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

1. Introduction

The seawater-recharged Reykjanes Geothermal System is located on the immediate onshore extension of the submarine Reykjanes Ridge in southwest Iceland (Fig. 1). Over 30 geothermal wells have been drilled in the Reykjanes Geothermal System for the production of geothermal electricity, and drill cuttings have been archived from depths exceeding 3000 m. Reykjanes drill cutting samples have proved useful for developing a broad understanding of the stratigraphy, hydrothermal alteration and evolution of the geothermal system at depth (i.e., Björnsson et al., 1972; Tómasson and Kristmannsdóttir, 1972; Sakai et al., 1980; Lonker et al., 1993; Franzson et al., 2002; Franzson, 2004; Freedman et al., 2009; Pope et al., 2009; Marks et al., 2010). The geological setting and nature of the recharge fluids in the Reykjanes Geothermal System also make it a useful analog for seafloor hydrothermal processes (Bischoff and Dickson, 1975; Elderfield et al., 1977; Mottl and Holland, 1978).

Geochemical bias in drill cutting samples may stem from: (1) the loss of clay minerals during sample collection and washing, because grain impacts during ascent preferentially remove less resistant mineral phases, (2) mixing due to the development of cutting beds on the sides of inclined holes, (3) mixing due to collapse and abrasion of material from shallower depths during ascent, (4) mixing during ascent due to cutting size and density differences, (5) mixing due to variations in drilling fluid pumping rate and drilling parameters, and (6) contamination from drilling equipment (Hulen and

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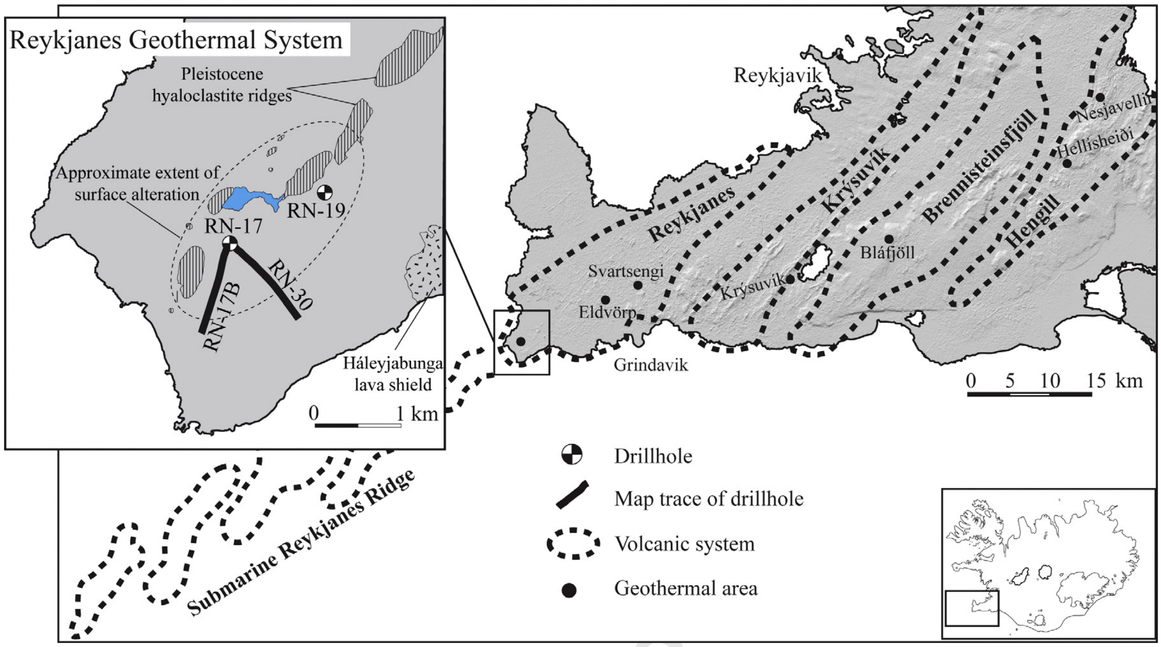

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Fig. 1. Location Map.

Sibbett, 1981; Bar-Cohen and Zacny, 2009). In contrast, drill core preserves depth relations, alteration mineral interrelations, and alteration mineral phases that are not always preserved in drill cutting samples (Kristmannsdóttir, 1982). Paragenetic alteration mineral relationships (i.e., episodic veining and wall rock interrelationships) are also much better preserved in drill core samples. While previous studies have acknowledged potential geochemical and preservation bias in drill cutting samples relative to drill core samples (Kristmannsdóttir, 1982; Wood, 1996; Solum et al., 2006), few studies have quantitatively evaluated the significance of this bias and the implications for geochemical studies.

The Iceland Deep Drilling Project (IDDP) recently collected three spot drill cores (RN-17B, RN-19, and RN-30) from geothermal wells in the Reykjanes geothermal system. The spot cores were recovered from true vertical depths ranging between ~2245 m and ~2570 m and in situ temperatures ranging from ~250 to 345 °C (Friðleifsson et al., 2005; Friðleifsson and Richter, 2010; Friðleifsson et al., 2014; Fowler et al., 2015). The purpose of this study is to compare wholerock geochemical results from the Reykjanes drill core samples to vertically adjacent drill cutting samples to understand the limitations of using drill cutting samples to elucidate subsurface lithology and alteration processes during geothermal energy exploration, and for addressing questions about seawater-crust elemental exchanges that are of interest to the seafloor hydrothermal research community.

Our results suggest that drill cutting samples significantly intermix material from different depth intervals and are biased toward preservation of more resistant phases including epidote, quartz, and albitized plagioclase, while less resistant hydrous alteration phases such as chlorite, actinolite, and anhydrite are selectively lost. The drill cutting samples investigated also show signs of trace element contamination from metal alloys used in down hole drilling equipment. It is widely acknowledged that drill core provides advantages in interpreting geologic relationships down hole, but the advantages need to be weighed against the increased cost of core drilling. Conclusions drawn about primary igneous protolith, alteration mineral interrelationships, and hydrothermal elemental exchanges based on drill cutting samples should be treated with caution, particularly when using drill cuttings from great depth.

2. Geology of the Reykjanes Peninsula

The Reykjanes Peninsula is a subaerial continuation of the submarine Reykjanes Ridge (Fig. 1). The direction of tectonic extension on the peninsula is highly oblique to the ridge spreading axis (Clifton and Kattenhorn, 2006). The four volcanic systems present on the peninsula (Reykjanes, Krísuvik, Brennisteinsfjöll, and Hengill) each have a distinct magma supply (Sæmundsson, 1979; Einarsson and Sæmundsson, 1987). The peninsula is divided into five neo-volcanic fissure swarms (Reykjanes, Grindavík, Krísuvik, Bláfjöll, and Hengill) characterized by an en echelon arrangement of post-glacial eruption sites, fissures and seismic activity (Jakobsson et al., 1979; Clifton and Kattenhorn, 2006). The Q5 Reykjanes and Grindavík neo-volcanic fissure swarms are indistinguishable in terms of petrology and major element chemistry (Jakobsson et al., 1979). Several active high-temperature geothermal areas on the peninsula result from a combination of extensional tectonics and active volcanism (Jakobsson et al., 1979; Arnórsson, 1995). The Reykjanes geothermal system occurs on the westernmost tip of the Peninsula, and is recharged by seawater that is subsequently modified by progressive reaction with the basaltic host rock and boiling (Tómasson and Kristmannsdóttir, 1972; Arnórsson, 1978).

