Geochemical bias in drill cutting samples versus drill core samples returned from
the Reykjanes Geothermal System, Iceland

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Abstract

The wholerock major and trace element composition of drill cutting samples are compared to drill core samples from adjacent depths in the seawater recharged Reykjanes geothermal system in Iceland. The first appearance of alteration minerals and lithologies in drill cutting samples is a useful tool for interpreting broad subsurface characteristics. However, use of drill cutting samples for determining igneous affinity and elemental exchanges during hydrothermal alteration is problematic. Samples recovered from immediately above and below the cored intervals in wells RN-17B and RN-30 demonstrate that drill-cutting samples are biased towards preservation of least altered primary igneous minerals and more resistant alteration minerals, including albite, quartz, and epidote, with preferential loss of finer-grained and less resistant minerals including

1 chlorite and actinolite. This selective recovery obscures elemental exchanges resulting
2 from hydrothermal alteration processes. For some elements, compositional variations
3 (enrichments and depletions) measured from 9.5 m of core exceeds that observed in
4 ~3000 m of cutting analyses. Concentration ratios of hydrothermally immobile elements
5 including Zr, Nb, V, Y, HREE, Hf, Ta and Th in deep (>2245 m) spot drill core samples
6 record bimodal, trace element-enriched and trace element-depleted precursor
7 compositions similar to subaerial Reykjanes Peninsula basalts. The same elements in
8 nearly 3000 m of drill cutting samples from well RN-17 overwhelmingly reflect the more
9 common trace element-enriched igneous precursor, demonstrating that mixing of drill
10 cutting samples obscures details of their igneous affinity. A new and different drill rig
11 was used to deepen well RN-17 below 2266 m in a sidetrack hole (RN-17ST), which
12 resulted in a change in drilling conditions, accompanied with an increased well deviation
13 angle from $\sim 0^\circ$ to $\sim 4^\circ$. Wholerock geochemical results for drill cutting samples from RN-
14 17ST are homogenous for virtually every element; suggesting the change in drilling
15 conditions resulted in extreme mixing of the drill cuttings. Anomalously high
16 concentrations of Cu, Ni, Cr and Ta in some drill cutting samples likely reflects
17 contamination of drill cutting samples by metal alloys used in drill bits and drill collars or
18 more resistant spinel and sulfide phases.

19

20 **1.0 Introduction**

21 The seawater-recharged Reykjanes Geothermal System is located on the immediate
22 onshore extension of the submarine Reykjanes Ridge in southwest Iceland (Figure 1).
23 Over 30 geothermal wells have been drilled in the Reykjanes Geothermal System for the
24 production of geothermal electricity, and drill cuttings have been archived from depths

25 exceeding 3000 m. Reykjanes drill cutting samples have proved useful for developing a
26 broad understanding of the stratigraphy, hydrothermal alteration and evolution of the
27 geothermal system at depth (i.e. Björnsson et al., 1972; Tomasson and Kristmannsdóttir,
28 1972; Sakai et al., 1980; Lonker et al., 1993; Franzson et al., 2002; Franzson, 2004;
29 Freedman et al., 2009; Pope et al., 2009; Marks et al., 2010). The geological setting and
30 nature of the recharge fluids in the Reykjanes Geothermal System also make it a useful
31 analog for seafloor hydrothermal processes (Bischoff and Dickson, 1975; Elderfield et
32 al., 1977; Mottl and Holland, 1978).

33

34 Geochemical bias in drill cutting samples may stem from: (1) the loss of clay minerals
35 during sample collection and washing, because grain impacts during ascent preferentially
36 remove less resistant mineral phases, (2) mixing due to the development of cutting beds
37 on the sides of inclined holes, (3) mixing due to collapse and abrasion of material from
38 shallower depths during ascent, (4) mixing during ascent due to cutting size and density
39 differences, (5) mixing due to variations in drilling fluid pumping rate and drilling
40 parameters, and (6) contamination from drilling equipment (Hulen and Sibbett, 1981;
41 Bar-Cohen and Zacny, 2009). In contrast, drill core preserves depth relations, alteration
42 mineral interrelations, and alteration mineral phases that are not always preserved in drill
43 cutting samples (Kristmannsdóttir, 1982). Paragenetic alteration mineral relationships
44 (i.e. episodic veining and wall rock interrelationships) are also much better preserved in
45 drill core samples. While previous studies have acknowledged potential geochemical and
46 preservation bias in drill cutting samples relative to drill core samples (Kristmannsdóttir,
47 1982; Wood, 1996; Solum et al., 2006), few studies have quantitatively evaluated the

48 significance of this bias and the implications for geochemical studies.

