 64 soundings. A highly conductive layer where the present production occurs at Reykjanes persists down to about 2.5 km depth, but below that depth there is a highly resistive core, with no sign of the presence of a magma chamber. This new MT model is highly relevant to selecting the site of the IDDP-2 borehole.

Þ. Friðriksson, et al., then reviewed modeling the fluid geochemistry of the production zone which is also very relevant to better definition of the drilling target at depth. The Reykjanes fluid is seawater modified by reaction with basalt at high temperatures, causing precipitation of secondary minerals such as quartz, anhydrite, epidotes and metal sulfides that require only a modest amount of dissolution of basalt. The budget of volatiles such as CO_2, He, and N_2 indicate that there is a large input of magmatic gas. Estimates of the flux of CO_2 in steam flowing through the reservoir imply a natural heat flux of 130 MWt through an area of only 2 km^2.

Ó. G. Flóvenz, et al., introduced another exciting possibility with respect to understanding the geophysical environment of Reykjanes. A European group is seeking funds from the European Commission FP-7 programme for a comprehensive controlled source seismic survey across the Reykjanes Peninsula, combining both onshore and offshore profiling. There would be a strong synergism between that seismic project and the IDDP-2, extending the information from the borehole into the third dimension

J. Elíasson emphasized the important need for mathematical modeling to understand the deep roots of the Reykjanes geothermal system in terms of the coupling of magmatic and hydrothermal systems. Forced convection probably occurs in the supercritical or superheated fluids that occur directly above the intrusions that are the heat source for the system that transfers heat to the freely convecting reservoir above.

A. Albertsson, the deputy director of HS Orka, then reminded the workshop of HS Orka's interest in the IDDP-2 as part of a general policy of supporting sustainable development of geothermal resources involving resource parks that cascade energy uses. Iceland's favorable geology makes it ideal as development platform to investigate deep resources and HS Orka welcomes international participation in this enterprise. At the present time, due to a temporary hiatus in geothermal drilling, there are no drilling rigs in Iceland capable of drilling the IDDP-2. However HS Orka is negotiating with drilling companies to drill the production wells for the expansion of the plant, so that a suitable rig should arrive soon.

Later talks discussed two different options of rigs that could drill these wells and the IDDP-2. B. Prevedel, of GFZ, described the InnovaRig, a very modern and sophisticated automated German drilling rig. Then S. Birkisson, of the Iceland Drilling Company, described the Benntec Euro Rig, capable of drilling to 6,000 m, which could also drill the IDDP-2.

S. Hickmann and G. Björnsson dealt with another important issue for the success in drilling the roots of high-temperature geothermal systems - that is the likelihood of intersecting a naturally occurring permeable fracture network. Permeability strongly depends on the nature of stress field at depth. It is recommended therefore that the IDDP science program should investigate the necessary geomechanical data, using a combination of borehole imaging logs (televiewer and sonic logs) and in-situ stress tests, together with the petrophysical measurements on cores. Several days of rig time would be necessary to implement this activity.

The next presentation by, T. Driesner and A. Stefánsson, described another powerful approach to specifying the nature of the drilling target of the IDDP-2 borehole. Combined hydrological, geochemical and geophysical numerical modeling of geothermal systems can predict the range of conditions and processes likely in the roots of high-temperature geothermal systems. These models can then be compared with available data on geology, geochemistry, and geophysics to refine the models and select the one most appropriate to refine the drilling and testing program for the IDDP-2. Ultimately, however, deep drilling will undoubtedly provide some surprises.

N. Tsuchiya shifted the focus from Iceland to the "Japanese Beyond the Brittle Project" (JBBP) that seeks to create high-enthalpy EGS systems in granitic rocks hot and deep enough to be undergoing plastic deformation. The brittle/ductile transition occurs at higher temperatures in basaltic or gabbroic rocks than in rhyolitic or granitic rocks but it is likely that the IDDP-2 will enter the transition zone and it is conceivable that natural fracture permeability may have to be enhanced to achieve desired flow rates.

F. Poletto then discussed using the drill bit as a seismic source during drilling to develop geophysical models of the area around and below the borehole, particularly to map faults in 3D by joint inversion of gravity and seismic data. The advantage of this approach in geothermal applications is that it is a passive method that does not need recording tools in a high-temperature well. Clearly this could be done in the production wells that will be drilled by HS Orka ahead of drilling the deep well.

The next five presentations were by post-graduate students, three of whom have been studying the Reykjanes Geothermal System. A. Fowler described the petrology and geochemistry of drill cores from the wells RN-17B (10 m of core) and RN-30 (23 m of core) that were cored and studied using funding from the US IDDP science team. The Icelandic geothermal industry does not normally obtain drill cores. However this study showed that drill cores are a very valuable addition to the armory of geothermal investigations. Fowler pointed out that, while drill cuttings indicate what rock types and primary and secondary minerals were penetrated by drilling, only the study of drill cores can reveal the relationship between them and the sequence of water/rock reactions, fracture generation and self-sealing that have occurred. Similarly cores are much better indicators of the protoliths of the rocks that form the geothermal reservoir.

Study of drill cuttings can fail to reveal some of the complexity present. For example, Fowler's work showed that drill cuttings immediately above and below the RN-17B core at ~ 2.8 km depth where the borehole temperature is ~345^{o}C, consist of apparently unaltered fresh basalt, whereas the core is composed of pervasively altered rocks of amphibolite grade and are predominantly hyaloclastite and volcanic sediments. Although fragments of vein filling epidote with fluid inclusions are visible in drill cuttings their parageneses was unclear. In the core two generations of epidote veining are obvious and three populations of fluid inclusions are present. A population of vapor-filled inclusions has salinities less than seawater and homogenization temperatures of 380 to 400^{o}C. A second population consists of liquid filled inclusions having salinities greater than seawater and homogenization temperatures <380^{o}C, close to the measured temperature at that depth. A third population of mixed vapor + liquid inclusions did not homogenize at any temperature, indicating that they trapped a boiling fluid. At some stage the Reykjanes system was boiling as deep as 2.8 km.

R. Seward described another study funded by the US IDDP team that is developing a novel system to obtain uncontaminated and unfractionated fluid samples at depth in flowing geothermal wells. This "Fluid Inclusion Tool" (FIT) lowers fractured quartz to the zone of interest in a well for some days so that the quartz crystals trap fluid inclusions. Using laser ablation ICP mass spectrometry, complete analyses of the included fluid can then be performed.

R. Libbey is studying sulfide minerals in three existing wells in the active Reykjanes geothermal system as a modern analog of ancient fossil volcanic metal sulfide (VMS) ore deposits. This has potential applications to geothermal exploration as ore minerals form in the upflow zones where rapid changes in PT conditions occur due to fluid mixing. At Reykjanes changes in the physico-chemical conditions in the system are recorded by the alteration and resorption of primary magmatic sulfides and replacement by pyrite and chalcopyrite enriched in noble metals. The outcome of this work will be a thermodynamic model to explain the systematics of these processes.

The fourth student presentation was by L. Patsa, who described her ambitious project to model how brine behaves as it flows through wells that tap high enthalpy geothermal reservoirs, across the entire production range of interest, i.e. 400-600^{o}C and 100-250 bars. The approach taken will consider momentum balance, energy balance, and mass balance, and the behavior of geothermal brine as a chemical and phase mixture, using integration of the thermodynamic properties of individual brine constituents.

