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Lu–Hf isotopic memory of plume–lithosphere interaction in the source of layered mafic intrusions, Windimurra Igneous Complex, Yilgarn Craton, Australia

O. Nebel [a,*], R.J. Arculus [a], T.J. Ivanic [b], Y.J. Nebel-Jacobsen [c]

[a] Research School of Earth Sciences, Australian National University, Canberra, ACT 0200, Australia
[b] Geological Survey of Western Australia, Department of Mines and Petroleum, Perth, WA 6004, Australia
[c] Centre for Sustainable Energy Systems, Australian National University, Canberra, ACT 0200, Australia

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ABSTRACT

Most layered mafic intrusions (LMI) are formed via multiple magma injections into crustal magma chambers. These magmas are originally sourced from the mantle, likely via plume activity, but may interact with the overriding lithosphere during ascent and emplacement in the crust. The magma injections lead to the establishment of different layers and zones with complex macroscopic, microscopic and cryptic compositional layering through magmatic differentiation and associated cumulate formation, sometimes accompanied by crustal assimilation. These complex mineralogical and petrological processes obscure the nature of the mantle sources of LMI, and typically have limited the degree to which parental liquids can be fully characterised. Here, we present Lu–Hf isotope data for samples from distinct layers of the Upper Zone of the Windimurra Igneous Complex (WIC), an immense late-Archean LMI in the West Australian Yilgarn Craton. Lu–Hf isotope systematics of whole rocks are well correlated (MSWD $= 5.6$, $n = 17$) with an age of $\sim 3.05 \pm 0.05$ Ga and initial $\varepsilon_{\mathrm{Hf}} \sim +8$. This age, however, is older than whole rock Sm–Nd and zircon U–Pb ages of the intrusion, both of which are ca. 2.8 Ga. Stratigraphically-controlled initial Hf isotope variations (associated with multiple episodes of emplacement at ca. 2.8 Ga) indicate isotope mixing between a near-chondritic and an ultra-radiogenic component, the latter with $\varepsilon_{\mathrm{Hf}}[2.8\ \mathrm{Ga}] > +15$. This Hf isotope mixing creates a pseudochron-relationship at the time of intrusion of ~ 250 Myr that is superimposed on subsequent radiogenic ingrowth after crystallisation, generating an age that predates the actual emplacement event. Mixing between late-stage crystallisation products (melt + crystals) from the Middle Zone and replenishing, plume-derived liquids was followed by crystal accumulation in a chemically evolving magma chamber. The ultra-radiogenic Hf isotope endmember in the WIC mantle source requires parent–daughter ratios consistent with very early formation in Earth history, akin to early Archean komatiitic plume sources. We propose that plume-derived melts that formed the Windimurra LMI reacted with ancient refractory lithospheric keels already underpinning ancient cratons, creating a melt with extremely high $\varepsilon_{\mathrm{Hf}}[t]$. Melting a refractory component with super-chondritic, time-integrated high Lu/Hf, in this case by plume–lithosphere interaction, simultaneously accounts for the extreme Hf isotope signals, Hf–Nd isotope decoupling, and difference in radiometric Lu–Hf and Sm–Nd ages.

1. Introduction

The Meso- to Neo-Archean is a particularly important time in Earth's history with changing modes of crustal formation and recycling, associated mantle- and plate-dynamics, and the evolution of the atmosphere (Condie and Kröner, 2008; Farquhar et al., 2000; Keller and Schoene, 2012; Konhauser et al., 2009; McLennan, 1988; Naeraa et al., 2012; Shirey and Richardson, 2011; Smithies et al., 2005). Two major rock types are our prime sources of data relating to the evolution of the coupled mantle-crust system during this time: komatiites and layered mafic intrusions (LMI) (e.a., Arndt et al., 2008; Campbell, 2005; Cawthorn, 1996; Ernst and Buchan, 2003). Both are associated with large volumes of mantle-derived melts and/or large degrees of mantle melting that required special circumstances of melting other than those observed, for example, at the site of the most voluminous magmatism at present-day represented by mid-ocean ridges (MOR). Most studies (e.g., Arndt, 2003; Arndt et al., 1998; Campbell, 2007; Davies, 1999; Ernst and Buchan, 2003; Griffiths and Campbell, 1991) favour models for the origin of both komatiites and LMIs

* Corresponding author.
E-mail address: oliver.nebel@anu.edu.au (O. Nebel).

