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Neoproterozoic Mafic Dykes of the Heimefrontfjella (East Antarctica)

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Abstract: Two generations of Neoproterozoic (post-Grenville-age) mafic dykes have been identified in the Heimefrontfjella. They show amphibolite-facies mineral assemblages in the Sivorg and Vardeklettane terranes and are only weakly metamorphosed in the Kottas Terrane. The older generation of mafic dykes gave a crystallization age of ~1033 Ma and has geochemical characteristics of continental tholeiites. Possible equivalents are the Equeefa dykes from Southern Africa. The age of the younger generation is poorly constraint by a single zircon SHRIMP age of 586 Ma. Geochemically, the second group of mafic dykes has a more primitive E-MORB composition, probably related to ocean-floor basalts of the Mozambique Ocean.

Zusammenfassung: In der Heimefrontfjella wurden zwei Generationen neoproterozoischer (post-grenvillisch) mafischer Gänge identifiziert. Sie wurden im Sivorg- und Vardeklettane-Terrane amphibolitfaziell, im Kottas-Terrane jedoch nur grünschieferfaziell metamorphosiert. Die älteren Gänge wurden auf ~1033 Ma datiert; ihre geochemische Charakteristik entspricht kontinentalen Tholeiiten. Sie könnten den Equeefa-Basalten Südafrikas entsprechen und den beginnenden Zerfall des Namaqua-Natal-Maud Orogens dokumentieren. Die jüngere Generation weist ein durch eine einzige Zirkon-SHRIMP Datierung nur schlecht belegtes Alter von 586 Ma auf. Die geochemische Zusammensetzung weist diese Gänge als E-MOR Basalte aus, die vermutlich Äquivalente der Ozeanboden-Basalte des Mosambik-Ozeans sind.

INTRODUCTION

The Heimefrontfjella was a site of complex tectonics during latest Mesoproterozoic (Grenvillian age) and latest Neoproterozoic/Cambrian times (JACOBS & THOMAS 2002, BAUER et al. 2003a). These two orogenic events are associated with the amalgamation of the supercontinents Rodinia and Gondwana, respectively. Although two distinct metamorphic and tectonic cycles have been distinguished (e.g. JACOBS et al. 1999), records of intervening events such as rift-related magmatism or Neoproterozoic sediments indicating an open Mozambique Ocean between East- and West-Gondwana are scarce. Metamorphosed mafic dykes that clearly post-date the Grenville-aged orogeny and pre-date the East African – Antarctic Orogeny are geological records for a time span, which covers the break-up of Rodinia, the opening and the closure of the Mozambique ocean (DALZIEL 1997, DALZIEL et al. 2000) in a very close distance to the Heimefrontfjella. These mafic dykes have initially been described by WORSFOLD (1967), JUCKES (1972) and SPAETH & FIELITZ (1987). They recognized their altered mineral assemblages and distinguished them from Mesozoic dykes, which are related to the opening of the southern Atlantic Ocean (SPAETH & SCHÜLL 1987). Previous studies confined the age of the metamorphosed dykes between the Grenville-aged wallrock gneisses (ARNDT et al. 1991) and a displacing thrust that gave a K-Ar biotite date of 473 ±11 Ma (JACOBS et al. 1995) (Fig. 1). A detailed geochemical study and two U-Pb zircon SHRIMP ages were published by BAUER et al. (2003b).

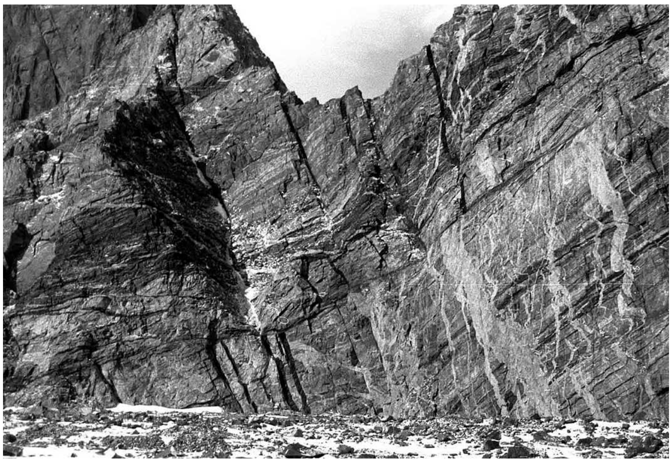

Fig. 1: Up to 6 m thick mafic dykes displaced along a southeast dipping thrust at Vikenegga (Kottasberge), view to SW.