Finally, Y. Mukuhira returned the discussion back to the JBBP from the perspective of the physics behind induced seismicity in and around the brittle-ductile transition zone. He reviewed large induced seismicity in EGS projects at Soultz (France), Cooper Basin (Australia), Basel (Switzerland), Landau (Germany), Geysers (USA), and Yanaizu-Nishiyama (Japan). The characteristics of large induced seismic events are dependent on the situation at the individual sites (state of stress, existing fractures, and the operational conditions). The factors that control the magnitudes of induced seismicity are not well understood and an appropriate technique to control magnitudes has not been established. However the JBBP will induce fractures in the ductile zone around 500^{o}C by creating an artificial brittle zone where the conditions will be quite different from those in "conventional" EGS operations. This will require further investigation of the physics of the brittle-ductile transition.

The New Zealand GNS is carrying out very comprehensive geophysical surveys and detailed modeling of subsurface geology including stress analyses of the Taupo Volcanic Zone, with the goal of preparing for deep drilling to explore for hotter and deeper geothermal resources. The formal presentations for the first day concluded with B. Mountain, NZ, on behalf of Julia K. Björke, a PhD study on experiments that simulate basalt-fluid interaction under subcritical and supercritical conditions. This is to be achieved by reacting unaltered basalt lava samples from the Reykjanes Peninsula with seawater. Then C. Massiot, also from GNS NZ, described work undertaken by herself and colleagues to utilize well logging data to characterize structures in the vicinity of deep boreholes, determination of *in-situ* stress conditions, and related rock property laboratory experiments, with relevance to the IDDP-2 at Reykjanes.

The first day of the workshop concluded with a field trip to the Reykjanes Geothermal Field, including stops at the Core Field Laboratory to examine some of the existing Reykjanes core, view one of the likely sites for drilling the IDDP-2, and visit the exhibition area of the Reykjanes Geothermal Power Plant.

2.2.2 Day Two

Day two continued this international theme with further presentations relevant to the New Zealand Deep Drilling Project (NZDDP) by G. Bignall and the Japanese Beyond Brittle Program (JBBP), by H. Muraoka. The proposed Deep Science Drilling Project in the Taupo Volcanic Zone in New Zealand will be designed to address the physical-chemical conditions and fluid-rock reactions below 4 km depth, the controls on permeability at mid-crustal depths, the location, evolution and interconnectivity of the hydrothermal systems, how fracture initiation, propagation and longevity might impact productivity of deep wells, and what are the potential industrial uses of high PT (supercritical) fluids.

The motivation behind the JBBP is to manage water losses and mitigate the impact of induced seismicity in the development of EGS projects in Japan, by creating connected fracture systems in hot ductile rocks. The idea grew out of the experience in 1995 when the well WD-1a reached a temperature of 500°C in a plastically deforming neogranite, in an overall compressive tectonic regime, at the Kakkonda Geothermal Field, Japan. There is an obvious synergism in the goals of the IDDP, NZDDP, and the JBBP and mutual cooperation is clearly desirable.

Somewhat similar conditions to those that are likely beneath the high-temperature geothermal systems of Iceland can be seen in “fossil” systems exhumed by erosion at Elba in Italy. D. Liotta, et al. compared these with information from deep geothermal boreholes at Larderello, like the San Pompeo-2 well. The study of exhumed fossil systems provides information on the temperatures and types of fluids present, and the nature of fractures and their connectivity, which is necessary for modeling the nature of the active systems. E. Spangenberg then shifted the emphasis to discussion of experimental studies planned to study rock properties at supercritical conditions at the GFZ- Potsdam.

The next two presentations concerned equipment that should be deployed to obtain samples or data from the high temperature and pressure exploratory borehole IDDP-1. A. Skinner spoke about improvements to the high temperature spot coring barrel, drill bits, and data logger that were developed for use in the IDDP and have been successfully deployed in obtaining cores from wells already drilled in the Reykjanes geothermal field. R. Ásmundsson described a wide-ranging program, largely funded by the European Union, to develop high-temperature down hole logging tools. The current temperature limitations are that above 300°C there are no commercial wireline tools available, above 400^{o}C heat shielded tools have very limited operational lifetimes, only a few available electronic components function above 300^{o}C, and organic tracers break down at 350^{o}C. Research and development efforts to address these lacks are underway in several European countries and the USA. The standard suite of logs usually deployed by ÍSOR in geothermal wells in Iceland should be augmented by the results of those activities.

2.3 Breakout Groups

Attendees at the meeting then split into three main subgroups (Geosciences, Fluid Handling, and Drilling) in order to have more focused discussions about prioritizing the activities that should be performed before, during and after drilling the IDDP-2, together with desirable associated activities. By far the largest group was Geosciences, so that as a practical matter discipline-oriented subgroups soon formed. Each breakout group began with brief (5-10 minute) presentations relevant to the topic being discussed by the whole group or by subgroups. The titles of these presentations are shown in the appendix. On Wednesday the breakout groups continued with writing assignments to prepare reports to be submitted to the whole meeting. All these reports appear below, as submitted without them having being edited into a uniform format. The Geoscience report is accompanied by a report on Hydrology.

2.3.1. Geosciences Breakout Session. - chaired by W.A. Elders and reported by G. Bignall

Recommendations for Geoscience Activities to be undertaken in Support of IDDP-2

The following discussion lists the essential, recommended and/or desirable science activities that should be undertaken in support of the proposed IDDP-2 well. Firstly the various activities are described that should be undertaken prior to drilling, to support decisions regarding well design, depth and targeting of the hole. The report then discusses activities during drilling and lastly geoscience activities post drilling.

2.3.1.1 Activities to be Undertaken **Prior** to Drilling

Over the years, considerable scientific data (including geological, chemical, geophysical and reservoir engineering information) have been acquired during previous developments at Reykjanes. The information already collected is an invaluable resource that has aided decisions which have been instrumental in the selection of Reykjanes as a site for the proposed IDDP-2 hole. However, much additional information is required to provide confidence to HS Orka and the IDDP consortium in advance of drilling the IDDP-2.

It is the consensus opinion of the geoscience team, that as much information as possible be obtained and interpreted in the next couple of years, ahead of drilling IDDP-2, utilizing information to be gained from proposed production/injection drilling in the Reykjanes field, plus, in particular, already collected geophysical information, to refine existing physical and chemical conceptual models of the area and increase the likelihood of commercial and scientific success of the IDDP hole.

In the first instance, it is essential to identify the presence of any magma pockets (i.e. thus avoiding the Krafla experience) that might occur in the path of the IDDP-2. Consideration should be given to use data from Krafla as a benchmark for identifying characteristics associated with magma, as a precursor for assessing the possibility of encountering magma at IDDP drill depths. It is recommended appropriate review of MT models at Krafla be carried out in the light of the discovery of magma at 2.1 km depth in the IDDP-1. An MT survey has been undertaken at Reykjanes and it is essential to complete and discuss the results of the 3D modeling of these data in the IDDP-2 area and to provide additional confidence in the existing resistivity model (combined with sensitivity analysis).