49

50 The Iceland Deep Drilling Project (IDDP) recently collected three spot drill cores (RN-

51 17B, RN-19, and RN-30) from geothermal wells in the Reykjanes geothermal system.

52 The spot cores were recovered from true vertical depths ranging between ~2245 m and

53 ~2570 m and *in situ* temperatures ranging from ~250 to 345°C (Friðleifsson et al., 2005;

54 Friðleifsson and Richter, 2010; Friðleifsson et al., 2014; Fowler et al., 2015). The

55 purpose of this study is to compare wholerock geochemical results from the Reykjanes

56 drill core samples to vertically adjacent drill cutting samples to understand the limitations

57 of using drill cutting samples to elucidate subsurface lithology and alteration processes

58 during geothermal energy exploration, and for addressing questions about seawater-crust

59 elemental exchanges that are of interest to the seafloor hydrothermal research

60 community.

61

62 Our results suggest that drill cutting samples significantly intermix material from

63 different depth intervals and are biased toward preservation of more resistant phases

64 including epidote, quartz, and albitized plagioclase, while less resistant hydrous alteration

65 phases such as chlorite, actinolite, and anhydrite are selectively lost. The drill cutting

66 samples investigated also show signs of trace element contamination from metal alloys

67 used in down hole drilling equipment. It is widely acknowledged that drill core provides

68 advantages in interpreting geologic relationships down hole, but the advantages need to

69 be weighed against the increased cost of core drilling. Conclusions drawn about primary

70 igneous protolith, alteration mineral interrelationships, and hydrothermal elemental

71 exchanges based on drill cutting samples should be treated with caution, particularly
72 when using drill cuttings from great depth.

73

74 **2.0 Geology of the Reykjanes Peninsula**

75 The Reykjanes Peninsula is a subaerial continuation of the submarine Reykjanes Ridge
76 (Figure 1). The direction of tectonic extension on the peninsula is highly oblique to the
77 ridge spreading axis (Clifton and Kattenhorn, 2006). The four volcanic systems present
78 on the peninsula (Reykjanes, Krísuvík, Brennisteinsfjöll, and Hengill) each have a
79 distinct magma supply (Sæmundsson, 1979; Einarsson and Sæmundsson, 1987). The
80 peninsula is divided into five neo-volcanic fissure swarms (Reykjanes, Grindavík,
81 Krísuvík, Bláfjöll, and Hengill) characterized by an en echelon arrangement of post-
82 glacial eruption sites, fissures and seismic activity (Jakobsson et al., 1978; Clifton and
83 Kattenhorn, 2006). The Reykjanes and Grindavík neo-volcanic fissure swarms are
84 indistinguishable in terms of petrology and major element chemistry (Jakobsson et al.,
85 1978). Several active high-temperature geothermal areas on the peninsula result from a
86 combination of extensional tectonics and active volcanism (Jakobsson et al., 1978,
87 Arnórsson, 1995). The Reykjanes geothermal system occurs on the westernmost tip of the
88 Peninsula, and is recharged by seawater that is subsequently modified by progressive
89 reaction with the basaltic host rock and boiling (Tómasson and Kristmannsdóttir, 1972;
90 Arnórsson, 1978).

91

92 Subaerially exposed basalt flows on the Reykjanes Peninsula west of the Hengill volcanic
93 system span a petrographic range from picritic basalts to tholeiitic basalts (Jakobsson et

94 al., 1978). Less than 2% of exposed basalt on the western Reykjanes Peninsula is picritic
95 (Jackobsson et al., 1978). Highly variable proportions of cumulate phases (olivine, spinel
96 and plagioclase) in the picritic basalts suggest the parental liquid was primitive basalt as
97 opposed to a true picrite (Gee et al., 1998; Revillon et al 1999). “Picritic” basalts in the
98 Reykjanes volcanic system are defined by high MgO, low trace element concentrations,
99 Nb/Zr ratios <0.7 , and are referred to as “trace element depleted (TED)” (Gee et al.,
100 1998; Peate et al., 2009). Tholeiitic basalts make up the preponderance of exposed lavas.
101 Compared to the “picritic basalts, the tholeiitic basalts are more evolved (MgO generally
102 $<8\%$), have high trace element concentrations, have Nb/Zr ratios >0.7 , and are referred to
103 as “trace element enriched (TEE)” (Gee et al., 1998; Kokfelt et al., 2006; Peate et al.,
104 2009).

