Ferropicritic dikes of Vestfjella, western Dronning Maud Land: Fe-enriched mantle source for late-stage Karoo magmas

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Summary Ferropicritic dikes (MgO = 12-18 wt. %, FeO_T > 14 wt. %) and their differentiates are found cross-cutting Jurassic continental flood basalts of the Karoo large igneous province (LIP) at Vestfjella, western Dronning Maud Land. The dikes show geochemical divergence: (1) Depleted ferropicritic types (D-FP) have $(La/Sm)_N$ 1.1-1.3, $(Sm/Yb)_N$ 3.2-4.5, and they show relative enrichment in Sr, Ti, and V, and depletion in P; (2) Enriched ferropicritic types (E-FP) have $(La/Sm)_N$ 1.5-1.7, $(Sm/Yb)_N$ 4.9-5.4, and they show overall enrichment in incompatible trace elements. The Vestfjella ferropicrites are geochemically unique among the Karoo LIP. Primarily high Fe contents of D-FP and E-FP may have been inherited from anomalously Fe-rich eclogite component entrained in a pyroxenitic mantle source. Low-degree melting at high pressures may also have contributed to the high Fe contents. In contrast to other known ferropicrite successions, the Vestfjella ferropicrites represent a quite late stage of plume-related volcanic activity.

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Introduction

Ferropicrites (Hanski and Smolkin, 1989) are primitive rocks (MgO = 12-18 wt. %) with exceptionally high Fe contents (FeO_T > 14 wt. %). They have been discovered in several continental flood basalt (CFB) provinces (e.g., Paraná-Etendeka, North Atlantic Tertiary Province, and Siberian Traps) and are commonly situated near the base of lava pile (Gibson et al., 2000). Ferropicrites are believed to be close to primary mantle melts, and their fractionated rare earth element (REE) ratios (e.g., $[Sm/Yb]_N > 2$) and low Al_2O_3 (~10 wt. %) contents imply deep mantle sources. The high Fe contents are thought to be a result of melting of secondary pyroxenite sources (Tuff et al., 2005), similar to those ascribed to oceanic island basalts (OIBs; e.g., Sobolev et al., 2005; Herzberg, 2006) related to a reaction between mantle peridotite and eclogite (recycled oceanic lithosphere) –derived melts (Yaxley and Green, 1998; Sobolev et al., 2005). OIBs are geochemically quite similar to, although less Fe-enriched, than ferropicrites in many respects. By inference, the purported pyroxenite source of ferropicrites, and specifically the eclogite component may be unusually Fe-rich (see Ichiyama et al., 2006).

Iron-rich picrites have recently been described from Vestfjella (Luttinen et al., 1998) and Ahlmannryggen (Riley et al., 2005), western Dronning Maud Land (WDML; Fig. 1). They are found as dikes belonging to the Jurassic Gondwana break-up related Karoo large igneous province (LIP), which is a classic example of CFBs and the bulk of which is located in southern Africa. Here we present petrographical and geochemical data on ferropicritic and geochemically related basaltic and meimechitic dikes that comprise the Vestfjella ferropicritic group (VFPG). We evaluate their origin and relationship to Karoo magmatism, and discuss possible factors that contribute to the petrogenesis of ferropicrites and Fe-rich OIB-type intra-plate volcanic rocks in general.

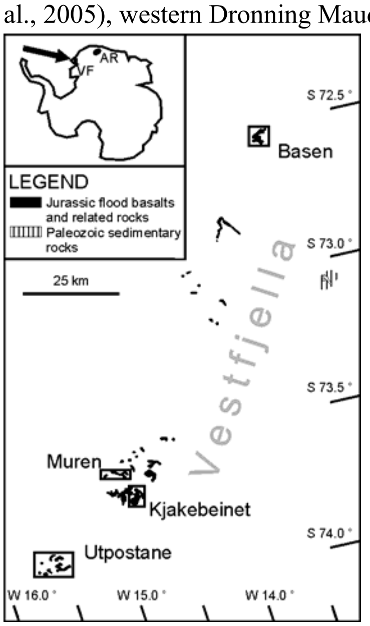

Figure 1. Map of Vestfjella. Ferropicrite localities are indicated. AR=Ahlmannryggen, VF=Vestfjella

Field relations, petrography, and olivine chemistry

The bedrock of Vestfjella (Fig. 1) is dominated by Jurassic tholeiitic CFBs (Luttinen and Siivola, 1997). The VFPG dikes cross-cut the ~180 Ma (Zhang et al., 2003) basalt flows in N-S and NE-SW directions at Basen, Kjakebeinet, Muren, and Utpostane (Fig. 1). The width of the dikes varies between 0.5 and 7 meters. They are mostly porphyritic, but the inner parts of some basaltic dikes contain equigranular subophitic parts.

