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Primary hydrous minerals from the Karoo LIP magmas: Evidence for a hydrated source component

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ABSTRACT

Large Igneous Provinces mark important and consequential events that span almost the entirety of the Earth's history. These punctuated geologically significant events that include earth processes from the core to the atmosphere have been linked to climate changes, mass extinctions, and even large-scale tectonic shifts. To begin to understand the role LIPs play in these important moments across Earth's lifespan, a thorough understanding of how they form in the first place is imperative. The ~180 Ma Karoo Continental Flood Basalt (CFB) Province has been heavily studied with one of the largest geochemical and geochronological databases available for a CFB; providing an excellent avenue to study in detail the petrogenesis of these large collections of magma. However, despite this large dataset, the origin of the Karoo CFBs is still debated, with many different and conflicting models proposed. Disparities in these models can often be traced down to the degree of influence a plume and/or the sub-continental lithospheric mantle (SCLM) had during the genesis of this magmatic province. Nine sills intruded into the Western Cape Province of the Karoo Basin were investigated using $^{40}Ar/^{39}Ar$ geochronology, whole rock geochemistry, and Sr, Nd, Pb isotopes. Five of these sills are peculiar as they contain hydrated minerals (biotite and hornblende), an unusual feature for Karoo basaltic rocks. Biotite and/or hornblende separates yielded statistically indistinguishable $^{40}Ar/^{39}Ar$ ages as plagioclase separates; indicating that the biotite and hornblende found within these samples are primary features requiring that water was present in the magma during the crystallization of those sills. Major and trace element geochemistry place these rocks into the low-Ti suite of the Karoo CFBs. Trace elements indicate the involvement of fluids over sediment within the source region for these Karoo magmas. All samples from the Western Cape Province display enriched Sr–Nd–Pb initial values with large variations in elemental concentrations for a restricted range of isotopic ratios. Assimilation models indicate these enriched isotopic contents and observed trends are not the result of crustal contamination and are representative of the composition of the source. The trace element and isotopic geochemistry as well as the primary hydrated minerals indicate that water present in the system at the time of formation came directly from one of the mantle sources, supporting the hypothesis that the SCLM was metasomatized by fluids plausibly as a result of the Proterozoic Kibaran Orogeny and/or the Permian Cape Orogeny. This first direct evidence of water within the mantle sources of tholeiitic CFBs, until now only theorized and modeled, potentially changes the fundamentals in how we approach our considerations of CFB generation as a whole.

1. Introduction

One of the most common controversies within petrogenesis studies of continental flood basalts (CFBs) is the contribution of the lithospheric mantle. The high melting rates required for the development of CFBs, attributed primarily to the presence of water content, large scale decompression melting, and/or high mantle temperatures (Campbell, 2001), are difficult to obtain uniquely from what is considered the cold and dry lithosphere. Many studies infer the presence of water within the mantle sources of CFB, including the sub-continental lithospheric mantle (SCLM), through means such as geochemical modeling or indirect evidence from associated mantle peridotite (Karoo e.g. Grégoire et al., 2003; Hopp et al., 2008; Jourdan et al., 2007a; Wang et al., 2016), however lack direct evidence.

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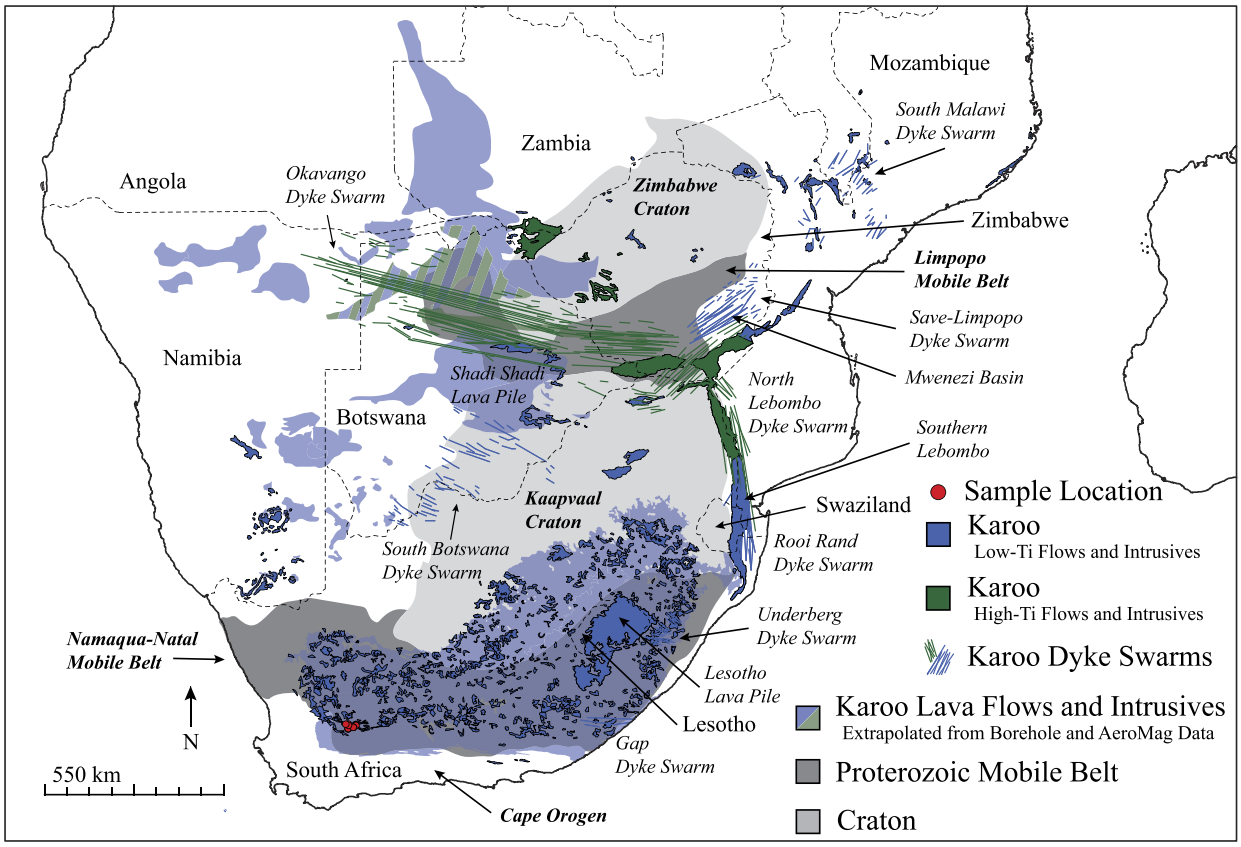

