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Highly siderophile element behaviour during flood basalt genesis and evidence for melts from intrusive chromitite formation in the Mackenzie large igneous province

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ABSTRACT

The 1.27 Ga Coppermine continental flood basalt (CFB) province in northern Canada represents the extrusive manifestation of the 2.7 Mkm^2 Mackenzie large igneous province (LIP) that includes the Mackenzie dyke swarm and the Muskox layered intrusion. New Re–Os isotope and highly siderophile element (HSE: Re, Pd, Pt, Ru, Ir, Os) abundance data are reported together with whole-rock major- and trace-element abundances and Nd isotopes to examine the behaviour of the HSE during magmatic differentiation and to place constraints on the extent of crustal interaction with mantle-derived melts. Mineral chemistry and petrography are also reported for an unusual andesite glass flow (CM19; 4.9 wt.% MgO) found in close proximity to newly recognised picrites (>20 wt.% MgO) in the lowermost stratigraphy of the Coppermine CFB. Compositions of mineral phases in CM19 are similar to the same phases found in Muskox Intrusion chromitites and the melt composition is equivalent to inclusions trapped within Muskox chromites. The apparently conflicting elevated HSE contents (e.g., 3.8 ppb Os) and mantle-like initial $^{187}\text{Os}/^{188}\text{Os}$ ($\gamma_{\text{Os}} = +2.2$), versus stable isotope ($\delta^{18}\text{O} = +12‰$) and lithophile element evidence ($\varepsilon_{\text{Nd}}i = -12.8$) for extensive crustal contamination, implicate an origin for CM19 as a magma mingling product formed within the Muskox Intrusion during chromitite genesis. Combined with Nd isotope data that places the feeder for lower Coppermine CFB picrites and basalts within the Muskox Intrusion, this result provides compelling evidence for direct processing of some CFB within upper-crustal magma chambers. The Coppermine CFB defines a ^{187}Re–^{187}Os isochron with an age of 1263 +16/−20 Ma and initial $\gamma_{\text{Os}} = +2.2 \pm 0.8$. The initial Os isotope composition for the Coppermine CFB is slightly higher than the near-primitive-mantle initial $^{187}\text{Os}/^{188}\text{Os}$ for the Muskox Intrusion ($\gamma_{\text{Os}} = +1.2 \pm 0.3$). This result is interpreted to reflect greater crustal contamination in extrusive CFB and the sensitivity of Os isotopes, compared with absolute HSE concentrations, for tracking crustal contributions.

Modelling of absolute and relative HSE abundances in global CFB reveals that HSE concentrations decrease with increasing fractionation for melts with <8 ± 1 wt.% MgO, with picrites (>13.5 wt.% MgO) from CFB ($n = 98$; 1.97 ± 1.77 ppb) having higher Os abundances than ocean island basalt (OIB) equivalents ($n = 75$; 0.95 ± 0.86 ppb). The differences between CFB and OIB picrite absolute Os abundances may result from higher degrees of partial melting to form CFB but may also reflect incorporation of trace sulphide in CFB picrites from magmas that reached S-saturation in upper-crustal magma chambers. Significant inter-element fractionation of (Re + Pt + Pd)/(Os + Ir + Ru) are generated during magmatic differentiation in response to strongly contrasting partitioning of these two groups of elements into sulphides and/or HSE-rich alloys. Furthermore, fractional crystallization has a greater role on absolute and relative HSE abundances than crustal contamination under conditions of CFB petrogenesis due to the dilution effect of continental crust, which has low total abundances of the HSE. Combined data for the basaltic and intrusive portions of the Mackenzie LIP indicate a mantle source broadly within the range of the primitive upper mantle. The majority of Archaean komatiites and Phanerozoic CFB also require mantle sources with primitive upper mantle to chondritic Re/Os evolution, with exceptions typically being from analyses of highly-fractionated MgO-poor basalts.