Another essential task is to review mapping the top of the brittle-ductile transition in the Reykjanes area. To achieve this goal, enhancing the current seismic network on the Reykjanes Peninsula should be undertaken, as soon as practical, to measure natural microseismicity, and incorporate national network data. We suggest a combined surface/borehole seismic network could be established that makes use of any suitable wells already drilled in the Reykjanes area, although we acknowledge the physical limitations of instrumentation down hole in the high temperature environment. Enhanced operational capability of down hole instrumentation is addressed elsewhere.

It is essential to obtain increased confidence in the model of the seismic velocity profile of the Reykjanes area through inclusion of any new data obtained from the established seismic network and consideration should be given to a calibration shot to generate more accurate velocity data for the Reykjanes area. A review is recommended of data already obtained from any passive seismic surveys undertaken in the Reykjanes area, with insights incorporated into geophysical models. The geophysical interpretations should be supplemented by maps of the active faults in the Reykjanes area. We suggest that, while drilling of the 6 production/injection drillholes to be drilled in the Reykjanes geothermal field ahead of IDDP-2, consideration should be given to utilizing drill-bit noise as active seismic sources in support of other seismic studies.

As a precursor to drilling IDDP-2, a review should be made of logging practices in Iceland, with consideration of what types of logs should be acquired from the IDDP-2. In Iceland, a standard package of logging activities is undertaken for conventional drilling operations. Discussion with experts of an expanded program should take place, as appropriate and tool dependent, including use of televiewer and sonic logs. This expanded program could be employed in tandem with any well drilling operations undertaken in the vicinity of the proposed IDDP-2 site. Operational practices should also be reviewed to maximize the effectiveness of wireline logging.

To increase our understanding of stress magnitudes in the Reykjanes area, as part of drilling operations for new production/injection wells, we recommend mini-frac tests be undertaken. Acquisition of downhole geophysical data, and information obtained from the use of televiewer, such as fracture orientations and characteristics, and stress directions, will complement insights gained from the local seismic array. Consideration should be given to new gravity and magnetic surveys that might complement/increase confidence in models describing the geophysical structure of the area.

The usual careful logging of cuttings and any core recovered from new production/injection wells preceding IDDP-2 should be undertaken. As far as possible this should be augmented with petrological, fluid inclusion and mineral isotope studies to increase knowledge of possible fluid types that might be encountered by IDDP, and to develop models of the evolution of the active hydrothermal system. Stratigraphic and structural information should be incorporated into a new 3D geological framework (e.g. Leapfrog Geothermal) model of the Reykjanes area, which will be revised as a consequence of new information obtained by IDDP-2.

2.3.1.2. Activities to be Undertaken **During** Drilling the IDDP-2

Cuttings collected during drilling should be logged in detail, with information regarding stratigraphy, structural insights and occurrence/distributions of hydrothermal mineral assemblages incorporated into a revised hydrological/conceptual and geological framework model (in 3D) of the Reykjanes area. We recommend fluid inclusion studies be incorporated in studies of drill cuttings (or core samples) during drilling, to provide insights on thermal-pressure-chemical conditions at the time of formation of the inclusions. Logging of cuttings, and core description should include observations during drilling of mineral textural relationships to provide an insight into P-T conditions.

A serious effort should be made to obtain drill cores as far as the technical and budgetary limitations allow. These cores obtained during IDDP drilling should be described and analyzed in detail, with particular reference to textural, mineralogical and chemical relationships that provide insights into the location of the drill hole within the magma-hydrothermal system, its P-T-X environment, and its evolution. In particular, core is needed to investigate the sequences of hydrothermal veins and alteration related to present hydrothermal conditions versus past conditions.

As part of drilling operations, again within the limitations of technology and budget, we recommend inclusion of a program of extended leak-off (minifrac) tests at appropriate depths (e.g. at casing shoes) to produce a depth profile of least principal stress. During drilling IDDP- 2, there is also a strong case to monitor microseismicity to produce additional constraints on in-situ stress field and resolve active structures acting as fluid conduits. This should be augmented by drill bit seismic imaging while drilling, to provide inferences on the presence of interfaces (e.g.

possible magma pockets or changes in fluid phases) ahead of the drill bit, as well as vertical seismic profiling in order to revise geophysical/velocity models.

A comprehensive logging program is recommended during breaks in drilling, including caliper, natural spectral gamma, resistivity, neutron, density, sonic, and temperature-pressure-spinner logs, although we acknowledge there may be constraints on the use of tools at the elevated thermal conditions expected to be encountered by IDDP-2.

2.3.1.3. Activities to be Undertaken **Post** Drilling IDDP-2

A range of post-drilling geosciences initiatives are recommended, encompassing petrological and mineralogical studies, processing and interpretation of logging data, rock property (laboratory) testing , and inclusion of new geophysical and chemical data into a revised conceptual model of the Reykjanes geothermal system, and new insights into heat and fluid flow on the Reykjanes Peninsula.

Petrological and mineralogical studies, including mineral isotope studies and analysis of fluid inclusions should be undertaken to provide insights into fluid origin and evolution of the hydrothermal system. In addition, a range of rock property measurements should be undertaken, including determination of full triaxial compress-ive strength (for relating breakout width to stress magnitudes), and thermo-elastic, seismic velocities (Vp and Vs) and frictional properties. Geophysical measurements on core should include electrical and thermal conductivity, magnetic susceptibility, permeability (before and after shearing tests), porosity and density.

Fracture characterization and determination of stress orientations and breakout geometry (if present) from the IDDP-2 televiewer data should be undertaken. Comparisons should be made with rock strength measurements on core and results from the mini-frac tests, and information gained from preceding drillholes, to establish a full 3D stress model and refine the structural model of the Reykjanes area (and to support targeting of conventional geothermal wells). The televiewer data should also be used to orientate recovered core.

2.3.2. Hydrology Report

Hydrology of the Reykjanes system in relation to IDDP-2, - Prepared by J. Elíasson, Ó. Sigurðsson, E. Júlíusson and T. Driesner

The hydrology of saline geothermal systems is significantly more complicated than that of dilute water systems. This is a result of a more complex phase diagram for saline water that shows a much wider temperature-pressure range of coexistence of two phase vapor+liquid compared to pure water, plus regions of coexistence of vapor+salt and liquid+salt (Fig. 1). Hence, the targeted “supercritical/superheated” conditions may be affected significantly by these relations. Preparation for the IDDP-2 drilling should consider the possible effects of this on achieving the project goals.

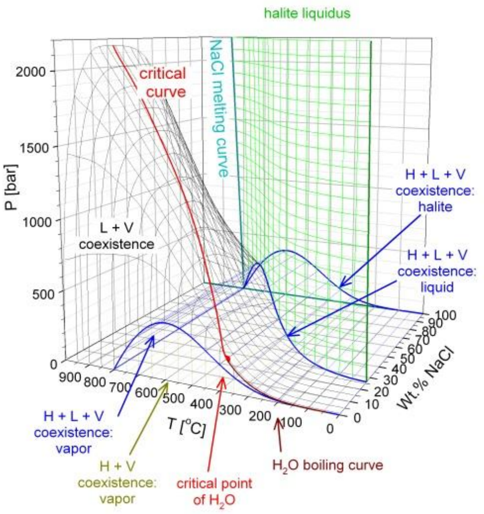


Fig. 1: Phase diagram of the system H_2O-NaCl from ambient to magmatic conditions. From Driesner and Heinrich (2007), Geochimica et Cosmochima Acta 71, 4880–4901.