Olivine (13-27 vol. %), clinopyroxene (29-42 vol. %), and plagioclase (27-34 vol. %) are the main minerals. In the meimechitic dikes, olivine is highly abundant (≤49 vol. %), whereas plagioclase (38-60 vol. %) and clinopyroxene (24-34 vol. %) clearly dominate in the basaltic samples. Olivine is found as euhedral to subhedral, commonly well-preserved phenocrysts in rocks with MgO > 10 wt. %; compositions analyzed from two ferropicritic samples fall in the range of $Fo_{79\text{-}88}$. Clinopyroxene is also euhedral to subhedral and is present as phenocrysts in rocks with MgO < 14 wt. %. Plagioclase has been observed as a phenocryst phase only in basaltic samples with MgO ~5 wt. %. In more primitive rocks, it mainly occurs as subhedral,

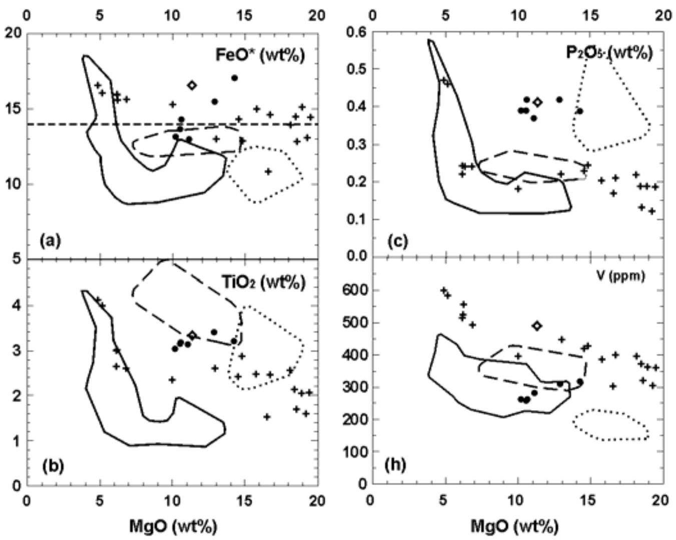

Figure 2. Major, minor, and trace element variation of VFPG. Symbols: cross = D-FP, filled circle = E-FP, diamond = 117-KHG. Fields of Vestfjella lavas (solid line; Luttinen et al. (1998) and Luttinen and Furnes (2000)), Ahlmannryggen ferropicritic rocks (dashed line; Riley et al. (2005)), and Nuanetsi picrites (stippled line; Cox and Bristow (1984) and Ellam and Cox (1989)) are shown for comparison.

interstitial elongated laths in the groundmass together with fine-grained prismatic clinopyroxene and oxides. Crystallized melt inclusions in olivine phenocrysts are abundant. They consist of clinopyroxene, micas, oxides, and euhedral kaersutite.

Geochemical division into enriched and depleted types

In addition to high FeO_T contents (11-17 wt.%), the VFPG dikes show varying degrees of incompatible element enrichment at a given MgO content (Fig. 2): six samples are significantly enriched in TiO_2, P_2O_5 and relatively depleted in V, and are designated as "enriched" ferropicritic types (E-FP). Most of the samples are moderately enriched in TiO_2, significantly enriched in V, but depleted in P_2O_5 relative to E-FP, and are designated as "depleted" ferropicritic types (D-FP). A high-Mg basaltic dike 117-KHG shows transitional features between E-FP and D-FP; notably high FeO_T (16.59 wt. %), TiO_2, and P_2O_5 typical of E-FP are coupled with high V typical of D-FP. Geochemically, VFPG represents a unique magma type within the Karoo LIP (Fig. 2).

The VFPG dikes have mildly to moderately fractionated $(La/Sm)_N$ ratios (D-FP, 1.1-1.3; E-FP and 117-KHG, 1.5-1.8) and strongly fractionated $(Sm/Yb)_N$ ratios (D-FP, 3.2-4.5; E-FP and 117-KHG, 4.9-5.4). Most of the samples have positive Eu-anomalies ($[Eu/Eu^*]_N$ 1.0-1.2). Mantle-normalized incompatible element patterns of D-FP indicate relative enrichment of Sr, Ti, and especially V and relative depletion of Nb and P. Many samples also show positive Ba and K anomalies. In contrast, the incompatible element pattern of E-FP has mostly primitive mantle-like elemental ratios typical of OIBs, small peak only at V, and small troughs at K, Sr, Zr, and Hf. Dike 117-KHG exhibits characteristic features of D-FP, but the overall concentration level is clearly higher.

