Preliminary Description of Rocks and Alteration in IDDP-2 Drill Core Samples Recovered from the Reykjanes Geothermal System, Iceland

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ABSTRACT

The Iceland Deep Drilling Project (IDDP) well IDDP-2 was drilled to 4,659 m in the seawaterrecharged and basalt-hosted Reykjanes geothermal system in Iceland. Spot drill cores were recovered between drilling depths of 3,648.00 m and 4,657.58 m. Temperature and pressure conditions at the base of IDDP-2 were over 426°C and 340 bar immediately following drilling, exceeding the critical point of seawater (406°C and 298 bar). The IDDP-2 cores are the first samples ever recovered from the supercritical roots of an active basalt-hosted hydrothermal system. We provide some preliminary hand sample descriptions, supplemented where possible by thin section petrography and mineral composition analyses for the IDDP-2 drill cores. The cores recovered between 3,648 m and the bottom of the hole at 4,659 m are from a sheeted dike complex and are generally pervasively altered. Despite the extensive alteration, veining is relatively minor and open space veins are very rare. Veins tend to be discontinuous and anastomosing and lack sharp wall rock contacts. They are interpreted as hydrothermal replacement veins formed in the transition zone between brittle and ductile deformation. Important initial findings include the transition from epidote-actinolite alteration to hornblende hornfels alteration at approximately 3,650 m, and the development of hydrothermal biotite in rocks below ~4,250 m. Felsic (plagiogranite) segregation veins are not common on the Reykjanes peninsula west of the Hengill volcanic system, but are present in minor amounts in most of the dikes cored below ~4,300 m. Detailed petrographic and geochemical analysis of the samples is on-going. We have also sampled what appears to be hypersaline supercritical/magmatic brine trapped in pore spaces of porous felsite veins and adjacent wall rock, which manifests as a yellow potassium-iron chloride salt that precipitates on the cut edge of the core as pore fluid evaporates. Some of the core at these depths was stained by hematite that formed on the outer core surface by oxidation of ferrous iron in the formation fluid reacting at elevated temperature with oxygenated surface water used as drilling fluid. Further evidence for supercritical brine is apparent in complex fluid inclusions within quartz that contain multiple solid phases. The drill core samples are of immense scientific value for studying chemical conditions in the supercritical roots of high-enthalpy geothermal resources and submarine hydrothermal systems, with implications for improved understanding of ore-forming processes.

1. Introduction

The IDDP is a consortium of industries including Hitaveita Surdurnesja (now HS Orka), Landsvirkjun, Orkuveita Reykjavíkur, the National Energy Authority of Iceland (Orkustofnun), Alcoa Inc. (2007-2012), and Statoil (For a historical review of the IDDP project see Friðleifsson et al., 2010). The main IDDP goal is to determine the economic feasibility of energy and chemical extraction from supercritical brines, by drilling 4-5 km deep at a rifted plate margin and intercepting hydrous supercritical fluids (Friðleifsson et al., 2014).

On January 25th, 2017, IDDP successfully deepened well RN-15 (now RN-15/IDDP-2) to a depth of 4,659 m in the Reykjanes geothermal system of southwest Iceland. All primary drilling goals were met, which included intercepting supercritical fluids, encountering permeability below the presently exploited geothermal reservoir, and recovering drill core samples. The temperature at the base of the hole was 426°C at a pressure of 340 bars, measured during drilling after 6 days of heating at the bottom. This exceeds the critical point of seawater (406 °C and 298 bar), even though the well had not recovered from cooling during drilling. Complete circulation loss was encountered below 3,200 m, which precluded recovery of drill cuttings. Drill core was obtained in nine out of thirteen coring attempts from drilling depths between 3,648.00 and 4,657.58 m. This paper focuses on preliminary observations and analyses of the drill core.

Background on recent IDDP activities, drilling conditions, and future directions of IDDP are provided in a companion papers (Friðleifsson and Elders, this volume). The IDDP-2 cores are the deepest samples drilled from Iceland and the only rock samples ever recovered from supercritical conditions in an active, basalt-hosted and seawater-recharged hydrothermal system. Studies of the IDDP-2 cores are not only an opportunity to further our understanding of igneous processes, hydrothermal alteration and fluid characteristics in the roots of the Reykjanes geothermal system, but also provide insights into geochemical processes operating in the roots of active, basalt-hosted submarine hydrothermal systems that form massive sulfide deposits.