Abb. 1: Bis zu 6 m mächtige, steilstehende mafische Gänge, versetzt durch eine nach SE einfallende Scherzone am Vikenegga (Kottasberge), Blick nach SW.

DISTRIBUTION AND ORIENTATION OF NEOPROTEROZOIC MAFIC DYKES

The distribution of the mafic dykes is shown in Figure 2. A total of 157 Neoproterozoic post-Grenvillian dykes have been mapped in Heimefrontfjella (27 in the Kottas Terrane, 128 in the Sivorg Terrane, and 2 in the Vardeklettane Terrane). In the annotation of the map sheets Vikenegga, Hanssonhorna and Worsfoldfjellet these dykes (MD) are shown as Neoproterozoic to Cambrian in age, since it was possible to identify them based on their relatively low metamorphic grade. On the other map sheets, they are summarized as amphibolites (A) within the group of intrusive magmatic rocks.

The generally steeply dipping mafic dykes (Fig. 3) strike NE-SW in the Sivorg Terrane and N-S in the Kottas Terrane. Some dykes are folded around gently NE plunging axes (FIELITZ & SPAETH 1991). These open to close fold structures are related

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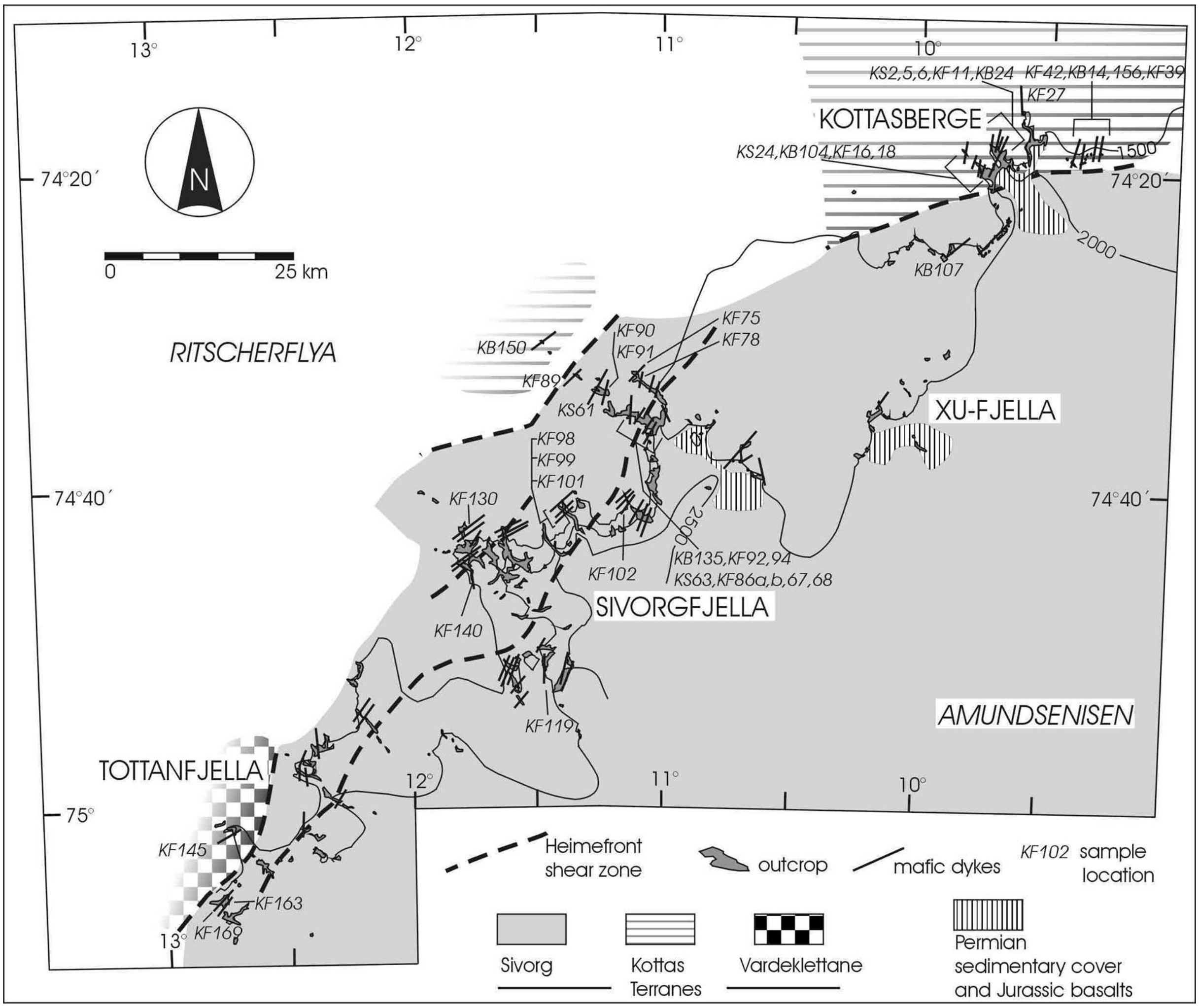