1. Introduction

Continental flood basalts (CFB) represent high-volume, short-time-scale events (1–10 Ma) where mantle-derived magmas are transported through and modified in the continental crust before erupting at Earth's

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surface (e.g., Coffin and Eldholm, 1992). CFB are typically closely associated with other magmatic components such as intrusions and dyke swarms and collectively compose a large igneous province (LIP). While the majority of LIP preserved today are Phanerozoic in age, one of the type examples is the Proterozoic Mackenzie LIP that occurs on the northwest Canadian Shield. Preserved components of this ~1.27 Ga event include the giant Mackenzie dyke swarm, the Muskox layered mafic–ultramafic intrusion and the Coppermine CFB that are interpreted to have formed due to impingement of a mantle plume beneath the region (Baragar, 1969; Baragar et al., 1996; Day et al., 2008; Dostal et al., 1983; Ernst and Baragar, 1992; Fahrig, 1987; Francis, 1994; LeCheminant and Heaman, 1989; Mackie et al., 2009). Preferential erosion of these components due to a broadly northward structural grain makes the Mackenzie LIP an ideal location for understanding volcanic–plutonic relationships and interactions between mantle-derived magmas and crust.

Uncertainties persist in our understanding of how LIP and their associated CFB were formed. Numerous studies have highlighted the importance of interaction between mantle-derived melts, the crust and continental lithospheric mantle to generate CFB (e.g., Carlson, 1984; Carlson et al., 1981; Chesley and Ruiz, 1998; Ellam et al., 1992; Horan et al., 1995; Li et al., 2010; Molzahn et al., 1996; Thompson, 1982; Xu et al., 2007). However, Day (2013) showed that systematic variations in Os and Nd isotopes appear to require different primitive melt compositions for some CFB and concluded that several CFB provinces may also tap mantle sources with recycled material, as suggested for the 1.1 Ga Keweenawan CFB (e.g., Shirey, 1997). Another long-held view is that high-MgO picritic compositions (>13.5 wt.%) with high Os concentrations are relatively impervious to the assimilation of crust or lithosphere, and they have ^{187}Os/^{188}Os values consistent with a primitive mantle or relatively depleted mantle source (e.g., Dale et al., 2009; Rogers et al., 2010; Schaefer et al., 2000). It has been suggested that such signatures reflect the dominant role of peridotite and hence a lack of recycled components and so these CFB may represent modern-day eruptive equivalents from a cooler mantle to some Archaean komatiites (e.g., Brügmann et al., 1987; Connolly et al., 2011; Puchtel et al., 2009; Wilson et al., 2003).

Here we expand on previous studies to determine the effect of crust–melt interaction processes by addressing the relationship between CFB and the magma chambers that feed them, and the effect that magma storage in the crust has on the chemical composition of mantle-derived melts. We have studied samples from the Coppermine River CFB (here after, the Coppermine CFB) using combined Re–Os and Sm–Nd isotope and highly siderophile element (HSE: Os, Ir, Ru, Pt, Pd, Re) abundance data, together with major- and trace-element abundances of whole-rock samples and mineral chemistry for an andesitic glass flow (CM19). In order to investigate the cause of geochemical variations in the Mackenzie LIP, we have utilized the HSE, which are useful tracers of crust–mantle differentiation processes because of their chalcophile and siderophile behaviour combined with the more compatible behaviour of Os, Ir and Ru relative to Pt, Pd and Re during igneous processes. In particular, Os isotopes are sensitive indicators of crustal inputs because elevated Re/Os in crustal materials leads to high-time-integrated ^{187}Os/^{188}Os. Combined with incompatible trace-elements and Nd isotopic variations, it is possible to identify contributions from distinct mantle and continental crustal reservoirs during fractional crystallization. Using these geochemical tools, we explore evidence for derivation of the Coppermine CFB from the Muskox Intrusion and quantitatively examine the controls on HSE fractionation during magmatic differentiation throughout the exposed ~4.4 km stratigraphy of the Coppermine CFB.

