**Petrology and geochemistry of the 2014-2015 Holuhraun eruption, central Iceland: compositional and mineralogical characteristics, temporal variability and magma storage**

Sæmundur A. Halldórsson1\*, Enikő Bali1, Margaret E. Hartley2, David A. Neave3, David W. Peate4, Guðmundur H. Guðfinnsson1, Ilya Bindeman5, Martin J. Whitehouse6, Morten S. Riishuus1‡, Gro B.M. Pedersen1, Sigurður Jakobsson1, Rob Askew1, Catherine R. Gallagher1, Esther R. Guðmundsdóttir1, Jónas Gudnason1, William M. Moreland1, Birgir V. Óskarsson1, Paavo Nikkola1, Hannah I. Reynolds1, Johanne Schmith1, Thorvaldur Thordarson1

1Nordic Volcanological Center, Institute of Earth Sciences, University of Iceland, Reykjavík, Iceland

2School of Earth and Environmental Sciences, University of Manchester, Manchester, UK

3Institut für Mineralogie, Leibnitz Universität Hannover, Germany

4Department of Earth and Environmental Sciences, University of Iowa, Iowa City, USA

5Department of Earth Sciences, University of Oregon, Eugene, USA

6Department of Geosciences, Swedish Museum of Natural History, Stockholm, Sweden

\*Corresponding Author: [saemiah@hi.is](mailto:saemiah@hi.is)

‡Now at: Faroese Geological Survey, Tórshavn, Faroe Islands

IES Holuhraun Eruption Team (in alphabetical order): R. Askew, C.R. Gallagher, E.R. Guðmundsdóttir, J. Gudnason, W.M. Moreland, B.V. Óskarsson, P. Nikkola, H.I. Reynolds, J. Schmith, T. Thordarson.

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**Abstract**

The 2014-2015 Holuhraun fissure eruption provided a rare opportunity to study in detail the magmatic processes and magma plumbing system dynamics during a six-month-long, moderate- to large-volume basaltic fissure eruption. In this contribution, we present a comprehensive dataset, including major and trace elements of whole-rock and glassy tephra samples, mineral chemistry, and radiogenic and oxygen isotope analyses from an extensive set of samples (n=62) that were collected systematically in several field campaigns throughout the entire eruptive period. We also present the first detailed chemical and isotopic characterization of magmatic sulfides from Iceland. In conjunction with a unique set of geophysical data, our approach provides a detailed temporal and spatial resolution of magmatic processes before and during this eruption. The 2014-15 Holuhraun magma is compositionally indistinguishable from recent basalts erupted from the Bárðarbunga volcanic system, consistent with seismic observations for magma ascent close by the Bárðarbunga central volcano, followed by dyke propagation to the Holuhraun eruption site. Whole-rock elemental and isotopic compositions are remarkably constant throughout the eruption. Moreover, the inferred depth of the magma reservoir tapped during the eruption is consistently 8±5 km, in agreement with geodetic observations and melt inclusion entrapment pressures, but inconsistent with vertically extensive multi-tiered magma storage prior to eruption. The near constancy in the chemical and isotopic composition of the lava is consistent with efficient homogenization of mantle-derived compositional variability. In contrast, occurrence of different mineral populations, including sulfide globules, which display significant compositional variability, require a more complex pre-eruptive magmatic history. This may include sampling of heterogeneous mantle melts that mixed, crystallized and finally homogenized at mid- to lower-crustal conditions.

**Introduction**

Observations of subaerial rifting episodes, both in Iceland and East Africa, have transformed our understanding of magma transport during the generation of new oceanic crust at divergent plate boundaries worldwide. The Icelandic rift system in particular represents a key locality to unravel the details of basaltic fissure eruptions, which are critical for the development of magma transport models (Wright et al, 2012). The models developed on the basis of observations in Iceland (e.g., Hartley et al., 2018) have therefore been widely referred to in relation to volcano-tectonic episodes, not only at submarine spreading centers (e.g., Tan et al., 2016), but also at other oceanic islands (e.g., Desmarais and Segall, 2007). The 2014-15 Holuhraun eruption is probably the best monitored moderate- to large-scale basaltic fissure eruption ever recorded. This eruption, north of Dyngjujökull in central Iceland, was unique among most recent Icelandic eruptions, with unprecedented pre-eruptive earthquake activity and ground deformation at the Bárðarbunga central volcano and its surroundings. The 2014-15 Holuhraun eruption, including the eruption precursor and associated collapse of the Bárðarbunga caldera, and its environmental effects, have been studied in detail (e.g., Sigmundsson et al., 2015; Gíslason et al., 2015; Riel et al., 2015; Ágústsdóttir et al., 2016; Gudmundsson et al., 2016; Ruch, 2016; Pedersen et al., 2017; Hartley et al., 2018). In terms of eruption style and size, the 2014-15 event is typical for eruptions that contribute most to the construction of the upper Icelandic crust. Detailed studies of this event are therefore likely to provide new insights into crustal formation.

In this study, we present a detailed petrological, mineralogical and geochemical characterization of the Holuhraun erupted products, including for whole-rock, glass and mineral data. We use geochemical data to confirm the association of the Holuhraun lava with the Bárðarbunga volcanic system, and evaluate temporal changes in the lava chemistry and mineralogy occurring during the eruption. The quality and density of our sample suite provides a temporal dataset matched by only a few other global localities (e.g., Kilauea: Garcia et al., 2000; Helz et al., 2014, and Piton de la Fournaise: Vlastélic and Pietruszka, 2015). Furthermore, we investigate mineral formation pressures, including the segregation of immiscible sulfide melt, and preservation of any mantle lithological heterogeneities evident in the Holuhraun volcanic products. Finally, the quality of geophysical monitoring of this event was exceptional, facilitating meaningful and unique comparisons between geochemical and geophysical data. This allows us to place fundamental petrological constraints on the magmatic processes at play, both preceding and during the 2014-15 eruption.

**Previous Petrological Studies of the 2014-15 Holuhraun Eruption**

Petrological studies of this eruption and its products have used small sample sets to determine first-order constraints on the magmatic plumbing system (Gudmundsson et al., 2016; Geiger et al., 2016; Gauthier et al., 2016). Gudmundsson et al. (2016) inferred that the Holuhraun eruption was fed from a magma reservoir located at a depth of about 12 km, based on several independent geobarometers, combined with surface gas compositions and geodetic modelling. Geiger et al. (2016) argued that the 2014-15 fissure eruption was fed from a complex, multilayered magma plumbing system spanning almost the entire thickness of the central Iceland crust (from 28 to 5 km depth) beneath Bárðarbunga, based on clinopyroxene and plagioclase thermobarometry. Furthermore, they inferred that mineral resorption textures and variable but overall low oxygen isotope ratios in the 2014-15 Holuhraun lava indicated that magma mixing and crustal assimilation at shallow depths beneath Bárðarbunga were key processes in modulating characteristics of the pre-eruptive petrology and geochemistry of the Holuhraun magma.

The study by Geiger et al. (2016) was based on just three whole-rock samples collected during a single week of an eruption that lasted for six months. The question is whether such a limited sample suite is truly representative of the entire eruption, or whether that study provides an incomplete picture of the main magmatic processes taking place within the plumbing system. Several studies have used multiple analyses of single lavas to assess the extent of compositional heterogeneity within individual eruptive events in Iceland. While significant whole-rock compositional variability has been found within some primitive (> 8 wt.% MgO) basalt lavas (e.g., Borgarhraun, Maclennan et al, 2003) and in eruptions that involved magma mixing (e.g., Fimmvörðuháls-Eyjafjallajökull 2010 AD, Sigmarsson et al., 2011; Veiðivötn 871 AD and 1477 AD, Zellmer et al., 2008), examples of the more typical evolved (< 8 wt.% MgO) basaltic lavas generally show limited chemical heterogeneity (e.g. Laki 1783 AD, Sigmarsson et al., 1991; Krísuvík Fires c. 1151 AD, Peate et al., 2009), even when a large volume of magma was erupted, as in the case of the Laki eruption. The extent of compositional variability can provide insights into how magma was stored prior to an eruption. If the Holuhraun magma was sourced from multiple deeper reservoirs, as argued by Geiger et al. (2016), then we might expect a greater degree of lava compositional variation than if the magma had drained from a single reservoir under the Bárðarbunga caldera, as has been suggested from seismic and geodetic observations. Even if whole-rock compositions show limited compositional variability, temporal changes in mineral compositions and textures can reveal information about timescales of magma transport and mixing (e.g. Rae et al., 2016; Hartley et al., 2016), pre-eruptive magmatic processes such as the progressive top-to-bottom emptying of the conduit system (e.g. Putirka, 1997) and changes in the extent of crystal mush disaggregation and entrainment (e.g. Neave et al., 2017).

**Sampling and Analytical Techniques**

Samples were collected systematically in several field campaigns over the entire 182-day course of the Holuhraun eruption (Fig. 1, **Fig. 2**, **Table S1**) by the IES Holuhraun Eruption Team. A total of 62 lava and tephra were selected for this study. The samples analyzed were erupted during the period from 29 August 2014 (day 1) to 18 February 2015 (day 174), and cover the entire course of the eruption with a high temporal resolution. **Figure 2** shows the temporal changes of the lava flow field. The sample archive comprises (i) direct fallout tephra; (ii) incandescent lava; and (iii) solidified lava. Tephra was collected either directly upon deposition, or shortly thereafter (later the same day or the following day). Incandescent lava was collected from active flow fronts using a shovel and quenched in water. Solidified lava samples were collected from the uppermost carapace of the flow (hypohyaline clinker, rubble or pahoehoe crust), deeper parts of the upper lava crust (hypocrystalline, coarser-grained and less vesicular), the core of the flow (sampled in inflation clefts in tumuli) and lava balls. Some solidified lava samples were collected on the day of emplacement; others were collected weeks to months after emplacement with eruption dates determined from satellite images. Collection of time-constrained lava samples was aided by satellite- and ground-based mapping of temporal changes of the lava flow field (Pedersen et al., 2017). Most lava sampling was carried out along the western and northern transient active flow fronts, and more sporadically inside the flow field or on the southern front during brief excursions by foot, car, or helicopter (**Fig. 2**). Proximal tephra samples were collected on the fluvio-glacial sand plain Flæður/Dyngjusandur in front of the Dyngjujökull outlet glacier. Ten glassy proximal tephra fall and scoria samples that span the entire course of the eruption were selected for detailed melt and fluid inclusion studies focusing on the petrogenesis, volatile systematics and degassing history of the Holuhraun magma (Hartley et al., 2018; Bali et al., 2018).

