Lamproite-hosted xenoliths of Vestfjella: implications for lithospheric architecture in western Dronning Maud Land, Antarctica

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Summary Lamproite-hosted xenoliths from Kjakebeinet (73º47'S, 14º53'W), southern Vestfjella, represent unique samples of the unexposed continental crust at the rifted margin of western Dronning Maud Land (WDML). The exposed bedrock of the ice-covered study area comprises Jurassic tholeiites and minor Permian sedimentary rocks. The xenoliths comprise mainly granulite facies metamorphosed igneous and sedimentary rock types; sediments of shallower origin and cognate phlogopitite and silicocarbonatite inclusions are also found. This heterogeneous suite of crustal xenoliths shows textural and compositional affinity to Proterozoic rock types of Heimefrontfjella and Mannefallknausane area. Two leucocratic gneissic tonalites, which probably represent middle crustal levels, yielded U-Pb SHRIMP zircon ages of ~1.0–1.3 Ga. The granoblastic mafic granulites probably represent unexposed lower parts of the continental crust: Mineral–whole-rock Sm-Nd isotope results imply compositional affinity to Proterozoic lower crustal xenoliths from Lesotho, South Africa, and equilibration of the Sm-Nd system during Grenvillean and Jurassic magmatic events. Highest pressures, 11-17 kbars, were recorded by mafic garnet granulites. Overall, these lamproite-hosted crustal xenoliths indicate extension of the Proterozoic Maud Belt crust to Vestfjella.

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Introduction

A minor suite of xenolith-rich lamproite dykes was discovered during the Finnish Antarctic Research Program (FINNARP) expedition in 1997-1998. These 159 Ma dykes cross-cut ~180 Ma flood basalts and represent the youngest magmatic event identified in the WDML (Luttinen et al., 2002). The Sr-Nd isotopic compositions of these dykes imply a mid-Proterozoic lithosphere below Kjakebeinet (Luttinen et al., 2002) whereas the spatially associated flood basalts have been emplaced through Archean lithosphere (Luttinen & Furnes, 2000). The lamproite-hosted xenoliths were sampled during the austral summer 2001 in order to address the age and architecture of the continental lithosphere in the Vestfjella region. The majority of the xenoliths represent crustal rock types, but they include phlogopitite and silicocarbonatite cognate inclusions as well, and minute, possibly mantle-derived nodules. This paper focuses on the petrography and mineralogy of the crustal xenoliths that represent unique samples of bedrock over the large coastal area to the west of Kirwanveggen, Heimefrontfjella, and Mannefallknausane (fig. 1). We use these data and preliminary Sm-Nd data and U-Pb SHRIMP ages to discuss possible relationships between the xenoliths and rock types of the adjacent areas.

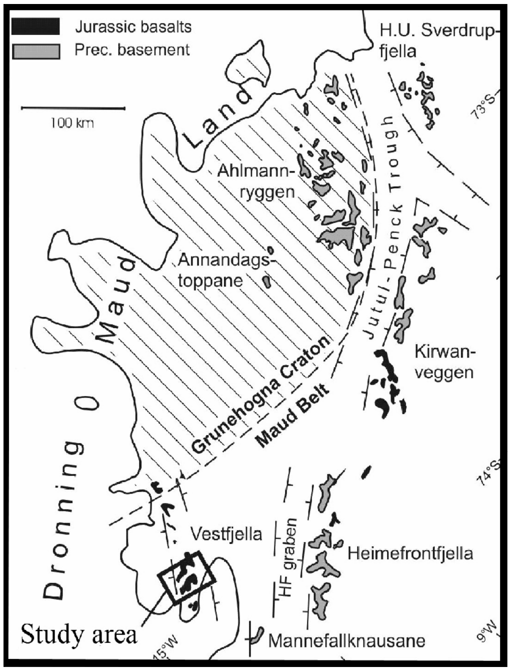

Figure 1. The western Dronning Maud Land, Antarctica. Archean craton, hatched; Precambrian basement, gray; Jurassic basalts, black (modified from Luttinen et al. (2002)).