2.3.2.1 **Before Drilling**

In our opinion, it is essential to develop a series of plausible conceptual models in which complex phase relations are being taken into account. This series of models should cover possible scenarios for the deep parts of the system below the well-known parts of the reservoir that currently reach down to ca. 2500 m. Possible scenarios include (Fig. 2)

- a tight, conductive deep zone below the reservoir formation down to the brittle-ductile transition
- a tight seal of finite thickness separating the currently exploited reservoir formation from a deeper, supercritical/superheated second reservoir
- 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.

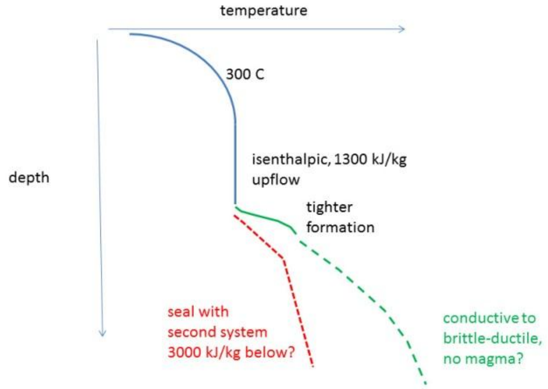


Fig. 2. Thermal structure of the upflow zone for different conceptual models of geothermal systems. Notice difference in thermal structure at depth.

Developing these models would ideally be complemented by methods that could help identifying flow patterns, i.e., by injecting tracers into possible recharge structures (however, this likely requires new, high temperature and pressure tracer types). Additional information is expected by combining this with stable isotope analyses of geothermal water.

Based on these conceptual model the new Swiss-Icelandic COTHERM project can provide numerical fluid flow simulations (cf. Coumou et al. (2009), Journal of Geophysical Research, 114, B03212, doi:10.1029/2008JB005764) of the behavior of the system, namely the distribution of fluid phase states with depth, thermal structure etc. COTHERM has already started and could provide this before the start of drilling.

2.3.2.2 **While Drilling**

We identified that the undisturbed temperature profile is likely the most sensitive indicator of the system's hydrothermal structure. If it were possible, in the ideal case, measuring the temperature profile with depth while drilling would distinguish between different model scenarios and provide information on risk of drilling deeper (e.g. indicating overpressured zones). However, it is very difficult to obtain reliable temperature data by direct measurements during drilling due to the thermal disturbance from the drilling process itself. However, any practical method capable of providing constraints on the fluid and thermal environments at depth in near real time would be most useful. Suggested methods include: alteration minerals in cuttings, fluid inclusions in cuttings, mud gas and mud temperature measurements, and continuous temperature-pressure logs acquired in the open hole.

Circulation loss/gain and associated pressure changes as well as injection test will complement the thermal information to understand the distribution of hydraulic properties in the system and identify similarities with the predicted properties of the different conceptual models.

2.3.2.3 **After Drilling**

In line with the above statements, we consider determination of a more accurate formation temperature profile essential to characterize the nature of the reservoir, which should be acquired once the well has returned to thermal equilibrium. Ideally, these measurements would be combined with thermal conductivity measurements (e.g., on cuttings and core) to yield a one-dimensional heat-flow profile along the borehole. This, in combination with the results from standard well testing procedures should be used to update the parameters used in numerical representations of the conceptual models and refine the model predictions to decide about the most likely reservoir nature. Based on this refined model, numerical simulations can be utilized to explore "what if" scenarios of reservoir responses to production or injection, or other well operations.

2.3.2.4 General

We recommend to base concepts, predictions, and interpretation of data on enthalpy-salinity-pressure relations and phase diagrams for saline fluids (Fig. 1 and 3) rather than approximations based on pure water diagrams.

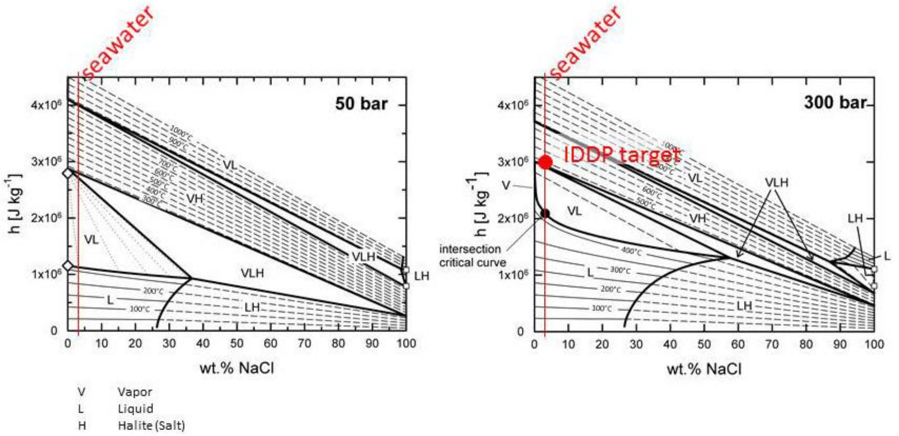


Fig. 3: Enthalpy-salinity diagrams for geothermal conditions. Thin solid lines: isotherms in single-phase regions, dashed: isothermal tie-lines in two phase regions. Based on Driesner (2007) Geochimica et Cosmochimica Acta 71, 4902–4919

2.4 Fluid Handling Breakout Group Report on the IDDP-2, - chaired and reported by R.O. Fournier.

The IDDP-2 drilling project intends to produce fluid from a source where the temperature is in excess of 400°C. We do not know in advance how high the temperature and pressure will be, or the composition of that fluid. However we must design wellhead equipment to handle whatever is produced. The best we can do is to construct possible depth-temperature profiles, drawing 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. 1.

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 to- 5.5 which is near neutral at the in-situ conditions.