Whole-rock major and selected trace element compositions were measured for all 62 lava and tephra samples using simultaneous ICP-OES at the University of Iceland. A full suite of trace elements was measured in 30 samples by ICP-MS at the University of Iowa. These two datasets are in good agreement (**Fig. SA1, Supplementary Material)**. However, to ensure coherency between with the trace element dataset generated by ICP-MS, and because the ICP-MS dataset involves a larger set of trace elements, we choose to focus on the data generated by ICP-MS. An additional 9 glassy tephra samples were analyzed for trace elements by ion microprobe at the University of Edinburgh (Hartley et al., 2018). Radiogenic isotopes (Hf-Pb) were analyzed in 12 whole-rock samples by MC-ICP-MS at the University of Iceland. Strontium and Nd isotopic ratios were measured by MC-ICP-MS at the University of Iceland in 8 and 7 samples, respectively. We also include new Hf-Pb data on an older Holuhraun lava (HRW-04), for which Sr and Nd isotope ratios were reported by Sigmarsson and Halldórsson (2015). Older eruptions at Holuhraun were studied by Hartley and Thordarson (2013), who argued that they represent two separate eruptions, one in 1797 (Holuhraun I) and another (Holuhraun II) sometime between 1862-64 or 1867, as can be inferred from Jónsson (1945). Oxygen isotope ratios were measured in 11 glassy tephra samples, and in mineral separates of plagioclase, pyroxene and olivine macrocrysts from a single tephra sample (MSR161014-1) by laser fluorination IRMS at the University of Oregon. Minerals and glasses in 19 thin sections were analyzed by electron probe micro-analyzer (EPMA) at the University of Iceland. Selected trace elements were also analyzed by EPMA in olivine macro- and microphenocrysts following methods outlined in Gómez-Ulla et al. (2017). Finally, sulfide globules were analyzed for sulfur isotopes (δ34S) by ion microprobe at the Swedish Museum of Natural History (NordSIMS). Full details of all analytical techniques and an evaluation of data quality are provided in the supplementary material.

**Results**

**Petrography**

Holuhraun lava samples (**Table S1**) are vesicular and macrocryst-poor (≤5 vol.%; macrocrysts are defined here as minerals with long axes >1 mm) in hand specimen. Crystallinity increases with distance from the eruptive vents. Rapidly quenched tephra samples from Holuhraun are similarly macrocryst-poor, with vesicularity up to 93 vol.% (Gudmundsdóttir et al. 2016); small fragments of non-vesicular glass are also found in some samples.

Plagioclase is the principal macrocryst phase in both lava and tephra samples (**Fig. 3a**); minor clinopyroxene and olivine are also present as macrocrysts (**Fig. 3a-f**). Rare Cr-rich magnesian clinopyroxene macrocrysts, distinguished by their dark green color, were also present in samples collected in the early stages of the eruption, on 4 September (sample JG040914) and 20 September (sample GP140920-01) 2014. Chromian spinel was found as inclusions in one olivine and two clinopyroxene macrocrysts. A single gabbro xenolith, consisting of clinopyroxene and plagioclase, is present in sample MSR161014-1, collected on 16 October 2014. Geiger et al. (2016) also identified several cm-sized gabbro fragments in their samples that were collected between 3 and 11 September 2014.

Both lava and tephra samples contain abundant microphenocrysts (defined here as minerals with long axes between 100 µm and 1 mm) of plagioclase and clinopyroxene, which are commonly in subophitic arrangement as is typical of Icelandic tholeiites (e.g., Jakobsson, 1979; **Fig. 3b**). Olivine microphenocrysts **(Fig. 3e**) are less abundant. Plagioclase, clinopyroxene and Fe-Ti oxides are present in the groundmass of lava samples and the oxides form skeletal grains interstitial to the other groundmass minerals (**Fig. 3b**). Most macrocrysts and microphenocrysts exhibit complex zoning patterns (**Fig. 3d**). Melt inclusions are common in macrocrysts and microphenocrysts and are discussed in companion papers (Hartley et al., 2018; Bali et al., 2018).

Holuhraun tephra samples contain abundant sulfides (**Fig. 3e and 3f**), but we note their absence in lava samples. Similar quenched immiscible sulfide liquid has been reported in basalts from the nearby Grímsvötn volcano (Sigmarsson et al., 2013). The Holuhraun sulfides are mostly found as spherical globules within the silicate glass in tephra samples (**Fig. 3f**), and also occasionally as inclusions within microphenocrysts (**Fig.** **3e**).

In summary, the textural and mineralogical features of Holuhraun lavas and tephras are similar to those observed in recent lavas associated with the Bárðarbunga volcanic system, including the older Holuhraun lava flows (Hartley and Thordarson, 2013), the 1862-64 Tröllahraun lava (Thórarinsson and Sigvaldason, 1972), and older Holocene lavas from the Veiðivötn fissure swarm, which extends southwest from the Bárðarbunga central volcano (Jakobsson, 1979; Halldórsson et al., 2008; Svavarsdóttir et al., 2017).

**Chemical and isotope composition of whole-rock and glass samples**

*Major Elements*

The 2014-15 Holuhraun whole-rock samples all have similar compositions, and contain 6.5-7.0 wt.% MgO and 1.8-2.1 wt.% TiO2 (**Table S3 and Fig. 4a**). Intra-flow variability in major element compositions is therefore limited. Of the major elements measured by ICP-MS, only Al2O3 exhibits a signal to noise ratio (σt/σr), where σt is the true variability within the sample set and σr is an estimate of analytical error (Maclennan et al. 2003), consistent with statistically significant variability at the 99% confidence level (**Table S4**). The 2014-2015 Holuhraun magma is classified as a moderately evolved olivine tholeiite, which is the most common magma type erupted within the Icelandic axial rift and erupted during flood lava eruptions on the fissure swarms of the volcanic systems (e.g., Jakobsson et al., 2008).

The 2014-2015 Holuhraun whole-rock samples lie in the center of the compositional field defined by Holocene and historic lavas of the Bárðarbunga volcanic system (e.g., Jakobsson, 1979; Hemond et al., 1993; Kempton et al., 2000; Steinthorsson et al., 2000; Momme et al., 2003; Kokfelt et al., 2006: Halldórsson et al., 2008; Hartley and Thordarson, 2013; Manning and Thirlwall, 2014). However, the 2014-15 Holuhraun whole-rock samples differ from many of the Holocene Bárðarbunga lavas, as they are unaffected by plagioclase accumulation, which is revealed by the data points dispersed towards lower MgO and TiO2 on **Figure 4a**. The 2014-15 Holuhraun whole-rock samples are also compositionally distinct from historical within-caldera lava units from the nearby Askja and Grímsvötn volcanoes (Hartley and Thordarson, 2013; Jude-Eton, 2013; Manning and Thirlwall, 2014), which display somewhat more evolved compositions, as evident from their lower MgO and higher TiO2 contents. Older and more primitive basalts of the Askja volcanic system (e.g., tuff cones on the NE and SW shores of Öskjuvatn) are compositionally similar to many lavas associated with the Bárðarbunga (Hartley and Thordarson, 2013), but to facilitate comparison between lavas of similar ages from different volcanic systems, we have excluded the older Askja erupted products from our figures. Finally, the whole-rock composition of the 2014-15 Holuhraun lava is similar to the older Holuhraun lava units (Hartley and Thordarson, 2013), although slightly more evolved (**Fig. 4b**).

In contrast to whole-rock data, glass compositions have a bimodal compositional distribution. The majority of glass compositions from naturally quenched tephra samples have 6.0-6.5 wt.% MgO and 1.8-2.3 wt.% TiO2, whereas glasses that experienced *in situ* crystallization of microlites (JS-140914-07, a glassy lava selvage) have ~ 5.5 wt.% MgO and ~ 2.5 wt.% TiO2 (**Fig. 4b**). The glass compositions of tephra clasts from the older Holuhraun eruptions are compositionally indistinguishable from the glass in the 2014-15 Holuhraun tephra population that underwent minimal *in situ* crystallization.

*Incompatible and Compatible Trace Elements*

Most trace elements in whole-rock samples display no significant variability at the 99% confidence level (**Table S4**). Indeed, the compositional variability of most elements is within the analytical precision of the ICP-MS data (see supplementary material). However, perhaps linked to heterogeneous distribution of sulfide globules (see discussions below), we note that Cu and W are the only trace elements with a variability that is significantly above the threshold for variability at p<0.01.

As is typical for Icelandic tholeiites, the 2014-2015 Holuhraun samples are enriched in LREE relative to HREE and are characterized by small positive Nb and Zr anomalies (**Fig. S1**). The 2014-15 Holuhraun whole-rock samples closely resemble whole-rock data from lavas elsewhere in the Bárðarbunga volcanic system and are nearly identical to the older Holuhraun lava units (Hartley and Thordarson, 2013) (**Fig. S2**). The incompatible trace element compositions of Holuhraun whole-rock samples also fall within the range of the tephra samples associated with Bárðarbunga (Óladóttir, 2009) (**Fig. S2**). Notably, the 2014-2015 Holuhraun samples are generally more depleted in incompatible trace elements than whole-rock samples from historic eruptions in the Askja and Grímsvötn systems (**Fig. S1**). A plot of the incompatible trace element ratios Sm/Yb vs. La/Dy (**Figure 5a**) clearly shows the compositional distinction between basalts from the Bárðarbunga, Askja and Grímsvötn volcanic systems, and demonstrates that the Holuhraun lava is associated with the Bárðarbunga volcanic system.