105

106 **2.0 Samples and Analytical Methods**

107 **Samples**

108 All sample names and depths in this study refer to the down hole depth as opposed to the
109 corrected true vertical depth (TVD), unless explicitly stated. Drill cuttings samples
110 analyzed for this study were taken from two intervals (2792 m and 2796 m) immediately
111 above the RN-17B core, two intervals (2878 m and 2886 m) below the RN-17B core, and
112 three intervals (2400 m, 2450 m, and 2500 m) above the RN-30 core (Figure 2). Drill
113 core samples analyzed for this study were taken from one interval in the RN-17B core
114 (2800.35 m; an altered crystalline basalt pillow) and two intervals from the RN-30 core
115 (<2510.5 -2 and 2512.53; hyaloclastite and coarse basalt, respectively). Skinner et al.
116 (2010) provide specifications for Reykjanes drill coring technology and sampling

117 procedure. We also include wholerock analytical results for drill cuttings sampled at 50 m
118 intervals between 350 m and 3050 m in well RN-17 (Marks et al., 2010). Drill cutting
119 and core samples were provided by IDDP and HS Orka hf.

120

121 Drill cuttings from above the RN-17B core in the interval from ~2530 to 2790 m consist
122 entirely of fine- to coarse-crystalline basalt (Helgadóttir et al., 2009; Figure 2). Drill
123 cuttings in the interval ~8 m above the RN-17B core (~2790 to 2798 m) contain
124 fragments of greenish, very altered glassy basalt with abundant quartz, epidote, and
125 actinolite (Helgadóttir et al., 2009). Drill cuttings from below the RN-17B core contain
126 fragments of light green, very altered, fine- to medium-grained crystalline basalt with a
127 fair amount of quartz (Helgadóttir et al., 2009). While altered fragments are present in
128 drill cuttings from above and below the RN-17B core, the samples are predominantly
129 composed of largely unaltered crystalline basalt fragments. Drill cuttings above the RN-
130 30 core in the interval from 2308 to 2510 m were derived from hyaloclastite (Figure 2),
131 composed of glassy basalt and greenish glass fragments that are altered to chlorite,
132 epidote, quartz, prehnite, and moderate amounts of pyrite (Sigurgeirsson et al., 2011). A
133 significant proportion of the cutting samples from above the RN-30 core contain
134 relatively unaltered crystalline basalt fragments.

135

136 The Jötunn Gardner Denver 700E drill rig (Iceland Drilling, Ltd.) was used to drill RN-
137 17 to ~2266 m in a near vertical hole when the drill pipe broke and a sidetrack hole was
138 necessary to continue drilling (Friðleifsson et al., 2005). The Geysir Drillmec HH-200S
139 drill rig (Iceland Drilling Ltd.) successfully completed the second attempted sidetrack

140 hole (RN-17ST) from 1816 m to 3082.4 m in a $\sim 4^\circ$ deviated sidetrack hole (Friðleifsson
141 et al., 2005). The Týr Drillmec HH-300 drill rig (Iceland Drilling, Ltd.) was used to drill
142 the deviated (SSW; 35° from vertical) RN-17B sidetrack of well RN-17 with a kick off
143 point at approximately 920 m depth (Helgadóttir et al., 2009). The Óðinn Drillmec HH-
144 220 drill rig (Iceland Drilling, Ltd.) was used to drill well RN-30, which was deviated
145 (SE; 35° from vertical) at a kickoff depth of approximately 550 m (Sigurgeirsson et al.,
146 2011). Mud was used as the drilling fluid for the cased interval, and water for the uncased
147 production interval. Mica was introduced to seal zones of lost circulation, when
148 encountered. Drill cutting samples were collected at 2 m intervals using a series of sieves
149 (generally < 1 mm mesh, depending on the coarseness of the cuttings). Cuttings were first
150 separated from the drilling fluid using vibrating sieves, and then washed with water for
151 archiving. A small subset of the bulk cuttings sample was thoroughly washed with water
152 and archived separately from the bulk sample.