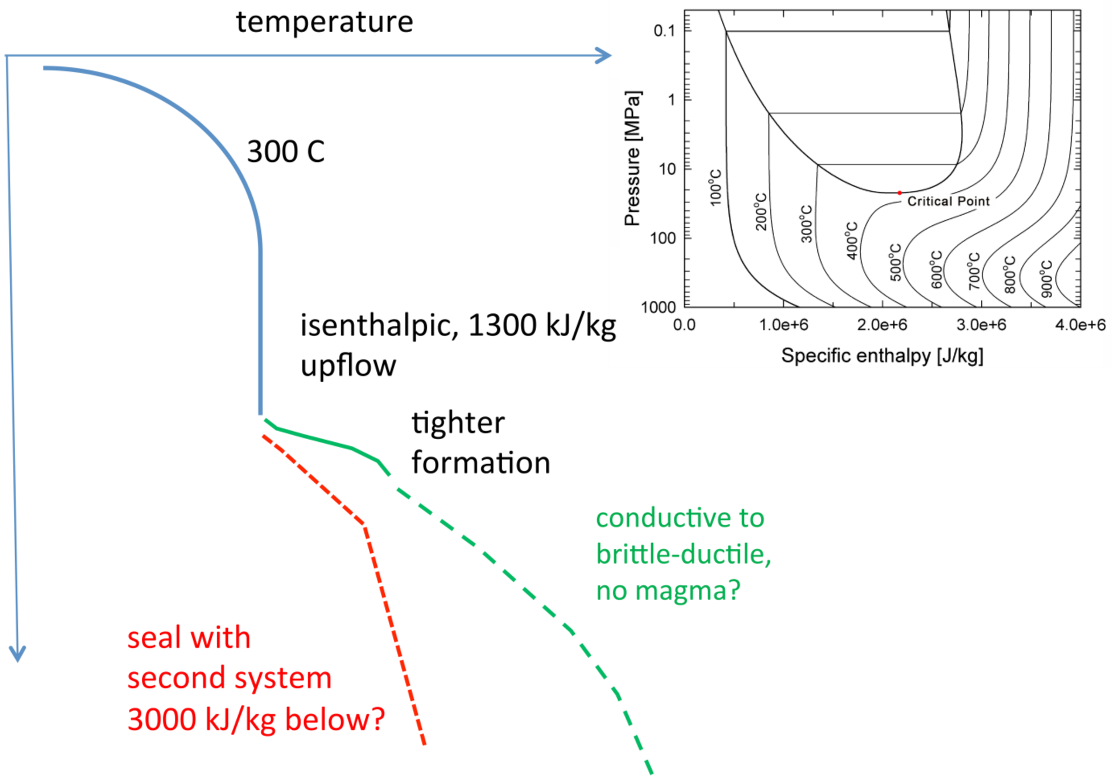
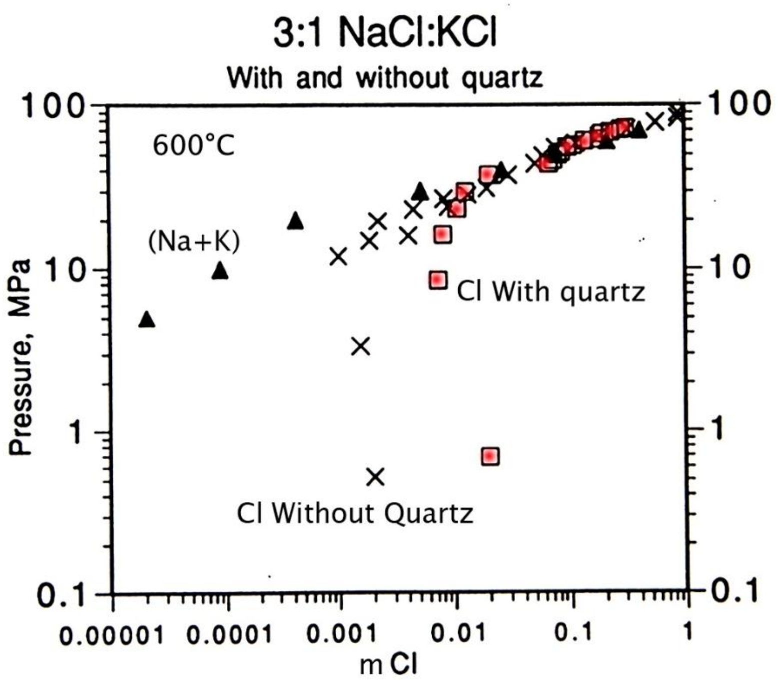


Figure 1. Contrasting depth temperature profiles beneath the presently exploited hydrothermal system.

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. Figure 2a shows conditions for the onset of generation of HCl° with decreasing pressure in the system NaCl-KCl-H_2O. There is about an order of magnitude increase in HCl° when dissolved silica is present. Figure 2b shows that HCL° is produced very efficiently when calcium chloride is present, even in the absence of silica.



Bicchoff et al. (1996), Geochim. Cosmochim. acta, p. 7–16

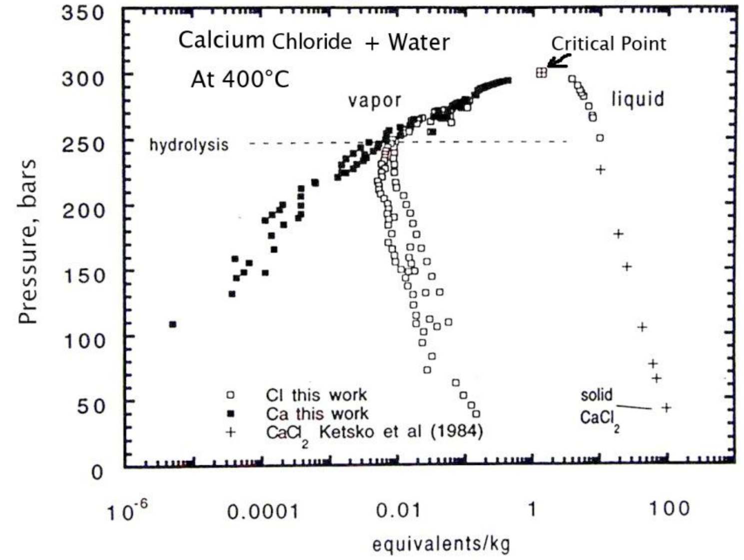


Figure 2a - The generation of associated HCl° in the system NaCl–KCl–H_2O–quartz at 600°C (R.O. Fournier and J.M. Thompson, 1993: Geochim. Cosmochim. Acta, v. 57, p. 4365–4375)

Figure 2b - The generation of HCL in the system $CaCl_2$-H_2O: Vapor-liquid relations from 380-500°C (Bischoff et al., 1996,: Geochim. Cosmochim. Acta, v. 60, p. 7-16)

In the above experiments increments of saline solution were extracted from a pressure vessel at constant temperature, resulting in drop in pressure within the container. HCl° was generated when pressure dropped sufficiently at constant temperature for salt to precipitate. In the real world this might occur in the formation as a result of production of fluid from a very hot reservoir where the rate of recharge is relatively slow (pressure drawdown). The HCl° that forms is highly associated and non-reactive. However, whenever that HCl° encounters liquid water it dissociates and becomes very reactive (corrosive). This will occur if the steam condenses on its way to the surface (or in surface piping), or where dry steam comes into contact with cooler liquid entering a well at a shallower level. To prevent HCl° from dissociating and becoming very corrosive, the wellhead pressure should be kept high during testing and production, and the well casing should be such as to prevent the influx of water into the well from the cooler overlying hydrothermal system.

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 at Krafla should provide insights about how to deal with silica precipitation in that environment.

As already noted, at this time 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. However, because the likelihood of producing black smoker-type brines is high, computer modeling of the behavior of dissolved metals in such brine during production should be undertaken soon, as a guide to methods of dealing with the problem of metal sulfide scaling.

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.

2.4.1 General Issues that need to be emphasized

- Personnel safety

- Well integrity
- The collection of reservoir fluids uncontaminated by drilling fluids

2.4.2 High-Priority Objectives for the Fluid Handling Group

2.4.2.1 **Before Drilling**

- Compile the data and the most likely geochemistry at the expected T & P so that we can properly design the wellhead and casing before drilling
- Use the experience at Krafla and Salton Sea to help constrain the design of wellhead and casing
- Develop a conceptual plan on how we will produce and sample high temperature fluids from the bottom of the well
- Develop a plan for thermal re-equilibration of the well.
- Develop a plan for the disposal of fluids and gases
- Develop a plan for determining when the fluid produced from the well is no longer contaminated by drilling fluid.