**Figure 5b** shows the transition metal (Sc, Ti, V, Cr, Mn, Fe, Co, Ni, Cu and Zn) concentrations of Holuhraun whole-rock samples (following Langmuir et al., 1977) in which concentrations are normalised to depleted MORB mantle (Salters and Stracke, 2004). Relative enrichments are evident for Sc, Ti, V, Mn, Fe, Cu and Zn, whereas Cr, Ni and Co all display relative depletions. Positive anomalies for Sc, Ti and Fe indicate only minor removal of Cr-poor clinopyroxene and Fe-Ti oxides, if any, whereas strong negative Cr and Ni anomalies are indicative of significant removal of olivine, spinel and Cr-rich clinopyroxene (e.g., Langmuir et al., 1977). The enrichments in Cu and Zn are also noteworthy. The concentrations of these chalcophile elements may be modulated by the sulfide globules present in the Holuhraun magma (see discussion below).

*Oxygen isotopes*

Oxygen isotope values measured in glassy tephra clasts and crystalline groundmass in lava samples, reported in δ18O notation, cover a restricted and low δ18O range between +3.58 and +3.87‰, with an average value of +3.77±0.07 ‰ (n=11: **Fig.** **5c, Table S5**). This range is similar to the uncertainty on standards run with these samples (the UWG-2 (5.80‰, Valley et al. 1995) and in-house UOG (6.52‰)). These values fall within the range of published data for Holocene basalts from the Bárðarbunga volcanic system (Sigmarsson et al., 2000; Bindeman et al., 2008). The 2014-15 Holuhraun δ18O values are similar to values of 3.4-4.2‰ obtained from historical eruptions of the Veiðivötn fissure system (i.e., the southern segment of the Bárðarbunga volcanic system). However, our δ18O values are significantly lower than the whole-rock δ18O values obtained by Geiger et al. (2016) for three samples from this same eruption (range from +4.4 to +5.4 ‰). Oxygen isotopic values of basaltic glasses from historical eruptions at the Askja (Hartley et al., 2013) and Grímsvötn systems (Bindeman et al., 2006) are also shown in **Fig. 5c,** as they can be directly compared with our laser fluorination data. Relative to the 2014-15 Holuhraun values, samples from the Askja and Grímsvötn systems generally display low δ18O values (range from +2.7 to +3.3 ‰).

Oxygen isotopic compositions of plagioclase, olivine and pyroxene macrocrysts were measured in sample MSR161014-1 and display a total range from +3.69 to +4.38‰ (**Fig.** **S3 and Table S5**). Again, our δ18O values are generally lower than those reported by Geiger et al. (2016) on gabbroic fragments contained in the 2014-15 Holuhraun lava (range from +4.0 to +5.0 ‰). Only our δ18O value for plagioclase overlaps with their values (**Fig.** **S3**). Macrocryst δ18O values are discussed further below.

*Radiogenic isotopes*

Whole-rock Sr and Nd isotope ratios for four 2014-15 Holuhraun lava samples were reported by Sigmarsson and Halldórsson (2015). We report new Sr, Nd, Hf and Pb isotopic ratios as well as Hf and Pb data for one of the older Holuhraun units in **Table S6**. Strontium and Nd isotope ratios range from 0.70311–0.70314 and 0.513050–0.513080, respectively, and are in good agreement with the values reported by Sigmarsson and Halldórsson (2015). Hafnium isotope ratios (176Hf/177Hf) range from 0.283190 to 0.283225 (**Fig. S4**). These are similar to previously reported values for Bárðarbunga, but are higher relative to published values for Grímsvötn and Askja samples (Koornneef et al., 2012; Manning and Thirlwall, 2014).

All of the measured 2014-2015 Holuhraun samples have 206Pb/204Pb < 18.45 (**Fig. 5d**), and are isotopically indistinguishable from basalts erupted within the Bárðarbunga volcanic system (Thirlwall et al., 2004; Kokfelt et al., 2006; Halldórsson et al., 2008; Manning and Thirlwall, 2014). In contrast, samples from the nearby central volcanoes of Grímsvötn and Askja mostly have 206Pb/204Pb > 18.45 (Thirlwall et al., 2004; Kokfelt et al., 2006; Kuritani et al., 2011; Manning and Thirlwall, 2014). Significantly, most Pb isotope ratios of Holuhraun are strikingly similar (i.e., within the external uncertainty of the measurements) to those obtained from historical lavas (i.e., since 871 AD) in the Bárðarbunga system.

**Major and trace element compositions of minerals**

The plagioclase, clinopyroxene and olivine compositions are summarized in **Fig. 6a-c** (see **Table S2**). These results are compared with the mineral compositions predicted to be in equilibrium with the main tephra glass composition (i.e., with MgO of 6-6.5 wt.%; gray field), which is assumed to be representative of the Holuhraun carrier melt. A range of equilibrium values, reflecting the variability of the glass composition, were calculated following the models of Namur et al. (2012) for plagioclase, Grove et al. (1992) for clinopyroxene, and Roeder and Emslie (1970) for olivine assuming a fixed of 0.3±0.03.

Plagioclase macrocryst core compositions are An70-91, whereas macrocryst rims and plagioclase microphenocrysts are An65-75 (**Fig. 6**). The cores of most plagioclase macrocrysts are too primitive to be in equilibrium with the Holuhraun carrier melt; similar observations have been described for other Holocene lava units from the Bárðarbunga volcanic system (e.g., the Thjórsá lava: Halldórsson et al., 2008).

Clinopyroxene macrocrysts and microphenocrysts are augitic in composition, with the exception of three Cr-rich diopside macrocrysts. Clinopyroxene macrocrysts have Mg# of 76-87 (**Fig. 6b**). They have variable Cr2O3 (up to 1.2 wt.% Cr2O3) and Al2O3 contents (1.5 to 4.7 wt.% Al2O3). Most macrocrysts have homogeneous cores with a thin overgrowth; however, some exhibit complex zoning patterns including sector zoning. In order to eliminate modifications of mineral compositions resulting from sector zoning, we plot Al2O3/TiO2 in **Figure 6d**. In general, the spread in Al2O3/TiO2 increases with increasing Mg#. This is particularly evident among the macrocrysts with Mg# > 82. In contrast, augite microphenocrysts with compositions in the range Mg# 78-81 exhibit less spread in Al2O3/TiO2. Their compositions overlap with those observed in the sector-zoned macrocryst population (i.e., those with Mg# < 81). Notably, many of the microphenocrysts are in textural and chemical equilibrium with the surrounding groundmass glass, whereas macrocryst cores are in equilibrium with more primitive melt compositions (**Fig. 6b**).

Typical olivine macrocrysts have homogeneous core compositions of Fo86-78 (**Fig. 6c**), and Ni contents between 850 and 1500 ppm (**Fig. 6e)**. Most macrocrysts (and microphenocrysts) follow a single trend showing slightly decreasing Ni contents with decreasing Fo (**Fig. 6e**). The exceptions are two crystals in which both cores and rims are distinctly richer in Ni and have higher Fe/Mn at a given Fo content than is observed for the main olivine population (**Fig. 6f)**. However, the Ca contents of all the olivine macrocrysts follow a single trend of decreasing Ca with decreasing Fo (**Table S2**). Olivine microphenocrysts have core compositions of Fo76-80 and follow the same compositional trends as the Ni-poor macrocryst population, but their Ca contents are more scattered, with Ca between 2100 and 2800 ppm.

In summary, plagioclase, clinopyroxene and olivine macrocryst rims and microphenocrysts generally lie close to the predicted equilibrium mineral compositions with the groundmass glass, whereas macrocryst cores are not in equilibrium (**Fig. 6a-c**). Groundmass minerals are frequently more evolved than the mineral compositions calculated to be in equilibrium with the tephra glass composition; this is attributed to variable extents of syn-eruptive crystallization during magma ascent and transport within lava flows.

**Chemical and sulfur isotopic composition of magmatic sulfides**

In agreement with observations from sulfide globules from MORB (e.g., Patten et al., 2012), the 2014-15 Holuhraun sulfides are characterized by somewhat variable textures (**Fig. 7a**), but differ from MORB sulfides as their size rarely exceeds about 20 μm (Francis et al., 1990). EDX maps of Holuhraun sulfide globules (**Fig. 7a**) reveal that they never quenched to a homogeneous phase, but have exsolved into fine-grained micrometric domains with highly variable Cu and Fe contents but minor variation in Ni. This can be interpreted as quenched monosulfide solid solution (MSS) and intermediate solid solution (ISS). In most cases, the exsolved domains were too small (<5 μm) to be analyzed separately by microbeam techniques.

Electron microprobe analyses of sulfide grains from the 2014-15 Holuhraun groundmass glass are shown in a ternary plot in **Figure 7b**, with the stability field of MSS at 1100°C adopted from Kullerud et al. (1969). In the Cu-Fe-Ni+Co-S system, the Holuhraun sulfides form a solid solution between pyrrhotite Fe(1-x)S, pentlandite (Fe,Ni)9S8, and chalcopyrite CuFe2S. As the Holuhraun sulfides display compositions intermediate between the pyrrhotite-pentlandite and chalcopyrite-cubanite-bornite joins, they cannot be classified into MSS or ISS end-members solely, only as mixtures thereof see also Keith et al., 2017). The fine-grained, heterogeneous texture which characterizes many Holuhraun sulfides may, at least partly, be responsible for the observed scatter in Cu contents (8.4 to 24.6 wt.%), as the analytical volume is likely to include the two exsolved phases in different proportions in different analyses, even when the bulk composition of the globules is the same. If this were the case, concentrations would simply reflect a binary mixing between end-member compositions of these phases (Keith et al., 2017). Sulfides with the least heterogeneous exsolution textures contained ~13 wt.% Cu and ~2.5 wt.% Ni. We deem these Cu and Ni contents to represent the bulk the 2014-15 Holuhraun sulfide composition. Thus, relative to magmatic MSS sulfides from MORB (Keith et al., 2017), the 2014-15 Holuhraun sulfides are enriched in Cu but depleted in Ni.