153

154 The 9.3m RN-17B core was recovered at an *in situ* temperature of 345°C , a TVD of
155 ~ 2560 m (2798.6 to 2807.9 m down hole depth), and is composed of basalt pillows,
156 hyaloclastite and lithic breccia, and volcanic sandstone (Friðleifsson et al., 2005;
157 Friðleifsson and Richter, 2010; Fowler et al., 2015). RN-30 consists of three sequential
158 cores totaling 22.5 m. The RN-30 cores were recovered at an *in situ* temperature of 345°C , a TVD of ~ 2240 m (2510.3 to 2532.8 m down hole depth), and are composed of a
159 series of fine and coarse crystalline basalt intrusions with an ophitic texture. Several
160 hyaloclastite slough blocks originating from an unknown depth above the core were
161

162 recovered overlying the upper most intact drill core. The lithology and alteration present
163 in the RN-30 drill cores was evaluated during sampling.

164

165 **Methods**

166 Mica introduced as a loss circulation prevention agent during drilling was carefully
167 removed from drill cutting samples by handpicking under a binocular microscope. Bulk
168 drill cutting and drill core samples were submitted to the Washington State University
169 (WSU) GeoAnalytical Laboratory for major element, trace element, and loss on ignition
170 (LOI) determinations using X-ray fluorescence spectrometry (XRF) and inductively
171 coupled plasma mass spectrometry (ICP-MS). Samples were ground at WSU in a
172 tungsten carbide ring mill prior to analysis. Samples analyzed by XRF were prepared
173 according to the methods outlined in Johnson et al. (1999) and analyzed using a Thermo-
174 ARL AdvantXP instrument. Samples analyzed by ICP-MS were prepared according to
175 the methods outlined in Jenner et al. (1990) and analyzed using an Agilent 4500 ICP-MS.
176 Polished thin sections of cuttings and core were examined using transmitted and reflected
177 light petrography. A Cameca SX-100 electron microprobe (EMP) at the University of
178 California Davis was used to obtain back-scattered electron (BSE) images and perform
179 mineral identification using the energy dispersive energy (EDS) spectrometer.

180

181 **3.0 Results**

182 BSE images of drill cutting samples from above and below the RN-17B core confirm the
183 cuttings predominantly consist of crystalline basalt, and are largely composed of igneous
184 plagioclase and clinopyroxene, along with fragments containing chlorite, epidote and

185 actinolite veins (Figure 3A and 3B). The top of the RN-17B core (2798.64 m) differs
186 from drill cuttings immediately above (2796 m) in that the core consists of hyaloclastite
187 shards pervasively replaced by hydrothermal hornblende and albite while relict igneous
188 plagioclase and clinopyroxene are absent (Figures 3A and 3C). A sample from the RN-
189 17B core (2800.35 m) is composed of a hydrothermally altered crystalline interior of a
190 basalt pillow that preserves an igneous texture similar to the cuttings (Figure 3D). In
191 contrast to the RN-17B cuttings, the RN-17B core is more pervasively altered with
192 albitized igneous plagioclase, actinolite after igneous clinopyroxene, and near complete
193 replacement of the pillow interior to chlorite + hornblende (Fowler et al., 2015). The drill
194 cuttings immediately above the core do include a few fragments of epidote, actinolite,
195 pyrite and titanite veins similar to those common throughout the RN-17B core (Fowler et
196 al., 2015; Figures 3B and 3D).

197

198 Drill cuttings from 2400 m in well RN-30 are largely composed of crystalline basalt
199 fragments containing igneous clinopyroxene showing incipient alteration to actinolite on
200 the grain edges, and igneous plagioclase with patchy replacement by albite, especially
201 along the grain edges. The sample also includes numerous fragments of hyaloclastite
202 composed of chlorite, quartz, secondary plagioclase, and titanite (Figure 4A). Cuttings
203 from 2450 m and 2500 m above the RN-30 core are similar to those from 2400 m, but
204 contain a higher proportion of altered hyaloclastite (Figures 4B and 4C). The
205 hyaloclastite fragments present in RN-30 drill cuttings have mineralogical similarities to
206 a hyaloclastite slough block recovered with the RN-30 core (Figure 4D).