Figure 1: Location map of the Reykjanes geothermal system and location of IDDP drilling activities. Lower right insert map shows drill holes where core samples have been recovered. Dark tracks show the projected surface trace of deviated drill holes.

2. Geological setting

The Reykjanes geothermal system is the immediate onshore continuation of the submarine Mid-Atlantic Ridge, and is located on the seaward tip of the Reykjanes Peninsula in southwest Iceland (Figure 1). Fluids in the Reykjanes geothermal system are composed of seawater chemically modified by reaction with the host basaltic rocks (Arnórsson, 1978). Deep fluids in the Reykjanes geothermal system have major element and metal concentrations comparable to those from basalt-hosted submarine 'black smoker' fluids (Hardardóttir et al., 2013). An important difference from hydrothermal samples obtained from seafloor vents is that the Reykjanes fluids sampled at the well head have been altered due to boiling in the production wells, which results in the precipitation of well scale, including metal sulfides, that deplete the fluid in many trace metals (Hardardóttir et al., 2009; Hardardóttir et al., 2013) including rare earth elements (Fowler and Zierenberg, 2015).

The Reykjanes geothermal area is less than 40 m above sea level and is capped by ~120 m of lava flows emplaced subaerially during interglacial periods. The lava flows flood low points around subglacially emplaced hyaloclastite tuff and pillow basalt ridges that formed during the Late Pleistocene. Subaerially emplaced basalts are underlain by a sequence of hyaloclastite tuff formations that are in places intercalated with lava flows. Between about 500 and 1000 m below the surface, a series of reworked hyaloclastite tuff sediments with occasional marine fossils are periodically intercalated with submarine pillow basalts, and below 1000 m submarine pillow basalt formations and intrusive rocks dominate (Franzson, et al., 2002; Franzson, 2004; Marks et al., 2010) with dikes becoming increasingly abundant at depth.

There is a predictable sequence of alteration minerals that varies with depth and temperature in the Reykjanes geothermal system. With increasing depth and temperature this includes the: smectite-chlorite, chlorite, chlorite-illite, epidote-actinolite, and hornblende alteration zones (Tómasson and Kristmannsdóttir, 1972; Lonker et al., 1993; Franzson, et al., 2002; Marks et al., 2010; Weisenberger at al. 2016). Localized contact metamorphic granoblastic hornfels zones have also been identified below about 2,000 m (Marks et al., 2011).

3. Previous IDDP Drilling at Reykjanes

Prior to drilling the IDDP-2 well, IDDP recovered drill core from three Reykjanes drill holes and attempted to drill a deep geothermal well at the Krafla geothermal field. Details of rock samples and alteration recovered by the IDDP-1 drilling effort in the Krafla geothermal field, which was terminated at a depth of 2,104 m when a rhyolite melt was intersected, are provided elsewhere (Elders et al., 2011; Schiffman et al., 2012; Zierenberg et al., 2012).

IDDP intended to deepen the 3,082 m deep RN-17 production well in the Reykjanes geothermal field to meet project goals, however this idea was abandoned when the well became blocked during production testing in November 2005 (Friðleifsson and Richter, 2010). While RN-17 could not be used as an IDDP well of opportunity, studies of RN-17 drill cuttings by the IDDP science team improved models of the volcanic structure, hydrothermal alteration at depth in the Reykjanes geothermal and provided an important foundation upon which subsequent IDDP studies could be built (e.g. Marks et al., 2010; Marks et al., 2011). While drill cutting studies continue to provide important insights into Icelandic geothermal systems at conventional drilling depths, the IDDP team recognized the need to collect drill core during a future IDDP drilling attempt, in recognition of the limitations of drill cutting samples recovered from extreme depths (e.g. Fowler and Zierenberg, 2016b).

Prior to the IDDP effort, drill core had not previously been recovered from the Reykjanes system. Coring equipment tests were performed in well RN-19, RN-17B and RN-30. The RN-19 test produced 2.97 m of core from 2,245 to 2,248 m (Mortensen et al., 2006; Friðleifsson and Richter, 2010; Ottolini et al., 2012; Fowler and Zierenberg, 2016a). The RN-17B test recovered 9.3 m of core from a drilling depth of ~2,800 m in a 35° inclined sidetrack of hole of RN-17 (Friðleifsson and Richter, 2010; Fowler et al., 2015), and the RN-30 test recovered three sequential cores totaling 22.5 m in length from a drilling depth of ~2510 m a 35° inclined hole (Fowler and Zierenberg, 2016a).

