A revised geochemical grouping of Gondwana LIP: Distinctive sources and processes at the Weddell and Limpopo triple junctions

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Summary The magma types belonging to the Gondwana large igneous province can be divided into two categories based on, respectively, their primitive mantle-like and fractionated Sm/Yb and Sr/Zr values, different Sr and Nd isotopic trends, and geographic affinity to the Weddell and Limpopo triple junctions. In the new grouping, the Ferrar magmas, the Karoo Central Area magmas, and the Kirwanveggen-Sembberget magmas from Dronning Maud Land are viewed as three major magmatic lineages generated at the Weddell triple junction. These Weddell group magmas were produced by voluminous low-pressure partial melting of possibly subduction-modified upper mantle and tended to be laterally transported over long distances. The Limpopo group magmas include the Karoo high-Ti magma types and various low-Ti types from Lebombo, Vestfjella, and Heimefrontfjella. They represent magmas that were produced at high pressure from an eclogite-bearing mantle source below the Kaapvaal craton. The distribution of the Limpopo group magmas was mainly confined within the rift valleys of the Limpopo triple junction. The chemically distinctive magma types probably reflect heterogeneities in the Weddell and Limpopo magma sources and lithospheric level differentiation within Archean (Limpopo group) and younger lithospheric terranes.

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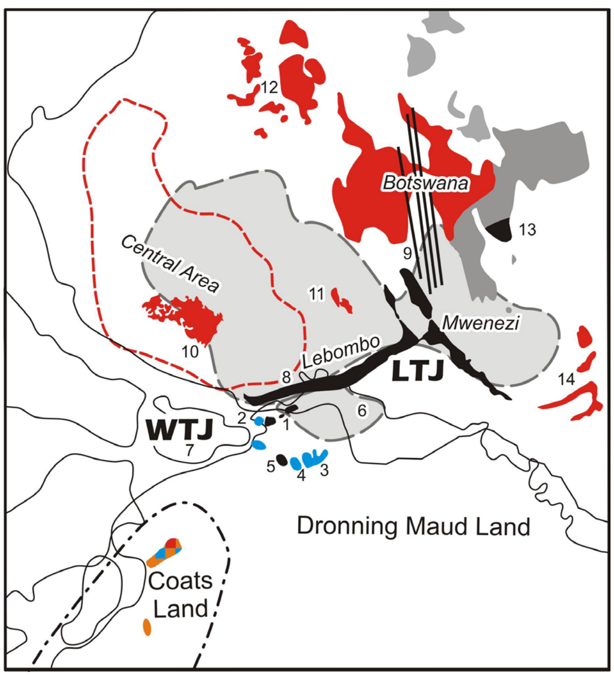

Figure 1. Distribution of Limpopo group (black), Weddell group (Ferrar–orange; Central Area–red; Dronning Maud Land–blue), and undifferentiated (dark grey) magmas in southern Africa and Antarctica. Dashed red line: Central Area dolerites; light-grey: Archean cratons. Weddell (WTJ) and Limpopo (LTJ) triple junctions are indicated. Locations: 1-Vestfjella, 2-Utpostane, 3-Kirwanveggen, 4-Sembberget, 5-Heime-frontfjella, 6-Ahlmannryggen, 7-Falkland, 8-Rooi Rand, 9-Ellisras, 10-Central Area, 11-Springbok Flats, 12-Mariental, 13-Batoka, 14-Malawi.

Introduction

The wide-spread ~180±3 Ma continental flood basalt suites of southern Africa, East Antarctica, and southeast Australia comprise the Gondwana large igneous province (LIP). Geochemical data, specifically the initial Sr isotopic ratios and concentrations of Ti and P, were originally utilized to divide the Jurassic magmas into geochemically and geographically distinctive Karoo and Ferrar provinces (Fig. 1). The Karoo province is composed of numerous chemically discernable magma suites that have been grouped into high-Ti and low-Ti types. Average magma transportation distances in the Karoo province appear to be short; relatively few correlations have been established between magma types from geographically isolated areas, apart from the wide-spread Central area magma type (Marsh et al., 1997; Luttinen and Furnes, 2000). The Ferrar magmas have also been grouped based on relatively high and low Ti concentrations, but both groups can be categorized as low-Ti tholeiites in the broader Gondwana context. Further subdivisions have not been proposed and the strikingly uniform compositions of the Ferrar magmas indicate extremely long transportation distances (Leat et al., 2006).