207

208 Results for wholerock analyses of drill cutting samples from above and below the
209 Reykjanes drill cores, along with select intervals in the drill cores are provided in Table
210 1. Immobile element concentrations and ratios in drill cutting samples from wells RN-17
211 (Marks et al., 2010), RN-17B, and RN-30 overwhelmingly reflect a TEE protolith
212 (Figures 5A through 5D). A higher proportion of TED protolith compositions are present
213 in drill core samples from wells RN-17B, RN-19 and RN-30, compared to what would be
214 expected based on the abundance of TED surface flows in the Reykjanes Volcanic
215 System,

216
217 The down hole wholerock geochemical variation of drill cutting samples from well RN-
218 17 and RN-17ST (Marks et al., 2010) are compared to samples from the adjacent RN-
219 17B sidetrack drill core (Figure 6). Cuttings from depths <2250 m generally have
220 elevated LOI, K₂O, Rb, Cs, Ba, Pb, Th and U, especially intervals identified as
221 dominated by clastic lithologies (breccia, hyaloclastite, pillow basalt breccia) (Figure 6).
222 Below 2250 m (corresponding to the horizontal dashed line on Figure 6), the
223 concentrations of most elements in RN-17ST drill cutting samples are essentially
224 invariable. In contrast, the 9.8 m long RN-17B core from this same interval reflects
225 geochemical heterogeneity comparable to, or even exceeding, that observed from the
226 entire ~3000 m of RN-17 drill cuttings (Figure 6). For example, Si, Na, and Ca
227 concentrations in RN-17B drill core samples show both enrichments and depletions that
228 exceed the range in the overlying ~3000 m of analyzed cutting samples.

229

230

231

232 **4.0 Discussion**

233 **Mixing of Drill Cuttings**

234 Mixing and homogenization of drill cuttings during transport from the subsurface to the
235 surface sampling location is influenced by gravity, viscous drag, buoyancy, impact from
236 other cuttings, and sidewall friction (Bar-Cohen and Zachny, 2009). These factors are in
237 turn controlled by drill bit type, rotation speed, weight-on-bit, and density and circulation
238 rate of drilling fluid (Hulen and Sibbett, 1981). In non-vertical holes, cutting beds
239 develop on the “hanging wall” of the borehole, and impacts to the beds from other
240 cuttings result in increased disaggregation (Bar-Cohen and Zachny, 2009). Mixing and
241 homogenization of the drill cutting samples included in this study is evidenced by nearly
242 ~3000 m of drill cuttings samples from well RN-17 (along with cuttings from more
243 limited depth ranges in RN-17B and RN-30) only reflecting a TEE basalt lithology. This
244 is in stark contrast to the three Reykjanes spot drill cores; RN-17B and RN-30 preserve
245 both TEE and TED protoliths and RN-19 (Ottolini et al., 2012) only preserves a TED
246 protolith (Figures 5A through 5D). Mixing of only a small amount of the TEE lithology,
247 which has higher immobile element concentrations, has likely obscured any TED affinity
248 beyond recognition in the cutting samples.

249

250 Drill cutting mixing and homogenization is more extreme at depths below 2266 m in well
251 RN-17. Concentrations of virtually all elements in bulk cutting samples below this depth
252 are essentially invariable (Figure 6). This interval coincides with the depth from which
253 the 9.8 m long RN-17B core was recovered. The geochemical variability of samples from
254 the RN-17B core is comparable to, or exceeds, that of nearly 3000 m of drill cuttings

255 from well RN-17, suggesting that cutting samples from below 2250 m in well RN-17 are
256 not representative of the true nature of the subsurface at these depths. The zone of
257 homogenized drill cuttings below ~2250 m in well RN-17 coincides with a change in
258 drilling rig (Jotunn to Geysir), an increase in well deviation from ~vertical to ~4°, a
259 change in down-hole drilling assembly, and most notably changes in drilling parameters
260 including a four-fold increase in torque and near doubling of the total weight-on-bit
261 (Friðleifsson et al., 2005).