4. The IDDP-2 Drill Cores

4.1 Descriptions of IDDP-2 Drill Core Samples

The following descriptions are primarily derived from hand sample descriptions completed onsite by the authors who comprised the IDDP-2 geologic team, supplemented where available by on-going petrographic and geochemical investigations, and should be taken as a preliminary report on the down hole geology. The intervals where drill core was recovered are provided on Table 1. More detailed descriptions of cores and core fragments will be made available in the IDDP-2 Scientific Drilling Reports.

IDDP-2 Core Run	Cored Interval (m)	Core Length (m)	Recovery (%)
3	3.648.0 - 3.648.9	0.52	58
5	2 965 5 - 2 960 9	2.95	00
5	5,805.5 - 5,809.8	5.65	90
6	3,869.8 - 3,870.2	0.15	38
7	4,089.5 - 4,090.6	0.13	11
8	4,254.6 - 4,255.3	0.28	40
10	4,309.9 - 4,311.2	0.22	17
11	4,634.2 - 4,642.8	7.58	88
12	4,642.8 - 4,652.0	9.0	98
13	4,652.0 - 4,659.0	7.0	80

Table 1: Drill cores recovered from IDDP-2. Core runs 1, 2, 4, and 9 did not recover intact core samples.

<u>4.1.1 Core 3 (3,648.00 m - 3,648.52 m)</u>

Core run 3 recovered segments of three medium-grained, greenish-grey diabase half dikes separated by chilled dike margins. The chilled margins are replaced by a very fine-grained mixture of epidote, actinolite, chlorite, albite, secondary clinopyroxene, magnetite and sphene. The diabase is pervasively altered with complete replacement of clinopyroxene by actinolite with less abundant hornblende, chlorite, and epidote. Igneous plagioclase is partly altered to albite, epidote and chlorite. Primary titanomagnetite is partly replaced by magnetite and sphene. The core is cut by several 1-5 mm thick discontinuous epidote-plagioclase-amphibole-quartz veins with dark amphibole-chlorite vein selvages (Figure 2A, 3A). The veins have irregular to gradational margins and lack clear open-space filling growth textures. Some veins show offsets where intersected by later veins while others merge together into anastomosing compound veins, but all veins have the same mineralogy. Sulfide minerals are present in the veins and groundmass alteration. The most abundant sulfide is intermediate solid solution (ISS) Cu-Fe sulfide with less abundant pyrrhotite and pyrite.

<u>4.1.2 Core 5 and 6 (3,865.50 m - 3,869.95 m)</u>

Core run 5 recovered 3.85 m of continuous core, with no missing intervals or coring gaps and no discernable systematic change in texture or mineralogy down core. The diabase recovered in Core 6 is identical in appearance and is interpreted to have sampled the same dike.



Core 3: 3648.12 - 3648.31 m



В

D

Core 5:3855.50 - 3855.54 m





Core 11:4638.00 - 4638.08 m

Figure 2: Drill core samples from the IDDP-2 well. See text for descriptions.



IDDP Core 3 3648.28 m



IDDP Core 8 4254.60 m

B



IDDP Core 5 3865.50 m





IDDP Core 11 4636.32 m



IDDP Core 11 4637.79 m



IDDP Core 13 4653.25 m

Figure 3: Representative rock textures from IDDP-2 drill cores, each image is a scan of a standard thin section (2.54 mm in short dimension). A. Core 3 3,648.28 m. Epidote-plagioclase-amphibole-quartz replacement veins cutting pervasively altered diabase dike. B. Core 5 3,865.50 m. Medium grained diabase dike. Clinopyroxene is completely replaced by actinolite and hornblende; plagioclase is generally unaltered. Hair-like amphibole vein cutting diagonally across (bottom left of center to top center) the sample is a typical expression of hydrothermal veining in this interval. C. Core 8 4,254.60 m. Fine grained basalt showing increasing grain-size away from the dark quenched margin (lower right corner). Early dark hornblende replacement veins developed in shear bands are cut by successive generations of hornblende-plagioclase±quartz veins. D. Core 11 4,636.32 m. Quenched margin of porphyritic diabase dike with flow alignment of plagioclase laths parallel to the margin. E. Core 11 4,637.79 m. Thin felsite vein network cutting partially altered diabase dike. Mafic minerals in the felsite are biotite > pyroxene pseudomorphed by hornblende. F. Core 13 4,653.25 m. Felsite vein cutting altered diabase with dark, fine-grained selvages of hornblende and magnetite.

