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Geology of the Sivorg Terrane, Heimefrontfjella, (East Antarctica), and new U-Pb Zircon Provenance Analyses of Metasedimentary Rocks

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Abstract: The Sivorg Terrane is the largest crustal block of the Heimefrontfjella. It consists of a thick supracrustal sequence of metavolcanic and metasedimentary rocks that are intruded by a wide range of predominantly granitic plutonic rocks. The protolith ages of the metavolcanic rocks have been dated at ~1170-1140 Ma and the granitoid intrusions at ~1110-1050 Ma. The best estimate for Grenville-age metamorphism in the Sivorg Terrane is 1090-1060 Ma. Unlike the other two terranes in the Heimefrontfjella, the Sivorg Terrane records intense reworking of Mesoproterozoic rocks during the Late Neoproterozoic-Cambrian East African – Antarctic Orogeny. U-Pb detrital zircon provenance analyses from two samples indicate that at least two age-groups of different supracrustal sequences crop out in the Sivorg Terrane. The older, preorogenic sequence gave youngest detrital ages of ~1140 Ma, which are interpreted as dating the maximum deposition age of the original sediment. These rocks also provide evidence of a Palaeoproterozoic to Archaean foreland. The second sample is dominated by Mesoproterozoic to late Neoproterozoic detrital zircons, with a significant proportion of ages ranging from 1100 to 980 Ma. The youngest ages significantly postdate the Grenville-age metamorphism, so the sediments must have been deposited after or during the Late Mesoproterozoic orogenesis and, as such, might represent remnants of a molasse deposit of the orogen.

Zusammenfassung: Das Sivorg Terrane nimmt die größte Fläche in der Heimefrontfjella ein. Das Terrane setzt sich aus einer mächtigen Abfolge suprakrustaler Einheiten, bestehend aus Metavulkaniten und Metasedimenten zusammen. Das Protolithalter der Metavulkanite ist ~1170-1140 Ma, Granitoidintrusionen ergaben Alter zwischen 1110 und 1050 Ma. Die grenvillische Metamorphose wurde mit 1090-1060 Ma datiert. Im Unterschied zu den anderen beiden Terranes in der Heimefrontfjella, weist das Sivorg-Terrane eine durchgreifende überprägung durch das spät-neoproterozoische/paläozoische East African – Antarctic Orogen auf. U-Pb Zirkon-Provenanz-Analysen zeigen, dass im Sivorg-Terrane zwei sehr unterschiedliche suprakrustale Einheiten aufgeschlossen sind. Eine prä-orogene Sequenz zeigt jüngste detritische Zirkone mit Altern von ~1140 Ma, welche als maximale Sedimentationsalter interpretiert werden. Diese Gesteine liefern auch Hinweise auf ein paläoproterozoisches Vorland. Die zweite Probe wird stark von mesoproterozoischen Zirkonen dominiert, wobei ein signifikanter Zirkonanteil Alter zwischen 1100-980 Ma aufweist. Die jüngsten Alter sind deutlich jünger als die grenvillische Metamorphose. Deshalb müssen diese Sedimente nach oder während der spät-mesoproterozoischen Orogenese abgelagert worden sein und könnten eine Molasse dieses Orogens repräsentieren.

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INTRODUCTION

The Sivorg Terrane is by far the largest terrane exposed in the Heimefrontfjella (Fig. 1). It is exposed in XU-Fjella, covers the entire Sivorgfjella and the larger part of Tottanfjella. The Sivorg Terrane is juxtaposed against the Vardeklettane Terrane in the SW and the Kottas Terrane in the NW by the Heimefront Shear Zone. The following description of the various lithological units and its structure is based to a large extent on ARNDT et al. (1991), JACOBS et al. (1996, 1999, 2003, 2004) and BAUER et al. (2003).