Fig. 2: Geological overview map of Heimefrontfjella with distribution and orientation of Neoproterozoic mafic dykes and sample locations (modified after BAUER at al. 2003b).

Abb. 2: Geologische Übersicht der Heimefrontfjella mit den Lokationen und der Orientierung neoproterozoischer mafischer Gänge (nach BAUER et al. 2003b).

Fig. 3: Amphibolite-facies mafic dykes at Scharffenbergbotnen, Sivorgfjella, clearly crosscutting the subvertical metamorphic foliation.

Abb. 3: Amphibolitfazielle mafische Gänge bei Scharffenbergbotnen, Sivorgfjella. Sie durchschlagen deutlich erkennbar die fast vertikale metamorphe Foliation.

to the Late Neoproterozoic-Cambrian tectonic overprint, which increases from west to east. The thickness of the dykes ranges between 8 cm and 30 m, however most of them are within the range of 1-2 m.

PETROGRAPHY AND GEOCHEMISTRY

The mafic dykes are metamorphosed at different grades. Generally, very fine-grained, greenschist-facies dykes are restricted to the Kottas Terrane in the northern Heimefrontfjella and the Vardeklettane Terrane in southwestern Heimefrontfjella (Fig. 2). Combined X-ray diffractometry and light microscopy revealed a metamorphic assemblage of mainly albite, chlorite, epidote, and clinozoisite. Minor components are titanite, quartz, and calcite. Relics of clinopyroxene and opaque ilmenite, the latter partly replaced by rims of leucoxene, are present in some samples. Many samples preserved a magmatic subophitic texture (Fig. 4), indicated by "shadows" of tabular plagioclase crystals surrounded by remnants of clinopyroxene. A few dykes are sheared and have been transformed to phyllonites.