Subaerially exposed basalt flows on the Reykjanes Peninsula west of the Hengill volcanic system span a petrographic range from picritic basalts to tholeiitic basalts (Jakobsson et al., 1979). Less than 2% of exposed basalt on the western Reykjanes Peninsula is picritic (Jakobsson et al., 1979). Highly variable proportions of cumulate phases (olivine, spinel and plagioclase) in the picritic basalts suggest the parental liquid was primitive basalt as opposed to a true picrite (Gee et al., 1998; Revillon et al., 1999). "Picritic" basalts in the Reykjanes volcanic system are defined by high MgO, low trace element concentrations, Nb/Zr ratios <0.7, and are referred to as "trace element depleted (TED)" (Gee et al., 1998; Peate et al., 2009). Tholeiitic basalts make up the preponderance of exposed lavas. Compared to the "picritic basalts, the tholeiitic basalts are more evolved (MgO generally <8%), have high trace element concentrations, have Nb/Zr ratios >0.7, and are referred to as 'trace element enriched (TEE)' (Gee et al., 1998; Kokfelt et al., 2006; Peate et al., 2009).

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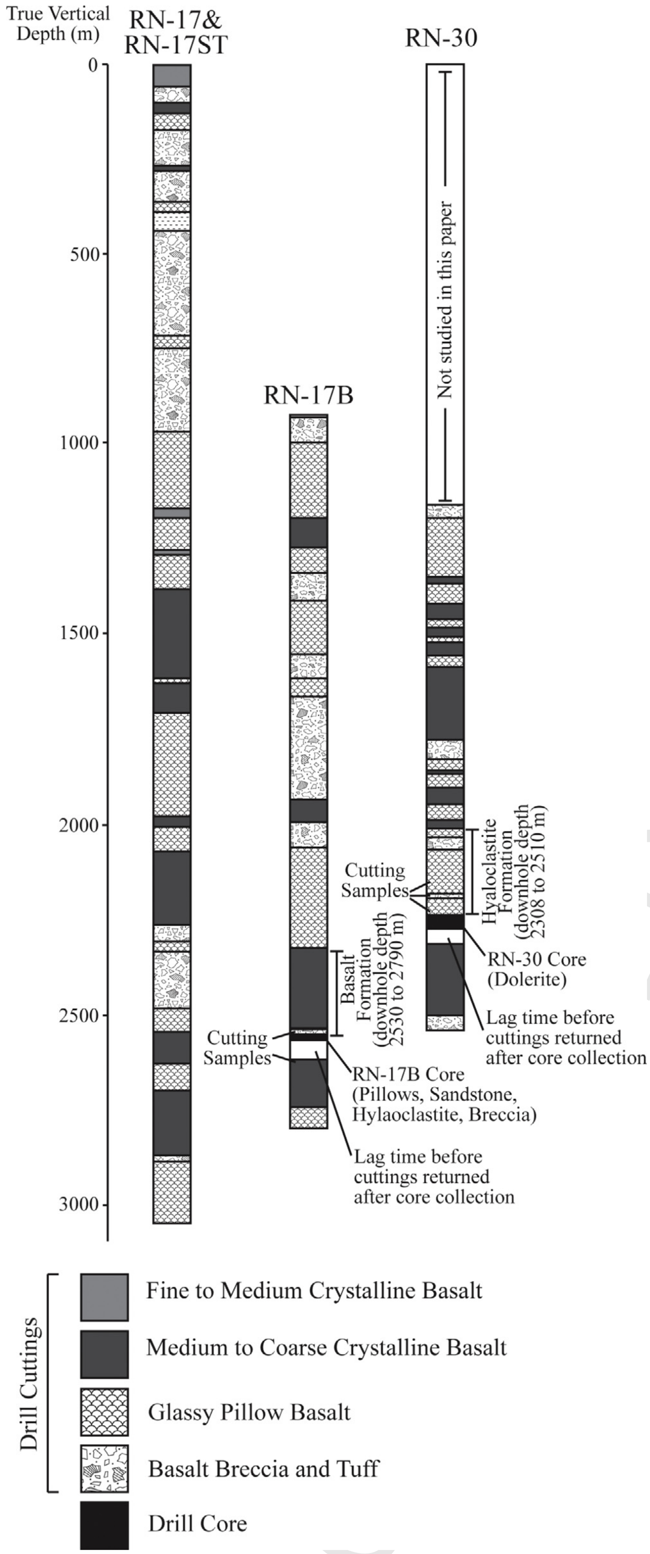

Fig 2. Drill logs.

3. Samples and analytical methods

3.1. Samples

All sample names and depths in this study refer to the down hole depth as opposed to the corrected true vertical depth (TVD), unless explicitly stated. Drill cuttings samples analyzed for this study were taken from two intervals (2792 m and 2796 m) immediately above the RN-17B core, two intervals (2878 m and 2886 m) below the RN-17B core, and three intervals (2400 m, 2450 m, and 2500 m) above the RN-30 core (Fig. 2). Drill core samples analyzed for this study were taken from one interval in the RN-17B core (2800.35 m; an altered crystalline basalt pillow) and two intervals from the RN-30 core (<2510.5–2 and 2512.53; hyaloclastite and coarse basalt, respectively). Skinner et al. (2010) provide specifications for Reykjanes drill coring technology and sampling procedure. We also include wholerock analytical results for drill cuttings sampled at 50 m intervals between 350 m and 3050 m in well RN-17 (Marks et al., 2010). Drill cutting and core samples were provided by IDDP and HS Orka hf.

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

The Jötunn Gardner Denver 700E drill rig (Iceland Drilling, Ltd.) was used to drill RN-17 to ~2266 m in a near vertical hole when the drill pipe broke and a sidetrack hole was necessary to continue drilling (Friðleifsson et al., 2005). The Geysir Drillmec HH-200S drill rig (Iceland Drilling Ltd.) successfully completed the second attempted sidetrack hole (RN-17ST) from 1816 m to 3082.4 m in a ~4° deviated sidetrack hole (Friðleifsson et al., 2005). The Týr Drillmec HH-300 drill rig (Iceland Drilling, Ltd.) was used to drill the deviated (SSW; 35° from vertical) RN-17B sidetrack of well RN-17 with a kick off point at approximately 920 m depth (Helgadóttir et al., 2009). The Óðinn Drillmec HH-220 drill rig (Iceland Drilling, Ltd.) was used to drill well RN-30, which was deviated (SE; 35° from vertical) at a kickoff depth of approximately 550 m (Sigurgeirsson et al., 2011). Mud was used as the drilling fluid for the cased interval, and water for the uncased production interval. Mica was introduced to seal zones of lost circulation, when encountered. Drill cutting samples were collected at 2 m intervals using a series of sieves (generally <1 mm mesh, depending on the coarseness of the cuttings). Cuttings were first separated from the drilling fluid using vibrating sieves, and then washed with water for archiving. A small subset of the bulk cuttings sample was thoroughly washed with water and archived separately from the bulk sample.

