

Mineralogical and geochemical evidence for polybaric fractional crystallization of continental flood basalts and implications for identification of peridotite and pyroxenite source lithologies



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A B S T R A C T

Continental flood basalts undergo crystallization at a variety of pressures in the crust and sometimes even in the mantle. Polybaric fractionation, when magmas may pause and undergo crystallization at different pressures, results in complex fractionation of major elements. Crystallization at high pressures where clinopyroxene is an early crystallizing phase can result in erupted compositions that have major element characteristics which mimic those expected for melts derived from pyroxenite-rich sources. The trace element compositions of early-crystallizing olivine can add further detail to crystallization histories and potentially allow an examination of the crystallization of basalts from melt segregation to the surface. The North Atlantic Igneous Province (NAIP) comprises sub-regions which had diverse crystallization histories. Plateau basalts of the British Palaeogene Igneous Province (BPIP) were generated by partial melting of mantle peridotite starting at ~ 3.8 GPa with melting ceasing by ~ 2.7 GPa. Major elements indicate that some basalts crystallized at < 1 GPa with plagioclase joining the liquidus before clinopyroxene. However, the majority of BPIP magmas crystallized clinopyroxene before plagioclase feldspar over the pressure range 1.0–2.0 GPa. Trace elements in olivine indicate crystallization of olivine + clinopyroxene over the pressure interval 1.6–2.0 GPa. However, olivine data also show that some near-primary magmas reached near-surface pressures without substantial modification by fractional crystallization. Olivines formed at ≥ 1.6 GPa have Ni and Ca contents that are consistent with an origin by partial melting of mantle peridotite with no role for pyroxenite being detected. This contrasts with the low pressure dominated crystallization histories exhibited by lavas from West Greenland and Iceland. Whole-rock data for many BPIP lavas exhibit CaO depletion at a given MgO content compared with those from West Greenland and Iceland, which might be cited as an indicator of pyroxenite in their source, but this is solely a consequence of augite fractionation at depth. An absence of augite phenocrysts in lavas may have resulted either from augite crystallization in the mantle or from a change from augite saturation to under-saturation with decreasing pressure, and consequent augite dissolution. The lack of any significant contribution from recycled oceanic crust to magmatism in the NAIP suggests that the petrological structure of the mantle plumes from which NAIP lavas were derived does not conform with the generally accepted models for mantle plumes such as those responsible for magmatism in Hawaii and the Siberian Traps.

1. Introduction

Continental flood basalts (CFB) must traverse continental lithosphere before eruption at the surface. For the North Atlantic Igneous Province (NAIP; Fig. 1), where the mantle was anomalously hot ($T_p \sim 1450$ – 1550 °C; Herzberg and Gazel, 2009; Hole and Millett, 2016; Matthews et al., 2016) melting of mantle peridotite was initiated at ~ 3.7 – 4.5 GPa (Hole and Millett, 2016; Hole, 2015) and melting ceased when magmas rising by adiabatic ascent along the olivine liquidus reached the asthenosphere-lithosphere boundary (LAB), which is also

the final pressure of melting (P_f). The depth to the LAB varies throughout the province from ~ 100 km beneath Disko Island (west of Greenland) to ~ 60 km beneath Baffin Island (Hole and Millett, 2016; Matzen et al., 2017). During ascent from the initial melting pressure (P_i) to the LAB, it is generally accepted that magmas crystallize olivine alone (e.g. Herzberg and Asimow, 2008, 2015; Putirka, 2008; Putirka et al., 2011). However, Herzberg and Asimow (2008) state that augite fractionation can occur in the mantle, an assertion that is corroborated by the existence of clinopyroxene-bearing xenoliths in Hawaiian lavas that are consistent with crystallization from a tholeiitic liquid at