The Sivorg Terrane is composed of a supracrustal sequence of layered metavolcanic and metasedimentary rocks that are intruded by a diverse suite of igneous rocks. No basement upon which the supracrustal gneisses were deposited has been recognised. The oldest metavolcanic rocks were dated at ~1170 Ma (JACOBS et al. 1999, 2003; Bauer et al. 2003), whilst syn- to post-tectonic meta-igneous rocks were dated from between ~1110 and 1050 Ma (ARNDT et al. 1991, JACOBS et al. 1999, 2003, BAUER et al. 2003). Based on these data, the best estimate for syn-tectonic metamorphism is ~1090-1060 Ma. The entire Mesoproterozoic litho-tectonic history of this terrane therefore spanned no more than 130 Ma (~1170 to 1040 Ma). The terrane represents part of the Maud Belt, which is thought to represent the extension of the ~1.1 Ga Namaqua-Natal Belt of Southern Africa into East Antarctica (see also JACOBS, 2009 this volume).

The Sivorg Terrane bears a strong deformational overprinting imposed during the Late Neoproterozoic to Early Palaeozoic, when the Late Mesoproterozoic rocks were reworked within the East African-Antarctic Orogeny (e.g. JACOBS & THOMAS 2004). The Kottas and Vardeklettane terranes lack this overprint. Therefore, the Heimefront Shear Zone with the Sivorg Terrane to the SE is interpreted as the western orogenic front of the East African-Antarctic Orogen.

LITHOLOGY

Banded gneisses

Approximately half of the exposed basement of the Sivorg Terrane is made up of various amphibolite grade banded gneisses that probably represent a thick supracrustal sequence. Some of these gneisses are compositionally layered, consisting of paragneisses, schists, quarzites, marbles and metapelites, clearly pointing towards sedimentary protoliths. A distinct