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

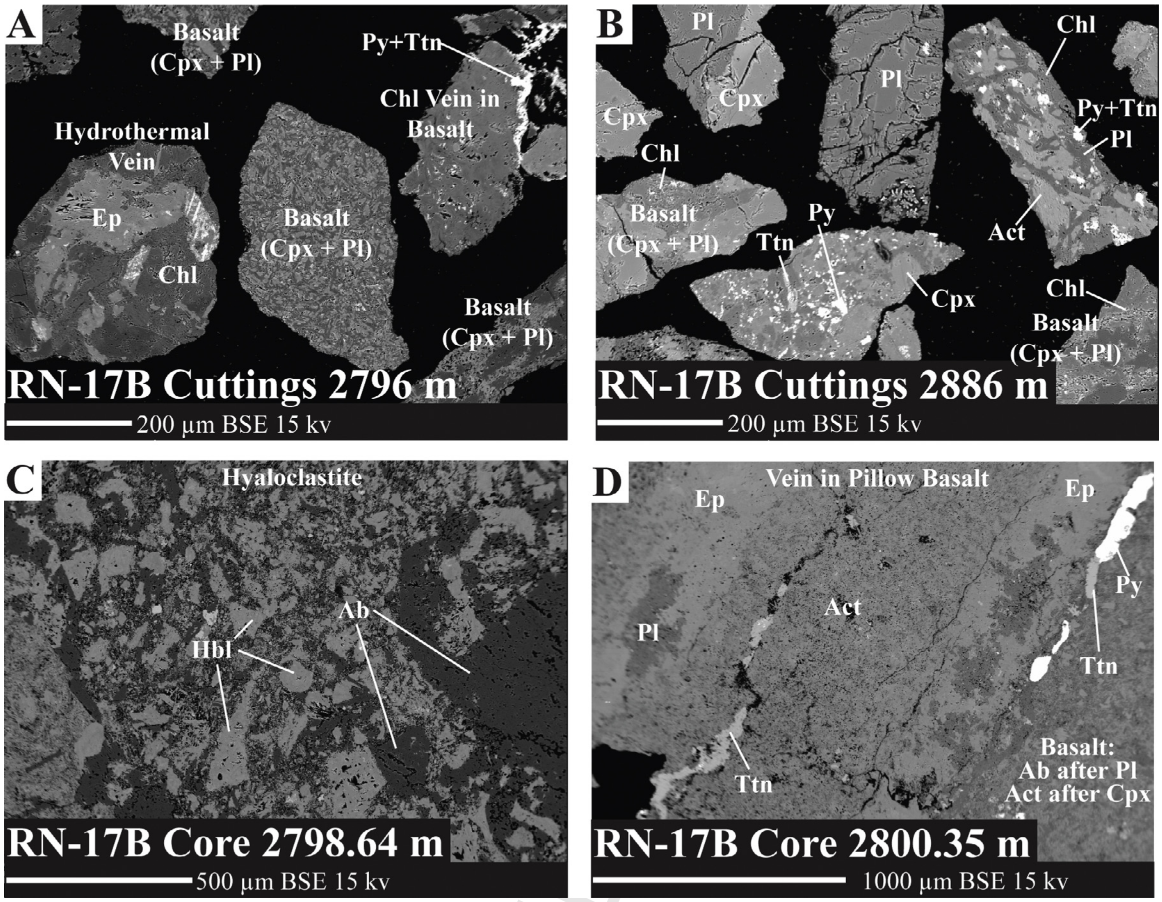

Fig. 3. RN-17B cutting BSE images.

Q7 The lithology and alteration present in the RN-30 drill cores were evaluated during sampling.

3.2. Methods

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

4. Results

BSE images of drill cutting samples from above and below the RN-17B core confirm the cuttings predominantly consist of crystalline basalt, and are largely composed of igneous plagioclase and clinopyroxene, along with fragments containing chlorite, epidote and actinolite veins (Fig. 3A and B). The top of the RN-17B core (2798.64 m) differs from drill cuttings immediately above (2796 m) in that the core consists of hyaloclastite shards pervasively replaced by hydrothermal hornblende and albite while relict igneous plagioclase and clinopyroxene are absent (Fig. 3A and C). A sample from the RN-17B core (2800.35 m) is composed of a hydrothermally altered crystalline interior of a basalt pillow that preserves an igneous texture similar to the cuttings (Fig. 3D). In contrast to the RN-17B cuttings, the RN-17B core is more pervasively altered with albitized igneous plagioclase, actinolite after igneous clinopyroxene, and near complete replacement of the pillow interior to chlorite + hornblende (Fowler et al., 2015). The drill cuttings immediately above the core do include a few fragments of epidote, actinolite, pyrite and titanite veins similar to those common throughout the RN-17B core (Fowler et al., 2015; Fig. 3B and D).

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

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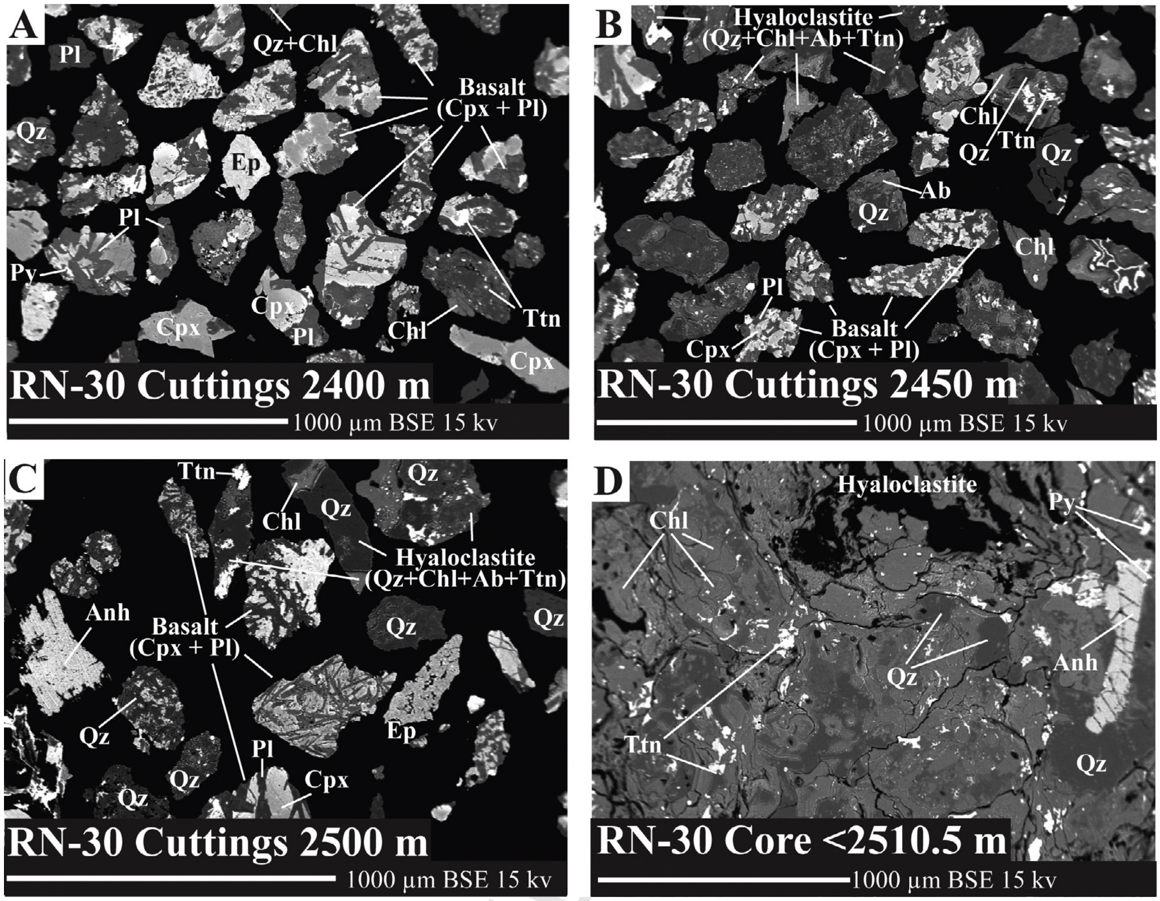

Fig 4. RN-30 cutting BSE images.