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with a plume origin via hot, upwelling mantle. Alternative hypotheses have been suggested, such as the promotion of melting via hydrous mantle domains (Grove and Parman, 2004; Parman et al., 2004).

Layered mafic intrusions are the most voluminous plutonic expressions of large igneous provinces and have been intensively studied for their unique mineral endowment (i.e., PGE, Cr, Ni, V, Ti). This economically important feature has made them an intense focus of the mining industry. Their typically intra-cratonic setting makes them also important rock associations for studying the evolution of cratonic domains and the role of crust-mantle interaction in their genesis (Cawthorn, 2007; Day et al., 2008; DePaolo and Wasserburg, 1979; Kruger, 1994; Kruger et al., 1987; O'Driscoll et al., 2009; Premo et al., 1990; Richardson and Shirey, 2008; Schoenberg et al., 1999). The parental magmas of LMI have traversed and inevitably, to some extent, interacted with extant sub-continental lithospheric mantle (SCLM) and crust *en route* to emplacement (Maier et al., 2000; Richardson and Shirey, 2008); interaction includes various magma mingling, assimilation, and contamination processes. Some of these magma interactions have been proposed to play a key role in enrichment of precious metals to ore-quality levels (e.g., Ihlenfeld and Keays, 2011; Maier, 2005). Prominent examples of huge LMI are the Archean Stillwater and the Proterozoic Bushveld Complexes, mostly renowned for their unique mineral associations. In both cases, mixing of magmas derived from asthenospheric and lithospheric sources has been recognised, with radiogenic isotopic systematics as key indicators (Maier et al., 2000; Richardson and Shirey, 2008). However, compared to other expressions of large igneous provinces, LMI have not been fully explored for their significance in crust-mantle evolution using the entire spectrum of modern isotopic tools.

Radiogenic isotope tracers allow insights into the time-integrated geochemical nature of source components and to trace crustal contamination, but are not compromised by differentiation processes; the latter is a complication that strongly affects elemental distributions. By definition, LMI are characterised by macroscopic layering of diverse mineral assemblages, as well as cryptic layering through geochemical zonation (Irvine, 1982). The segregation of crystalline phases as cumulates (Cawthorn, 1996) results in non-equivalence of the bulk compositions of the layers with the contemporaneous melts from which the assemblages crystallised. This renders studies of their putative parental liquids extremely difficult so that isotopic studies become key tools for the characterisation of the mantle sources of LMI. Nevertheless, isotopic studies can not only be compromised by crustal contamination, but also by alteration and metamorphism, particularly of Archean-aged igneous bodies (e.g., Moorbath et al., 1997), so care has to be taken in the selection of the isotopic approach to be used.

In this contribution, we investigate the ^{176}Lu–^{176}Hf characteristics of a huge, 2.8 Ga old LMI, the Windimurra Igneous Complex (WIC) in the Yilgarn Craton in Western Australia (Ahmat, 1986; Ivanic et al., 2010). The Lu–Hf isotopic system appears to be among the most robust with respect to alteration/metamorphism in old igneous rocks (Blichert-Toft, 2001; Blichert-Toft et al., 1999; Polat and Münker, 2004; Rizo et al., 2011), as a result of the relatively immobile nature of heavy rare earth elements (HREE, including Lu) and high-field strength elements (HFSE, including Hf). Despite its enhanced resistance to alteration/metamorphic processes compared with other isotope systems, as e.g., Rb–Sr, it has so far only sparsely been applied to investigations of LMI, as opposed to studies of komatiites, which are more numerous (Blichert-Toft and Arndt, 1999; Blichert-Toft et al., 2004; Blichert-Toft and Puchtel, 2010; Puchtel et al., 2013). We focus on fresh rock material from drill cores of the Upper Zone of the WIC. Our aim is to investigate Lu–Hf systematics in macroscopic layers in search for a tool to study and to better understand (i) LMI mantle source(s) in general, and in particular (ii) the nature of the local cratonic lithospheric mantle that has been shown to contain Hadean roots (Tessalina et al., 2010) and may have played a role in preserving Hadean detrital zircon populations (Harrison, 2009; Thern and Nelson, 2012).