Clinopyroxene is essentially completely replaced by dark green amphibole, which includes intergrown actinolite and hornblende. In contrast, plagioclase and titanomagnetite appear essentially unaltered. There are a few <1 mm hairline veins of dark-green to black amphibole (Figure 2B, 3B) that cut the core at various angles, with large changes in vein direction along a single vein. A few discontinuous and diffuse 1-3 mm wide veins and patches of lighter colored, more felsic, diabase are present. Plagioclase is more abundant in these veins and some has a cloudy appearance due to symplectic intergrowth of plagioclase and quartz. Clinopyroxene (replaced by amphibole) is less abundant compared to the surrounding diabase and anhedral quartz is present as a minor phase. The textural relationships and the mineralogy suggest these are late-stage differentiated igneous segregations as opposed to hydrothermal alteration features.

<u>4.1.3 Core 7 (4,090.00 m - 4,090.12 m)</u>

Core run 7 recovered 120 mm of fine-grained altered diabase dike generally similar in texture and composition to the dike recovered in Cores 5 and 6. The recovered core was broken into 4 disk-like fragments along planer fracture perpendicular to the core axis. There is a weak lineation on the fracture surfaces that is roughly parallel on each fracture surface when the core is pieced back together. Clinopyroxene is generally 2 x 2 mm in cross section, with some grains more elongated, up to 4 mm. The elongated clinopyroxene and the 2-4 mm, slightly elongated plagioclase laths show weak aligned that apparently define the lineation on the core fractures. There are sparse blocky plagioclase phenocrysts/glomerocrysts up to 5-6 mm. This dike is pervasively altered, but igneous clinopyroxene is still present, although subordinate to hydrothermal amphibole. Examination of the cut surfaces of core pieces shows that some plagioclase is slightly cloudy and greenish, apparently due to incipient alteration. The finergrained interstitial patches show more pervasive greenish-blue patchy alteration and/or late-stage plagioclase-quartz symplectic intergrowth. There are some sparse 1-2 mm patches of sulfide, dominantly pyrrhotite, but including some Cu-Fe sulfide that appears to be authigenic rather than immiscible magmatic sulfide.

<u>4.1.4 Core 8 (4,254.60 m - 4,254.88 m)</u>

The core, and majority of fill fragments collected on top of the core, consist of fine- to mediumgrained basalt completely replaced by very fine-grained hornblende, secondary calcic plagioclase, and subordinate metamorphic titanomagnetite and ilmenite (Figure 3C). The veining, sheering and recrystallization suggest this interval may be a screen between younger dikes, but it is not clear if the protolith was a submarine lava or an older, fine-grained dike margin. A thin quench zone is present in two of the core pieces, but subsequent alteration and deformation make it unclear if this is a dike margin or the glassy rind on a pillow. This unit is composed of approximately 60% black to dark green, equant to slightly elongate hornblende with a ~1 mm grain-size that replaces original clinopyroxene, and locally, plagioclase. Approximately 30-35% of the rock is calcic plagioclase, most of which psuedomorphs igneous plagioclase. There are minor Na-rich plagioclase patches that are likely relict albite replacement, but this plagioclase now has intermediate compositions with sub equal Na and Ca. Plagioclase in the matrix tends to be equant and coarser grained (~2 mm). A weakly defined foliation approximately perpendicular to the core axis is developed locally. The earliest vein set consists of discontinuous monomineralic green amphibole replacement veins. These veins are offset by dark hornblende-magnetite replacement veins developed in shear-bands. The shear bands include abundant fine-grained calcic plagioclase and fine-grained disseminated magnetite and ilmenite.