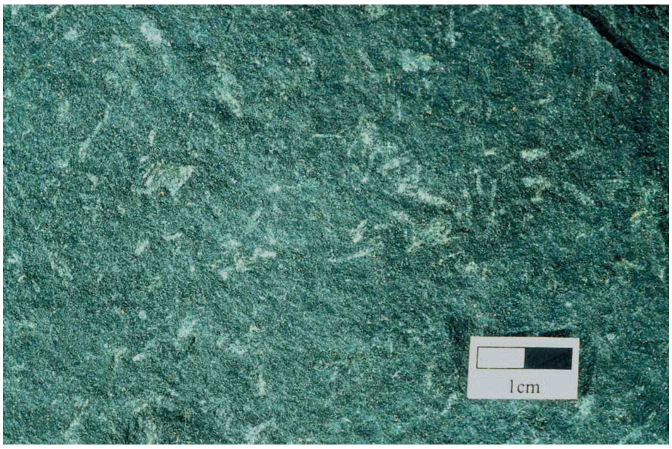

Fig. 4: Sample KF89 (Christophersennabben, Sivorgfjella) showing a subophitic texture. The feldspar crystals are completely replaced by albite, clinozoisite, quartz, and white mica.

Abb. 4: Probe KF89 vom Christophersennabben, Sivorgfjella, mit subophitischem Gefüge. Die Feldspatkristalle sind vollständig durch Albit, Klinozoisit, Quarz und Hellglimmer ersetzt.

Amphibolite-facies dykes contain a metamorphic assemblage of green hornblende, plagioclase, interstitial biotite and chlorite as major constituents. Quartz, epidote and rutile are minor components; trace amounts of apatite and ilmenite are present. The grain size is fine to medium-grained and the minerals show an equigranular granoblastic fabric. A wide-spaced schistosity is defined by the preferred orientation of phyllosilicates. All samples collected in the Sivorg Terrane of central and southern Heimefrontfjella show mineral assemblages indicative for amphibolite-facies metamorphism.

The samples represent two geochemically different groups. Group I samples were collected in all parts of the Heimefrontfjella whereas most samples (but not all) of Group II dykes are restricted to the Sivorg Terrane.

Group I dykes

Group I dyke samples are basaltic to basaltic andesite in composition with SiO_2 contents ranging from 44.9 to 55.4 wt.% and average FeO_{tot} values of 11.3 wt. %. Using the classification diagram of WINCHESTER & FLOYD (1977), the samples plot within the fields of subalkaline basalts, few samples show a transitional alkaline affinity with relatively high Nb/Y values (Fig. 5a). The subalkaline suite plots in two clusters, which differ in their Ti/Zr ratio: a fairly coherent cluster with Zr/TiO_2 *0.0001 values around 0.05 and a rather scattered cluster with values exceeding 0.06. This pattern depends mainly on considerable variation of the TiO_2 content, ranging from 1.35 to 3.82 wt. %. The Zr/TiO_2 ratio is commonly used as an indicator of different lithospheric mantle sources and/or crustal contamination. In the Zr/Y *versus* Zr diagram (PEARCE & NORRY 1979), the samples scatter across the within-plate basalt field (Fig. 5b).

Total REE abundances of three selected samples (KF 11, KF 14, KF 18) are variable (50-192 ppm), but their REE patterns, normalized to C1 chondrite (MCDONOUGH & SUN 1995) are similar (Fig. 6a). A low LREE/HREE enrichment, indicated by (La/Yb)n ratios between 4.45 and 2.78, and a very small Eu anomaly (Eu/Eu* 0.91-1.03) are all features characteristic of continental tholeiites (DUPUY & DOSTAL 1984). In contrast, KB 156 yields a high total REE abundance of 293 ppm and a $(La/Yb)_n$ ratio of 22.5, more typical for basalts with a calc-alkaline chemistry.