2.4.2.2 **During Drilling**

- Case the well to isolate the upper part of the convective system
- Monitor gases and hydrogen and oxygen isotopes in order to anticipate drilling problems and possible changes in reservoir conditions with depth in real time.
- Attempt to monitor temperature with depth during drilling (e.g. T measurements at casing points, fluid inclusions, mineral assemblages)
- Evaluate if it is possible to improve the size and integrity of cuttings

2.4.2.3 **Post Drilling**

- Monitor thermal re-equilibration of the well
- Obtain uncontaminated fluid and gas samples from the high temperature zone
- Maintain high temperature/pressure in the well to control precipitation and corrosion problems
- Use the fluid temperature and composition to evaluate the optimal methods for utilization of the well (e.g. direct use, heat exchange, etc.)
- Re-evaluate the pre-drilling fluid disposal and production plans

Anticipate expected temperature and pressure of our drilling target using the existing thermal data from the well field. At what depth do we expect the transition from convective to conductive heat transfer?

2.3.5 Drilling Breakout Group – Chaired and reported by Dennis L. Nielson

A comprehensive report on the drilling of IDDP-1 is currently in progress by Landsvirkjun. This report should be comprehensive, and the committee recommends its completion to aid in the planning of IDDP-2. That report, plus the analysis of the failure of the well head on IDDP-1 will supersede the discussions presented here.

2.3.5.1 IDDP-2 DRILLING OBJECTIVES

Safety

Safety will be a paramount issue for drilling of IDDP-2. As was demonstrated in IDDP-1, drilling could take place in geothermal environments that have higher temperatures and pressures than have been drilled previously. We can also expect fluid with extreme corrosion and erosion potential. This presents drilling difficulties and challenges for standard materials, well designs and fluid handling protocols. IDDP-1 provided valuable experience in operational procedures, design of casing and project management. 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.

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 will be designed and built to collect the scientific samples and data required by the IDDP. The drilling group is relying on the casing plan than has already been established for the IDDP-1 with significant redundancy. However, as outlined below, there are several areas where improvement of equipment and materials will be required for project success. Lessons learned from IDDP-1will be applied to the design of IDDP-2 and management of drilling operations to mitigate risk.

2.3.5.2 IDDP-1 LESSONS LEARNED

General Design Issues

The report underway on the "Lessons Learned from the IDDP-1" should be finished as soon as possible. The design of the IDDP-1 well was based on pressures and temperatures following the boiling point curve to the critical point of water. The well deviated from these design aspects when rhyolite was encountered. When drilling into frontier environments, like we are discussing with all of the IDDP holes, 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. These issues are discussed below.

Site Selection

The Geologic team is asked to identify the targets that are likely to give the expected temperature, pressure and permeability required for production of superheated geothermal fluids It is understood that there are constraints on the location of the IDDP-2 that are related to permitting and infrastructure issues. However, consideration must be given to the impact of drilling and testing on existing surface structures and the possible impact on other wells. There was some amount of concern expressed concerning the proximity of the IDDP-2 location to existing infrastructure.

Wellhead Design

One of the critical issues concerning IDDP-1 was the failure of all valves in the well head during flow. The reasons for their failure are not presently understood; however, the well head of IDDP-1 was scheduled to be removed for inspection soon after this conference. Following its removal, an investigation of the failure of all valves will be undertaken.

The failure of the well head required that the well be controlled by injection of cold water. This quenching is thought to have resulted in casing failure. The committee agreed that in the future planning should include contingencies that would avoid the requirement to quench the well. A thorough inspection of the failure of master valves is essential for the continuation of IDDP. New design developments (or improvement of existing designs) are required for valves that can cope with the predicted high temperatures, pressures, corrosion and the production of particulate material under high pressure. The initial flow test will put a great strain on the valve if corrosive material, cuttings or other solid particles are expected. Stainless steel cladding of expansion spool and wellhead valve appears to have provided a good option, but this should be investigated and tested before implementation.

Casing

The casing program of IDDP-1 was in general satisfactory, and we anticipate that this will be the preliminary design for IDDP-2. However, the material selection for the production casing, especially if acidic fluid (HCl) is expected should be re-evaluated. From experience in the IDDP-1 an acidic environment in the deeper part of the Reykjanes geothermal system is likely.
Once the report of the drilling of IDDP-1 is complete, the casing design for IDDP-2 should be re-evaluated. For IDDP-2, casing sizes should be compatible with standard drill bit sizes.

Cementing

The cementing program should be revised from IDDP-1.

- The Dickerhoff-Schlumberger cement slurry proved to be satisfactory.
- Cementing of the 9-5/8” was not of full quality. It is suspected that water and air pockets resulted in incomplete coverage,. The cementing was impaced by the failure of standard packers at high temperature.
- Consider reverse circulation cementing for the deeper casing.

Drillstring Design

The drillsting design should be revised from that used for the drilling of IDDP-1. Modeling of the string under expected conditions should be undertaken prior to drilling

The drill string utilized for IDDP-1 may have been too stiff, the stabilizer clearances too narrow, and the 8-1/2” collars too heavy.

Drilling Fluid

The Loss of Circulation seal material from Schlumberger was adequate.

Consider high pore pressures, which could limit with how deep we can drill.

Icelandic geothermal systems have relatively good rock stability in the production zones below 1000 m depth.

Cement Plugs for Side Tracking and Wellbore Stability

Use the same cement as for casing cementing.

Use fiberglass cementing strings.

Review procedures for handling lost circulation

It is important to properly clean the drill string after cementing. Inject rubber balls.

Materials Selection

An overriding issue from the IDDP-1 experience was the selection of materials that could resist corrosion, erosion and thermal impacts of the production of fluids. Sigrun Karlsdottir reported on materials studies that are presently underway. It is clear that this type of work should continue and it should be integrated into the design process for IDDP-2.

What to do if we drill into magma

For a 4500 m deep well in a volcanic high temperature field, the chance of hitting magma is significant. Therefore, it is important to have an exit strategy and a protocol to follow and present to the management.

How to identify we have drilled into magma?

- A predictive sequence of events; increased torque, decrease in hook load
- Need to analyze drilling data from previous instances

First reaction:

Pull back as much as possible to minimize the chance of getting stuck

- Maintain circulation to cool the magma for at least 20 hours before pulling out.

When out:

- It is highly unlikely we will be able to continue drilling.
- Decide it will be safe to produce from the well or should a cement a plug be inserted
- How long should the well be cooled after pull out and complete the well if that is possible?

Other Issues

Collect a database of information from all wells that have drilled into magma (or other very high temperatures) to study general lessons learned:

- IDDP-1 and K-39, Iceland
- Puna , Hawaii, USA
- Menengai, Kenya
- Kakkonda, Japan

3.0 Overall Conclusions and Recommendations of the Workshop

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^{o} south on the Mid-Atlantic Ridge produce supercritical fluids, more dilute than seawater, with temperatures measured 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 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.