262

263 **Implications of Drill Cutting Preservation Bias for Inferring Chemical Exchanges**

264 The impression gained from examination of the drill cutting samples is that the drilled
265 section is dominantly unaltered basalt. The variation in LOI, Si, Na, Mg, and Ca, for
266 example, would be consistent with minimal fluid/rock alteration under low water/rock or
267 rock-dominated conditions. One would also infer that the degree of alteration and
268 chemical exchange decreases down hole, with a significant decline below 2250 m. In
269 stark contrast, the RN-17B core shows pervasive alteration and includes zones of
270 significant metasomatic addition and hydrolytic depletion of Si, Na, Mg, and Ca.
271 We used the method of Humphris et al. (1998) to visualize bulk elemental differences
272 between drill cutting and drill core samples (Figure 7, upper diagram). A value equivalent
273 to half the detection limit was used for non-detect data. Data normalized using this
274 method fits the equation of a circle, and points plot along an arc of radius one. The
275 concentration of each component in the drill cutting sample and the selected drill core
276 sample is squared, the squares are summed, and the square root of the summed value is
277 normalized to one. Elements with similar concentrations in drill core and drill cuttings

278 samples cluster about a point along the arc, while elements that are gained or lost in the
279 drill cutting samples relative to the drill core sample plot at increasing distance from the
280 cluster along the arc. While this technique is useful for rapidly visualizing compositional
281 differences between two samples, a drawback is that small differences in elements with
282 very low concentrations result in large shifts on the diagram. To evaluate the magnitude
283 of absolute concentration differences, we plotted elemental data on radar diagrams
284 (Figure 7; middle and lower diagrams). A benefit of visualizing compositional data on
285 radar diagrams is that concentration changes due to dilution (or enrichment) of a major
286 constituent are readily apparent. Grouping of elements in order of increased, decreased,
287 or invariable concentrations allows quick evaluation of the effect of choosing different
288 protoliths for normalization. The ordering of elements on the radar diagrams is informed
289 by the results of the Humphris et al. (1998) diagrams.

290

291 A large source of error in any approach to quantify geochemical bias in drill cutting
292 samples stems from the choice of protolith composition used for normalization. Because
293 drill cutting samples consist of mixtures of lithologies recovered over several meters at
294 minimum (i.e. Kristmannsdóttir, 1982; Figure 4), there is no unique protolith. In the case
295 of Reykjanes drill cutting samples; the mixtures potentially include TEE basalts, TED
296 basalts, crystalline material, and originally glassy material. Immobile element
297 concentrations and ratios in the Reykjanes drill cutting samples suggest that the influence
298 of TED lithologies is very minor (Figure 5). Because the RN-30 cutting samples we
299 analyzed contain a mixture of material derived from crystalline basalt and hyaloclastite,
300 we chose to normalize the drill cutting to both a crystalline protolith (2512.53 m) and a

301 hyaloclastite protolith (<2510.5-2) in an attempt to understand the geochemical
302 exchanges recorded by these cuttings. Wholerock analytical data for drill core samples
303 used for comparison to drill cutting samples are presented in Table 1.
304
305 When normalized to the crystalline protolith sample, RN-30 drill cuttings appear to have
306 gained MgO, K₂O, Rb, Cs, Pb and U, and have elevated LOI (Figure 7A). Alkalis, MgO,
307 Pb and U (and elevated LOI) are characteristically gained from seawater by alteration of
308 glassy basaltic protolith in seafloor hydrothermal recharge zones (Thompson, 1973;
309 Humphris and Thompson, 1978a,b; Hart and Staudigel, 1982; Chen et al., 1986;
310 Staudigel et al., 1996; Alt, 1995; Alt et al., 1996; Bach et al., 2001, 2003). In contrast,
311 these same elements have been depleted from RN-30 basalts that were cored directly
312 below the interval from which the cuttings were sampled (Table 1). The apparent gain of
313 alkalis, MgO, Pb and U (and elevated LOI) in RN-30 drill cutting samples calculated
314 assuming a crystalline basalt precursor suggest the hyaloclastite drill core sample may be
315 a more appropriate choice of protolith for the cuttings overlying the drill core. This is
316 consistent with the interpretation that the interval overlying the drill core is a
317 hyaloclastite unit, based on elevated proportion of originally glassy protolith material,
318 which is evident in BSE images of RN-30 drill cutting samples analyzed (Figure 4).
319
320 We therefore normalized RN-30 drill cutting samples to a hyaloclastite sample recovered
321 with the drill core (<2510.5-2) from RN-30, as shown on Figure 7B. This choice of
322 protolith produces apparent elemental biases for RN-30 drill cutting samples that are
323 more consistent with what we observe for RN-17B drill cutting samples normalized to a