Origin and evolution of VFPG

Alteration, contamination and fractionation

Detailed modelling of hydrothermal alteration and magmatic differentiation of the VFPG is beyond the scope of this study. We are mainly concerned whether or not the geochemical signatures of these dikes have been significantly modified by such processes. Given that the VFPG dikes are petrographically quite fresh and that individual dikes are geochemically homogenous, alteration has not significantly affected the bulk composition of these rocks. Although large ion lithophile elements (LILE) probably have been mobile to some extent, systematically different Ba and K in D-FP samples from southern and northern Vestfjella probably reflect magma heterogeneity over the study area. The wide range of MgO contents (4.8-27.5 wt. %) and the porphyritic nature of the samples imply that fractional crystallization played a major role in the evolution of VFPG. The ferropicritic D-FP samples probably represent near-primary magmas based on the correspondence between the Mg-numbers of whole-rocks (68-71) and theoretical equilibrium melts (69) derived from the most primitive olivine (Fo_{88}) phenocrysts (see Roeder and Emslie, 1970). Abundant olivine phenocrysts, high Mg-numbers (>70), MgO (>18 wt. %), and high Ni (> 800 ppm) contents indicate olivine accumulation in the meimechitic rocks. Overall, the variations of major elements are accordant with fractional crystallization of the phenocryst assemblages olivine (MgO > 14 wt. %), olivine and clinopyroxene (MgO = 7-14 wt. %), and olivine, clinopyroxene, and plagioclase (MgO < 7 wt. %). Finally, based on primitive mantle affinities and notably the mantle-like Th/Ta (1-2) and Pb/U (5-10) ratios, the VFPG dikes probably represent rare examples of relatively uncontaminated magmas in the Karoo LIP. Consequently, the relatively enriched geochemical signatures of E-FP and 117-KHG are not produced by contamination of D-FP type parent magma. The VFPG dikes and the ferropicritic samples in particular, may thus correspond to near-primary magma compositions and provide information on mantle source regions.

Mantle sources

The distinct geochemistry of E-FP, D-FP, and dike 117-KHG indicate that their parental magmas have been derived from compositionally heterogeneous mantle under varied melting conditions. The varied geochemical signatures indicate distinctive sources for D-FP (and 117-KHG) and E-FP magmas and the high $(La/Sm)_N$ and $(Sm/Yb)_N$ ratios of dike 117-KHG therefore probably reflect low-degree partial melting of the D-FP source at relatively high pressure. The strongly fractionated REE of E-FP may similarly reflect high pressure and low-degree melting or light REE-enriched sources or both.

High $(Sm/Yb)_N$ ratios and low Al_2O_3 contents indicate that garnet was present in the mantle residue of the ferropicrite source. Experimental partial melts of garnet peridotites are poor in FeO_T and TiO_2 (e.g., Walter, 1998) and their MgO contents are too high to represent parental magmas for Vestfjella ferropicrites. Experimental garnet pyroxenite partial melts, however, extend to high FeO_T and TiO_2 typical of ferropicrites (see Hirschmann et al., 2003; Kogiso et al., 2003) and the relatively high Ni contents (> 500 ppm) of the Vestfjella ferropicrites are also compatible with olivine-free mantle residue (see Sobolev et al., 2005), making garnet-pyroxenite a plausible source for VFPG.

The diagnostic positive Sr, Ti, and V anomalies in the geochemical signature of D-FP and dike 117-KHG may help to characterize the pyroxenite source of these magmas. These anomalies reveal a resemblance to signatures typical of gabbroic rocks in which cumulus plagioclase, Fe-Ti oxides, and clinopyroxene concentrate Sr, Ti, and V relative to REE and HFSE (Fig. 3). Given that (1) cumulate Fe-Ti gabbros may comprise a significant portion of subducted oceanic crust (e.g. Hertogen et al., 2002), (2) eclogitization does not significantly affect the geochemistry of subducted oceanic crust (e.g., Becker et al., 2000), and (3) the cumulate signature is expected to be at least partly inherited into partial melts derived from eclogite-peridotite mixtures (Sobolev et al., 2000), a "ghost" cumulate signature in the pyroxenite source could explain the high concentrations of Fe, Sr, Ti, and V in D-FP and dike 117-KHG.

