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Isotopic (Pb, Sr, Nd, C, O) evidence for plume-related sampling of an ancient, depleted mantle reservoir

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ABSTRACT

The exact mantle source for carbonatite melts remains highly controversial. Despite their predominant occurrence within continental (lithospheric) domains, the radiogenic isotope data from young (<200 Ma) carbonatite complexes worldwide overlap the fields defined by present-day oceanic island basalts (OIBs). This feature suggests an intimate petrogenetic relationship with asthenospheric mantle. New Pb, Sr, C, and O isotopic data are reported here for constituent minerals from the Oka carbonatite complex, which is associated with the Cretaceous Monteregian Igneous Province (MIP), northeastern North America. The Pb isotope data define linear arrays in Pb–Pb isotope diagrams, with the corresponding Sr isotope ratios being highly variable (0.70314–0.70343); both these features are consistent with open system behavior involving at least three distinct mantle reservoirs. Compared to the isotope composition of known mantle sources for OIBs and carbonatite occurrences worldwide, the least radiogenic $^{207}Pb/^{204}Pb$ (14.96 ± 0.07) and $^{208}Pb/^{204}Pb$ (37.29 ± 0.15) isotopic compositions relative to their corresponding $^{206}Pb/^{204}Pb$ ratios (18.86 ± 0.08) reported here are distinct, and indicate the involvement of an ancient depleted mantle (ADM) source. The extremely unradiogenic Pb isotope compositions necessitate U/Pb fractionation early in Earth's history (prior to 4.0 Ga ago) and growth via a multi-stage Pb evolution model. The combined stable (C and O) and radiogenic isotopic compositions effectively rule out crustal/lithosphere contamination during the petrogenetic history of the Oka complex. Instead, the isotopic variations reported here most likely result from the mixing of discrete, small volume partial melts derived from a heterogeneous plume source characterized by a mixed HIMU–EM1–ADM signature.

1. Introduction

Radiogenic isotope compositions of the Earth's mantle exhibit large-scale heterogeneities (e.g., Hofmann, 1997), but the origin and distribution of the compositional variations remain unresolved. Four mantle components, i.e., DMM (depleted MORB-mid-ocean ridge basaltic mantle), EM1 (enriched mantle 1), EM2 (enriched mantle 2), and HIMU (high μ (mu) = $^{238}U/^{204}Pb$), have been identified based on the Nd, Pb, and Sr isotope data for OIBs (oceanic island basalts) and MORBs (Zindler and Hart, 1986). Additional mantle reservoirs, FOZO (focus zone) and "C", have been recognized on the basis of unique Pb and He isotope compositions (Hanan and Graham, 1996; Hart et al., 1992).

Compared to their silicate (e.g., basaltic) counterparts, mantle-derived carbonatitic melts hold several advantages as insightful probes into the elemental and isotopic nature of the Earth's mantle. Their low melt viscosities result in rapid ascent rates through the lithosphere and crust (Treiman, 1989), and their enrichment in incompatible elements (e.g., Nd, Sr) results in minimal contamination and perturbation of their inherited mantle source isotopic signatures (e.g., Bell and Simonetti, 2010; Bell and Tilton, 2001). For example, Bell et al. (1982) advocated for the existence of a long-lived, time-integrated depleted upper mantle reservoir beneath eastern North America on the basis of Sr isotope signatures for Canadian carbonatites varying in age range between ~2.7 and ~0.1 Ga. Additionally, Bizzarro et al. (2002) reported the existence of an unradiogenic mantle reservoir preserved in the deep mantle for at least 3 b.y. based on Hf isotopic results for carbonatites and kimberlites from Greenland and eastern North America.

A considerable amount of radiogenic and stable isotope data for carbonatites and associated alkaline silicate rocks has been reported within the last 20 years (e.g., Andersen and Taylor, 1988; Bell, 1998; Grünenfelder et al., 1986; Simonetti and Bell, 1994; Tilton and Bell, 1994). However, various interpretations/models have been put forward to explain the origin of the associated alkaline silicate rocks, and these include: 1) low degrees partial melting of a metasomatized upper mantle (e.g., Olafsson and Eggler, 1983); 2) fractional crystallization from a homogeneous, mantle-derived melt in a closed system (e.g., Balaganskaya et al., 2007; Brassinnes et al., 2005); 3) liquid immiscibility between a carbonatitic melt and a conjugate parental alkaline silicate magma

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(e.g., Ivanikov et al., 1998); 4) rheomorphism of fenites at crustal levels, in particular for rocks of ijolitic and syenitic composition (e.g., Kramm, 1994).

The Cretaceous Oka carbonatite complex within southern Québec (Canada) contains both carbonatite and associated alkaline silicate rocks (e.g., alnoite, ijolite), and is the most westerly alkaline intrusive center associated with the Monteregian Igneous Province (MIP; Fig. 1). Recent, detailed in-situ U/Pb geochronological investigations of apatite, niocalite, and perovskite reveal that the magmatic activity (maximum extent) at Oka was a prolonged event, which occurred between 109.9 ± 2.7 and 139.9 ± 2.5 Ma ago (Chen and Simonetti, 2013, 2014; Chen et al., 2013b). Treimain and Essene (1985) proposed that the carbonatite and associated silicate rocks (i.e., okaite, ijolite) were derived from a common primary magma and formed via liquid immiscibility. In contrast, on the basis of U–Pb ages, major and trace element geochemistry, and radiogenic isotope data, Chen & Simonetti (2013, 2014) and Chen et al. (2013b) suggested that the carbonatites and associated alkaline silicate rocks are the result of open system behavior involving mixing of different pulses of small volume partial melts. Previous investigations have attributed the origin of the MIP-related alkaline plutons to melting of lithospheric mantle at the time of the opening of the North Atlantic Ocean (Faure et al., 1996), or of mantle plume origin (Eby, 1985; Foland et al., 1988; Roulleau and Stevenson, 2013). The MIP has also been linked to the intrusions of the New Hampshire White Mountains and the New England seamount chain as expressions of the Great Meteor hotspot track (Fig. 1a; Eby, 1985; Foland et al., 1988; Heaman and Kjarsgaard, 2000; Zurevinski et al., 2011).