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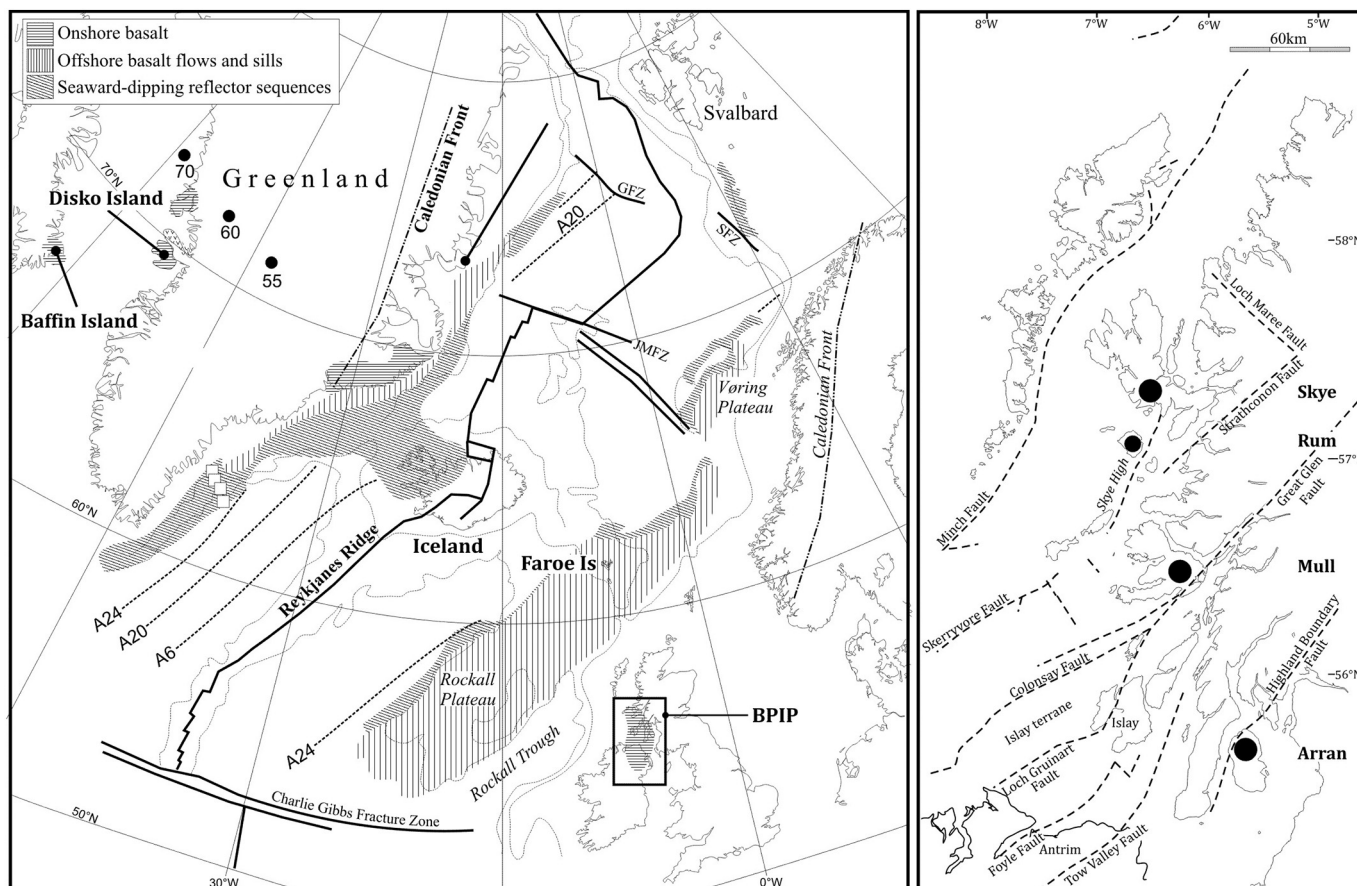


Fig. 1. (A) Reconstruction of the North Atlantic region at about 65 Ma showing the locations referred to in the text. Pecked lines labelled A6 etc., are seafloor magnetic anomalies. Black dots numbered 55–70 are plume-head positions at the time indicated and are taken from Lawver and Muller (1994). JMFZ, Jan Mayen Fracture Zone. After Hole and Millett (2016). (B) Detail of the British Palaeocene Igneous Province showing the position of the main magmatic centres mentioned in the text and the main structural features of the region. After Hole et al. (2015a).