Sulfur isotopes values (δ34S) were obtained on eight sulfides large enough to permit spot analyses using an ion microprobe (see **Table S7**). The δ34S values, which are the first reported for Icelandic magmatic sulfides, range from -6.9 to -1.1‰ (**Fig. 7c**). Thus, they reveal some of the most negative δ34S values ever obtained from Icelandic lavas (Sakai et al., 1980; Torssander, 1989) and minerals found as incrustations in association with cooling lava flows, such as sulfate-bearing or native sulfur incrustations precipitated close to the surface, or inside cracks (Torssander, 1988). Only one δ34S measurement, of native sulfur precipitated during cooling of the 1970 Hekla basaltic icelandite lava flow (Torssander, 1988), is lower than the 2014-15 Holuhraun sulfides.

The fine-grained, heterogeneous texture of the 2014-15 Holuhraun sulfides may be at least partly responsible for the low and variable δ34S values. We note that at least one sulfide with δ34S of -6.9‰ shows clear evidence for exsolution of Cu-rich and Cu-poor domains, whereas more homogeneous sulfides generally display a narrower δ34S range (**Fig. 7c**). As substantial (several per mil) instrumental mass fractionation (IMF) occurs during SIMS analyses of sulfide minerals (e.g., Kita et al., 2011; Whitehouse, 2013; Hauri et al., 2016), it is possible that the Cu-poor pyrrhotite standard we adopted during analyses may not be an appropriate matrix-matched reference material for Cu-rich sulfides in the 2014-15 Holuhraun samples. However, assuming that monosulfides behave like disulfides, for which there is no effective difference in IMF during SIMS analysis of pyrite and chalcopyrite, the δ34S values obtained in this study for the 2014-15 Holuhraun sulfides should be representative. To further test this, we plotted δ34S values as a function of Cu content (inset figure in **Fig. 7c**) and noted that although five out of the six analyzed sulfides show a rather restricted range in Cu contents (~11 to 15 wt.%), their δ34S values vary from -1 to -6‰. This suggests that the measured δ34S variations in the Holuhraun sulfides are not biased by their Cu contents. The implications of the sulfide δ34S values are discussed further below.

**Discussion**

**Compositional assignment of the 2014-15 Holuhraun magma to the Bárðarbunga volcanic system**

The 2014-15 Holuhraun lava was erupted within the tectonic expression of what has previously been described as the southern sector of the Askja fissure swarm (e.g., Einarsson and Sæmundusson, 1987). However, it has been proposed on the basis of geophysical observations that the 2014-15 Holuhraun lava was fed from a dyke that originated beneath the Bárðarbunga volcanic system to the southwest, and was accompanied by caldera subsidence at Bárðarbunga as magma was withdrawn (Guðmundsson et al., 2016). A subsurface link with the Bárðarbunga volcanic system is consistent with compositional data. For example, Sigmarsson and Halldórsson (2015) showed that the 2014-15 Holuhraun lava has a similar Sr-Nd isotopic composition to recent lavas from the Bárðarbunga volcanic system, and is distinctively different to basalts from the nearby Askja, Grímsvötn and Kverkfjöll volcanic systems. This isotopic fingerprinting of the Holuhraun magma to the Bárðarbunga volcanic system is also seen in our new Pb and Hf isotope data, in particular when considering Pb isotopic characteristics of historical eruptions (**Fig. 5d**). Furthermore,on the basis of trace element ratios (e.g., Zr/Nb and Ba/Sr), Geiger et al. (2016) concluded that the 2014-15 Holuhraun lava resembles the other two historic Holuhraun lavas that can, in turn, be easily distinguished from historical eruptions associated with the Askja caldera (Hartley and Thordarson, 2013). The compositional assignment of the 2014-15 Holuhraun magma to Bárðarbunga system is further demonstrated using incompatible rare earth element ratios (Sm/Yb and La/Dy), as historical eruptions from the Askja and the Grímsvötn systems define different fields relative to Bárðarbunga magmas (**Figure 5a**). The compositional distinction between the 2014-15 Holuhraun eruptive products and those of the Bárðarbunga and Grímsvötn volcanic systems is also of importance, as a magmatic connection between Bárðarbunga and Grímsvötn was proposed for the 1996 Gjálp eruption. During this episode, a dyke intrusion beneath the rim of the Bárðarbunga caldera was interpreted to have remobilized a batch of magma that was situated at shallow levels in the crust southeast of Bárðarbunga and subsequently erupted at Gjálp (Pagli et al., 2007). However, the chemical and isotopic composition of the Gjálp magma resembles recent magmas erupted at Grímsvötn central volcano (Sigmarsson et al., 2000) rather than recent eruptions on the Bárðarbunga system. In summary, the 2014-15 Holuhraun magma closely resembles the recent eruptive products associated with the Bárðarbunga system. We find no evidence from elemental or isotopic data for involvement of magma types from Grímsvötn or Askja during this eruption.

Bindeman et al. (2006) argued that magmas erupted from the Grímsvötn volcanic system during historical times (at least since 13th century) have been fed from a long-lived and homogeneous reservoir of magma with low δ18O because of its interaction with a low-δ18O Icelandic crust (Hattori and Muehlenbachs, 1982). Similar magma reservoirs might exist beneath other volcanic systems in Iceland, but with different δ18O values imposed by (i) differences in the local crustal composition (e.g., Bindeman et al., 2012) and (ii) the degree of crustal contamination that might allow lavas to be matched to specific volcanic systems based on their δ18O value. In conjunction with the chemical and isotopic data discussed above, it is notable that the 2014-15 Holuhraun magma displays δ18O values that are very similar to those reported from historical eruptions in Bárðarbunga (**Fig. 5c**), whereas recent eruptions at Askja and Grímsvötn, and some older units in the Bárðarbunga system, all have lower δ18O. Although the available data are somewhat limited, they are consistent with the notion that magmas erupting within Bárðarbunga have been fed from a relatively homogeneous δ18O reservoir, at least throughout the past thousand years. The fact that the Bárðarbunga system produces magma with higher average δ18O than the Askja and Grímsvötn systems suggests that these volcanoes have fundamentally different magma plumbing and storage systems. One possibility is that Bárðarbunga magmas are stored at deeper levels within less hydrated crustal rocks than those of the Askja or Grímsvötn systems (e.g., Hartley et al., 2013). We will further discuss the implications of the 2014-15 Holuhraun lava belonging to the Bárðarbunga system below.

**Temporal variations, intra-flow variability and comparison with other basaltic lavas in Iceland**

Major element abundances in the 2014-15 Holuhraun lava and tephra samples reveal little temporal variation in magma composition (**Fig. S5**). Most of the observed compositional variation falls within the analytical uncertainty (2σ) of the analytical techniques, and is statistically insignificant. The small variations above analytical noise in Al2O3 (**Table S4**) probably reflect minor changes in the plagioclase content of the Holuhraun lava. However, this variation is not significant enough to have a notable influence on the overall chemical composition of the lava. For example, changes in the Sr/Nd ratio of whole rock samples (**Fig. 8a**), which might be expected to increase following plagioclase accumulation, are statistically insignificant.

Ratios of highly incompatible trace elements (e.g., La/Yb) are statistically invariant throughout the eruption (**Fig. 8a**). Additionally, Hf and Pb isotope ratios (**Fig. S4; Fig. 8b**) are nearly uniform in all samples, considering the external precision of the analyses. We also note that the variability in Pb isotopes for the 2014-15 Holuhraun lava is similar to the variability reported for Pb isotope ratios in the Thjórsá lava – a large volume (~25 km3) fissure eruption that also originated within the Bárðarbunga volcanic system (Halldórsson et al., 2008). The fact that these key tracers of mantle heterogeneity remain constant in whole-rock samples throughout the eruption suggests that any primary compositional variations in the melts feeding the 2014-15 Holuhraun magmatic system have been effectively masked by melt mixing and homogenization prior to eruption (e.g., Maclennan, 2008).

Oxygen isotope values in the melts remain constant throughout the first 48 days of the eruption (**Fig. 8c**). This indicates that the Holuhraun magma did not experience significant and sporadic shallow crustal contamination nor mixing with more evolved and/or primitive magmas during transport and ascent from the last location of magma storage to the surface (c.f. Geiger et al. (2016), who argue for both these processes). The apparent absence of distinctive chemical signatures acquired (i) during transport in a dyke and (ii) as the first magma rose towards the surface, suggest that the Holuhraun magma obtained its δ18O characteristics during storage in a crustal reservoir.

Macrocrysts of plagioclase, olivine and clinopyroxene too primitive to have been in equilibrium with the melt were present throughout the eruption (**Fig. S6**). Although Cr-rich clinopyroxene and high Fe/Mn olivine are only evident near the start of the eruption, the occurrence of primitive olivine and clinopyroxene macrocrysts is still less common than that of high-An plagioclase. If primitive macrocrysts were entrained from mush horizons along the dyke path as suggested by Hartley et al. (2018), the entrainment process must have been continuous as opposed to sporadic, and must have occurred over the entire course of the eruption. We observe no significant changes in the composition of the microphenocryst population throughout the eruption.