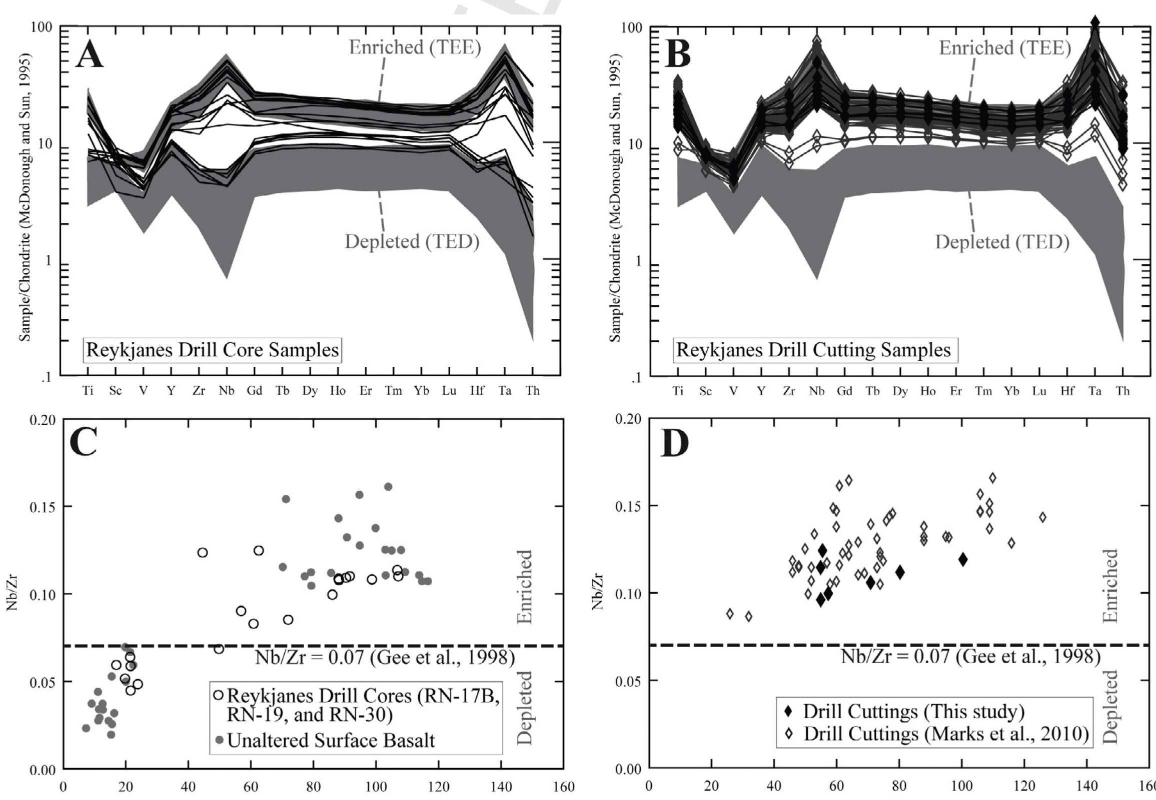

Fig. 5. Wholerock spider diagrams.

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Table 1

Sample/Depth (m)	2400	2450	2500	2792	2796	2878	2886	2512.53	<2510.5-2	2800.35
Drill Hole	RN-30	RN-30	RN-30	RN-17B	RN-17B	RN-17B	RN-17B	RN-30	RN-30	RN-17B
Sample Type	Cuttings	Cuttings	Cuttings	Cuttings	Cuttings	Cuttings	Cuttings	Core	Core	Core
Lithology[a,b,c]	Glassy Basalt	Breccia	Glassy Basalt	Basalt	Basalt	Basalt	Basalt	Coarse Basalt	Hyaloclastite	Basalt Pillow
Major Elements by XRF (Wt.%)										
SiO_2	48.59	50.19	49.11	49.67	49.16	48.50	50.08	49.20	57.15	44.53
TiO_2	1.76	1.53	1.10	1.18	1.41	1.28	1.03	1.76	1.07	1.21
Al_2O_3	13.09	14.85	14.72	14.05	13.74	13.33	14.41	13.68	9.39	14.92
FeO*	12.39	10.68	10.14	11.51	11.81	11.23	9.74	13.04	8.03	11.54
MgO	6.43	7.72	8.32	7.46	7.28	8.31	8.01	6.87	8.92	10.99
MnO	0.19	0.12	0.17	0.27	0.25	0.22	0.20	0.22	0.12	0.23
CaO	9.91	7.48	10.38	11.11	10.68	13.35	13.09	11.17	4.55	8.69
Na_2O	3.08	2.30	2.77	3.03	3.11	1.72	1.92	2.58	0.84	2.39
K_2O	0.10	0.17	0.07	0.06	0.06	0.04	0.05	0.05	0.15	0.06
P_2O_5	0.16	0.15	0.10	0.09	0.13	0.09	0.10	0.17	0.18	0.11
LOI (%)	3.15	3.95	3.14	1.26	1.57	1.56	1.20	<1.00	4.89	4.43
TOTAL	98.85	99.14	100.03	99.68	99.20	99.63	99.84	98.74	95.29	99.10
Trace Elements by XRF (ppm)										
V	352	316	312	322	341	333	276	336	198	349
Cr	233	300	205	296	230	360	309	221	121	94
Ni	91	104	65	149	143	113	99	101	70	73
Cu	137	124	53	160	125	105	87	157	424	<7.4
Zn	96	83	29	121	119	106	84	95	96	179
Trace Elements by ICP-MS (ppm)										
Sc	44.15	44.46	47.53	45.05	44.86	48.53	45.00	44.58	27.85	43.32
Rb	1.48	1.60	5.18	0.40	0.45	0.71	0.83	0.27	2.55	0.60
Sr	131.02	112.64	115.88	151.00	146.23	134.78	136.29	152.07	81.07	71.88
Y	29.50	29.35	23.92	24.03	26.87	21.92	21.86	28.12	19.85	28.00
Zr	95.85	76.15	52.86	53.73	68.87	54.10	56.23	89.65	56.97	57.92
Nb	11.37	8.48	6.03	5.14	7.26	6.69	5.58	9.76	7.09	4.82
Cs	0.08	0.04	2.15	<0.014	<0.014	0.02	0.02	<0.014	0.03	0.02
Ba	36.11	101.98	34.80	19.47	22.24	22.33	25.79	33.36	100.53	20.29
La	8.70	6.92	4.12	3.97	5.66	4.43	4.67	7.66	5.11	6.54
Ce	20.44	16.73	10.11	9.81	13.82	10.79	11.32	18.47	12.76	15.93
Pr	2.87	2.42	1.51	1.53	2.09	1.65	1.72	2.67	1.86	2.38
Nd	13.27	11.78	7.29	7.58	10.19	8.15	8.30	12.52	8.91	11.46
Sm	3.85	3.57	2.49	2.53	3.24	2.58	2.61	3.80	2.58	3.41
Eu	1.47	1.35	1.04	1.02	1.24	1.01	1.02	1.37	0.86	1.41
Gd	4.82	4.65	3.36	3.42	4.09	3.34	3.38	4.55	3.16	4.33
Tb	0.86	0.85	0.64	0.65	0.76	0.62	0.62	0.84	0.56	0.76
Dy	5.61	5.57	4.41	4.45	5.09	4.16	4.16	5.30	3.50	5.08
Ho	1.18	1.19	0.97	0.94	1.08	0.89	0.89	1.14	0.74	1.10
Er	3.28	3.29	2.69	2.66	2.96	2.43	2.46	3.17	2.01	3.07
Tm	0.47	0.48	0.39	0.40	0.43	0.36	0.36	0.45	0.30	0.45
Yb	2.91	2.94	2.48	2.49	2.72	2.23	2.20	2.84	1.76	2.87
Lu	0.46	0.47	0.40	0.39	0.43	0.35	0.35	0.44	0.28	0.47
Hf	2.63	2.14	1.52	1.58	1.96	1.58	1.59	2.41	1.53	1.69
Ta	0.73	0.55	1.44	0.29	0.42	0.39	0.36	0.68	0.48	0.33
Pb	2.19	1.14	1.30	0.84	0.90	0.69	0.58	<0.204	0.39	0.72
Th	0.73	0.48	0.36	0.26	0.37	0.29	0.31	0.49	0.25	0.34
U	0.26	0.82	0.63	0.09	0.13	0.11	0.11	0.14	0.13	0.12
Nb/Zr	0.12	0.11	0.11	0.10	0.11	0.12	0.10	0.11	0.12	0.08