110–150 km depth (Keshav et al., 2007). Magmas may pause at the LAB or within the lithosphere prior to eruption, and in the British Palaeocene Igneous Province (BPIP), which is a sub-province of the NAIP, there is a large body of evidence that suggests that magmas paused at the Moho at about 30 km depth, or equivalent to $\sim 0.9 \pm 0.15$ GPa (Thompson, 1974, 1982; Hole et al., 2015a; Millett et al., 2016). Individual batches of magma may have undergone polybaric fractionation. Thompson (1974, 1982) on the basis of melting experiments, as well as major, trace element and isotopic compositions of lavas, proposed that some mafic BPIP lavas underwent fractionation at 1.6–1.7 GPa as well as at ~ 0.9 GPa. Conversely, at Disko Island, very primitive and near primary magmas were erupted through ~ 100 km of lithosphere and seem not to have paused to fractionate to any great extent in the crust (Larsen and Pedersen, 2000, 2009; Hole and Millett, 2016; Matzen et al., 2017).

O'Hara (1968) showed that with increasing pressure of crystallization, the liquidus fields of olivine and clinopyroxene contracted and that the field for clinopyroxene crystallization expanded at the expense of olivine. Experimental phase equilibria (e.g. Villiger et al., 2004, 2007; Whitaker et al., 2007) show that for fractional crystallization of peridotite-derived magmas at ~ 1 GPa, clinopyroxene (Cpx) crystallizes in compositions with Mg# (molecular % $\text{MgO}/\text{MgO} + \text{FeO} + \text{Fe}_2\text{O}_3$) ≤ 65 whereas the same magma crystallizing at 1 atm would have olivine as the sole liquidus phase at Mg# 65. With increasing pressure of fractionation, Cpx becomes a liquidus phase at progressively higher Mg# (Fig. 2) which results in an expansion of the Cpx stability field at the expense of olivine as noted by O'Hara (1968). For a typical BPIP primary magma generated by volatile-free melting of mantle peridotite

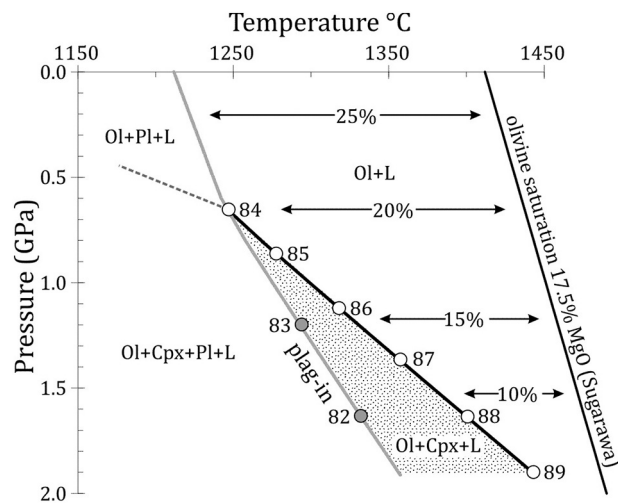


Fig. 2. Schematic representation of the pressure, temperature and composition (P , T , X) relationships for the crystallization of a typical BPIP primary magma. (a) Phase relationships calculated using Petrolog3 for the primary magma to Skye lava SK982 (Thompson, 1982; Hole and Millett, 2016). The white dots are the approximate Fo content (Mg#) of olivine that crystallizes at the Ol + Cpx + L cotectic, and the grey dots the same for the Ol + Cpx + Pl + L cotectic. % figures on the arrows are the approximate % of olivine that can crystallize on the Ol + L liquidus at a given pressure before reaching the Ol + Cpx + L cotectic. The olivine saturation curve was calculated using the method of Sugarawa (2000) with the final pressure of melting (P_f) from PRIMELT3 solutions (Hole and Millett, 2016) acting as a proxy for the pressure of melt segregation.

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