Although significant compositional variability has been found within some primitive (> 8 w.t% MgO) basalt lavas from Iceland, large-volume basaltic lavas generally show limited chemical heterogeneity. We demonstrate this point by comparing the 2014-15 Holuhraun with other Icelandic basaltic lavas of different compositions and from different parts of the rift system for which large datasets are available in **Figure 8d** (Maclennan et al., 2003; Sinton et al., 2005; Eason and Sinton, 2009; Passmore et al., 2012). The homogeneity of whole-rock compositions from relatively evolved lavas such as Holuhraun and Laki contrasts sharply with the heterogeneity of primitive lavas erupted from the western and northern rift zones. The heterogeneity observed in the primitive lavas is beyond what can be expected from crystal accumulation (Eason and Sinton, 2009), suggesting that these magmas experience fundamentally different crustal magma storage conditions before eruption. The Holuhaun and Laki appear to belong to a group of magmas which are likely to have undergone extensive mixing and fractional crystallization in the crust prior to eruption.

In summary, the uniform composition of the 2014-15 Holuhraun whole-rock and tephra glass samples suggest that (i) the magma erupted from a well-mixed reservoir, and (ii) the erupted magma all underwent the same processes of transport, degassing, crystallization and contamination from magma storage zone to vent. Only macrocrysts, and plagioclase in particular, are indicative of the involvement of different magma bodies over the history of the Holuhraun magma.

**Melt-mineral relationships and evidence for the preservation of mantle-derived heterogeneities**

Although compositions of Holuhraun lava and tephra samples are geochemically indistinguishable from one another, minerals carried by the Holuhraun magma exhibit significant major, trace element and oxygen isotopic variations. In addition, there is clear evidence forthe presence of distinct populations of plagioclase, olivine and clinopyroxene macrocrysts in the Holuhraun magma that have compositions too primitive to have crystallized directly from the 2014-15 Holuhraun carrier melt.

First-order constraints on disequilibrium between macrocrysts and their carrier melt can be established with oxygen isotope data from lava sample MSR161014-1 (**Fig. S3**). According to the equilibrium mineral isotope fractionation model of Bindeman (2008), olivine, clinopyroxene and plagioclase in equilibrium with the composition of MSR161014-1 (δ18O = +3.83 ‰) are expected to have δ18O values of +3.1, +3.6 and +4.0 ‰, respectively. Thus, the analyzed macrocrysts have heavier oxygen isotope ratios than predicted for the case of equilibrium with their carrier melt by about +0.7 ‰ for olivine, +0.2 ‰ for clinopyroxene and +0.4 ‰ for plagioclase. This suggests that the analyzed macrocrysts in sample MSR161014-1 were not direct crystallization products of the 2014-15 Holuhraun carrier magma, but record more mantle-like δ18O values, that are still 1.5‰ lower in δ18O than normal mantle (Eiler, 2001). This observation is in line with pervasive δ18O(melt-mineral) disequilibrium between melts and their crystal cargo in other medium- to large-volume basaltic fissure eruptions in Iceland (Bindeman et al. 2006, 2008).

The compositions of primitive clinopyroxene macrocrysts (**Fig. 6d**) also reveal disequilibrium with the 2014-15 Holuhraun carrier melt (Table S2). Pyroxene-melt equilibrium was evaluated using the following criteria: (1) Clinopyroxenes must show textural equilibrium with the surrounding melt; (2) The exchange coefficient of Fe-Mg between clinopyroxene and liquid, , must fall within the equilibrium range of 0.27±0.03 (Grove et al., 1992; Putirka et al., 2003); (3) Clinopyroxene enstatite-ferrosilite (EnFs) and diopside-hedenbergite (DiHd) components must be in equilibrium with their carrier melt. Predicted EnFs and DiHd components in equilibrium with the 2014-15 Holuhraun carrier melt were calculated following Mollo et al. (2013), and compared with measured clinopyroxene EnFs and DiHd components. Clinopyroxenes was deemed to be in equilibrium with its carrier melt if the difference between the predicted and measured EnFs and DiHd components was less than 15%. This last step was necessary because fast cooling can produce disequilibrium partitioning between clinopyroxene and melt (Mollo et al., 2013). From a total of 160 measured clinopyroxene compositions, 40 microphenocryst-groundmass glass pairs satisfied the above criteria. Our calculations suggest that the clinopyroxene compositions closest to be equilibrium with the groundmass glass are generally the Al- and Ti-rich sectors of sector zoned crystals.

Part of the variation among different major and minor elements in clinopyroxene is likely controlled by sector zoning (e.g., Skulski et al., 1994; Welsch et al., 2016). The effect of sector zoning on element partitioning is masked when element ratios are examined in this set of clinopyroxenes (**Fig. 6d**). Variation in Al2O3/TiO2 in most of the moderately evolved macrocrysts (Mg#<82) and microphenocrysts is relatively small, regardless of the presence or absence of sector zoning (average 5.0, 1σ=0.9). In contrast, primitive clinopyroxene macrocrysts that are not sector zoned have higher and more variable Al2O3/TiO2 (average 6.3, 1σ=1.8). Similar large variation is observed in Cr2O3 contents among the primitive clinopyroxenes (average 0.52, 1σ=0.28), whereas the more evolved crystals are Cr2O3–poor with little variation (average 0.15, 1σ=0.07) (**Table S1**). While the higher Al2O3/TiO2 and Cr2O3 contents in the primitive macrocrysts are consistent with the effect of fractional crystallization, the large variation in these values is not. This variation can be explained by two processes. The increased jadeite (Na, Al) component in some of the studied macrocrysts may result from crystallization at higher pressures (e.g., Putirka et al., 1996). On the other hand, a subset of high Mg# clinopyroxene with moderate Al2O3, but elevated TiO2, Na2O and low Cr2O3 contents may have crystallized from a parental melt which had somewhat higher Ti, Na and lower Cr than the melt that produced the majority of the pyroxenes macrocrysts. Our thermobarometric calculations (see below) indicate that, Cr-rich clinopyroxenes aside, the variation of crystallization pressures is not significantly larger among the most primitive macrocrysts (Mg#>82, Paverage=2.0 kbar, 1σ =0.7) than among the evolved ones (Paverage=1.5-2.4 kbar depending on method, 1σ =0.5) (**Fig. 10, Table S8**), therefore we suggest that the compositional variation among the primitive clinopyroxene macrocrysts more likely reflects crystallization from primitive melts with somewhat variable composition rather than differences in crystallization pressure.

Similar relationships, although less significant, are observed in the case of olivine macrocrysts. Variation in Ni contents and Fe/Mn are within the range observed for primitive olivines from the axial rift zone in Iceland (Sobolev et al., 2007, Shorttle and Maclennan, 2011) (**Fig. 6e and 6f**). Most olivine compositions can be reproduced by a single liquid line of descent (based on the model in Herzberg et al., 2016). A small group of Ni-rich and Mn-poor olivines fall off the main trends (**Fig. 6e and 6f**). High Ni contents could reflect a large difference between the temperature of melt extraction from the mantle source and the temperature of olivine crystallization (e.g., Matzen, et al., 2013; 2016). While there is clear evidence that Ni partitioning between olivine and silicate melt is dependent on temperature, there is no clear relationship between Fe-Mn partitioning and temperature. Therefore, we suggest that the olivines with low Mn contents and associated high Fe/Mn (**Fig. 6f**) could have crystallized from a different parental melt composition. The elevated Ni contents in this group of olivines are also consistent with crystallization from a melt derived from a slightly different source. In the case of the 2014-15 Holuhraun magma, the source of the low-Mn, high-Fe/Mn olivine is not generated by partial melting of pyroxenite as suggested by Sobolev et al. (2007). Rather it might be a garnet-bearing peridotite source, deep in the melting column (Herzberg, 2011) where Mn is sequestered by garnet during melting while Ni and Ca remain largely unaffected.

In summary, most of the compositional variation observed in 2014-15 Holuhraun clinopyroxene and olivine macrocrysts can be attributed to fractional crystallization of a melt parental to the 2014-15 Holuhraun magma. This primitive melt is at least partly represented by the primitive melt inclusions trapped in plagioclase macrocrysts (Hartley et al., 2018). However, different macrocryst populations require different parental melts, most likely pointing towards heterogeneities in the mantle source, these processes being responsible for generating compositionally variable melts which later mixed (e.g., Slater et al., 2001) to produce the 2014-15 Holuhraun magma.

**Formation and implication of magmatic sulfides in the Holuhraun melt**

In **Figure 9**, we compare the 2014-15 Holuhraun sulfides to olivine- or groundmass glass-hosted MSS magmatic sulfides from mid-ocean ridge, back-arc and island arc settings (Keith et al., 2017), and magmatic sulfides from Kilauea volcano, Hawaii (Stone and Fleet, 1990; Fleet and Stone, 1991). The 2014-15 Holuhraun sulfides have similar Fe/S to MORB sulfides, but their low Ni/Cu is more similar to magmatic sulfides from back-arc and island arc settings. Sulfides from Kilauea have Ni/Cu intermediate between MORB and the 2014-15 Holuhraun magma.

The fine-grained and heterogeneous textures of the 2014-15 Holuhraun sulfides (**Fig. 7a**) are likely to be at least partly responsible for the somewhat variable Fe/S ratios, as some of the phases could not be analyzed individually by microprobe. While 2014-15 Holuhraun sulfides do not always represent a homogeneous sulfide liquid, the low Ni/Cu ratios are unlikely to be the result of measuring unmixed domains. To demonstrate this, we calculated the composition of sulfide melt and MSS in equilibrium with the average whole-rock composition using the parameterization of Li and Audetat (2015). The calculated Ni/Cu (gray box in **Fig. 9**) is in agreement with the Ni/Cu measured in some of the most homogeneous sulfide blebs found in the 2014-15 Holuhraun magma (**Fig. 7a**). These homogeneous sulfides contain ~13 wt.% Cu.