Regional geology

The Precambrian basement of the Vestfjella mountain range is covered by a thick (>1 km) Mesozoic supracrustal sequence dominated by Jurassic basalts (Luttinen & Furnes 2000). The basement comprises of an Archean craton and a Proterozoic mobile belt that represent extensions of the Kaapvaal craton and the Natal belt of southern Africa, respectively. The Grunehogna craton has a ~3 Ga granitic basement and the overlaying ~1 Ga sedimentary and volcanic Ritscherflya succession is intruded by the mafic 800-1000 Ma Borgmassivet sills (Groenewald et al., 1995). The 1600-900 Ma Maud orogenic belt (Arndt et al., 1991; Groenewald et al., 1995) comprises, at Heimefrontfjella and Mannefallknausane, 1130-1045 Ma, deformed orthogneisses. Heimefrontfjella granulite facies gneisses in the west are separated from amphibolite facies gneisses in the east by a c. 500 Ma mylonite zone (Groenewald et al., 1995). Aeromagnetic studies imply that the suture, developed during the 1000 Ma Grenvillean orogeny (Jacobs et al., 1996), may be beneath Vestfjella (Corner 1994).

The crustal xenoliths

The xenoliths are typically rounded, 3-40 cm in diameter, and mainly represent granulite facies metaigneous and metapelitic rock types. Metabasaltic and metasedimentary xenoliths, probably of lower metamorphic facies and shallower origin, and quartz-rich augen gneissic samples are also present. On the basis of modal and mineral chemical data, the compositions of the metaigneous samples vary from ultrabasic to acid. The mineralogical traits of the various rock types are summarized in table 1.

Table 1. Petrographic descriptions

Group	Rock type	Mineralogy	Texture
Mafic granulite e.g. Xe-16	Garnet granulite	Clinopyroxene plagioclase garnet apatite magnetite ± hornblende ± aegirine	Granoblastic. Anisotropic pseudomorphs after garnet comprises on cryptocrystalline material and occasionally enclose fresh almandine-pyrope. Clinopyroxene show symplectic rims with plagioclase. Plagioclase un-twinned.
Mafic granulite e.g. Xe-11	Meta hornblende pyroxenite -pyroxene hornblende metagabbro	Diopside hornblende plagioclase magnetite apatite calcite	Granoblastic. Igneous layering preserved. Ultramafic layers. Clinopyroxene symplectic with oligoclase. Altered brown hornblende rich in magnetite inclusions.
Mafic granulite e.g. P-6	Meta olivine gabbro - gabbronorite	Plagioclase clinopyroxene biotite apatite zircon ± orthopyroxene ± quartz ± olivine	Gneissic, mafic bands are granoblastic. Pyroxenes have chloritized and minorly uralitizated. Plagioclase albite-twinned.
Felsic granulite e.g. Xe-1	Tonalite gneiss	Plagioclase quartz apatite zircon ± almandine ± rutile ± aegirine?	Granoblastic, plagioclase un-twinned. Secondary, fibrous orthoclase occur along the grain boundaries.
Felsic granulite e.g. Xe-6	Alkalifeldspar granite gneiss	K-feldspar quartz plagioclase ± apatite ± zircon	Equigranular. Feldspars strongly altered. Secondary, fibrous orthoclase is abundant along the grain boundaries.
Felsic granulite e.g. Xe-10	Quartz diorite gneiss	Plagioclase quartz augite apatite zircon rutile magnetite	Granoblastic. Curved grain boundaries. Igneous layering preserved. Quartz undulose, augite show narrow symplectic rims.
Augen gneiss e.g. Xe-5	Augen gneiss	K-feldspar quartz zircon chlorite ± plagioclase ± aegirine? ± apatite	Augen texture, medium-grained. Mafic bands comprise of fine-grained low-Al chlorite/amphibole.
Supracrustal rock types	Metabasalt	Quartz K-feldspar graphite richterite	Aphanitic. Encloses graphite material and pieces of sandstone. Richterite occur as spherulitic aggregates near by dyke contact.
	Granulite facies metapelites	K-feldspar quartz kyanite rutile spinel ± almandine ± orthopyroxene ± zircon	Gneissic, heterogenous. Coronae textures.
	Metasandstone	Plagioclase quartz jadeite magnetite amphibole monazite	Inequigranular; polygonal granoblastic plagioclase surrounds larger grains of saussuritized plagioclase and aggregates of undulose quartz.
	Coalshale	Graphite quartz plagioclase	Graphite layers are interlayered by polygonal albite. Quartz contains graphite dust.