[a] Helgadóttir et al. (2009).
[b] Sigurgeirsson et al. (2011).
[c] Fowler et al. (2015).

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

The down hole wholerock geochemical variation of drill cutting samples from well RN-17 and RN-17ST (Marks et al., 2010) are compared to samples from the adjacent RN-17B sidetrack drill core (Fig. 6). Cuttings from depths <2250 m generally have elevated LOI, K_2O, Rb, Cs, Ba, Pb, Th and U, especially intervals identified as dominated by clastic lithologies (breccia, hyaloclastite, pillow basalt breccia) (Fig. 6). Below 2250 m (corresponding to the horizontal dashed line on Fig. 6), the concentrations of most elements in RN-17ST drill cutting samples are essentially invariable. In contrast, the 9.8 m long RN-17B core from this same interval reflects geochemical heterogeneity comparable to, or even exceeding, that observed from the entire ~3000 m of RN-17 drill cuttings (Fig. 6). For example, Si, Na, and Ca concentrations in RN-17B drill core samples show both enrichments and depletions that exceed the range in the overlying ~3000 m of analyzed cutting samples.

5. Discussion

5.1. Mixing of drill cuttings

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

Drill cutting mixing and homogenization is more extreme at depths below 2266 m in well RN-17. Concentrations of virtually all elements in bulk cutting samples below this depth are essentially invariable (Fig. 6). This interval coincides with the depth from which the 9.8 m long RN-17B core was recovered. The geochemical variability of samples from the RN-17B core is comparable to, or exceeds, that of nearly 3000 m of drill cuttings from well RN-17, suggesting that cutting samples from below 2250 m in well RN-17 are not representative of the true nature of the subsurface at these depths. The zone of homogenized drill cuttings below ∼2250 m in well RN-17 coincides with a change in drilling rig (Jotunn to Geysir), an increase in well deviation from ∼vertical to ∼4°, a change in down-hole drilling assembly, and most notably changes in drilling parameters including a four-fold increase in torque and near doubling of the total weight-on-bit (Friðleifsson et al., 2005).

5.2. Implications of drill cutting preservation bias for inferring chemical exchanges

The impression gained from examination of the drill cutting samples is that the drilled section is dominantly unaltered basalt. The variation in LOI, Si, Na, Mg, and Ca, for example, would be consistent with minimal fluid/rock alteration under low water/rock or

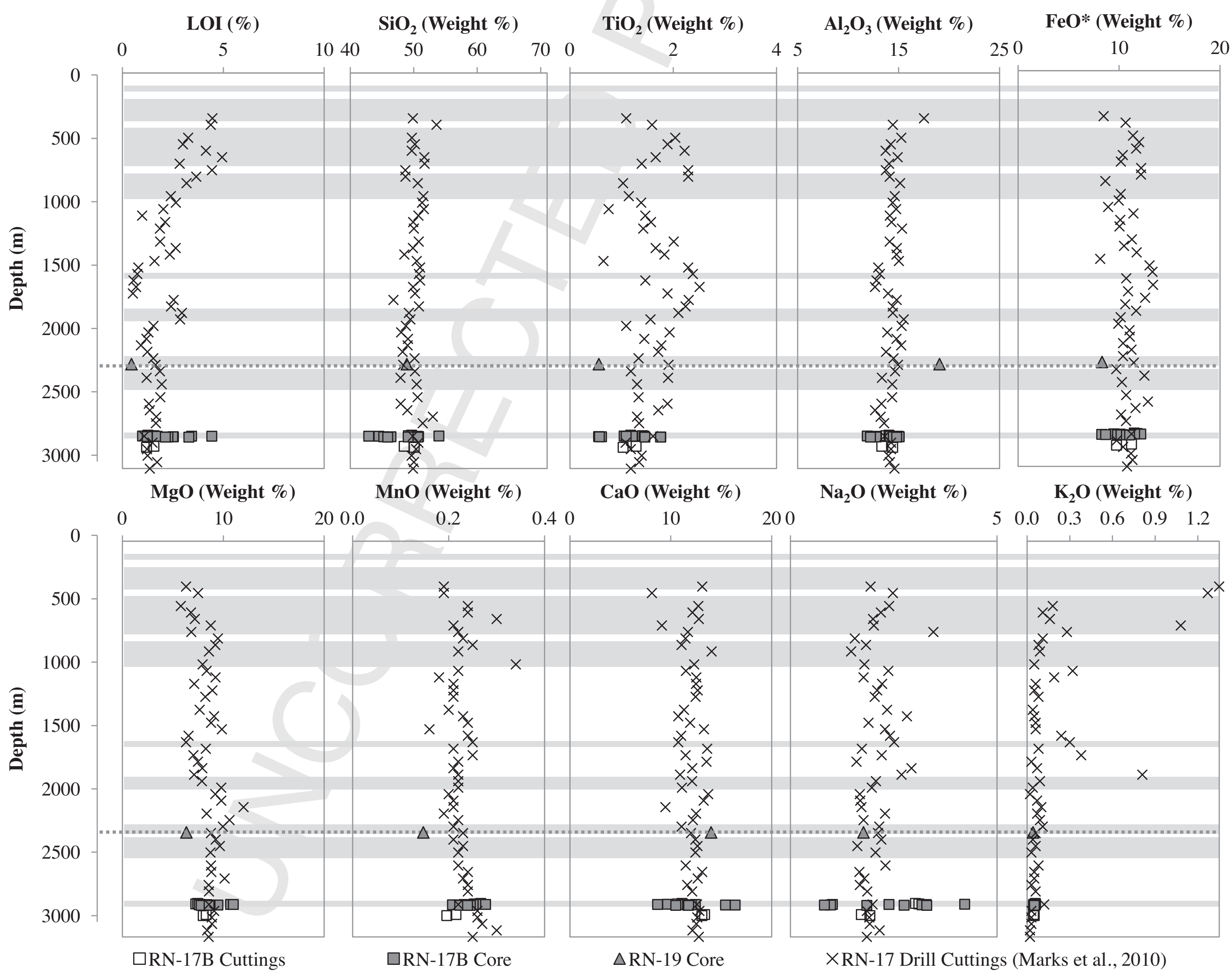

Fig 6. RN-17 depth chemistry.