Keith et al. (2017) have recently shown that magmatic sulfide compositions vary systematically in lavas from different tectonic settings. They concluded that different oxygen fugacity of magmas from different settings is largely capable of explaining this difference: early sulfur saturation of reduced MORB can explain the high Ni/Cu of MORB sulfides, whereas late-stage sulfur saturation of more oxidized arc magmas would be sufficient to generate the low Ni/Cu in arc sulfides. On the basis of Fe-XANES measurements of Fe3+/∑Fe of basalt glasses from Reykjanes Ridge (Shorttle et al., 2015) and Iceland (Hartley et al., 2017), it has been demonstrated that domains of the Icelandic mantle are likely to be more oxidized than normal MORB (fractionation-corrected Fe3+/ ∑Fe is ∼ 0.05 higher). As more sulfur can be dissolved in oxidized than reduced magmas, oxidized magmas are likely to reach sulfur saturation comparatively later in their evolution. Moderately evolved melt inclusions in macrocrysts from Holuhraun also support a case of relatively oxidized conditions, as they contain more sulfur than is expected for saturation below the FMQ oxygen buffer, and indicate oxygen fugacity as high as FMQ+0.5 (Bali et al., 2018). Using the model of Nikolaev et al. (2016), we have calculated oxygen fugacity of ~ FMQ +0.7 in the Holuhraun melt at the time of olivine-spinel crystallization. This confirms that the Holuhraun melt is more oxidized than typical MORB, which likely form at or near FMQ (Cottrell and Kelley, 2011). This observation supports the presence of oxidized domains in the Icelandic mantle (e.g., Shorttle et al., 2015).

The low Ni/Cu in the 2014-15 Holuhraun groundmass glass (**Fig. 5d**) and in sulfides may result from extensive olivine fractionation, which will preferentially remove Ni relative to Cu from melt and ultimately drive magmas to be more oxidized by the removal of Fe2+. In the case of 2014-15 Holuhraun event, parental melts which ultimately mixed to form the erupted magma could have inherited the oxidized nature of its source (Shorttle et al., 2015; 2016) and, following extensive olivine fractionation, become even more oxidized. The 2014-15 Holuhraun magma therefore reached sulfide saturation later in its evolution than an equivalent MORB magma (**Fig. 9b**). Notably, melt inclusion data both from the 2000 Hekla basaltic icelandite eruption (Moune et al., 2007) and the 2014-15 Holuhraun event (Bali et al., 2018) predict the onset of sulfide saturation when magmas from these volcanoes reach MgO≈6.5 wt.%, consistent with significant fractional crystallization before eruption and sulfide saturation.

Of the eight sulfide grains analyzed, six display δ34S between -3.2 and -1.1‰, which partially overlap with δ34S estimates for the depleted MORB mantle (the DMM endmember is taken as δ34S = -1.4 ±0.5 ‰; Labidi et al., 2014) (**Figure 7c**). This confirms that the 2014-15 Holuhraun sulfide globules are mainly related to primary high-temperature magmatic processes, and not to contamination with secondary (hydrothermal) material because hydrothermal sulfides typically display δ34S values up to +20‰ (Sakai et al., 1980; Seal, 2006). Negligible fractionation of sulfur isotopes is expected during the segregation of magmatic sulfides from silicate melts (Labidi and Cartigny, 2016). Assuming that most of the magmatic sulfur is reduced and that crustal sulfides have not been assimilated into the magma, the low δ34S values (down to -6‰) for the 2014-15 Holuhraun sulfides might therefore indicate that the Icelandic mantle is characterized by lower δ34S values than DMM. Highly negative δ34S values have previously been identified in hotspot lavas from the Mangaia, which display radiogenic isotope characteristics consistent with derivation from recycled oceanic crust (Cabral, et al., 2013). The idea that δ34S values lower than DMM are present in the Icelandic mantle, and due to the recycling of oceanic crust, requires further testing using a larger dataset of magmatic sulfides in concert with a Cu-rich monosulfide standard and robust analyses of different phases present in such grains.

**Constraints on magma storage from clinopyroxene-melt thermobarometry**

We modeled the pre-eruptive storage temperature of the 2014-15 Holuhraun melt based on tephra glass compositions (Yang et al., 1996), olivine-tephra glass pairs (Ford et al., 1983; Gudfinnsson and Presnall, 2001) and clinopyroxene-tephra glass pairs (Putirka, 2008). Regardless of the geothermometer applied, groundmass glass compositions return a temperature of about 1170°C. Before carrying out thermobarometric calculations to estimate pre-eruptive storage pressures, clinopyroxene analyses were divided into two groups: one containing all clinopyroxene compositions measured in this study, and another containing only compositions in equilibrium with the Holuhraun carrier melts (see criteria in the section on melt-mineral equilibria above).

We calculated crystallization pressures for both groups of clinopyroxene analyses following the method described by Neave and Putirka (2017), whereby equilibrium melts were determined by iteratively matching clinopyroxene compositions to a broader range of suitable melt compositions from the Bárðarbunga system, using a database compiled from: (a) 189 groundmass glass and 117 melt inclusion (Hartley et al., 2018) compositions from 2014-15 Holuhraun; and (b) 236 tephra glass compositions from Bárðarbunga volcanic system (Óladóttir, 2009). We also performed equivalent calculations using the clinopyroxene analyses reported by Geiger et al. (2016). Clinopyroxene analyses were first tested for Fe-Mg ±10% and DiHd ±7.5% equilibrium against all melt compositions in a given database using the models of Putirka (2008) and Mollo et al. (2013) respectively; clinopyroxene-melt pairs exceeding these thresholds were excluded from thermobarometric calculations as they are unlikely to have recorded equilibrium conditions at depth (Mollo et al., 2013; Neave and Putirka, 2017). Clinopyroxene analyses that had not already been filtered for equilibrium with the Holuhraun carrier melts were subjected to a further test for CaTs ±50% equilibrium based on the model of Putirka et al. (1999). We used an intentionally conservative approach when applying thresholds on the principle that discarding equilibrium pairs is preferable to accidentally accepting disequilibrium ones. Pressure and temperature estimates for equilibrium clinopyroxene-melt pairs were then determined by iteratively solving equations 33 and 1 from Putirka (2008) and Neave and Putirka (2017), respectively, and used to refine equilibrium melt matching criteria in subsequent iterations.

Results from the clinopyroxene-melt barometry calculations are summarized in **Figure 10 and Table S8**. Depending on the degree of filtering performed before undertaking barometric calculations, clinopyroxenes measured in this study return well-defined peaks in probability distributions between 1.5 kbar (textural equilibrium not verified) and 2.5 kbar (textural equilibrium verified) when they are matched against melt compositions from Holuhraun and Bárðarbunga (**Figure 10a, b, d, e**). Rare Cr-rich clinopyroxene record slightly pressures of 3.1-4.4 kbar but are not simply related to the erupted Holuhraun melt and may have been entrained during magma transport. The overall range in calculated crystallization pressures is similar to the barometer’s uncertainty (standard error of estimate (SEE) = ±1.4 kbar). Our calculated crystallization pressures are somewhat lower than the 4.6-4.7 kbar reported by Gudmundsson et al. (2016), who used Equation 30 from the Putirka (2008) as a barometer but did not take its systematic overestimation of true crystallization pressures into account (~1.5 kbar overestimation at <5 kbar; Neave et al., 2013; Neave and Putirka, 2017). However, assuming a mean crustal density of 2860 kg.m-3 (Carlson and Herrick, 1990), our most robust mean pressure estimate of ~2.3±1.4 kbar from clinopyroxenes screened for textural equilibrium indicate a magma storage depth of ~8.3±5.0 km (uncertainties are based on the SEE of the barometric equation; the standard error (SE) of the mean pressure itself is much lower: 2SE = 0.2 kbar, i.e., ~0.7 km), which is wholly consistent with regional geodetic observations of a deflating source at 8-12 km beneath Bárðarbunga central volcano (Gudmundsson et al., 2016) as well as the depth to the seismic swarm (Sigmundsson et al., 2015; Ágústsdóttir et al., 2016). Melt inclusion olivine-plagioclase-augite-melt (OPAM) equilibration pressures preserved in all macrocryst phases record similar pressure range (Hartley et al, 2018). Therefore, we suggest that most of the mineral phases originate from a similar depth range. As pointed out earlier, the 2014-15 event is typical for eruptions that contribute most to the construction of the upper Icelandic crust. As a result, our depth estimates for Holuhraun underline the importance of mid-crustal crystallization processes during the generation and accretion of the Icelandic crust. Neave and Putirka (2017) also reached a similar conclusion in their study of various eruptions from the neovolcanic rift zones of Iceland.

Crystallization pressures for clinopyroxene compositions measured by Geiger et al. (2016) were re-calculated using the melt-matching method of Neave & Putirka (2017) and Holuhraun and Bárðarbunga melt datasets. Matching to both datasets returned a mean pressure of 3.0 kbar (range 0.6-4.5 kbar) and poorly defined probability distributions (**Fig. 10c, f**). A pressure of 3.0 kbar much is lower than the 4.8 kbar mean pressure (range 0.3-8.8 kbar) reported by Geiger et al. (2016), reflecting their use of a barometer that has subsequently been shown to systematically overestimate pressure (Neave & Putirka, 2017) and their assumption that observed whole-rock compositions represent putative equilibrium liquids for a wide range of clinopyroxene compositions. The wide pressure range described by Geiger et al. (2016) was somewhat reproduced in our calculations with their data and probably reflects greater uncertainty in their pressure-sensitive clinopyroxene Na2O analyses rather than vertically extensive storage throughout the crust: Geiger et al. (2016) reported more disperse clinopyroxene Na2O contents than we observed for otherwise similar clinopyroxenes (1σ = 0.053 wt.% versus 0.038 wt.%). Furthermore, we disregard using the plagioclase-melt barometer of Putirka (2008) because it is too uncertain (±2.5 kbar, i.e. ±9 km) to meaningfully interpret petrological data in light of high-resolution geophysical observations from the 2014-2015 Holuhraun eruption. Putirka (2008) also noted that this barometer performs poorly when tested against experimental data and cautioned against its use except in highly restricted circumstances. In contrast to Geiger et al. (2016), we thus find no evidence that the Holuhraun eruption was fed from a multi-tiered magma storage region. Instead we suggest that the majority of clinopyroxene macrocrysts grew within a narrow, mid-crustal depth interval and that modest spreads in calculated pressures probably stem from uncertainties in our analyses and the fundamental limitations of thermobarometric models rather than polybaric storage.