2. Geologic background

The WIC is located in the Murchison Domain of the Youanmi Terrane of the Archean-aged Yilgarn Craton (Fig. 1, small inset, Ivanic et al., 2010). It is intermediate in size between the Stillwater and Bushveld LMI, has a seismically-determined thickness of 10 km, and is the largest known intrusion of its kind in Australia with an areal extent of 2500 km^2 (Wyche et al., 2013). It is part of the c. 2810 Ma Meeline Suite, which includes several intrusions of similar lithological associations as e.g., the c. 2810 Ga Youanmi Igneous Complex. Immediately to the southwest lies the 2800 ± 6 Ma Narndee Igneous Complex, a neighbouring LMI that belongs to the hornblende-bearing Boodanoo Suite (Ivanic et al., 2010). The age of the WIC was first constrained by Sm–Nd whole rock analyses of surface exposed rocks of the Complex, yielding an age of 2.80 ± 0.02 Ga (previously reported in Mathison and Ahmat (1996) and Mueller and McNaughton (2000), listed in Table 1, from I. Fletcher, pers. communication; Fig. 2A). This was subsequently confirmed by U–Pb analyses of rare zircon from a pegmatitic gabbro phase in the Middle Zone of the Complex with an age of 2813 ± 6 Ma (Wingate et al., 2012). The intrusions of the Meeline Suite are interpreted to have intruded into pre-existing, i.e. >2815 Ma granite–greenstone lithologies of the Murchison Domain of the Youanmi Terrane (Ivanic et al., 2010).

From an extensive sample collection comprising several km of diamond drill core originally obtained by Maximus Resources Lt., nineteen hand-sized samples were selected for Lu–Hf isotopic and petrological analysis from two cores in the Upper and uppermost Middle zones (Fig. 1). The lithologies identified in the cores include a variety of ultramafic, mafic, and anorthositic types dominated by fayalitic olivine, plagioclase, pyroxene, minor magnetite and ilmenite (unless in magnetitites), and trace apatite in the upper stratigraphic sections. Lower sections of the Upper Zone include magnetitites alternating with anorthositic layers. No primary hydrous minerals were identified in thin section in any of the samples, and all appear macroscopically fresh. However, microanalytical investigation has revealed replacement of some pyroxene by chlorite. The Upper Zone is ∼1 km thick, with a base defined by the appearance of cumulate magnetite, and with many petrological and mineralogical similarities to the Upper Zone of the Bushveld Complex. However, the Upper Zone of the WIC is unique among LMI in the lack of primary hydrous minerals, accompanying an extremely Fe-rich tholeiitic character overall (some samples are up to 55 wt.% total Fe as Fe_2O_3, as magnetite cumulates and olivine-rich cumulates, see Nebel et al. (in press) for details); both features suggest very low water contents and minimal hydrous crustal contamination.

3. Analytical methods

Between 0.5–1 kg of drill core material was pre-crushed in a hydraulic press and subsequently powdered in an agate mill. Approximately 100 mg of sample powder were spiked with a ^{176}Lu–^{178}Hf enriched isotope tracer and dissolved in a HF–HNO_3 acid mixture in 15 ml Savillex vials. Dissolution was performed at ca. 130–140 °C on a hotplate for 48 h. After the initial dissolution, all samples were evaporated to dryness and repeatedly dissolved in concentrated nitric acid in order to break CaF bonds. Traces of HF were added to keep Hf in solution. Only after a clear sample