Group II dykes

Group II dykes are basaltic in composition with SiO_2 contents ranging from 43.93 to 53.66 wt. %. In the basalt classification diagram (Fig. 5a), the samples plot in a fairly coherent cluster in the field of subalkaline basalts (some symbols represent two samples with identical Zr/TiO_2 and Nb/Y ratios). The variation of the TiO_2 content is less pronounced, ranging from 1.08 to

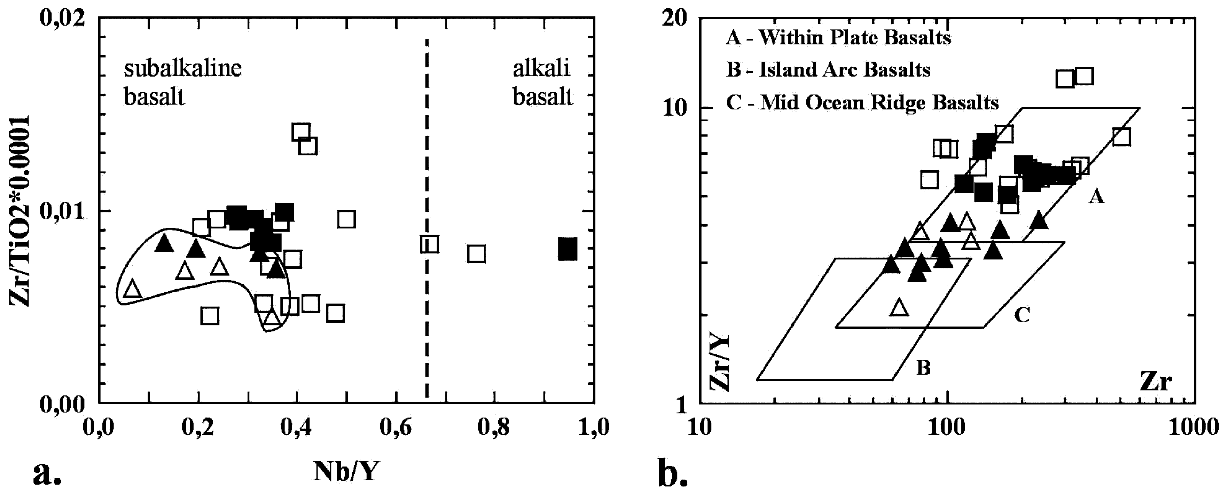

Fig. 5: Geochemical classification of mafic dykes from Heimefrontfjella: (a) using the Zr/TiO_2-Nb/Y diagram of Winchester & Floyd (1977); Squares = Group I dykes, triangles = Group II dykes; open symbols = greenschist-facies samples from Kottas Terrane; filled symbols = amphibolite-facies samples from Sivorg and Vardeklettane terranes. (b) using the Zr/Y-Zr plot of PEARCE & NORRY (1979).

Abb. 5: Geochemische Klassifikation der mafischen Gänge: (a) im Zr/TiO_2-Nb/Y Diagramm von Winchester & Floyd (1977); Quadrate = Gänge der Gruppe I, Dreiecke = Gänge der Gruppe II; offene Symbole = grünschieferfazielle Proben vom Kottas-Terrane; gefüllte Symbole = amphibolitfazielle Proben vom Sivorg- und Vardeklettane-Terrane; (b) Darstellung im Zr/Y-Zr Diagramm von PEARCE & NORRY (1979).