The early sheer bands are cross cut by at least three generations of amphiboleplagioclase±magnetite±quartz veins. The later veins contain proportionally more plagioclase and quartz, and at least one of these veins contains trace mm-size biotite books. Cu-Fe sulfides are present, especially in earlier shear-bands and later quartz bearing veins.



Figure 3. A. Felsite vein cutting diabase. The cut surface of the core shows hematite staining. Yellow KFeCl salts precipitated on the top cut surface of the core. B. Chilled dike margin. C. Euhedral hydrothermal biotite, approximately 1 mm in diameter, coating fracture surface shown in Fig. 2D. Exposed crystals were stained red by hematite during the coring operation. D. Open-space filling quartz overgrowing hydrothermal biotite (black and reflective, approximately 1 mm across) coating the fracture shown in Figure 2D.

<u>4.1.5 Core 10 (4,309.90 m - 4,310.12 m)</u>

Core run 10 recovered a fine-grained basaltic intrusion with a texture suggesting emplacement as a dike, but the limited recovery precludes determination of the orientation of this intrusion. The protolith contained sub equal amounts of elongated tabular plagioclase up to 2 mm with interstitial subhedral clinopyroxene about 1 mm across, and a few percent anhedral 1 mm titanomagnetite grains. The lower two core pieces are weakly porphyritic due to the presence of

less than 1% blocky plagioclase phenocrysts up to 3-4 mm and rare pyroxene phenocrysts up to 2-3 mm. The rock is extensively, but not completely, altered. Phenocrysts and coarser groundmass plagioclase laths are more often clear and glassy, but much of the matrix feldspar is cloudy white to light bluish-green. Clinopyroxene is greenish due to extensive replacement by amphibole, but brown glassy clinopyroxene is preserved in places. The interstitial material is completely replaced by amphibole, which is locally intergrown with biotite and secondary plagioclase. Disseminated fine-grained anhedral sulfide is common, with Cu-Fe sulfide more abundant than pyrrhotite and pyrite.

Locally, the core is cut by plagiogranite segregation veins and patches, the best developed of which is a 2 cm thick band dipping at approximately 70° to the core axis. Given the ~ 30° inclination of the drill hole, the vein may have originally been approximately horizontal. Where best developed, the plagiogranite is approximately 70% feldspar, most of which is anhedral and cloudy white due to symplectic intergrowth with quartz. However, there are some euhedral, 2 mm blocky plagioclase crystals that are relatively clear. The plagiogranite contains approximately 20% green amphibole, which replaces original pyroxene that show a range of grain size from < 1 mm equant crystals to acicular crystals < 1 mm in cross section and up to 3-4 mm long. There is ~5% fine-grained sub to euhedral titanomagnetite disseminated through the rock. Healed fractures cutting through some of the plagiogranite have a small amount of subhedral grey quartz.

4.1.6 Cores 11,12, and 13 (4,634.20 m – 4,657.58 m)

The IDDP-2 hole was drilled to a depth of 4,626 meters using a 216 mm bit and recovered 102 mm diameter core. The open hole was logged from the base of the casing shoe (2,940 m) to the bottom of the hole at 4,623 m using a suite of logging while tripping tools. A pressure-temperature log was run to a depth of 4,560 m following 6 days of heating at the bottom of the hole. The major feed zone in the open section of the hole occurs at about 3,450 m, with several smaller feed zones, the deepest of which is at 4,550 m (Friðleifsson and Elders, this volume). The bottom hole temperature was ~426° C (Friðleifsson and Elders, this volume), but the well had clearly not thermally equilibrated, so this is a minimum estimate of the *in situ* temperature, yet clearly above the critical temperature for fluid with seawater salinity (406° C). Following insertion of a 178 mm lining, three consecutive core runs were conducted using a 152 mm bit that cut 67 mm core. Core run 11 recovered 7.58 m of continuous core, with no missing intervals or coring gaps. Core run 12 recovered 9.00 m of continuous core, and Core run 13 recovered 5.58 m of continuous core.