Recently accumulated geochemical data indicate intercalation of Karoo and Ferrar dolerites at the junction of the South American, African, and Antarctic lithospheric plates. Elliot and Fleming (2000) recognized a single Ferrar-type basalt suite in the Karoo Central Area and, based on the coincident Sr-Nd isotopic trends of the Central Area magmas and Ferrar magmas, made the seminal proposition that these voluminous suites, and possibly all Gondwana low-Ti magmas, were in fact derived from the same source, located at the Weddell triple junction (Fig. 1).

Here we present a revised geochemical grouping of Gondwana LIP magma types into two categories. We believe that the revised grouping clarifies the relationships of geochemically different magma types and reflects on fundamental petrogenetic questions regarding the sources and processes related to the Gondwana breakup magmatism.

Revised geochemical grouping of the Gondwana LIP

The revised grouping is founded on the rare earth element (REE) characteristics of Gondwana LIP magmas that define three populations based on Sm/Yb values (Fig. 2a). The high-Ti magmas from the Lebombo-Mwenezi-Tuli region, Ahlmannryggen, and Botswana (Fig. 1) are readily distinguished by their notably high Sm/Yb values (>3). The key feature of figure 2a is, however, that it subdivides the low-Ti magmas into two distinctive categories. The Ferrar magmas, the Central Area magmas, the Botswana magmas, the Kirwanveggen and Sembberget magmas, and the Utpostane magmas exhibit low, mildly fractionated Sm/Yb values (~1.1–1.7), whereas the low-Ti magmas of Lebombo, Ahlmannryggen, Vestfjella, and Heimefrontfjella exhibit more strongly fractionated Sm/Yb values (~1.7 – 2.9). Rocks with strongly fractionated Sm/Yb values (>1.7), including the high-Ti magmas, are almost exclusively associated with the rifted arms of the Limpopo triple junction (Fig. 1); these suites are designated here as the Limpopo group. Given that the Weddell triple junction has been proposed to represent the source of the Ferrar and the Central Area magmas (Elliot and Fleming, 2000) and that the Kirwanveggen, Sembberget, and Utpostane magmas are also spatially associated with the Weddell Sea, the low Sm/Yb (<1.7) group is designated here as the Weddell group.

Initial isotopic data for the Limpopo and Weddell groups show overlap, but the two groups show divergent Sr and Nd isotopic trends (not shown; cf., Elliot and Fleming, 2000; Riley et al., 2006). The Limpopo group records highly variable ε_{Sr} (–10 to +130) and ε_{Nd} (+9 to –19) values that plot along the mantle array and extend to values typical of the Kaapvaal lithospheric mantle. The Weddell group has a wider range of ε_{Sr} values (0 to +150), but a notably more restricted range of ε_{Nd} values (mainly +2 to –5) than the Limpopo group. The relatively tight trend is compatible with mixing of depleted mantle and upper crustal material (e.g., Hergt et al., 1991; Riley et al., 2006) Recognizing the limitations of the available REE and isotopic data, we have sought for other possible diagnostic features of the Limpopo and Weddell groups.

High field strength element (HFSE) ratios (e.g., Zr/Y) that readily differentiate the high-Ti magmas cannot discriminate the low-Ti types of the Limpopo and Weddell groups. Comparison of the Limpopo and Weddell groups shows that Sr/Zr values are generally higher in the former at given MgO concentration (Fig. 2). Secondary alteration and plagioclase fractionation are not regarded to be responsible for the different Sr/Zr values.