Mafic granulites

The mafic granulies are divided into (1) medium-grained, quartz-free, granoblastic granulites and (2) fine-grained, silica-saturated granulites. (1) Two subtypes of medium-grained, quartz-free, granoblastic granulites are: i) garnet granulites (pl [An_{4-28}] 26-50%; cpx 15-38%; grt 10-22%; hbl 0-10%; opq 8-15%) and ii) garnet-free granulites with relict ultramafic igneous layers (cpx 35-56%; hbl 35-46%; pl [An_{6-23}] 0-18%; mt 6%). The mineralogy of the latter corresponds to metamorphosed hornblende pyroxenite-pyroxene hornblende gabbro. Both types contain abundant titanoferous magnetite. Plagioclase in the garnet granulites is anhedral, and mainly un-twinned. Garnet has been strongly altered to mixture of magnetite and silicates (<1µm); some of the pseudomorphs have cores of fresh almandine-pyrope. Clinopyroxene has cpx-plagioclase symplectite rims. Brown hornblende, when present, is euhedral to anhedral. The garnet-free samples contain ultramafic layers of ferro-pargasitic-hastingsitic hornblende and cpx-plagioclase symplectite. There are three types of plagioclase; anhedral, un-twinned [An_{6-23} from rim to core], subhedral poikilitic albite-twinned, and interstitial, notably unaltered albite [$An_{3.5}$]. The un-twinned type shows fine-grained reaction coronae. On the basis of mineral compositions, the quartz-free granulites have a mildly alkaline character and presumably represent cumulates.

(2) Fine-grained, silica-saturated granulites (pl [An_{0-57}] 49%; cpx 24%; ±ol 18% ±opx ±q) are probably melanosomes

of gneissic rock types; one sample contains a tonalitic leucosome. Subhedral plagioclase is albite-twinned; augite and slighty chloritized enstatite are subhedral. The leucosome vein contains K-feldspar, lacks pyroxenes, and plagioclase is more calcic [An_{21-100}], than in the melanosome [An_{15-35}].

Felsic granulites

The felsic granulites represent metaigneous rock types. Most of them can be classified as tonalites (q 29-40 %; pl [An_{0-32}] 50-60 %; minor grt) and alkalifeldspar granites (K-fsp 50-60%; q 30-40%; pl [An_{2-15}] 0-10%). One of the felsic granulites is quartz dioritic (pl [An_{25-28}] 65%; cpx 18%; q 14 %). The medium-grained, equigranular tonalites show a granoblastic to moderately lineated texture. Anhedral plagioclase is un-twinned and mafic minerals are rare. Fibrous, probably lamproite-derived orthoclase is found along grain boundaries. The medium- to coarse-grained, equigranular alkali feldspar granite gneisses are dominated by anhedral K-feldspar which is strongly altered to clay minerals. Rare subhedral plagioclase shows albite-twinning. The quartz diorite shows relict igneous layering. The grain boundaries are curved and contain magnetite. Anhedral plagioclase includes albite-twinned and un-twinned grains and anhedral augite has narrow symplectic coronae.

Metapelites

The metapelites have sheared and migmatitic appearances. The presence of undulose kyanite, anhedral almandine, and spinel and orthopyroxe as minor corona phases indicate high metamorphic grade. Rutile grains are rounded and constitute a major phase in some samples.

Supracrustal rock types

Small fragments of sandstone (pl [An_{5-24}] 70%; q 30%) represent a common xenolith type. Typically, they are mantled by a green aphanitic rim of diopside and quartz. An aphanitic basaltic xenolith includes fragments of coal shale and sandstone. A discrete coal shale xenolith has also been discovered. The fine-grained sandstone shows inequigranular texture; coarser plagioclase and undulose quartz are surrounded by polygonal granoblastic, mainly albite-twinned, plagioclase. The basaltic xenolith contains corroded quartz, fine-grained unidentified feldspar, polygonal albite, and a high proportion of opaque, iron-silicate material; the overall appearance of the basaltic xenolith is chaotic. The fine-grained coal shale consists of deformed coal layers and intercalated layers of polygonal albite and polycrystalline, undulose quartz with dispersed inclusions of coal dust.