324 crystalline protolith (Figure 7C). We normalized RN-17B drill cutting samples to a
325 pillow basalt sample from the RN-17B core (2800.35 m), as there was little evidence of
326 glassy protolith material in the cuttings overlying that cored interval (Figure 3). Our
327 protolith choices are supported by: 1) consistent results for the three RN-30 cutting
328 samples, despite different proportions of crystalline and hyaloclastite lithologies in each
329 of the samples; and 2) agreement of results for elemental bias in RN-17B and RN-30
330 cuttings, despite very different samples being used for normalization in each case. Our
331 results suggest that Na₂O, CaO, and Cr are generally gained, while MgO, and Zn are
332 generally lost from both RN-17B and RN-30 drill cutting samples (Figure 7B and 7C).
333 The cuttings also have lower LOI compared to the core samples, again suggesting bias in
334 cutting samples towards material with lower degrees of alteration. SiO₂, Cu and Ni are
335 gained in RN-17B cuttings, while U, Th, and Pb are generally gained, and SiO₂ and Cu
336 are lost, from RN-30 drill cuttings (Figures 7B and 7C).

337

338 Drill cuttings concentrate more resistant alteration mineral phases, which more readily
339 survive grain impacts and more rigorous drilling parameters (Hulen and Sibbett, 1981).

340 Albitized plagioclase, or plagioclase with albitized rims is ubiquitous in the Reykjanes
341 cuttings samples studied (Figures 3 and 4), and preferential preservation of this phase
342 provides a mechanism to increase both Na and Ca in drill cuttings. Elevated CaO is also
343 potentially hosted in epidote, which is common in cuttings from the intervals studied
344 (Helgadóttir et al., 2009; Sigurgeirsson et al., 2011). In the case of RN-17B, elevated
345 SiO₂ likely reflects the high proportion of quartz logged in the cutting samples

346 (Helgadóttir et al., 2009), in contrast to the RN-17B core samples where quartz is entirely
347 absent (Fowler et al., 2015).

348

349 Less resistant alteration minerals are easily disaggregated and lost from cuttings during
350 sample washing and collection (Hulen and Sibbett, 1981). Loss of MgO, Zn and LOI
351 from all drill cuttings is consistent with loss of fine-grained chlorite and or actinolite
352 during sieving and collection of drill cutting samples at the surface. Chlorite
353 $[(\text{Mg}_5\text{Al})(\text{AlSi}_3\text{O}_{10})(\text{OH})_8]$ and actinolite $[\text{Ca}_2(\text{MgFe})_5(\text{Si}_8\text{O}_{22})(\text{OH})_2]$ in the Reykjanes
354 geothermal system both host Mg (Lonker et al., 1993), and significantly contribute to
355 LOI due to the structural hydroxyls. While there are no available analyses of Zn in
356 Reykjanes chlorite or actinolite, Zn is known to rarely substitute into the chlorite and
357 actinolite structures (Deer et al., 1992).

358

359 U, Pb and Th are typically enriched in lithologies erupted on the seafloor that are present
360 in the hydrothermal recharge zone (Alt, 1995). Gain of these elements in the RN-30 drill
361 cutting samples is a reflection of the abundance of hyaloclastite fragments in these
362 samples. Elevated concentrations of these elements in RN-30 drill cutting samples
363 potentially reflect preferential preservation of a resistant phase hosting these elements,
364 possibly apatite.

365

366 Offset of clustering elements from unity (dashed line) in the cutting samples from RN-30
367 (Figure 7A), is a reflection of the high SiO_2 content resulting from numerous quartz veins
368 present in the hyaloclastite sample used for normalization. The offset of the clustering

elements from unity is an artifact of the closed nature of compositional data (i.e. sum to 100% or 10^6 ppm restriction), where addition of a large proportion of a particular element or oxide, in this case silica, necessarily reduces the concentration of other elements by dilution, even though they may not have been removed from the rock. Dilution (or addition) shifts clustering elements away from unity, and is apparent in drill cutting samples from RN-30 (Figure 7). In RN-30 cutting samples, this is due to an unusually high concentration of quartz veins in sample <2510.5-2. The high concentration of SiO_2 veins in the core sample chosen for normalization (2512.53) therefore yields apparent depletion in SiO_2 in the RN-30 cuttings samples (particularly the sample from 2400 m), and a shift of the clustering elements towards false enrichment in the cuttings samples (Figure 7).