**Implications of whole-rock, glass and mineral compositions for magmatic processes preceding and during the 2014-15 Holuhraun eruption**

Hudson et al. (2017) related persistent and deep seismicity near the Bárðarbunga volcano before and after the eruption, to movement of melts bypassing a mid-crustal reservoir underlying the caldera. As this seismicity was laterally offset from the center of the Bárðarbunga caldera by ~12 km, they suggested that a similar melt channel is likely underlying the caldera, but is aseismic because of the presence of partial melt under the caldera. The extend of this aseismic zone should therefore provide fist order constrains on the lateral extent of the magma storage region underneath Bárðarbunga. Clinopyroxene-melt barometry indicates magma storage and crystallization in the mid-crust, with the pressure of magma storage not changing significantly over the course of the eruption (**Fig. 11**). The estimated depth range is consistent with the (i) depth of the observed seismic swarm (5-7 km: Sigmundsson et al., 2015; Ágústsdóttir et al., 2016), (ii) abrupt decrease in depths of seismicity at 6-7 km under the Bárðarbunga caldera (e.g., Hudson et al., 2017) and (iii) depths determined from geodetic measurements and surface gas compositions reported by Gudmundsson et al. (2016). Although the data presented here do not resolve the horizontal dimension, and therefore cannot be used to constraint the lateral extent of the magma storage region underneath Bárðarbunga, our modelling suggests that the main processes of crystallization during magma storage occurred at the same depth as seismic and geodetic processes.

As we see no evidence in composition of the 2014-15 Holuhraun lava for mixing with more evolved and/or primitive magmas during the eruption, for example melts that bypassed this mid-crustal reservoir (e.g., Hudson et al., 2017), the role of a deeper reservoir during the eruption was likely very limited. At least, it is not detectable in the composition of the Holuhraun melt. Although macrocrysts too primitive to be in equilibrium with the 2014-15 Holuhraun carrier melt crystallized at deeper levels in the crust, it is important to stress that these were most probably transported from mush horizons into the Bárðarbunga magma reservoir only shortly prior to the onset of seismicity on 16 August 2014 (Hartley et al., 2018).

Therefore, the coincidence of these diverse observations at a depth of ~ 8 km favors a model involving lateral transport of magma from a storage region close to the Bárðarbunga central volcano to the 2014-15 Holuhraun eruption site. An essential argument from a geochemical perspective that supports this idea, is that historical eruptions associated with the Bárðarbunga volcanic system have near-identical chemical and isotopic characteristics as the 2014-15 Holuhraun lava (e.g, **Fig. 5d**). This suggests that these magmas have all been sourced from a common magma reservoir that has remained active over this period, regardless of the particular eruption site within the Bárðarbunga fissure swarm.

Although the lava emplacement dynamics changed significantly with time during the eruption (Pedersen et al. 2017), the geochemical homogeneity of the erupted lava and the small range in barometric estimates suggest that magma was supplied from a remarkably constant storage depth. This suggests that the eruption was supplied by a single magma reservoir that was not replenished by magma from a deeper source during the eruption. With the exception of the primitive macrocrysts that are not in equilibrium with the 2014-15 Holuhraun carrier melt, we find no evidence that during the eruption, the Holuhraun magma remobilized a vertically extensive series of stacked magma bodies with differing compositions following the last equilibration depth of the magma. This observation contrasts with the interpretations of Geiger et al. (2016), who argued for multi-tiered magma storage over a wide depth range in the Holuhraun magmatic system. It also differs from recent observations for mid-ocean ridge eruptions on the East Pacific Rise (e.g., Cross et al., 2010; Tan et al., 2016) and eruptions associated with the Axial Seamount (Sigmundsson, 2016, and references therein), in which lava chemistry was used to argue for tapping of multiple magma reservoirs (Chadwick et al., 2016). Instead, we suggest that the 2014-15 Holuhraun magma was tapped from a well-mixed mid-crustal reservoir. Significantly, this reservoir must have been of substantially larger volume than that estimated for other oceanic island volcanoes, e.g., between 0.1-0.3 km3 under Piton de la Fournaise (Vlastelic & Pietruszka, 2015) and ~0.2 km3 under Kilauea (Pietruszka et al., 2015). Considering the volume of the magma erupted at Holuhraun, in addition to any magma stored in a dyke feeding the eruption (Sigmundsson et al., 2015; Guðmundsson et al., 2016), a plausible volume for the magma reservoir underneath Bárðarbunga is likely to be close to 2 km3. This is likely to be large enough to be detectable with geophysical methods. Interaction of a spreading ridge and an upwelling mantle plume beneath Iceland, and therefore enhanced magmatic production, is the most probably explanation for the evidently large contrast of stored magma in the roots of the aforementioned oceanic island volcanoes.

The low δ18O values evident in the 2014-2015 Holuhraun magma are commonly observed in Icelandic basaltic fissure eruptions (e.g., Muehlenbachs, et al., 1974). Such values, far from equilibrium with mantle oxygen (+5.5‰, Eiler, 2001), are frequently explained by assimilation of the hydrothermally altered Iceland crust and/or mixing with pre-contaminated magma batches with lower δ18O (Eiler et al. 2000; Bindeman et al. 2006, 2008). Precise end-member isotopic compositions for such assimilants are difficult to constrain, but pristine MORB glasses display δ18O values largely between +5.3 and +5.8 ‰ (Eiler et al., 2000; Eiler, 2001). Bindeman et al (2006, 2008) found mantle-like δ18O values in many olivines from low-δ18O large-volume fissure eruptions from the Eastern Rift Zone and argued for a presence of a mantle-like δ18O component in the region, but suggested that the Icelandic plume could be a bit depleted, perhaps to 4.8‰. Hartley et al. (2013) also reported δ18O values, obtained via SIMS, of +4.7 to +5.2 ‰ in primitive melt inclusions from the older Holuhraun lava, suggesting that the oxygen isotopic ratio of the mantle source beneath could be as low as +4.7 ‰. Furthermore, glasses from the nearby Kistufell table mountain, which are some of the most primitive basaltic glasses yet measured in Iceland (MgO up to 10.5 wt.%), display δ18O as low as 4.2 ‰ (Breddam, 2002). Similarly, based on a detailed study of plagioclase, Winpenny and Maclennan (2014) argued that near-primary mantle-derived melts with δ18O as low as +4.3 ‰ are sampled by the Theistareykir volcanic system. However, even if domains within the Icelandic mantle have δ18O as low as 4.2 ‰ (see also Thirlwall et al., 2006), input from a low-δ18O source is still required to generate the δ18O values of 3.7 ‰ measured in the 2014-15 Holuhraun carrier liquid. As δ18O values would generally increase during fractional crystallization, these low δ18O values cannot be generated solely by low-pressure fractional crystallization. Thus, despite the evidence for magma storage prior to eruption at mid-crustal levels around ~8 km depth, the 2014-15 Holuhraun magma most likely acquired its low δ18O by assimilating hydrated, low-δ18O meta-basalts in a mid-crustal reservoir close to the Bárðarbunga volcano. Contamination at such depths can be expected as hydrous meta-basaltic assemblages are expected to be present throughout the uppermost ~11 km of the Icelandic crust (see discussion in Hartley et al., 2013). Over 1 to 2 ky, i.e, a period equivalent to historical time in Iceland, this reservoir likely remained in steady state and fed eruptions that had relatively homogeneous magma compositions with δ18O around +3.7 ‰ (**Fig. 5c**).

Geiger et al. (2016) inferred that the Holuhraun eruption was fed from a complex, multi-tiered plumbing system spanning almost an entire section of the central Iceland crust (from 28 and 5 km depth) beneath Bárðarbunga. Furthermore, they related mineral resorption textures and low, but variable, δ18O in the Holuhraun lava to magma mixing and crustal assimilation at shallow level beneath Bárðarbunga, which they considered to be an important pre-eruptive process. However, this interpretation is inconsistent with the temporal compositional uniformity of the erupted magma over the course of the Holuhraun eruption. Instead, the eruption was dominated by extraction from a uniform magma reservoir at a single depth. Unless contaminants with δ18O representative of andesitic or rhyolitic melts in the upper crust have completely homogenized throughout the 2014-15 magma during ascent, there is no evidence in the temporal record of the erupted magma for mixing with any such material. The lack of chemical variability over the course of the eruption probably rules out significant shallow crustal contamination and input of more evolved and/or primitive magmas during the transport and ascent of the Holuhraun magma from its last location of storage to the surface. Finally, regardless of whether the crystals carrying these signals were entrained into the Holuhraun magma from crystal mush horizons (e.g. Passmore et al., 2012; Neave et al., 2014) or from the surrounding wall rock, the Holuhraun crystal cargo preserves evidence for heterogeneity in melt compositions beneath Bárðarbunga which is not evident in the Holuhraun whole-rock and glass compositions (Hartley et al., 2018).