Fig. 1. Sketch map of the African portion of the Karoo Continental Flood Basalt (CFB) Province's distribution and constituent suites. Modified and created after Jourdan et al. (2007a), Jourdan et al. (2006), and Svensen et al. (2012).

The Karoo Large Igneous Province (LIP) represents one of the largest Continental Flood Basalts on the planet, with an estimated area greater than 3×10^6 km ^{2}. Exposures can be found in Africa (Fig. 1), along the Princess Martha Coast of Western Dronning Maud Land in Antarctica, and dykes throughout the Falkland Islands (Duncan et al., 1984). The province consists of a vast cover of lava flows, a huge network of sills and dykes (including giant dyke swarms), as well as localized intrusive centers. The Karoo CFBs has been the subject of extensive geochronology studies conducted over the last decade with currently over 100 precise geochronologic data (Duncan et al., 1997; Encarnacion et al., 1996; Jones et al., 2001; Jourdan et al., 2005, 2006, 2008; Luttinen et al., 2015; Sell et al., 2014; Svensen et al., 2012). The estimated duration of the main volume of the Karoo Province has been constrained by ^{40}Ar/^{39}Ar (Jourdan et al., 2008; recalibrated with the ^{40}K constants of Renne et al., 2011) and chemical abrasion thermal ionization mass spectrometry (CA-TIMS) U–Pb (Sell et al., 2014; Svensen et al., 2012) results to an interval from ~179 to 184 Ma.

Many different models have been proposed to explain the formation of the Karoo LIP. The differences between the models revolve around the relative contributions of a deep mantle plume and the uppermost mantle (Duncan et al., 1984; Heinonen et al., 2014; Jourdan et al., 2007a; Sweeney and Watkeys, 1990). An important constraint on these models is the ability for heat transfer from the ascending plume or asthenospheric mantle to cause subcontinental lithospheric mantle melting, or if previous charging by fluids provides a fertile and/or relatively hydrated SCLM allow for melt to be generated via decompression processes. Many studies have proposed that the SCLM, below southern Africa, has been substantially hydrated/metasomatized (Grégoire et al., 2003; Hopp et al., 2008; Jourdan et al., 2007a; Wang et al., 2016); however, no *direct* evidence has been found of these fluids in the rocks of the Karoo LIP. Recent studies suggesting that degassing of volcanic rocks can occur at the surface indicating that some rocks, which appear to contain little water, can in fact arise from hydrated sources (Aubaud et al., 2005). ^{40}Ar/^{39}Ar geochronology and major-element, trace-element, and Sr, Nd, Pb geochemical data of biotite and hornblende-bearing sills from the Western Cape Province of the Karoo CFB Province are presented, all together demonstrating that the hydrous minerals (biotite and hornblende) are primary in nature, early in the activity of the Karoo magma emplacement, and suggest the first direct evidence of the presence of water in the mantle source.

2. Geologic setting and previous results

2.1. Karoo geochemistry

The African portion of the province encompasses much of southern Africa and comprises a range of rock types from nephelinites, picrites, tholeiites, rhyolites, to E-MORB like basalts (Fig. 1). The tholeiites constitute the majority of the Karoo CFB rocks and have been subsequently divided into two subgroups; a high-Ti and low-Ti suite; divided based on TiO_2 contents (high-Ti $>$ 2–2.5 weight percent [wt.%]; low-Ti $<$ 2–2.5 wt.%) as well as P_2O_5 and incompatible trace element concentrations (Duncan et al., 1984). The two tholeiite suites are strongly controlled by location. The high-Ti suite is localized along the cratonal boundaries of the Kaapvaal and Zimbabwe cratons (Fig. 1), while the low-Ti suite is more widespread and voluminous than the high-Ti suite, primarily being concentrated in southern Africa; southern Lebombo, the Lesotho flows, Namibia, and Botswana (Fig. 1).