Contamination by Drilling Equipment

Elevated Cr in all of the drill cutting samples is potentially hosted in more resistant titanomagnetite or a spinel phase, however drill logs do not suggest elevated concentrations of these minerals. An alternate Cr source is potential contamination by Cr-rich steel alloys, which are commonly used in drill bits, stabilizers, and drill collars (Hulen and Sibbett, 1981).

Ni and Cu are elevated in cuttings immediately above and below the RN-17B core beyond concentrations of these elements in any of the TEE drill core lithologies, while Ta in the RN-30 sample from 2500 m is elevated and Nb is elevated in sample RN-17B 2796 (Figures 7B and 7C). We normalized Ni and Cu in RN-17B cuttings and Ta in RN-30

392 drill cutting samples to the immobile element Zr in each sample to avoid the influence of
393 sample dilution (or enrichment) by any single element due to the closed nature of
394 compositional data (Figure 8). An explanation for these anomalous concentrations is
395 contamination from down hole drilling equipment. Non-magnetic drill collars used to
396 apply weight on bit are manufactured from Ni-Cu alloys (Hulen and Sibbett, 1981). Ta
397 and Nb contamination potentially results from grinding samples in a tungsten carbide ring
398 mill (Hickson and Juras, 1986). However Ta and Nb contamination is not observed in any
399 of the drill core samples (Fowler and Zierenberg, in prep), suggesting the contamination
400 may be from worn drill bits, which are also composed of tungsten carbide (Hulen and
401 Sibbett, 1981).

402

403 It is unlikely that the elevated alkali concentrations result from contamination by lost
404 circulation prevention agents (Mica; K, Rb, Cs), because extreme care was taken to
405 thoroughly wash and hand pick mica from cutting samples submitted for analysis (Marks
406 et al., 2010). Elevated concentrations of K, Rb, Cs, Ba and Pb in RN-17 drill cutting
407 samples at shallow intervals (<500 m) and associated with clastic lithologies (Figure 5)
408 are consistent with enrichments of the same elements observed in hydrothermally altered
409 drill core and dredged samples from shallow oceanic basement rocks (Thompson, 1973;
410 Humphris and Thompson, 1978a,b; Hart and Staudigel, 1982; Chen et al., 1986;
411 Staudigel et al., 1996; Alt et al., 1995; Alt et al., 1996; Bach et al., 2001, 2003). In
412 seafloor hydrothermal systems, these elements are sequestered in the upper oceanic crust
413 in alteration minerals formed during low temperature seawater circulation. These same
414 elements are subsequently depleted from basaltic rocks at depth that have undergone

415 higher temperature alteration in hydrothermal upflow zones (Alt, 1995). Clastic
416 lithologies present at depth in the Reykjanes system were originally emplaced on the
417 seafloor and have subsided over time to the current depths (Björnsson et al., 1972;
418 Friðleifsson and Richter, 2010).

419

420 **5.0 Conclusions**

421 Drill cutting samples from well RN-17 preserve element enrichments on the scale of 10's
422 to 100's of meters as evidenced by elevated alkalis, Ba, U, and Pb in shallow drill cutting
423 samples collected at 50 m intervals associated with lithologies emplaced on the seafloor.
424 The same drill cutting samples homogenize basalt so that affinities to the groups TEE and
425 TED are not discernable in the cuttings, but are preserved in Reykjanes drill core
426 samples. Greater depth, slight drill hole inclination, increased weight on bit and torque
427 homogenize drill cutting samples on scales >50m, as evidenced from drill cuttings below
428 2266 m in RN-17. Drill cutting samples normalized to drill core samples suggest that
429 chlorite and actinolite have disaggregated and been lost during sampling of drill cuttings,
430 while more resistant phases including quartz, plagioclase and epidote have been
431 preferentially retained. Contamination of drill cuttings samples by alloys used in down
432 hole drilling equipment is apparent from elevated Cu, Ni, Ta and Nb in drill cutting
433 samples. The first appearance of alteration minerals and lithologies in drill cutting
434 samples is a useful tool for interpreting broad subsurface characteristics. However, use of
435 drill cutting samples for determining igneous affinity and elemental exchanges during
436 hydrothermal alteration is problematic. While problems of cutting homogenization are
437 difficult to avoid, the bias in selective retainment of the more resistant, coarse-grained

438 minerals can in part be addressed by sampling and analyzing the fine-grained cuttings
439 fraction.

440

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