Augen gneisses

Three medium-grained augen gneissic (q+K-fsp+chl/amph) samples were studied. The augens are composed of cross-hatched microcline. Quartz is mainly polycrystalline, sometimes shows a poorly developed ribbon-quartz texture, and comprises, together with strongly altered feldspar, granoblastic boundaries between the augens. Thin mafic layers of very fine-grained, low-aluminium chlorite or amphibole typify these gneisses.

Isotope geochemistry

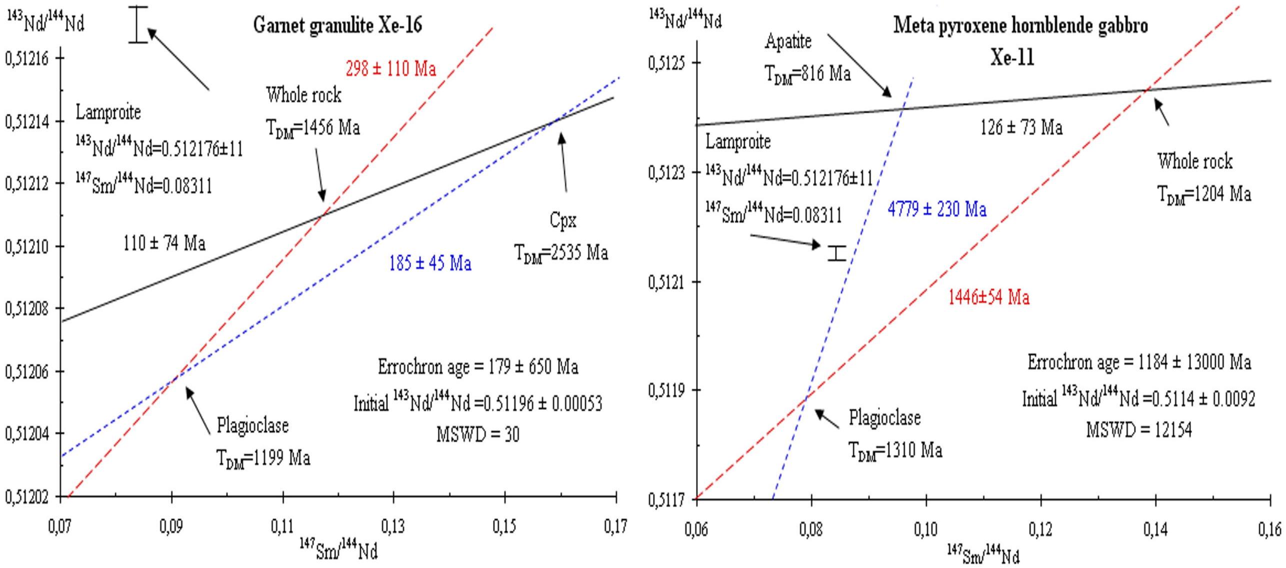

Figure 2. Results of Sm-Nd-study on mafic garnet granulite and quartz-free, layered granulite. Depleted mantle model ages after DePaolo (1981).

Two mafic granulites were analysed for their Sm-Nd isotopic compositions to obtain information on their ages and the nature of their source materials. In addition to whole-rock powders, hand-picked mineral separates were analyzed. The interpretation of mineral whole-rock Sm-Nd isotope data on representative samples of mafic garnet granulites and garnet-free mafic granulites is complicated by lamproite overprint, evidenced, e.g., by minor secondary phlogopite and carbonate at grain boundaries. Neither of the analysed samples yielded precise ages (fig.2). Mineral-whole rock errochrons, depleted mantle model ages (DePaolo, 1981), and feasible ages of the opening of the Sm-Nd system are shown in fig.2.