**Conclusions**

1. The magma erupted at Holuhraun between 29 August 2014 and 22 February 2015 is an olivine tholeiite, typical of basalts erupted from the Icelandic axial rift system.
2. The 2014-15 Holuhraun magma is compositionally similar to Holocene basalts associated with the Bárðarbunga volcanic system. Notably, historical eruptions on the Veiðivötn fissure swarm, a southwest fissure system of the Bárðarbunga volcanic system, reveal compositions which are almost indistinguishable from the 2014-15 Holuhraun magma. This is consistent with seismic observations for magma ascent beneath and nearby the Bárðarbunga central volcano followed by lateral dyke propagation to the Holuhraun eruption site.
3. Major element, trace element and isotopic compositions of the erupted magma are remarkably uniform, and show no systematic temporal variation over the course of the eruption. This is surprising given the long duration (174 days) of the eruption and the large volume of lava (1.44 km3), but appears to be a characteristic feature of many fissure-fed eruptions in Iceland.
4. Late-stage sulphur saturation, probably due to the oxidized nature of the 2014-15 Holuhraun melt, triggered sulfide immiscibility and the formation of sulfide globules. These sulfides are characterized by unusually low Ni/Cu, which likely results from extensive olivine fractionation, followed by late-stage saturation of sulfur in the 2014-15 Holuhraun magma.
5. Primitive plagioclase as well as minor clinopyroxene and olivine macrocrysts, were likely entrained into the 2014-15 Holuhraun magma, either from crystal mush horizons or from the surrounding wall rock, during magma ascent.
6. Minor and trace element chemistry of macrocrysts carried by the Holuhraun magma preserve evidence for mixing of compositionally diverse mantle melts. However, the compositional variability of melts parental to the Holuhraun magma has been effectively masked during concurrent mixing and crystallization, producing the homogeneous bulk magma composition observed.
7. Clinopyroxene-melt barometry indicates that the Holuhraun magma resided at about 8±5 km depth before the onset of the eruption, consistent with geophysical estimates for depth to the magma reservoir.
8. Despite evidence for magma storage prior to eruption within the mid-crust, the 2014-15 Holuhraun magma most likely underwent some minor crustal contamination which is difficult to constraint further because of great uncertainty in end-member values.
9. A lack of chemical variability over the course of the eruption rules out significant shallow crustal contamination and input of more evolved and/or primitive magmas during the transport and ascent of the Holuhraun magma from its last location of storage to the surface.

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**Figure Captions**

**Figure 1.** The 2014-15 Holuhraun lava field as imaged by a LANDSAT on 2 April, 2015, 33 days after the eruption terminated (from Pedersen et al., 2017). The inset map of Iceland in the upper right corner shows the outline of the Bárðarbunga (B) fissure swarm (dark gray) and location of nearby central volcanoes discussed in the text (A: Askja, G: Grímsvötn and K: Kverkfjöll). Although not indicated on the map, Gjálp is located between Bárðarbunga and Grímsvötn.

**Figure 2.** Map showing the temporal evolution of the 2014-15 Holuhraun lava field and sampling locations. Dates presented as YYYY-MM-DD with numbers listed in each map refer to sample ID numbers in Table S1.

**Figure 3.** Petrography of the 2014-2015 Holuhraun erupted products.

1. Back-scattered electron (BSE) image of glomerophyric plagioclase and augite in a highly vesicular tephra sample MSR-291014. Note the presence of sulfide bleb in the glass.
2. BSE image of lava sample WM-1491-4 with high crystallinity.
3. BSE image of complex concentric zoning in an augite microphenocryst from sample JAS-130914.
4. BSE image of a zoned plagioclase macrocryst from sample TTJIJ-081014. Inset shows Na and Ca X-ray maps.
5. BSE image of sulfide and silicate melt inclusions in an olivine microphenocryst from a glassy lava selvage; sample JG-230914.
6. Photomicrograph of glomerophyric plagioclase, augite and olivine as well as sulfide blebs in tephra sample TTJIJ-081014-02.

**Figure 4**. a) MgO-TiO2 variation of whole-rock samples of the 2014-2015 Holuhraun volcanic products. Also plotted are Holocene Bárðarbunga whole-rock compositions (see text for details) and samples associated with recent basaltic eruptions in the Askja caldera (Hartley and Thordarson, 2013) and at Grímsvötn (Jude-Eton, 2013; Manning and Thirlwall, 2014).

b) MgO-TiO2 variation of whole-rock and tephra glass samples of 2014-15 Holuhraun. Also plotted are the older Holuhraun units (Hartley and Thordarson, 2013) and tephra associated with the Bárðarbunga volcanic system (Óladóttir, 2009). In both figures, symbol size is similar to the uncertainty of the measurements. Arrows indicate the effects of plagioclase (Pl.) accumulation.

**Figure 5**. a) Trace element ratios (Sm/Yb vs. La/Dy) of the 2014-15 Holuhraun plotted against recent basaltic eruptions associated with the Bárðarbunga, Askja and Grímsvötn volcanic systems (Óladóttir, 2009; Kuritani et al., 2011; Hartley and Thordarson, 2013; Manning and Thirlwall, 2014). Historical eruption of the Bárðarbunga volcanic system (Vatnaöldur 871 and Veiðivötn 1477) are indicated with a different symbol (Kokfelt et al., 2006; and Zellmer et al., 2006). b) Transition metal contents of 2014-15 Holuhraun whole-rock samples (after Langmuir et al., 1977), with concentrations normalized to depleted MORB mantle (Salter and Stracke, 2004). Enrichments relative to DMM are evident for Sc, Ti, V, Mn, Fe, Cu and Zn whereas Cr, Ni and Co all display negative anomalies, presumably due to extensive olivine and spinel fractionation. c) Oxygen and (d) Pb isotope composition of the 2014-15 Holuhraun magma. In c) and d), we compare Holuhraun to recent basaltic eruptions from the Bárðarbunga, Askja and Grímsvötn volcanic systems, with historical eruptions indicated with different symbols (see text for details on the data used for comparison).

**Figure 6.** Stacked histograms showing the compositions of (a) plagioclase, (b) clinopyroxene and (c) olivine macrocrysts, microphenocrysts groundmass crystals from the 2014-2015 Holuhraun eruption. Also shown are compositions of clinopyroxene and plagioclase in a gabbroic xenolith found in the Holuhraun magma (xeno.). Gray fields indicate compositions that are inferred to be in equilibrium with the carrier liquid. These relatively wide fields reflect the compositional variability observed in the groundmass glass and the uncertainty in the equilibrium constants between melts and minerals.Compositional variation of clinopyroxene (d) and olivine (e and f) from the 2014-2015 Holuhraun eruption. Arrows on Fig. e and f indicate mineral compositions calculated along crystallization paths at 1 atm (see text). Dashed curves in (e) are predicted olivine compositions from mixture of a primitive and an evolved melt derived from the same source (Herzberg et al., 2016). Gray field in (f) represent the Fe/Mn ratios in olivine crystallized from a melt derived from a peridotite source (Sobolev et al., 2007). The external analytical uncertainty (2σ) is shown on Figures d, e and f.

**Figure 7**. a) EDX maps of sulfide globules from Holuhraun. Note the heterogeneous distribution of Cu, Fe and Ni and crisp boundaries between compositional domains. Bulk Cu contents and δ34S values are given next to the respective sample names. All scale bars are 10 mm. b) Ternary plot of Holuhraun sulfide compositions in the Cu-Fe-Ni+Co-S system. The stability field of monosulfide solid solution (MSS) at 1100°C is adopted from Kullerud et al. (1969). Compositional field of MSS, intermediate solid solution (ISS) and mixed MSS+ISS in MORBs are also plotted for comparison from Keith et al. (2017). c) Sulfur isotope composition of magmatic sulfides from Holuhraun compared to Icelandic lavas (Sakai et al., 1980; Torssander, 1989) and incrustations found in association with cooling lava flows (Torssander, 1988). The inset figure shows δ34S as a function of Cu content (wt.%). The lack of clear correlation suggests that the large spread in δ34S is independent of the Cu content of the analyzed sulfide grain. A total of 5 out of the 6 analyzed sulfides show a rather restricted range in Cu content (~11 to 15 wt.%), despite their wide variation in δ34S (-1 to -6‰).

**Figure 8.** Temporal variation of (a) trace element ratios, (b) Pb isotopic ratios. The range in Pb isotopes reported for the Thjórsá lava is shown with the gray bar, and is comparable to the range in the Holuhraun magma. (c) Oxygen isotopic ratios in the 2014-2015 Holuhraun basalt. (d) MgO vs. K2O/TiO2 variations in the 2014-15 Holuhraun lava compared to other Icelandic basaltic lavas of different composition and from different parts of the rift system for which large datasets are available. See text for details.

**Figure 9.** A: Measured Ni/Cu vs. Fe/S in magmatic sulfides from Holuhraun. Ni/Cu in equilibrium with the Holuhraun bulk rock was calculated based on Li and Audetat (2015). B: Ni/Cu in mss vs. host silicate melt MgO. At a given MgO of the host melt, the Holuhraun sulfides generally have lower Ni/Cu relative to MORB sulfides but similar to island arc sulfides (Keith et al., 2017). This observation demonstrates the relatively oxidized nature of the Holuhraun magma.

**Figure 10**. Results of thermobarometric calculations from the 2014-2015 Holuhraun eruption. Crystallization pressures for Holuhraun clinopyroxenes are calculated following the method of Neave and Putirka (2017), using different clinopyroxene populations matched against either (a-c) Holuhraun or (d-f) Bárðarbunga melt compositions. For each sub-figure, the left-hand panel shows the composition of the clinopyroxene and the range of calculated crystallization pressures. The right-hand panels show kernel density estimates of the calculated crystallization pressures. Barometry results shown in red are based on Putirka (2008); results corrected for the systematic error on Putirka (2008) barometer (Neave et al., 2013) are shown in black. The most probable crystallization pressures are 1.5-2.5 kbar; this range is within the standard error of the barometer calibration.

**Figure 11.** Clinopyroxene-liquid barometry shown as a function of time. The output is the University of Iceland cpx analyses ("equilibrium" and "all") melt-matched against the Holuhraun glass+MI dataset. Shaded region is the dyke path according to Ágústsdóttir et al. (2016) with depth converted to pressure assuming crustal density of 2860 kg/m3 (Carlson and Herrick, 1990).

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