This study reports new, in-situ Sr, Nd and Pb isotopic compositions of calcite and apatite from both carbonatite and associated silicate rocks at Oka. Previous investigations report the major and trace element compositions and U–Pb ages for apatite, niocalite, and perovskite (Chen and Simonetti, 2013, 2014; Chen et al., 2013b), and the composition of melt inclusions within magnetite (Chen et al., 2013a) for carbonatite and associated silicate rocks investigated here. The stable $\delta^{13}C$ and $\delta^{18}O$ values for calcite are also documented, which constrain the nature of the mantle sources involved in the generation of the Oka complex. The combined stable and radiogenic isotope data help delineate the petrogenetic relationship between the carbonatites and associated alkaline silicate rocks at Oka, and more importantly, the mantle sources that contribute to the generation of Oka and MIP-related intrusions.

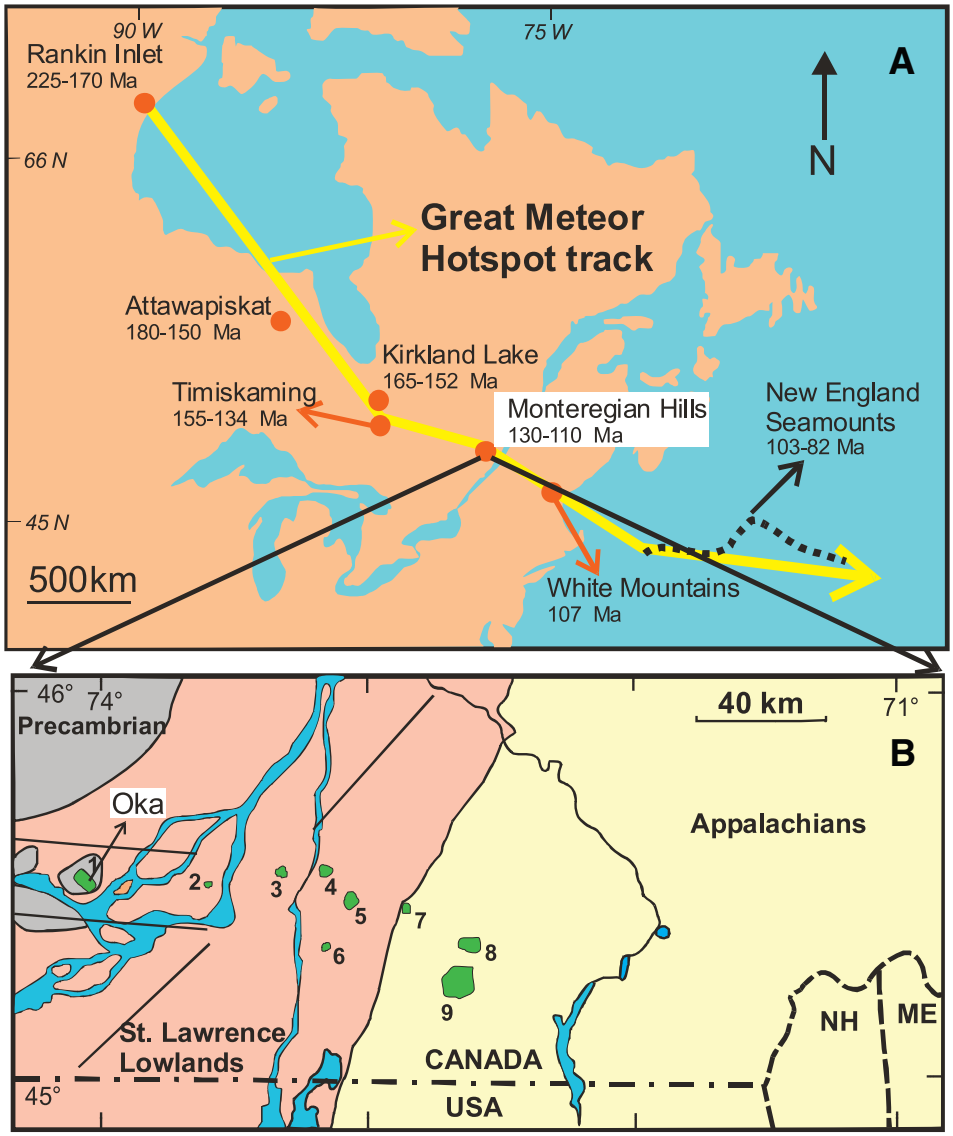

Fig. 1. Map of eastern North America showing the Great Meteor hotspot track (A; Heaman and Kjarsgaard, 2000; Zurevinski et al., 2011), and inset (B) illustrates the location of MIP-related intrusions including Oka (Chen and Simonetti, 2013; Faure et al., 1996); MIP-related intrusions labeled in inset (B) are: 2 — Royal; 3 — Bruno; 4 — St. Hilaire; 5 — Rougemont; 6 — Johnson; 7 — Yamaska; 8 — Shefford; 9 — Brome.