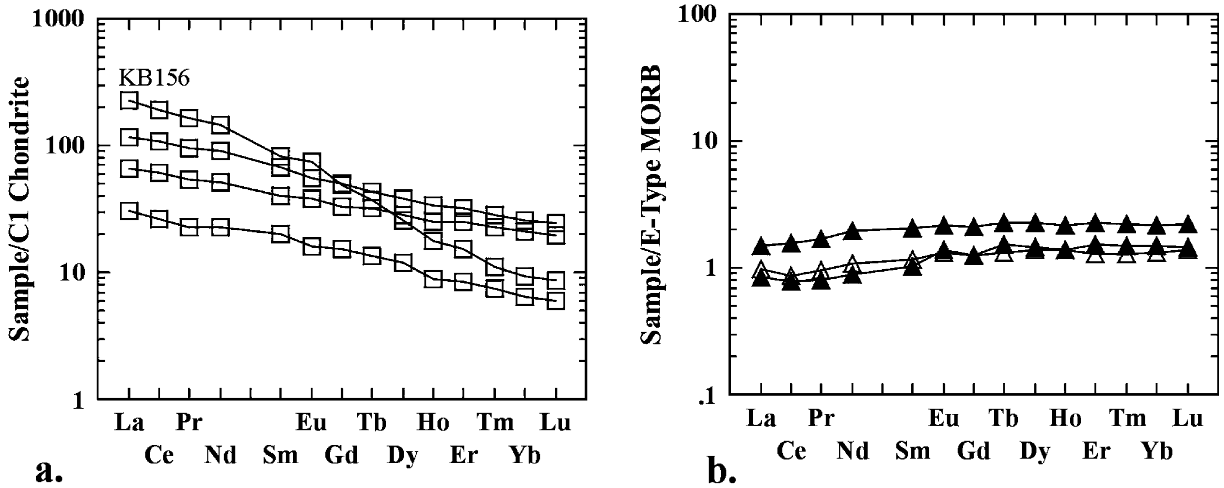

Fig. 6: REE patterns of selected dykes: (a) Group I samples normalized to C1 chondrites (McDonough & Sun 1995). (b) Group II dykes normalized to E-MORB (Sun & McDonough 1989).

Abb. 6: SEE-Verteilung ausgewählter Gänge: (a) Proben der Gruppe I normiert gegen C1 Chondrite (McDonough & Sun 1995); (b) Proben der Gruppe II normiert gegen E-MOR Basalte (Sun & McDonough 1989).

2.91 wt. %. It should be noted, that the average FeO_{tot} content of 12.5 wt. % is even higher than that from the Group I dykes. The precursor rocks may be characterized as high-Fe tholeiites. Due to their significantly lower Zr/Y ratios, Group II samples form a scattering cluster across the mid-ocean-ridge basalt (MORB) and within-plate basalt fields (Fig. 5b) in the Zr/Y versus Zr diagram (Pearce & Norry 1979). Total REE concentrations of three selected samples (KB 135, KF 89 and KF 98) are moderate, ranging between 50 and 90 ppm. LREE are very moderately enriched, as indicated by $(La/Yb)_n$ ratios of 1.33, 1.25, and 1.03. The relatively uniform REE pattern of this group remarkably resembles those of E(enriched)-MORB basalts (Fig. 6b).

GEOCHRONOLOGY

Sample KB 156 was collected from a greenschist-facies dyke (Group I) at the easternmost nunatak of the Kottas Terrane, i.e. northwest of the Heimefront Shear Zone (HSZ, Fig. 2). The sample contains two types of zircon grains. The majority of the zircons are clear small crystals up to 150 μm long and with large length/width ratios of up to 6. In cathodoluminescence images these zircons show a weak prism-parallel zoning (Bauer et al. 2003b). The second, subordinate zircon type is round and brown and is probably inherited.

Fifteen areas were analysed in the first group of needle-type zircons, which gave a weighted mean $^{207}Pb/^{206}Pb$-age of 1033.4 ±7.1 Ma. This age is interpreted as a crystallization age and is probably close to the emplacement of the mafic dyke.

Sample KB 135 was collected from an amphibolite-facies mafic dyke (Group II) in Scharffenbergbotnen, northern Sivorgfjella. The dyke intrudes gneisses of supracrustal, probably volcanic origin and is located close to the HSZ (Fig. 2). From approximately 1.5 kg sample material, only a single, c. 240 μm long zircon grain was extracted, which broke into a number of pieces during sample preparation. The fragments represent a clear zircon that gave a uniform luminescence (Bauer et al. 2003b). Six analyses gave a weighted mean $^{207}Pb/^{206}Pb$-age of 586 ±7 Ma. This age is interpreted as a crystallization age and should be close to the emplacement age of the dyke.