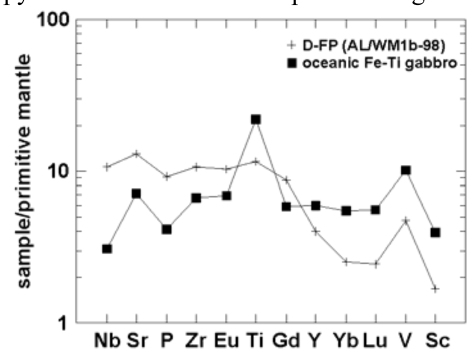

Figure 3. Primitive mantle-normalized trace element signatures of D-FP and an oceanic Fe-Ti gabbro (average of Coogan et al. (2001)). Normalizing values are after Sun and McDonough (1989), except for V and Sc after McDonough and Frey (1990).

The E-FP signature also shows a small peak at V, indicative of an Fe-enriched, Fe-Ti gabbro-bearing source. High-pressure melting (indicated by high $[Sm/Yb]_N$ ratios) may also contribute to the high Fe contents of E-FP, however; experimental partial melts of pyroxenite show positive correlation between pressure and Fe contents of the melts (e.g., Hirschmann et al., 2003). Ferropicritic dike 117-KHG with exceptionally high FeO_T of 16.59 wt.% and fractionated $(Sm/Yb)_N$ may represent the combined effects of magma generation at unusually high pressures and from Fe-rich sources (Fe-Ti gabbro component).

Previous discussions on the ferropicrites have also considered the possible influence of water-bearing sources in the Fe-contents of these rocks and opinions differ as to whether ferropicrites represent hydrous (Hanski, 1992) or anhydrous (Gibson, 2002) magmas. Although we regard that the source composition and melting conditions are the principal factors leading to production of Fe-rich melts, the presence of euhedral kaersutite crystals within inclusions in unaltered olivines of the VFPG dikes indicates that, at the time of the liquid/crystal entrapment, H_2O contents were high enough (2-3 wt. % (Stone et al., 1997)) to stabilize magmatic amphibole.

Relationships with mantle plumes and the Karoo LIP

According to Gibson (2002), the presence of ferropicrites near the base of CFB successions indicates successful tapping of high-Fe melts only if suitable sources are incorporated in the mantle plume starting-heads; in hot plume tails such melts would be diluted by extensive peridotite melting. The evidence from VFPG dikes may challenge this point of view. The VFPG dikes cross-cut at least 1200 m of flood basalt strata and equivalent ferropicritic lava flows are not known in the Karoo LIP. In addition, recent $^{40}Ar/^{39}Ar$ dating of one ferropicritic dike yielded a possible plateau corresponding to ~164 Ma, possibly indicative of crystallization age (Zhang et al., 2003). Consequently, as the most voluminous phase of Karoo magmatism lasted from 184 to 178 Ma (Jourdan et al., 2005), the VFPG dikes appear to represent a late volcanic stage of the Karoo LIP. The general model envisaged by Gibson (2002), however, may also apply to late stages of mantle plumes. We propose that during the waning stage of plume activity in the Karoo LIP, Fe-enriched pyroxenite sources melted in distinct batches and gave rise to Vestfjella ferropicrites that intruded the preceding flood basalts.

Summary

Ferropicritic dikes are found in Jurassic continental flood basalts of the Karoo LIP at Vestfjella, western Dronning Maud Land. The dikes represent near-primary mantle melts (Fo_{79-88} olivine), have not been significantly affected by crustal contamination or secondary alteration, and are geochemically unique among the volcanic rocks of the Karoo LIP. Together with their meimechitic (accumulated) and basaltic (fractionated) equivalents, the ferropicritic dikes of Vestfjella can be divided into two groups based on their distinct trace element geochemistry: (1) Depleted ferropicritic types (D-FP) have $(La/Sm)_N$ ratios of 1.1-1.3, $(Sm/Yb)_N$ ratios of 3.2-4.5, and show relative enrichment in Sr, Ti, and V, and depletion in P; (2) Enriched ferropicritic types (E-FP) have $(La/Sm)_N$ of 1.5-1.7, $(Sm/Yb)_N$ ratios of 4.9-5.4 and show an overall enrichment of incompatible trace elements. Our preliminary results indicate that the high Fe contents of D-FP and E-FP may have been inherited from anomalously Fe-rich eclogite components entrained in pyroxenitic mantle source. Low-degree melting at high pressures, implied by fractionated REE patterns and low Al_2O_3 contents, may also have contributed to the high Fe contents, especially in the case of E-FP. In contrast to other known ferropicrite successions, the Vestfjella ferropicrites represent late-stage plume-related volcanic activity.

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