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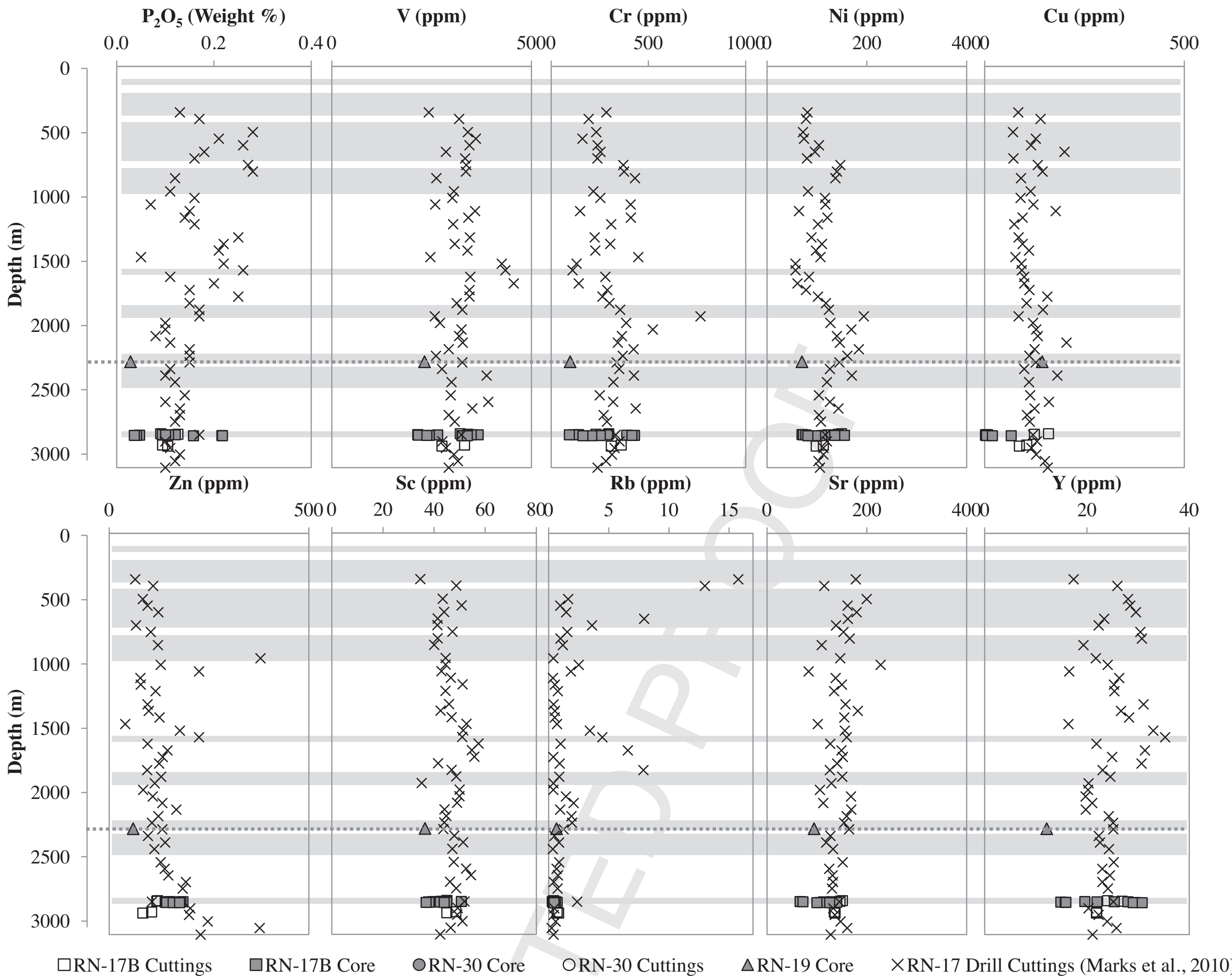

Fig 6. (*Continued*)

rock-dominated conditions. One would also infer that the degree of alteration and chemical exchange decreases down hole, with a significant decline below 2250 m. In stark contrast, the RN-17B core shows pervasive alteration and includes zones of significant metasomatic addition and hydrolytic depletion of Si, Na, Mg, and Ca.

We used the method of Humphris et al. (1998) to visualize bulk elemental differences between drill cutting and drill core samples (Fig. 7, upper diagram). A value equivalent to half the detection limit was used for non-detect data. Data normalized using this method fits the equation of a circle, and points plot along an arc of radius one. The concentration of each component in the drill cutting sample and the selected drill core sample is squared, the squares are summed, and the square root of the summed value is normalized to one. Elements with similar concentrations in drill core and drill cuttings samples cluster about a point along the arc, while elements that are gained or lost in the drill cutting samples relative to the drill core sample plot at increasing distance from the cluster along the arc. While this technique is useful for rapidly visualizing compositional differences between two samples, a drawback is that small differences in elements with very low concentrations result in large shifts on the diagram. To evaluate the magnitude of absolute concentration differences, we plotted elemental data on radar diagrams (Fig. 7; middle and lower diagrams). A benefit of visualizing compositional data on radar diagrams is that concentration changes due to dilution (or enrichment) of a major constituent are readily apparent. Grouping of elements in order of increased, decreased, or invariable concentrations allows quick evaluation of the effect of choosing different protoliths for normalization. The ordering of elements on the radar diagrams is informed by the results of the Humphris et al. (1998) diagrams.

A large source of error in any approach to quantify geochemical bias in drill cutting samples stems from the choice of protolith composition used for normalization. Because drill cutting samples consist of mixtures of lithologies recovered over several meters at minimum (i.e., Kristmannsdóttir, 1982; Fig. 4), there is no unique protolith. In the case of Reykjanes drill cutting samples; the mixtures potentially include TEE basalts, TED basalts, crystalline material, and originally glassy material. Immobile element concentrations and ratios in the Reykjanes drill cutting samples suggest that the influence of TED lithologies is very minor (Fig. 5). Because the RN-30 cutting samples we analyzed contain a mixture of material derived from crystalline basalt and hyaloclastite, we chose to normalize the drill cutting to both a crystalline protolith (2512.53 m) and a hyaloclastite protolith (<2510.5–2) in an attempt to understand the geochemical exchanges recorded by these cuttings. Wholerock analytical data for drill core samples used for comparison to drill cutting samples are presented in Table 1.