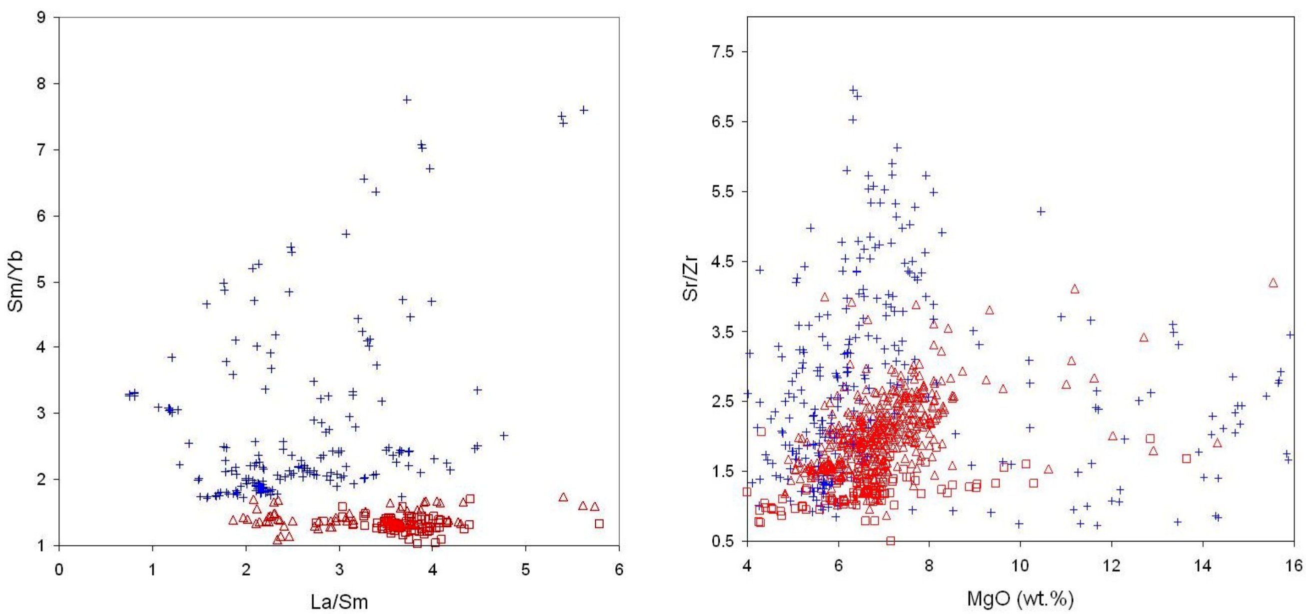

Figure 2. Variations in La/Sm vs. Sm/Yb (left) and MgO vs. Sr/Zr values (right) of Gondwana LIP magmas. Red symbols refer to Weddell group magmas (Karoo–triangles; Ferrar–squares) and blue crosses to Limpopo group magmas. The data sources are available from the first author upon request.

Magma sources and differentiation processes

The geographic distribution, the fractionated Sm/Yb values, and the overall isotopic trend of the Limpopo group magmas associate them with the Archean Kaapvaal craton. However, the base of the Kaapvaal lithosphere is, at least in places, at ≥200 km depth, well below the intersection of dry peridotite solidus and mantle adiabat. We propose that the mantle source of the Limpopo group included an eclogite (recycled oceanic crust) component that facilitated production of picritic parental magmas below thick lithosphere (cf., Tuff et al., 2005). The predominance of high Sr/Zr values in the Limpopo group can be largely attributed to subsequent interaction of the mafic magmas with the Kaapvaal lithosphere. Based on correlations between La/Sm, Sm/Yb, Sr/Zr, Nb/Y, and ε_{Nd} values, the high-Ti trends probably represent hybrid magmas of lithospheric and asthenospheric mantle material (e.g., Ellam et al., 1992). The low-Ti trends are more compatible with incorporation of lower Kaapvaal crust into these magmas.

An important subgroup of Limpopo magmas from south Vestfjella and Heimefrontfjella is characterized by low La/Sm (0.8 to 1.8) and ε_{Sr} (–2 to –16), and high ε_{Nd} (+2 to +8) values, and may have effectively avoided interaction with Archean lithosphere, due to their location outside or just at the boundary of the Kaapvaal craton (Fig. 1). The high Sr/Zr values of these otherwise mid-ocean ridge basalt-like rocks reflect selective Sr-enrichment, a distinctive "ghost plagioclase" fingerprint, rather than general enrichment of highly incompatible elements typical of many Limpopo group magmas. The "ghost plagioclase" fingerprint is not readily ascribed to lithospheric contamination, and may lend support to and provide an insight into the proposed eclogite-bearing mantle source of the Limpopo magmas: It resembles the cumulate fingerprint associated with eclogite-bearing Hawaiian magma sources (Sobolev et al., 2000) and is compatible with generation of these Limpopo group magmas at great depths where the eclogite-derived fingerprint was not diluted by peridotite-derived melts.

