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Time constraints on the origin of large volume basalts derived from O-isotope and trace element mineral zoning and U-series disequilibria in the Laki and Grímsvötn volcanic system

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Abstract

The 1783–1784 AD fissure eruption of Laki (Iceland) produced 15 km^3 of homogeneous basaltic lavas and tephra that are characterized by extreme (3‰) ^{18}O-depletion relative to normal mantle. Basaltic tephra erupted over the last 8 centuries and as late as in November 2004 from the Grímsvötn central volcano, which together with Laki are a part of a single volcanic system, is indistinguishable in δ^{18}O from Laki glass. This suggests that all tap a homogeneous and long-lived low-δ^{18}O magma reservoir. In contrast, we observe extreme oxygen isotope heterogeneity (2.2–5.2‰) in olivine and plagioclase contained within these lavas and tephra, and disequilibrium mineral-glass oxygen-isotope fractionations. Such low-$\delta^{18}O_{glass}$ values, and extreme 3‰ range in $\delta^{18}O_{olivine}$ have not been described in any other unaltered basalt.

The energy constrained mass balance calculation involving oxygen isotopes and major element composition calls for an origin of the Laki–Grímsvötn quartz tholeiitic basaltic melts with δ^{18}O = 3.1‰ by bulk digestion of low-δ^{18}O hydrated basaltic crust with δ^{18}O = −4‰ to +1‰, rather than magma mixing with ultra-low-δ^{18}O silicic melt. The abundant Pleistocene hyaloclastites, which were altered by synglacial meltwaters, can serve as a likely assimilant material for the Grímsvötn magmas.

The (^{226}Ra/^{230}Th) activity ratio in Laki lavas and 20th century Grímsvötn tephras is 13% in-excess of secular equilibrium, but products of the 20th century Grímsvötn eruptions have equilibrium (^{210}Pb/^{226}Ra). Modeling of oxygen isotope exchange between disequilibrium phenocrysts and magmas, and these short-lived U-series nuclides yields a coherent age for the Laki–Grímsvötn magma reservoir between 100 and 1000 yrs. We propose the existence of uniquely fingerprinted, low-δ^{18}O, homogeneous, large volume, and long-lived basaltic reservoir beneath the Laki–Grímsvötn volcanic system that has been kept alive in its position above the center of the Icelandic mantle plume. Melt generation, crustal assimilation, magma storage and homogenization all took place in only a few thousands of years at most.

Keywords: Laki; oxygen isotopes; diffusion; segregation; U-series disequilibria

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1. Introduction

The presence, size, location and longevity of magma reservoirs are key properties of volcanic systems. These variables are constrained by geophysical observations such as seismic tomography [1] of active volcanic systems. Isotopic and trace elemental variations within and between individual crystals in igneous rocks provide valuable insights into timescales of magmatic processes on the order of days to hundreds of years which are unattainable by most other methods [2–4]. Short-lived radionuclides with half-lives comparable to those of magma segregation and differentiation provide complementary time constraints [5–7], and have previously been used to demonstrate surprisingly short timescales of generation and eruption of large volume magma bodies [5]. In this study, we use both approaches to discuss the longevity and origin of the basaltic magma from the Laki–Grímsvötn volcanic system in Iceland (Fig. 1).

The 1783–1784 eruption of Laki was the largest basaltic eruption of the last millennium, and is often compared to large igneous provinces ([8], and references therein). It produced a ‘dry fog’ of sulfate aerosols that severely impacted the Icelandic population and lowered temperatures in the N hemisphere for 2 years [8–11]. This magmatic system remains active today (Fig. 1), but its activity after 1784 is confined to the subglacial Grímsvötn caldera under Vatnajökull glacier, with one exception — the 1996 Gjálp eruption of somewhat more differentiated basaltic icelandite on the northern flank of Grímsvötn central volcano [12,13].