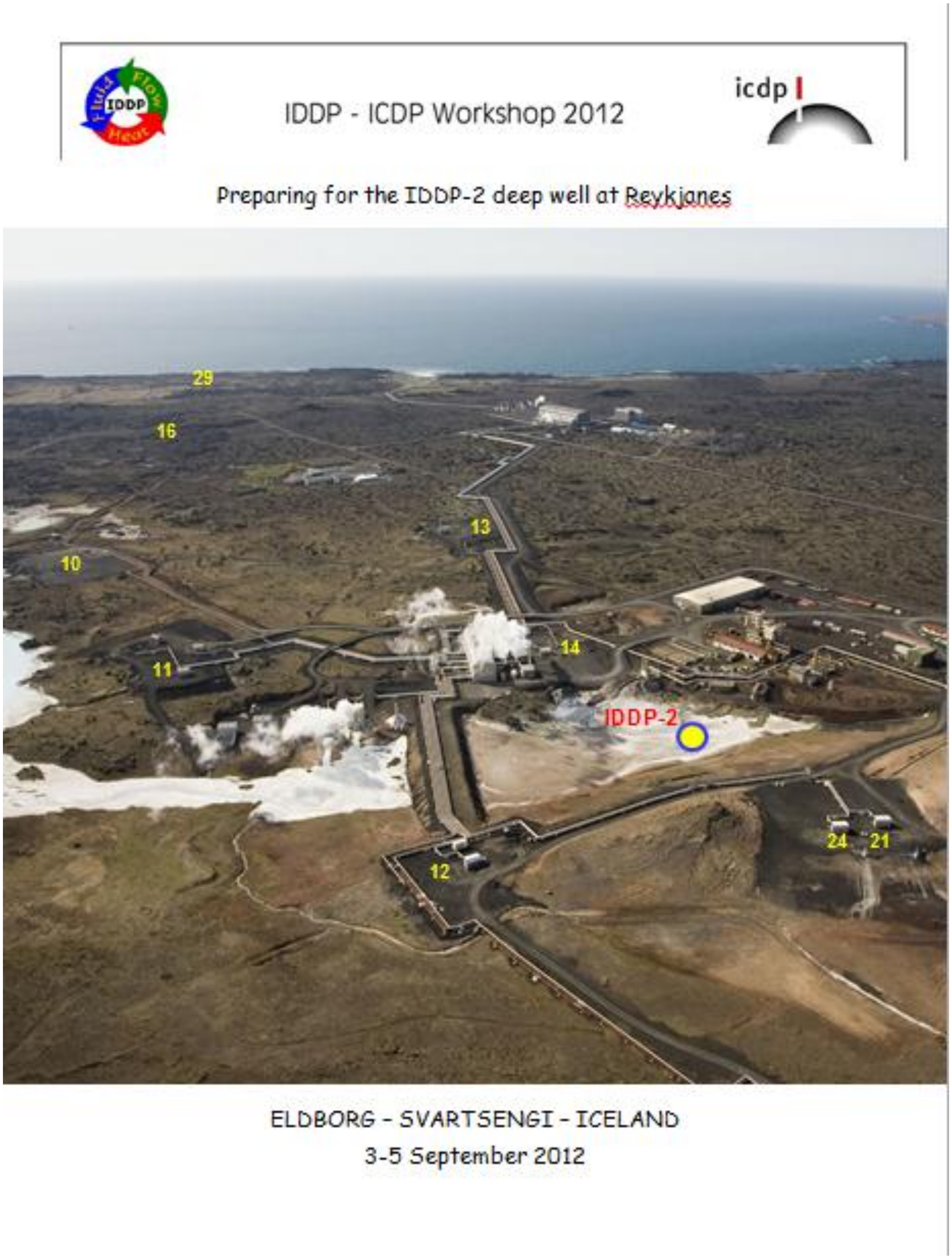
There are caveats to a too simplistic application of a black smoker model to the Reykjanes system. The Reykjanes Peninsula is not covered by 2-3 km of seawater, its crustal thickness is three times that of typical ocean crust, and in the Pleistocene the Reykjanes geothermal system was covered by a thick, insulating, ice cover that introduced dilute water into the system, and caused P/T gradients to adjust to that environment. The effects of that recent history and the consequent pressure drop as the ice sheet disappeared can still be recognized in the geothermal gradients, the hydrothermal alteration, and in the fluid inclusions.

Another approach is to make analogies with comparable "fossil" deep magma-hydrothermal systems that are exposed at outcrop in NW Scotland and East Greenland, where there is abundant evidence of high-temperature supercritical fluid flow in tensional environments associated with the opening of the Atlantic Ocean. The implication is that fracture permeability persists deep into the hot ductile zone.

The discussions and suggestions from both the engineering and scientific participants were very wide ranging and to implement all of them clearly it would be 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.

4.0 Appendix

Workshop Program and List of Participants



IDDP - ICDP Workshop 2012

Preparing for the IDDP-2 deep well at Reykjanes

ELDBORG - SVARTSENGI - ICELAND
3-5 September 2012

IDDP-ICDP Workshop 2012

Opening Address

Júlíus J. Jónsson, CEO HS Orka hf

Distinguished audience

I have the pleasure to open this ICDDP-ICDP Workshop and to welcome all of you distinguished international and domestic participants.

The IDDP project has now been ongoing for some 12 years - and despite some misgivings - we have the feeling that we might be approaching the goal we set initially – to realize significant increase in the power potential of production wells, and eventually real increase in power production. As you will hear later this morning the IDDP-1 well in Krafla is currently the hottest production well in the world and has a production potential of some 35 MWe.

I understand from my colleagues in IDDP, that the purpose of this workshop is to review several key questions:

- What is the current status of the IDDP project
- Are we on the right track
- Will be able to continue – or are there some “show-stopper” in sight

Assuming that recommendation will be that IDDP should continue into the next drilling phase – namely drilling well IDDP-2 here at Reykjanes, I also understand that this workshop will address several additional very important R&D questions:

- How shall we proceed before, during and after drilling IDDP-2
- Do we need to solve some technical problems before drilling
- Is it likely that we will be able to continue during the next 2-3 years

The most challenging task then will be to secure the funding for the drilling, probably in connection to the necessary drilling for the planned Reykjanes extension.

I think I can be so frank to speak for all the CEO group for the IDDP Consortium - to say that we have good faith in the deep drilling project – and address our thanks to all of you participants here – and wish you a very successful IDDP-ICDP Workshop.