The interval cored at the bottom of the hole contains four half dikes separated by three chilled dike margins. A chilled margin at 4,636.25 m indicates the dike in the upper part of Core 11 chilled against the underlying dike (Figure 4B). Plagioclase phenocrysts define a flow alignment parallel to the dike margin (Figure 3D). The upper dike in Core 11 is a porphyritic basalt with a groundmass that consists of 1 mm euhedral to subhedral glassy (where unaltered) green-brown clinopyroxene (65-70%) separated by 1 mm long euhedral plagioclase laths (20-25%), and less than 5% 1 mm euhedral titanomagnetite. Phenocrysts include elongate plagioclase (5%) up to 5 mm, and occasional 3 mm euhedral, greenish, partially altered olivine. Plagioclase typically shows igneous textures and zoning, but the crystals have a dusty appearance, suggesting subtle alteration, that follows compositional zoning in the plagioclase. Pyroxene is partially to completely replaced by hornblende. The upper part of Core 11 is cut by conjugate veins less than

1 mm wide filled with dark hornblende (Figure 2C). Hornblende, intergrown with biotite, forms dark selvages and as well as irregular diffuse alteration patches. Hydrothermal mineral veins are not common down core, and those present are predominantly hairline fractures filled with hornblende. There is little to no sulfide associated with the alteration.

Felsite segregation veins are more prominent in the deeper cores. The veins range in width from 2 to 30 mm wide (Figure 4A). They commonly branch and intersect with no offset margins. The dominant minerals are subhedral plagioclase and rounded quartz set in a matrix of fine, sugary intergrown quartz and plagioclase. In contrast to the dusty appearing plagioclase in the host rock, the plagioclase in the felsite veins appears clear. The symplectic intergrowths of plagioclase and quartz that characterize the more felsic zones in shallower core are lacking. Some of the felsite veins contain up to 5% mafic minerals, including pyroxene, which is generally replaced by hornblende, and biotite. The ratio of pyroxene to biotite is variable and either phase can dominate. The contacts of the felsite veins with the wall rock are very sharp (Figure 2D, 3E), but in some instances euhedral plagioclase crystals cross the boundary. In some instances, fragments of wall rock are included within the felsite vein. The veins are typically (but not ubiquitously) stained red with a thin hematite film that is only present on the outer, drill-cut surface and rare pre-coring open fractures (Figure 2C, 2D); the core interior, exposed by fracturing or cutting the core after recovery, are not hematite stained. Cut felsite vein surfaces are often stained yellow due to post-coring/post saw-cut evaporation of pore fluid that precipitates yellow potassium-iron chloride salt as the core dries (Figure 4A). Open fractures are rare, but one open fracture bounding a felsite veins was coated with coarse-grained, euhedral hydrothermal biotite (Figure 2D, 4C). Euhedral, prismatic quartz crystals, including some that are doubly terminated, over grow the biotite (Figure 4D). This represents the sole occurrence of open space filling quartz in the recovered core. The quartz contains sparse fluid inclusions that range from vapor-dominated, to nearly filled with precipitated salts. The facture surface and adjacent core surface were coated by a thick film of hematite, and deep-red hematite-bearing fluid oozed out of the fracture when the core was first recovered. A second mineralized fracture coated by hydrothermal biotite occurs down core and is associated with crystals of a Cu-Fe sulfide mineral (ISS?), and euhedral prismatic crystals tentatively identified as hydrothermal pyroxene.

The lower intrusion in Core 11 is glomeroporphyritic with both plagioclase and clinopyroxene glomercrysts. Clinopyroxene is more abundant than plagioclase. Some plagioclase occurs as 1-2 mm elongated crystals, but generally the plagioclase is somewhat irregular shaped and forms a weakly felted matrix that is interstitial to clinopyroxene. The lower intrusion has ~5-8% equant titanomagnetite crystals, which appears to be more abundant than in the upper dike. Some plagioclase has what appears to be greenish alteration in hand specimen. Clinopyroxene in the lower intrusion appears more altered than in the overlying (and younger) dike. The lower dike is typically homogeneous and appears to coarsen down hole in Core 12. Felsite veins are less common than in the overlying dike. Locally, there are irregular-shaped plagioclase-rich 'felsite' patches and small networks of thin branching veins, usually with width and length dimensions less than 10 mm, but up to 50 mm (Figure 3E). The patches are dominated by plagioclase and quartz, with minor mafic minerals that include biotite and black pyroxene.

The glomeroporphyritic half dike is the thickest dike recovered, with a downhole extent of 14.4 m. Given the $\sim 40^{\circ}$ inclination of the drill hole at this depth, the dike would have a minimum

thickness greater than 9 m, assuming the dike is vertical. At the base of the dike there is a rapid decrease in grain-size and the dike is chilled against the underlying half dike.