This paper has been motivated by the discovery that not only the 1783–1784 Laki basalt [14,15], but both older and younger tephra from the Grímsvötn are unusually depleted with respect to oxygen isotopes, down to 3‰, demonstrating that this low-δ^{18}O value persisted for at least 8 centuries. At the same time, the isotopically homogeneous glass contains mineral populations that exhibit extreme isotope disequilibria, not found elsewhere in any fresh igneous rock. These isotopic disequilibria and zoning allow estimation of the time these phenocrysts spent in contact with the δ^{18}O depleted basalt. Moreover, we measured (^{226}Ra/^{230}Th) and (^{210}Pb/^{230}Th) activity ratios in a few whole-rock samples in order to assess the timescales of magma formation. The timescales derived from oxygen isotope disequilibria between minerals and melt are compared with those inferred for the melt from ^{210}Pb–^{226}Ra–^{230}Th radioactive disequilibria. Finally, we discuss a new model for the origin of low-δ^{18}O basalts, such as the one from Laki.

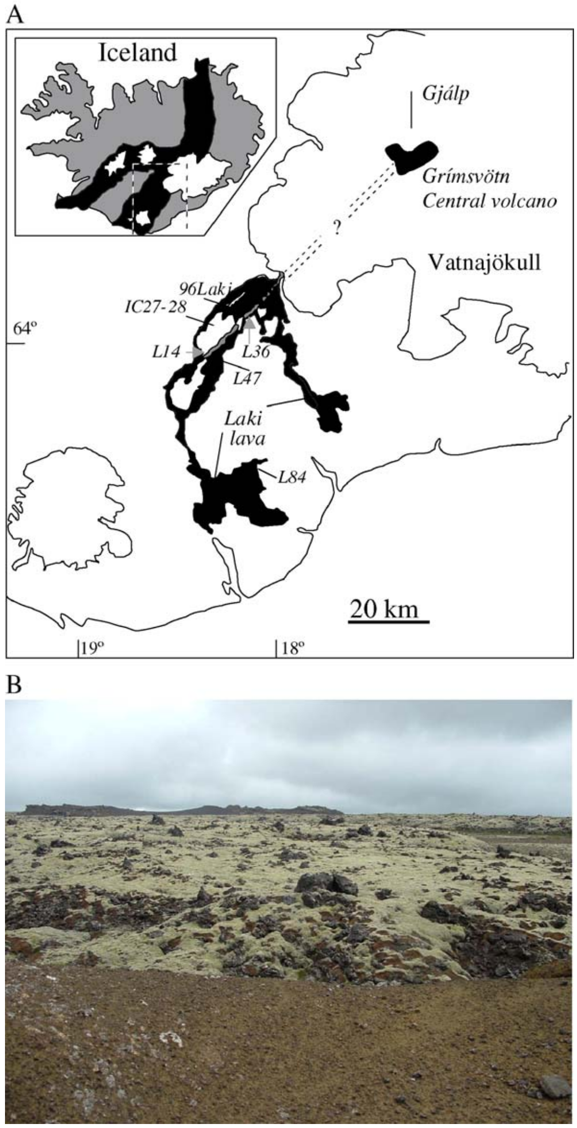

Fig. 1. A. Laki–Grímsvötn volcanic system, the 60 km-long fissures of 1783–1784 eruption extended progressively toward the subglacial Grímsvötn caldera that represents the central volcano of the Laki–Grímsvötn volcanic system. Sample localities for Laki lava and tephra, and hyaloclastites are shown (see Table 1). B. A field photograph of the Laki lava flow with Pleistocene hyaloclastites in the foreground. Notice tuffaceous character of the hyaloclasites.

1.1. Geological and petrological context of Laki–Grímsvötn magma system

The Laki–Grímsvötn magma system is located in the Eastern Volcanic Zone of Iceland, with the Grímsvötn central volcano sitting above the Iceland hotspot (Fig. 1). Frequent, small (<1 km^3) subglacial eruptions occur at Grímsvötn and many of these penetrate the glacier surface and deposit tephra, which records the temporal variations