2. Geological background and samples

The Coppermine CFB are a ~4.4 km thick sequence of predominantly sub-aerially erupted volcanic rocks exposed to the northeast of the Great Bear Lake, on the northwest Canadian Shield (Baragar, 1969; Baragar et al., 1996; Fig. 1). The Coppermine CFB was erupted onto graded fluvial and shallow marine sediments of the Dismal Lake and 1.66 Ga Hornby Bay groups that unconformably overlie 1.8–2.2 Ga Wopmay Orogen gneiss and Epworth metavolcanics (Hofmann, 1980; Bowring and Ross, 1985; Fig. S1). This succession is interpreted to reflect a marine transgression followed by uplift and shallow submergence prior to eruption of the Coppermine CFB (Kerans et al., 1981). The Coppermine CFB forms part of the Mackenzie LIP event that also comprises the Muskox layered intrusion and the Mackenzie dyke swarm, with an extent of 2.7 Mkm^2 (e.g., LeCheminant and Heaman, 1989). The Coppermine CFB is exposed immediately north of the Muskox layered intrusion, close to the focus of the Mackenzie dyke swarm. Close spatial association, similar palaeo-magnetism and U–Pb geochronology indicate that these all formed during the same 1.267–1.272 Ga event (Fahrig, 1987; LeCheminant and Heaman, 1989; French et al., 2002; Mackie et al., 2009).

Samples analysed in this study are from the Copper Creek (0–2.9 km) and Husky Creek members (2.9–4.44 km) of the Coppermine CFB and were collected in 1998 and 1999 by L.J. Hulbert along a ~50 km NW–SE trending transect. The Coppermine CFB has typically been broken into two main formations, the Copper Creek that consists of ~150 flows of 10–25 m thickness and which are sub-divided into Lower (0 to ~1 km), Middle (~1–1.8 km) and Upper (~1.8–2.9 km) members, and the Husky Creek Formation that are irregularly interbedded within sandstones (Baragar, 1969). This relationship has been interpreted to reflect rapid emplacement of the Copper Creek Formation, followed by impersistent volcanism during emplacement of the Husky Creek Formation (Baragar et al., 1996). We also present new data for recently recognised units from the Lower Copper Creek Formation including picritic (>15% modal olivine) flows, and an unusual glassy andesite flow (CM19).

3. Analytical methods

Mineral major- and minor-element analyses were performed on a polished thick section of CM19 using a *Cameca* SX-100 electron microprobe analyser at the University of California, Santa Barbara. Mineral compositions were determined in wave-length dispersive spectral mode using an accelerating potential of 15 keV, a 10–15 nA beam current, with beam focus of 1 μm. Peak and background counting times of 20 s and standard ZAF (PAP) correction procedures were used. Plagioclase compositions were determined using a 10 nA beam current, a 5 μm beam size, and longer counting times to avoid mobilisation of Na or K. Natural and synthetic standards were used for calibration. Drift was within counting error through the analytical session. Detection limits (3σ above background) were <0.03 wt.% for all elements listed.

Major element analyses were determined by standard X-ray fluorescence spectrometry methods employing standard fused glass and pressed pellet techniques at the Geological Survey of Canada and the University of Leicester, UK. Loss-on-ignition was measured by gravimetric analysis at 900 °C. Samples were prepared and analysed with international standards, with an external error of better than ± 3% for major elements (2σ) as demonstrated by the inter-laboratory comparisons of differently prepared powders of CM19, as well as Muskox Keel Dyke samples (Table S1). Trace elements were determined on 100 mg of homogenized whole rock powder using a *Perkin Elmer* ELAN 6000 inductively coupled plasma mass spectrometer (ICP-MS) at the University of Durham using standard analytical procedures (e.g., Day et al., 2008, 2010). Data were calibrated and monitored relative to accepted values of international standards (BHVO-1, AGV-1, BE-N, SRM 688) and internal standards (GP13, EH01), with a reproducibility generally better than ± 3% for basaltic materials (Table S2).

Neodymium isotope analyses were performed on ~100 mg of unleached whole rock powder aliquants at the University of Durham using procedures outlined in Day et al. (2008, 2010) using a *ThermoFisher* Neptune Multi-Collector ICP-MS. Standard reproducibility