DISCUSSION AND CONCLUSIONS

The mafic dykes of the Heimefrontfjella have been grouped based on their geochemical composition. Group I is characterized by high Zr/Y and $(La/Yb)_n$ ratios and represents a variable suite of (continental) within-plate tholeiite basalts, but in detail the dykes show a quite heterogeneous composition. Common features such as high Zr/Y and $(La/Yb)_n$ ratios indicate significant components of crustal origin in the parental magma(s). The geochronological data of sample KB 156 indicate that the Grenville-age metamorphic basement of Heimefrontfjella was intruded by continental tholeiites at about 1030 Ma. This age is about 30 Ma younger than the post-tectonic pegmatites of northern Heimefrontfjella (~1060 Ma, Arndt et al. 1991) but c. 45 Ma older than the mineral cooling ages from amphibolites and pegmatites west of the HSZ (Ar-Ar hornblende ~1012 Ma, Jacobs et al. 1999, K-Ar muscovite ~960-987 Ma, Jacobs et al. 1995).

Group II dykes have low Zr/Y and $(La/Yb)_n$ ratios, which are characteristic for a magma derived from a MORB-source asthenosphere. The 586 ±7 Ma intrusion age of a Group II dyke from Scharffenbergbotnen predates the oldest Late Neoproterozoic-Cambrian metamorphic zircon ages at ~555 Ma (Jacobs et al. 2003). MORB-type mafic dykes of latest Neoproterozoic age in the Heimefrontfjella suggest the existence of nearby oceanic crust. The Mozambique Ocean between West and East Gondwana still existed at that time, but based on palaeogeographic reconstructions for the Late Neoproterozoic, this ocean was already closing (e.g. Dalziel 1997, Gose et al. 1997).

It seems unlikely that two magmatic events, which produced nearly 160 dykes (and more may been hidden beneath the ice) are restricted to an area of only 130 km x 30 km. The question arises, whether group I and II dykes are part of a greater magmatic province, i.e. are there possible correlatives in adjacent areas? Unmetamorphosed mafic rocks with geochemical signatures of continental tholeiites are known from the Ritscherflya Supergroup of the Grunehogna craton. There, a Late Mesoproterozoic sedimentary sequence is intruded by the Borgmassivet intrusives and is overlain by the Ahlmannryggen flows (Peters 1989). Moyes et al. (1995) obtained an age of ~1000 Ma for the Borgmassivet intrusive rocks using combined Rb-Sr and Sm-Nd whole rock data. This age is poorly constrained and has been under debate, but Groenewald et al. (1991) point to similarities between the Ritscherflya Supergroup of the Grunehogna Craton and the Umkondo Supergroup of the Kaapvaal Craton. Robust U-Pb zircon SHRIMP geochronology for the Umkondo dolerites give an age of 1105 ±2 Ma (Hanson et al. 1998). No robust geochronological data for the basalts from Borgmassivet are available; however, if they are contemporaneous to the Umkondo dolerites, both were formed prior to the Grenvillian deformation in completely different tectonic regimes. Since the Borgmassivet basalts are characterized as high-Mg tholeiites (Peters 1989), whilst the Heimefrontfjella dykes as high-Fe tholeiites, a correlation of Group I dykes from Heimefrontfjella with mafic flows and intrusives of the Grunehogna Craton seems to be unlikely.

For both dyke groups of Heimefrontfjella no direct correlatives have been identified in adjacent areas of Antarctica. In SE Africa, the Equeefa mafic dyke suite (Thomas et al. 1992) is a potential correlative to the older dykes of Heimefrontfjella. It intrudes the Grenville-age basement of the Mzumbe Terrane in Natal. These mafic rocks have been dated at 1024 ±32 Ma using the Rb-Sr whole rock method (Eglington & Kerr 1989). The mafic suite is made up of massive metagabbros, olivine metanorite, and porphyritic metadolerite. The dykes are metamorphosed to amphibolite-facies and were deformed during the final stages of the Grenvillian orogeny. Geochemical characteristics such as a small negative Eu anomaly (Eu/Eu* = 0.8), Fe-enrichment and marked LREE enrichment are common for continental tholeiites. Thomas et al. (1992) suggested an origin of the magma by partial melting of an enriched mantle source, and the Equeefa suite is envisaged as a high level representative of extensive sub-crustal underplating. According to Jacobs et al. (1993), the Kaapvaal-Grunehogna Craton and the Grenville-aged orogen at its southern margin underwent a prolonged phase of SW-NE directed convergence. The shape of the craton and the geometry of the major shear zones point to indentation tectonics (Jacobs et al. 1993). The mafic dykes of Group I in Heimefrontfjella as well as the Equeefa suite in Natal are oriented perpendicular to the main Grenvillian structural trend of the orogen, which is parallel to σ 1 (Fig. 7). This is a preferred orientation of late-tectonic mafic dyke swarms in indentation regimes (Fahrig 1987). The heterogeneous composition of Group I can be the result of long-lasting magmatism during late stages of continental collision, starting with a phase of magmatic underplating of thickened continental crust, followed by a phase of orogenic collapse or beginning rifting.