The Weddell group magmas have similar Sm/Yb to those of mid-ocean ridge basalts and lack high Sr/Zr typical of the cumulate fingerprint. Based on their low Sm/Yb values and the Sr-Nd isotopic trend, they were segregated from garnet-free sources and were not influenced by Archean components. It is possible that eclogitic source components were present, but the low-pressure melts extracted just from the top of the partially molten mantle column would have been dominated by peridotite-derived melts. The upper crust-like geochemical fingerprint typical of the Weddell group magmas has been traditionally ascribed to subduction-modified mantle sources (Hergt et al., 1991).

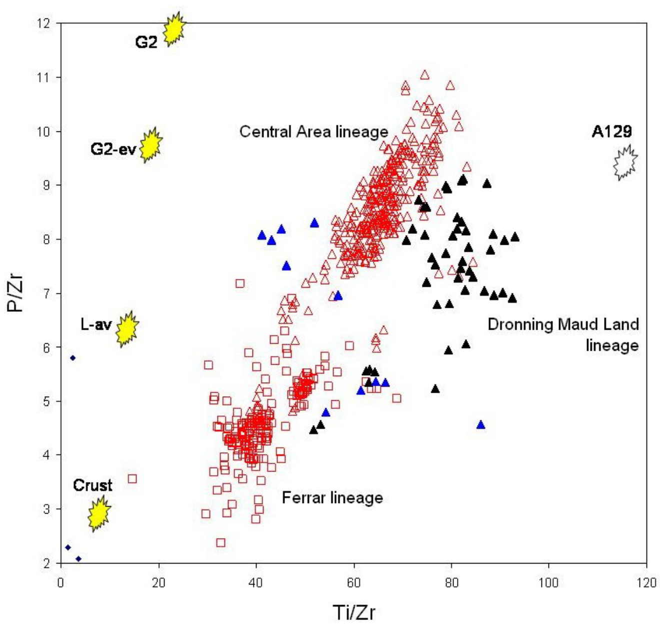

Figure 3. Variations of Ti/Zr vs. P/Zr in the three magmatic lineages of the Weddell group. Blue triangles indicate dolerites from Coats Land. Possible asthenospheric (Rooi Rand dike A129) and lithospheric source components are indicated (crust; average lamproite (L-av); evolved (G2-ev) and normal (G2) group 2 kimberlites).

Geochemical provinciality of Gondwana LIP

In the new grouping, the Ferrar magmas comprise one of the three major magmatic lineages of the Weddell group (Fig. 3). Based on geochemical differences, such as systematically lower Ti/Zr and P/Zr values in the Ferrar magmatic lineage, the co-magmatic lava sequences of the Central Area, the Springbok Flats, the Mariental area, the Ellisras basin, Botswana, the wide-spread dolerites associated with the Central Area magma types, and probably the southern Malawi basalts and some of the Coats Land dolerites, make up another major magmatic lineage of the Weddell group (Fig. 3). The Kirwanveggen lavas, the similar lavas of Sembberget (Luttinen and Leat, unpublished), and the 3-km-thick Utpostane gabbro intrusion represent a third geochemically different magmatic lineage of the Weddell group (Fig. 3).

The Ferrar and Central Area lineages, and probably also the Kirwanweggen–Sembberget–Utpostane lineage, represent notably wide-spread magmatism (Fig. 1) that was facilitated by extensive low-pressure partial melting and dispersal of magmas from the Weddell triple junction which is viewed as the principal site of magma production at ~180 Ma (cf., Elliot and Fleming 2000). Judging from the mid-ocean ridge basalt-like Sm/Yb values of the magmas, the continental lithosphere in the proto-Weddell Sea region was markedly thin by ~180 Ma.

The Limpopo group includes various high-Ti and low-Ti magma suites. The high-Ti vs. low-Ti character probably reflects relatively lower and higher degrees of melting, respectively, and the low-Ti magma volumes were probably relatively small due to partial melting under high pressure conditions below the thick Kaapvaal lithosphere. The distribution of magmas appears to have been largely controlled by the rift arms of the Limpopo triple junction. These factors may explain the short transportation distances and the fact that low-Ti lavas belonging to the Limpopo and Weddell groups are nowhere intercalated. The Limpopo triple junction could represent a pre-Karoo lithospheric structure (Jourdan et al., 2006) that facilitated emplacement of high-Ti magmas and low-Ti magmas that were generated from fusible eclogite-bearing mantle sources beneath the Kaapvaal craton.

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