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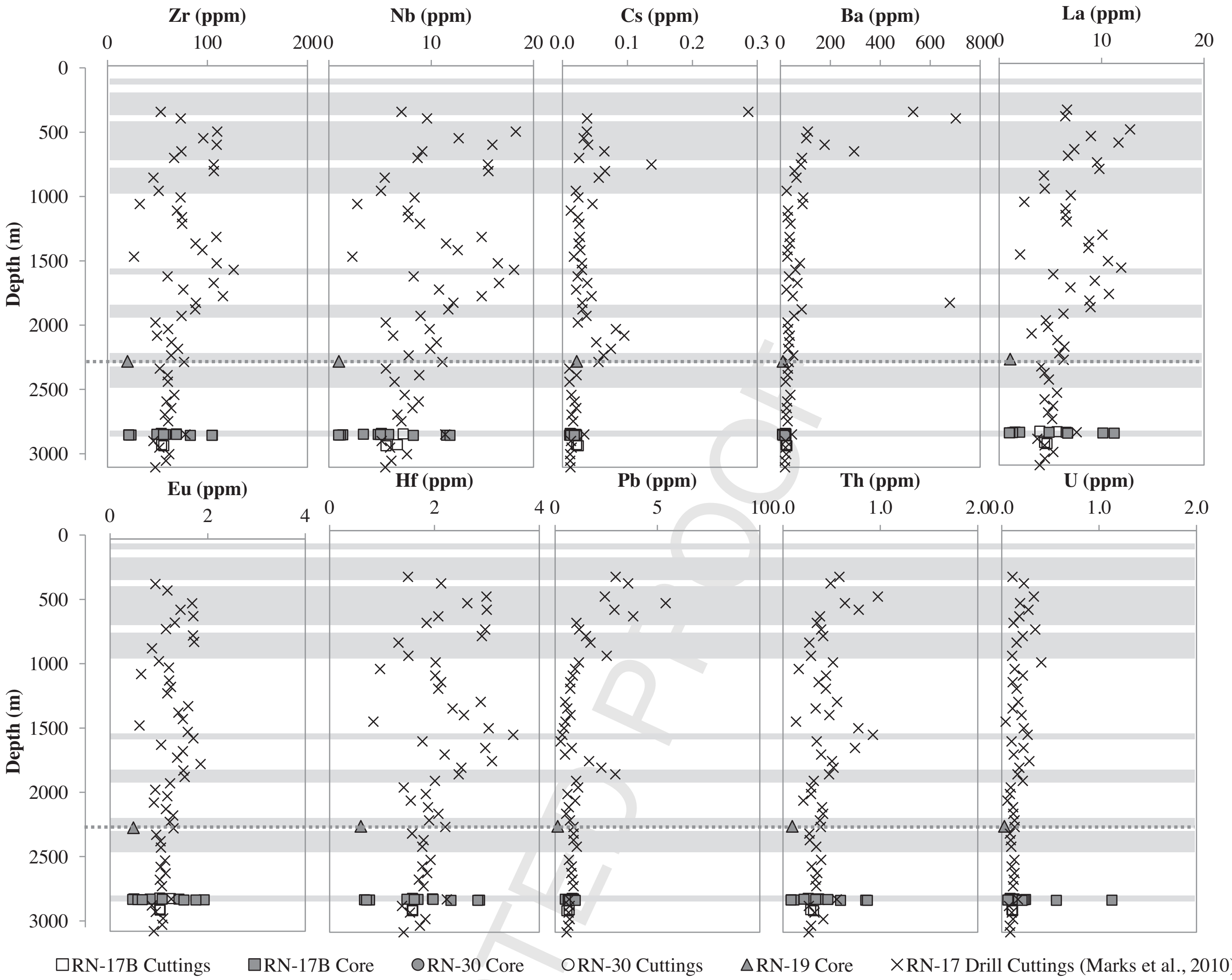

Fig 6. (*Continued*)

When normalized to the crystalline protolith sample, RN-30 drill cuttings appear to have gained MgO, K_2O, Rb, Cs, Pb and U, and have elevated LOI (Fig. 7A). Alkalis, MgO, Pb and U (and elevated LOI) are characteristically gained from seawater by alteration of glassy basaltic protolith in seafloor hydrothermal recharge zones (Thompson, 1973; Humphris and Thompson, 1978a,b; Hart and Staudigel, 1982; Chen et al., 1986; Staudigel et al., 1996; Alt, 1995; Alt et al., 1996; Bach et al., 2001, 2003). In contrast, these same elements have been depleted from RN-30 basalts that were cored directly below the interval from which the cuttings were sampled (Table 1). The apparent gain of alkalis, MgO, Pb and U (and elevated LOI) in RN-30 drill cutting samples calculated assuming a crystalline basalt precursor suggest the hyaloclastite drill core sample may be a more appropriate choice of protolith for the cuttings overlying the drill core. This is consistent with the interpretation that the interval overlying the drill core is a hyaloclastite unit, based on elevated proportion of originally glassy protolith material, which is evident in BSE images of RN-30 drill cutting samples analyzed (Fig. 4).

We therefore normalized RN-30 drill cutting samples to a hyaloclastite sample recovered with the drill core (<2510.5–2) from RN-30, as shown on Fig. 7B. This choice of protolith produces apparent elemental biases for RN-30 drill cutting samples that are more consistent with what we observe for RN-17B drill cutting samples normalized to a crystalline protolith (Fig. 7C). We normalized RN-17B drill cutting samples to a pillow basalt sample from the RN-17B core (2800.35 m), as there was little evidence of glassy protolith material in the cuttings overlying that cored interval (Fig. 3). Our protolith choices are supported by: 1) consistent results for the three RN-30 cutting samples, despite different proportions of crystalline and hyaloclastite lithologies in each of the samples; and 2) agreement of results for elemental bias in RN-17B and RN-30 cuttings, despite very different samples being used for normalization in each case. Our results suggest that Na_2O, CaO, and Cr are generally gained, while MgO, and Zn are generally lost from both RN-17B and RN-30 drill cutting samples (Fig. 7B and C). The cuttings also have lower LOI compared to the core samples, again suggesting bias in cutting samples towards material with lower degrees of alteration. SiO_2, Cu and Ni are gained in RN-17B cuttings, while U, Th, and Pb are generally gained, and SiO_2 and Cu are lost, from RN-30 drill cuttings (Fig. 7B and C).

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

Albitized plagioclase, or plagioclase with albitized rims is ubiquitous in the Reykjanes cuttings samples studied (Figs. 3 and 4),