The older, underlying dike at the base of Core 12 is a medium- to fine-grained intrusive with a heterogeneous texture with irregular patches that are coarser, finer, or richer in interstitial material. Based on hand sample observations, this intrusion is classified as a two-pyroxene diabase. The dominant texture consists of 2-3 mm elongate plagioclase (55%) with occasional pheno/glomercrysts of blocky plagioclase up to 4 mm. Plagioclase is generally clear and appears unaltered. Clinopyroxene (15%) appears as blocky, black, 2 mm euhedral crystals that are rarely elongated, up to 4 mm. Orthopyroxene (20%) is beer bottle brown, euhedral, and 1-2 mm. Patches of fine-grained, late-stage interstitial material make up 7-8% of the rock, and consist of concentrated irregular shaped 5-10 mm patches of fine-grained plagioclase, orthopyroxene, and clinopyroxene that appear slightly greenish and slightly altered. There are occasional 1-2 cm patches of coarser grained rock with the same composition. There is patchy overprinting alteration where some of the pyroxene is altered to amphibole, but other patches where all crystals appear fresh. Titanomagnetite (2-3%) is fine grained and not abundant in coarse-grained patches, but occurs as fine-grained aggregates in the fine-grained interstitial material, and often occurs with sulfide, which appears to be pyrrhotite.

The uppermost core fragments in Core 13 contain a chilled dike margin, but the orientation of these core fragments is uncertain, so the age relationship of the lowermost half dike to the overlying half dike remains to be determined by more detailed petrographic analysis. The intrusion in Core 13 is characterized by a heterogeneous texture and composition with patchy alteration. Euhedral plagioclase (60 to 65%) forms a matrix of thin, elongated and felted crystals 2-3 mm long, with 30% 1-2 mm interstitial dark clinopyroxene, and 5-8% 1-2 mm subhedral titanomagnetite. There is patchy development of coarser, blocky to glomerocrystic plagioclase up to 3-4 mm. Plagioclase appears generally fresh, but pyroxene is partly altered to amphibole. Variation in grain size is difficult to discern due to the ubiquitous hematite staining coating the cored surface. Diffuse, centimeter-scale clots of coarser-grained material appear throughout the dike and are separated on the scale of centimeters (a 10 cm length of core may contain two to four cm-sized clots) giving the cut core a spotted appearance. The boundaries of the clots are indistinct and gradational and may suggest partial assimilation or magma mixing/incorporation of crystal mush. The coarser-grained clots tend to have slightly more pyroxene, and the plagioclase and pyroxene can approach 4 mm in size. Fine-grained, sugary textured mm-wide feldspar + quartz zones with indistinct boundaries may represent healed fractures or thin zones thermal recrystallization. A few cm-scale felsite segregation veins are present in this half dike. In contrast to felsite veins at shallower depths, amphibole pseudomorphing pyroxene is the dominant mafic phase and biotite does appear to be present either in the veins or in the altered wall rock. The wall rock adjacent to the felsite veins is typically flooded with abundant finegrained hornblende and secondary magnetite (Figure 3F). The dark selvedge can extend outward from the felsite vein edges to distances similar to the vein width.

4.2 Mineral Compositions

Here we present preliminary results for electron microprobe analyses of key primary and secondary minerals in the IDDP-2 drill cores. Data is currently available for samples from cores 3 through 10; analysis of minerals in cores 11 through 13 is in progress.

Primary and hydrothermal pyroxene in the Reykjanes geothermal system are compositionally distinct; primary pyroxene is augitic in composition while hydrothermal pyroxene ranges in composition from diopside to hedenbergite (Figure 5A), consistent with observations from RN-17 drill cuttings (Marks et al., 2011). Both primary and secondary pyroxenes are present in the IDDP-2 cores, and fall in the compositional ranges reported for pyroxene in shallower portions of the system. Hydrothermal clinopyroxene is most abundant in the quenched margins of the sheeted dikes recovered in Core 3 (Figure 5A), both replacing the glassy margin and in veins cutting the glassy margin. Veins crossing from the quenched margin through the older wall rock change from dominantly clinopyroxene to dominantly amphibole at the dike contact. Formation of hydrothermal clinopyroxene may be favored by initial alteration of the glass to low-aluminum Mg-Fe smectite.