Discussion

Estimates of pressure

Given the general compositional layering of continental crust (Rudnick and Fountain, 1995), we expected the felsic granulites to record lower equilibration pressures than the mafic ones. The commonness of dis-equilibrium textures hampered quantitative testing of this assumption and we have estimated the pressure conditions on the basis of the observed mineral assemblages. Overall, the mineral assemblages indicate relatively high pressures: The presence of garnet and anatectic veins in the tonalite gneisses refer to 5–14 kbar pressures and the reaction relationship opx + pl = grt +cpx + q suggests higher granulite facies conditions for the layered quartz diorite. For pressure of the mafic granulites we used basalt-eclogite transformation diagrams of Green and Ringwood (1967) for quartz tholeiitic and alkali basalt compositions at 1100 °C. The stability data of TiO_2-rich hornblende provides additional pressure constraints for the layered pyroxene hornblende metagabbros. Summarizing, the garnet granulite mineral assemblage refers to a pressure range of 11–17 kbar, whereas the silica-saturated, garnet-free samples imply a maximum pressure of 14 kbar. The pyroxene hornblende metagabbros indicate pressures of 5-8 kbar. Therefore, the garnet granulites probably represent lower crustal cumulate rocks, whereas the pyroxene hornblende metagabbros may have been derived from the middle crust. The felsic granulites lack suitable mineral assemblages, but their composition is more typical of upper crustal levels. Based on the assemblage of kya, q, K-fsp ±opx ±spl, the metapelites have probably recrystallized at 8 – 11 kbar (cf. Spear 1993).

Correlations to the lithosphere of the adjacent areas

Two felsic granulites have been precisely dated using SHRIMP on zircon separates (J. Jacobs, personal communication, 2006). The samples produced similar age ranges from ~1.3 Ga in the zircon cores to ~950 Ga at the rims, with a pronounced peak at ~1.0–1.1 Ga. The ~1 Ga ages are indistinguishable from the previous U-Pb zircon ages of felsic granulites from Heimefrontfjella and Mannefallknausane, some 100 km of Kjakebeinet (Arndt et al., 1991). The bedrock of Mannefallknausane is dominated by megacrystic A-type granitoids that range from apparently isotropic to strongly sheared types (Luttinen & Siivola, 1996), not unlike some of the augen and alkali feldspar granite gneisses reported in this study. The ~1.3 Ga ages at the cores of tonalite gneiss zircons represent a previously undetected population of U-Pb ages in WDML (Arndt et al., 1991).

Sm and Nd isotopic data for two mafic granulites are shown in Fig. 2. The whole-rock mineral data failed to yield isochrons. The whole-rock Sm-Nd isotopic compositions of the mafic granulites have probably been influenced by infiltration of lamproitic material judged from the presence of secondary phlogopite and carbonate along the grain boundaries and abundant fluid inclusions of apatite. The effect of contamination may have been significant due to notably high concentrations of Nd in the host lamproite (Luttinen et al., 2002). The whole-rock Sm and Nd composition of mafic granulites, however, is indistinguishable from that of the 1.4 Ga lower crustal xenoliths of Lesotho (Rogers and Hawkesworth, 1982) and Mesozoic gabbros of Vestfjella (Vuori et al., 2004). We do interprete some new geochronological constraints on the basis of the mineral fractions of the mafic granulites. In the case of pyroxene hornblende metagabbro the notably low $^{147}Nd/^{144}Nd$ value and the T_{DM} model age (DePaolo, 1981) of 1.31 Ga of plagioclase point to a Precambrian light REE-enriched source; this is also supported by the two-point plagioclase-whole rock "isochron". This layered mafic granulite and the petrographically similar samples may represent the unexposed middle crustal levels of the ~1.1. Ga granulite terrane that extends to the west of the Heimefrontfjella shear zone (Fig 1.). We speculate that they correspond to mafic magmatism that was associated with a ~1.1. Ga bimodal magmatic event that produced the rapakivi-like A-type granitoids of Mannefallknausane (T. Rämö, personal communication, 2007). Bearing in mind the voluminous flood basalt magmatism in WDML ~20 Ma prior to the lamproite intrusion, the Mesozoic age of the mafic garnet granulite sample Xe-16 may reflect resetting of the isotopic system, but it is also quite possible that the sample represents juvenile, Mesozoic crust. The high-grade metapelites seem to represent previously unrecognized lithology in the granulite terrane. Age data for the supracrustal xenoliths are lacking; the metasandstones and coal shales may correlate with the wide-spread Palaeozoic sedimentary cover. The basaltic xenolith is tentatively linked to the Jurassic flood basalt sequence that constitutes the bedrock in Vestfjella and caps the stratigraphic sequences at several locations in WDML.

Concluding remarks

The lamproite-hosted xenoliths indicate extension of the Proterozoic crust to Vestfjella. The upper crustal felsic igneous rocks show affinity to the Proterozoic rock types recorded on Heimefrontfjella and Mannefallknausane. Dominating granulite facies metamorphosis indicates that the study area lay within the granulite facies boundary and is therefore close to Archean Proterozoic suture.

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