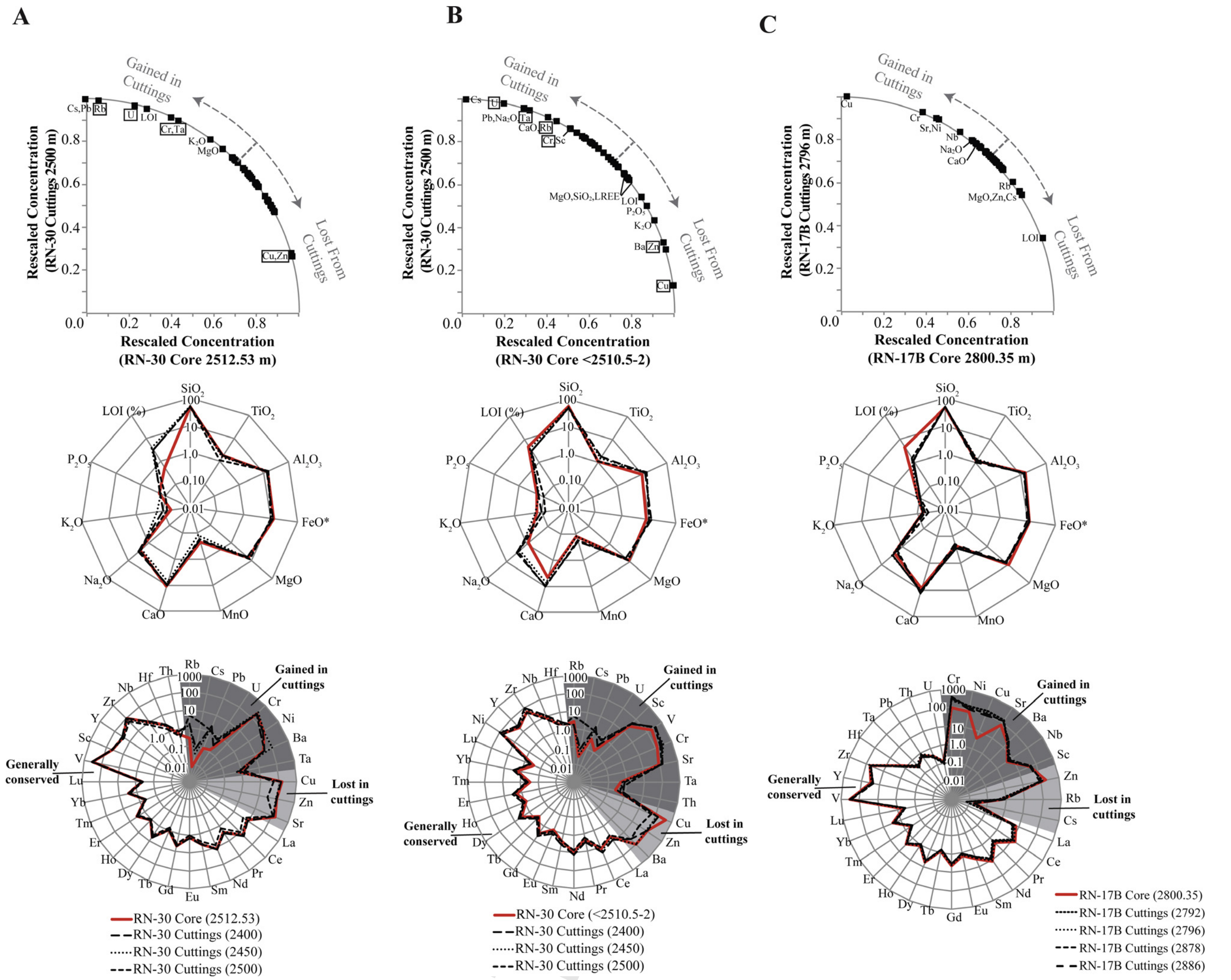

Fig. 7. Drill cutting chemical bias plots.

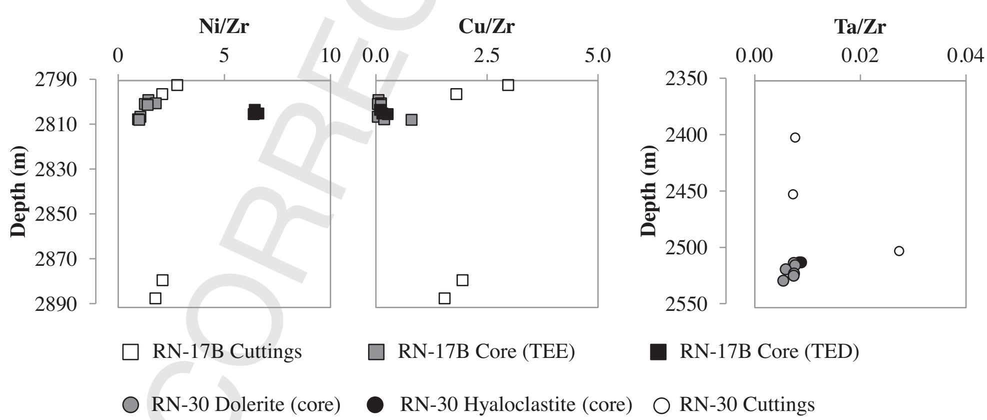

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Fig 8. Drill cutting contamination plots.

and preferential preservation of this phase provides a mechanism to increase both Na and Ca in drill cuttings. Elevated CaO is also potentially hosted in epidote, which is common in cuttings from the intervals studied (Helgadóttir et al., 2009; Sigurgeirsson et al., 2011). In the case of RN-17B, elevated SiO_2 likely reflects the high proportion of quartz logged in the cutting samples (Helgadóttir et al., 2009), in contrast to the RN-17B core samples where quartz is entirely absent (Fowler et al., 2015).

Less resistant alteration minerals are easily disaggregated and lost from cuttings during sample washing and collection (Hulen and Sibbett, 1981). Loss of MgO, Zn and LOI from all drill cuttings is consistent with loss of fine-grained chlorite and or actinolite during sieving and collection of drill cutting samples at the surface. Chlorite $[(Mg_5Al)(AlSi_3O_{10})(OH)_8]$ and actinolite $[Ca_2(MgFe)_5(Si_8O_{22})(OH)_2]$ in the Reykjanes geothermal system both host Mg (Lonker et al., 1993), and significantly contribute to

LOI due to the structural hydroxyls. While there are no available analyses of Zn in Reykjanes chlorite or actinolite, Zn is known to rarely substitute into the chlorite and actinolite structures (Deer et al., 1992).

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

Offset of clustering elements from unity (dashed line) in the cutting samples from RN-30 (Fig. 7A), is a reflection of the high SiO_2 content resulting from numerous quartz veins 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 (Fig. 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 (Fig. 7).

5.3. 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 (Fig. 7B and C). We normalized Ni and Cu in RN-17B cuttings and Ta in RN-30 drill cutting samples to the immobile element Zr in each sample to avoid the influence of sample dilution (or enrichment) by any single element due to the closed nature of compositional data (Fig. 8). An explanation for these anomalous concentrations is contamination from down hole drilling equipment. Non-magnetic drill collars used to apply weight on bit are manufactured from Ni-Cu alloys (Hulen and Sibbett, 1981). Ta and Nb contamination potentially results from grinding samples in a tungsten carbide ring mill (Hickson and Juras, 1986). However Ta and Nb contamination is not observed in any of the drill core samples (Fowler and Zierenberg, in prep), suggesting the contamination may be from worn drill bits, which are also composed of tungsten carbide (Hulen and Sibbett, 1981).

It is unlikely that the elevated alkali concentrations result from contamination by lost circulation prevention agents (Mica; K, Rb, Cs), because extreme care was taken to thoroughly wash and hand pick mica from cutting samples submitted for analysis (Marks et al., 2010). Elevated concentrations of K, Rb, Cs, Ba and Pb in RN-17 drill cutting samples at shallow intervals (<500 m) and associated with clastic lithologies (Fig. 5) are consistent with enrichments of the same elements observed in hydrothermally altered drill core and dredged samples from shallow oceanic basement rocks (Thompson, 1973; Humphris and Thompson, 1978a,b; Hart and Staudigel, 1982; Chen et al., 1986; Staudigel et al., 1996; Alt, 1995; Alt et al., 1996; Bach et al., 2001, 2003). In seafloor hydrothermal systems, these elements are sequestered in the upper oceanic crust in alteration minerals formed during low temperature seawater circulation. These same elements are subsequently depleted from basaltic rocks at depth that have undergone higher temperature alteration in hydrothermal upflow zones (Alt, 1995). Clastic lithologies present at depth in the Reykjanes system were originally emplaced on the seafloor and have subsided over time to the current depths (Björnsson et al., 1972; Friðleifsson and Richter, 2010).

6. Conclusions

Drill cutting samples from well RN-17 preserve element enrichments on the scale of 10's to 100's of meters as evidenced by elevated alkalis, Ba, U, and Pb in shallow drill cutting samples collected at 50 m intervals associated with lithologies emplaced on the seafloor. The same drill cutting samples homogenize basalt so that affinities to the groups TEE and TED are not discernable in the cuttings, but are preserved in Reykjanes drill core samples. Greater depth, slight drill hole inclination, increased weight on bit and torque homogenize drill cutting samples on scales >50m, as evidenced from drill cuttings below 2266 m in RN-17. Drill cutting samples normalized to drill core samples suggest that chlorite and actinolite have disaggregated and been lost during sampling of drill cuttings, while more resistant phases including quartz, plagioclase and epidote have been preferentially retained. Contamination of drill cuttings samples by alloys used in down hole drilling equipment is apparent from elevated Cu, Ni, Ta and Nb in drill cutting samples. 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. While problems of cutting homogenization are difficult to avoid, the bias in selective retainment of the more resistant, coarse-grained minerals can in part be addressed by sampling and analyzing the fine-grained cuttings fraction.

Uncited references Q9

Brandon et al. (2007), Chauvel and Hémond (2000), Hemond et al. (1993), Koornneef et al. (2012), McDonough and Sun (1995), Nielsen et al. (2007) and Skovgaard et al. (2001).

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