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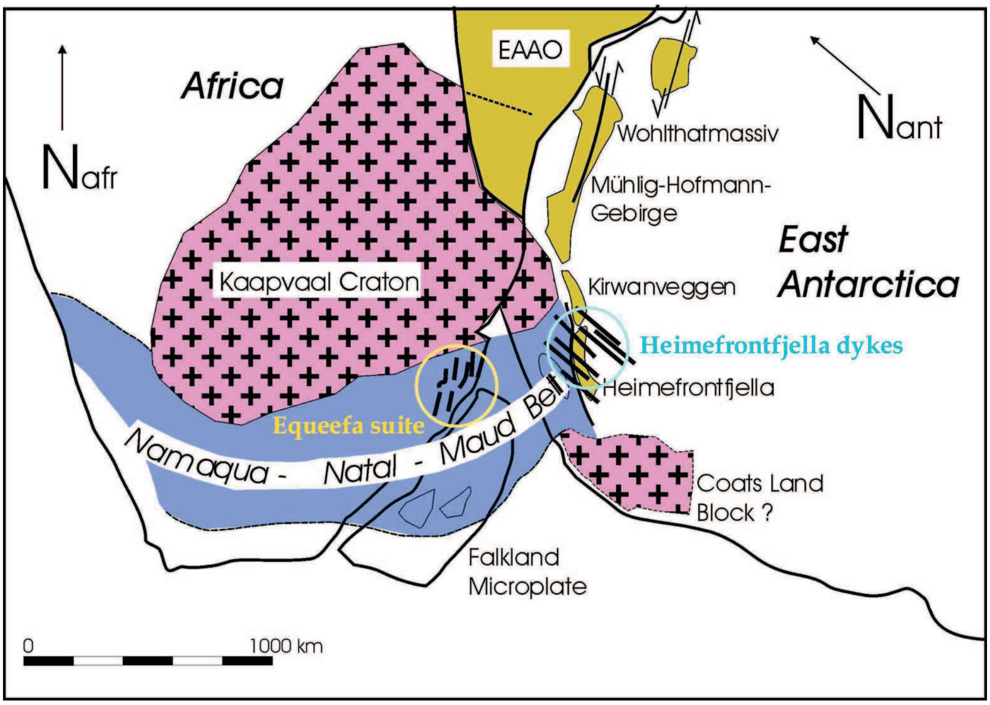

Fig. 7: SE Africa and parts of East Antarctica in a Gondwana reconstruction. Note that the post-Grenvillian dykes in Natal and Heimefrontfjella are oriented subperpendicular to the former continental margin of the Kaapvaal Craton; EAAO = East African–Antarctic Orogen.

Abb. 7: Südöstliches Afrika und Teile Ostantarktikas in einer Gondwana-Rekonstruktion. Bemerkenswert ist die Lage der postgrenvillischen Gänge in Natal und der Heimefrontfjella; sie liegen nahezu rechtwinklig zum ehemaligen Kontinentalrand des Kaapvaal-Kratons; EAAO = Ostafrikanisch – Antarktisches Orogen.

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