Primary and hydrothermal plagioclase in the IDDP-2 drill cores are often distinguishable based on the petrography relations, e.g. hydrothermal plagioclase in veins. They also appear to be distinguishable geochemically with hydrothermal plagioclase extending to very high anorthite number (percent anorthite), but with relative low MgO concentration (Figure 5B). Electron microprobe analyses confirm the presence of primary igneous plagioclase in cores 3 through 10, although cores 5, 6 and 7 are dominated by primary igneous plagioclase and cores 3, 8 and 10 contain a significant proportion of secondary plagioclase.

Amphibole in cores 3 through 10 ranges from actinolitic/ferroactinolitic through hornblendic/ferrohornblendic in composition, while cores 5&6 include edenite/ferroedenite amphibole (Figure 5C). Cores 5, 7 and 10 largely contain hornblendic amphibole. In many cases early actinolite amphibole is overgrown by and/or replaced by hornblende.

As mentioned earlier, a post-drilling yellow salt precipitate is prevalent on saw-cut surfaces and is related to samples that have an intense hematinic stain on the outer core surface. The iron stained zones are often spatially associated with felsite veins. Semi-quantitative analyses of the salts using energy dispersive X-ray spectroscopy suggest that the most abundant phase is a potassium-ferrous iron chloride with the composition of Javorieite (KFeCl₃). Other phases detected include halite and morphologically distinct K-Fe chloride salts with appreciable concentrations of Mn, Cu, Zn or Al. Aqueous solutions of the salt retain a yellow ferrous chloride color and do oxidize to precipitate ferric oxides when stored at room temperature in containers open to the atmosphere. The salt appears to precipitate in the lab due to evaporative concentration of hydrothermal brine trapped in the intergranular pore space of the rocks, and seems to be most prevalent in the felsite veins and the deepest half dikes. Mixing of the hydrothermal brine and oxygenated surface waters used as cooling fluid at elevated temperatures down hole appears to be responsible for the hematite staining that coats the surface of the deep cores. Efforts to further characterize the deep hydrothermal brine are on going.



Figure 5. Mineral compositions based on electron microprobe analyses. A=pyroxene; B=plagioclase; C=amphibole

5. Conclusions

Our investigation of the recovered drill cores is in the preliminary stages, but the following conclusions seem to be supported by the observations at hand. The IDDP-2 cores include the first samples recovered from active, supercritical geothermal conditions in a seawater-recharged hydrothermal system similar to deep-sea black smokers. The lithological section underlying the presently exploited hydrothermal system at Reykjanes is typical of sheeted complexes in oceanic crust and ophiolites. Logging measurement confirm that permeable feed zones are present at temperature and pressure conditions in excess of the critical point of seawater in the deepest section of the well. The alteration assemblage in the shallowest recovered core includes albite chlorite, epidote, actinolite and quartz; the typically assemblage of epidote-actinolite facies alteration that characterizes production reservoir at Reykjanes. However, rocks at this depth are cut by veins with hornblende and anorthite, indicating that these rocks have not fully equilibrated to amphibolite facies alteration. Below this depth, veins become relatively uncommon and open space veins are nearly absent, consistent with transition from the brittle to the ductile regime. Despite the lack of veining and the excellent preservation of igneous textures, most rocks are pervasively altered with most pyroxene replaced by hornblende, and less apparent alteration of plagioclase. Albite, epidote and chlorite are not present as alteration phases below ~3,450 m, and quartz is at best only a minor phase. The alteration is characterized by hornblende and calcic plagioclase, but actinolite persists as a metastable alteration mineral in the amphibolite alteration facies. Hydrothermal biotite has been identified for the first time in the Reykjanes system and is commonly observed in the deepest drill cores. Felsic segregation veins become increasingly common in the sheeted dikes with depth, and some contain igneous biotite and zircon. We appear to have sampled hyper saline supercritical (magmatic?) brine in the intergranular pore space of the deepest drill cores, and these fluids are the target of future fluid sampling and fluid inclusion investigations. The IDDP-2 cores provide an unprecedented opportunity to investigate geochemical reactions occurring under supercritical conditions, and should provide continued insight into fluid/rock reactions that control the composition of fluids that form basalt-hosted massive sulfide systems.

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