	IDDP-ICDP WORKSHOP 2012					
	AGENDA					
2.9.2012	SUNDAY - Visitors Arrival					
3.9.2012	**MONDAY:**			Presenters:	Institute	**Session Chair:**
9:00 - 9:05	Opening Address			Júlíus J. Jónsson	HS Orka hf (HS)	Greg Bignall
9:05 - 9:15	IDDP achievments -overview			Guðm. Ómar Friðleifsson	HS Orka hf (HS)	
9:15 - 9:25	Purpose of this IDDP-ICDP workshop			Wilfred A. Elders	UC Riverside	
9:25 - 9:40	Drilling of IDDP-1 at Krafla in 2009			Bjarni Pálsson et al	Landsvirkjun (LV)	
9:40 - 9:55	IDDP-1 flow test - status report			Sigurður H Markússon et al.	Landsvirkjun (LV)	
9:55 - 10:10	IDDP-1 wellhead and flow line design			Kristinn Ingason et al.	Mannvit	
10:10 - 10:20	**Discussion**					
10:20 - 10:35	**Coffee break**					
10:35 - 10:45	IDDP-2 site at Reykjanes - overview			Guðm. Ómar Friðleifsson	HS Orka	Wilfred Elders
10:45 - 11:00	New 3D MT intepretation for Reykjanes			Knútur Árnason et al	Iceland GeoSurvey (ISOR)	
11:15 - 11:30	Fluid Chemistry at Reykjanes - overview			Þráinn Friðriksson et al	Iceland GeoSurvey (ISOR)	
11:30 - 11:45	Enhanced Exploration at Reykjanes in relation to the FP-7 call			Ólafur G. Flóvenz et al.	Iceland GeoSurvey (ISOR)	
11:45 - 12:00	Deep Root Suprastate Reservoir Properties			Jónas Elíasson	University of Iceland	
12:00 - 12:10	IDDP-2 and HS Orka hf - Deep Vision			Albert Albertsson	HS Orka	
12:10 - 12:20	**Discussion**			all		
12:20 - 13:20	**Lunch break**					
13:20 - 13:35	InnovaRig - experience and future			Bernard Prevedel	ICDP - OSG - GFZ Potsdam	G.Omar Friðleifsson
13:35 - 13:50	Jardboranir - Bentec Rig			Sturla Birkisson	Iceland Drilling Ltd	
13:50 - 14:05	Conceptualizing stress and permeability fields in deep roots of geothermal systems			S. Hickmann - Grímur Björns	USGS and RG	
14:05 - 14:20	COTHERM - integration of thermo-hydrologic, geochemical and geophysical modeling with real data on two geothermal systems in Iceland			Thomas Driesner et al.	ETH Zurich	
14:20 - 14:35	Field and Experimental Observations of brittle failure under ductile condition. Perspective for JBBP			Noriyoshi Tsuchiya	Tohoku University, Japan	
14:35 - 14:50	Drill-bit seismic while drilling as a tool for geothermal exploration: method, results and operational aspects			Flavio Poletto	OCS, Trieste, Italy	
14:50 - 15:10	**Discussion**			all		
15:10 - 15:30	**Coffee break - followed by Student Session**					
15:30 - 15:40	Geochemistry and petrology of IDDP cores RN-17B and RN-30 from the Reykjanes Peninsula			Andrew Fowler	UC Davis, USA	Wilfred Elders
15:40 - 15:50	High-T downhole fluid sampling by quartz fluid inclusions: A progress report			Ryan Seward	Univ. Oregon, USA	
15:50 - 16:00	Sulfide Mineralization in the Reykjanes Geothermal Field: Applications to Geothermal Exploration			Ryan Libbey	McGill, Canada	
16:00 - 16:10	Fluid and flow behaviour of supercritical geothermal fluids - creation of a well simulation model			Lena Patsa	Univ.BC. Canada	
16:10 - 16:20	Physics behind induced seismicity in/around the brittle-ductile transition zone			Yusuke Mukuhira	Tohoku Univ. Japan	
16:20 - 16:30	Experimental basalt fluid interactions at supercritical and superheated steam conditions: Implications for the IDDP (PhD study for JKB)			B. W. Mountain & J.K.Björke	GNS & Wellington U. NZ	
16:30 - 16:45	Structural settings and nature of permeability in a black smoker			Cecile Massiot et al.	GNS New Zealand	
16:45 - 17:00	**Discussion**			all		
17:15 - 20:00	**Reykjanes Field trip**					
4.9.2012	**TUESDAY**					
9:00 - 9:15	Update on Proposed Deep Science Drilling (2014-15) in the Taupo Volcanic Zone, New Zealand			Greg Bignall	GNS, Taupo, New Zealand	G.Omar Friðleifsson
9:15 - 9:30	Japanese Beyond Brittle Project - JBDP			Hirofumi Muraoka	Hirosaki University, Japan	
9:30 - 9:40	Supercritical fluids from exhumed and uplifted geothermal systems			Liotta & Ruggieri	CEGL - CNR, Italy	
9:40 - 9:55	Experimental investigation of physical rock properties, above the CP			Spangenberg-Kummerow	GFZ Germany	
9:55-10:10	High Temperature Coring Tools			Alister Skinner	ASCS Scotland	
10:10 - 10:25	High P-T downhole logging Tools			Ragnar Ásmundsson	Iceland and NZ	
10:25 - 10:45	**Coffee break**					
10:45 - 11:00	**Discussion and split into break-out groups**					
10:30 - 12:30	**GeoScience**	**Drilling Technology**	**Fluid Handling and Pilot production**			
Session Chair:	Wilfred Elders	Dennis Nielsson	Robert Fournier			
	5-10 min presentations:	5-10 min presentations:	5-10 min presentations:			
10:30-10:40	Mark Reed	Sverrir Þórhallsson	Sigrún N. Karlsdóttir			
10:40 - 10:50	Robert Zirenberg	Kristinn Ingason	Halldór Ármansson			
10:50 - 11:00	Andri Stefánsson & T. Driesner	Sigrún N. Karlsdóttir	Jiri Muller			
11:00 - 11:10	Ted Bertrand	Þór Gíslason	Trausti Hauksson			
11:10 - 11:20	Steve Hickman		Geir Þórólfsson			
11:20 - 11:30						
11:30 - 11:40	Giovanni Ruggieri					
11:40-11:50	Ómar Sigurðsson					
11:50 - 12:30	**Pleanry Discussion from all break-out groups**					
12:30 - 13:30	**Lunch Break**					
13:30-15:00	**Break-out groups continue (possibly in sub-groups as well)**					
15:00-15:30	**Coffee break**					
15:30 - 17:00	**Plenary - Break-out groups preliminary summary -**					Wilfred Elders
17:30	**Blue Lagoon**					
19:30	**Workshop Dinner**					
5.9.2012	**WEDNESDAY**					
9:00 - 10:30	**Break-out groups - summary and recommendations**					
10:30 - 11:00	**Coffee break**					
11:00 - 12:30	**Plenary Discussion and Summary**					Greg Bignall
12:30 - 13:30	**Lunch break**					
13:30 - 15:00	**Break-out groups - report writing**					
15:30 - 16:00	**Coffee break**					
16:00 - 17:00	**Final session - workshop close**					G.Omar Friðleifsson
17:00 - 19:00	**IDDP-DeepVision and SAGA meeting**					
6.9.2012	**THURSDAY - Visitors Departure**					

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IDDP-ICDP WORKSHOP 2012
AGENDA
Break out sessions

GEOSCIENCE:

Mark Reed	Black smoker thermobarometry
Robert Zierenber	Core versus cuttings
Andri Stefánsson & Thomas Driesner	Fluid Phase Relation and Fluid Properties of saline Geothermal Systems
Ted Bertrand	2D and 3D MT interpretation from Taupo NZ
Steve Hickman	Conceptualizing stress and permeability fields in deep roots of geothermal systems
Sverre Panke	Seismic imaging and interpretation of basaltic sequences
Giovanni Ruggieri	Information on super-critical fluids from fluid inclusion studies in exhumed and uplifted geothermal systems
Jacques Varet	Deep drilling of an oceanic ridge directly from the continent (Djibouti)
Ómar Sigurðsson	Reykjanes reservoir - overview

DRILLING TECHNIQUE:

Sverrir Þórhallsson:	Challenges in drilling very hot wells
Kristinn Ingason et al.:	IDDP-1 well design -overview discussion
Sigrún N. Karlsdóttir :	Corrosion of casing material in sour and high temperature geothermal wells
Þór Gíslason	IDDP-2 design option

FLUID HANDLING AND PILOT PRODUCTION

Sigrún N. Karlsdóttir & Ásbjörn Einarsson:	Corrosion Tests in IDDP-1
Halldór Ármannsson	IDD1 fluid chemistry expanded
Jiri Muller :	Geothermal Tracers under Supercritical Conditions (High T and P)
Trausti Hauksson:	IDDP-1 flow test - expanded
Geir Þórólfsson:	HS Orka wellhead experience

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