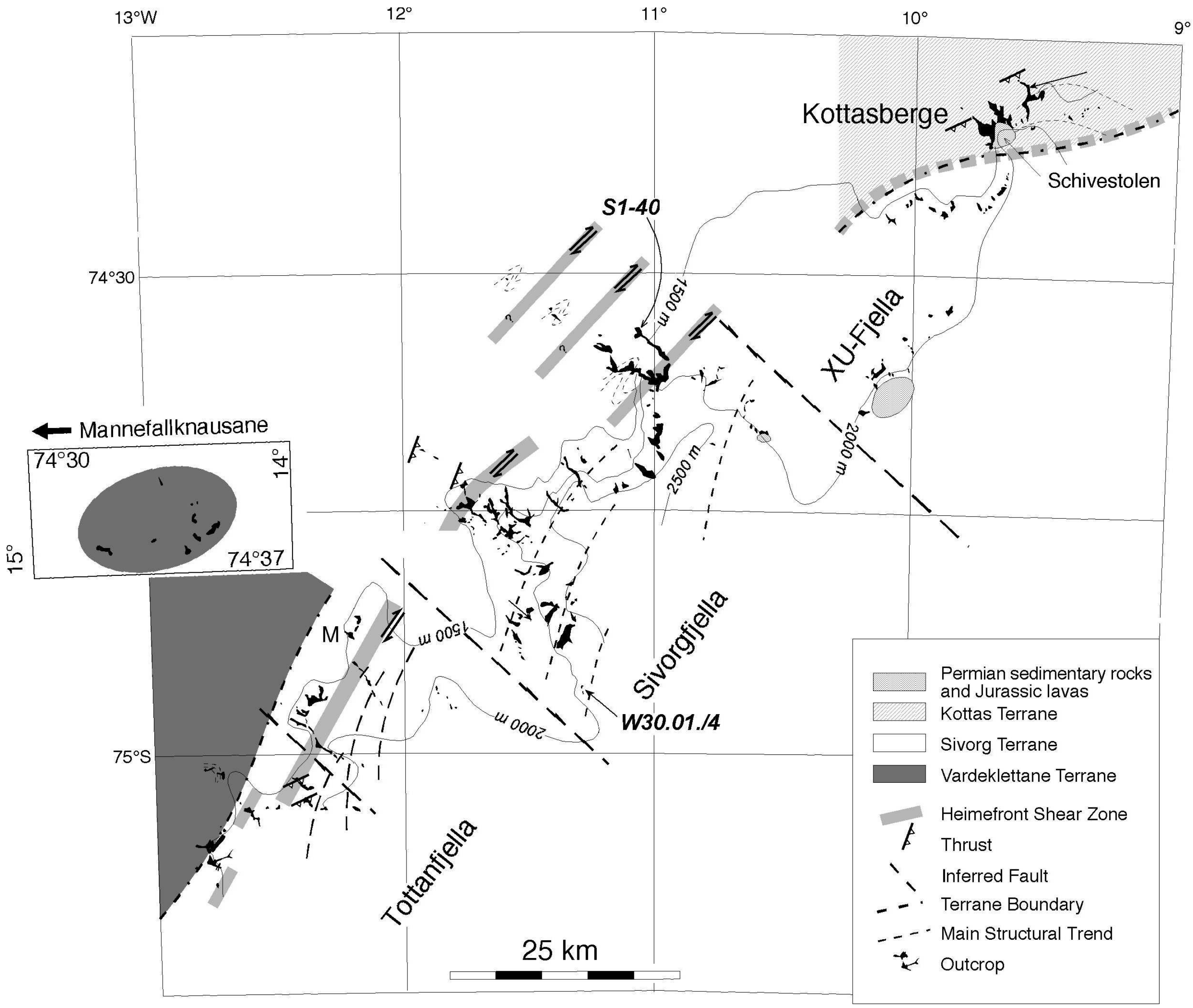

Fig. 1: Geological overview map of Heimefrontfjella, showing the extent of the Sivorg, Kottas and Vardeklettane terranes. Sample locations of zircon provenance analysis samples are indicated.

Fig. 1: Geologische Übersichtskarte der Heimefrontfjella, die die Abgrenzung der Sivorg-, Kottas- und Vardeklettane-Terrane zeigt. Probenlokationen der Zirkon-Provenanz-Analysen sind dargestellt.

suite of "bimodal" banded gneisses is composed of a sequence of interlayered felsic granitic gneisses and mafic amphibolites with sharp lithological boundaries. These bimodal gneisses are thought to represent metavolcanic rocks.

Banded felsic-mafic (bimodal) gneisses (SMV1, SMV2)

These gneisses are well exposed in northern XU-Fjella, northern Sivorgfjella and SE Sivorgfjella. They are characterised by predominantly fine- to medium-grained, pink granoblastic leucogranitic gneisses (SMV1) that are interlayered on a cm- to 100 m-scale with mafic gneisses (amphibolites) and to a lesser extent with intermediate, mesocratic gneisses (Fig. 2A, 2B). Felsic gneisses make up ~70 % of the exposed area. The pink leucogneisses have broadly granitic composition with minor amounts of hornblende, garnet, epidote and titanite. Magnetite occurs as large idioblasts up to 10 mm in size, with a characteristic white reaction halo. Due to the high magnetite concentration, these pink felsic gneisses have magnetic susceptibilities that are considerably greater than other rocks in the mountain range (Jacobs et al. 2004). Some parts show stromatic migmatisation and feldspar blastesis. Geochemically, the pink leucogneisses have high silica contents appropriate to a rhyolitic composition (Bauer et al. 2003). Zircons from four samples of pink felsic gneisses gave U-Pb crystallisation dates, which fall into two groups. Two samples gave 1171 ±25 Ma and 1161.2 ±9.5 Ma, whilst two gave younger dates of 1098 ±11 Ma, and 1086 ±10 Ma (Bauer et al. 2003, Jacobs et al. 2003). We interpret the older group of ~1170 Ma as a good estimate for the crystallisation age of the felsic volcanic protolith rocks, whilst the younger ages suggest that these lithologically and geochemically similar felsic gneisses might represent syn-tectonic granite sheets that intruded the metavolcanic rocks and were thereafter intensely transposed

Fig. 2 A-F: A wide range of supracrustal rocks can be found in Heimefrontfjella. (A): Metavolcanic rocks make up large quantities of the supracrustal gneisses in the Sivorg Terrane. Here is a typical sequence of dominantly felsic metavolcanic rocks (SMV1) at Hansenveggen (sheet Hanssonhorna). (B): Dominantly felsic metavolcanic rocks (SMV1) at Flisegga (sheet Cottontoppen). (C): Dominantly mafic volcanic rocks at Flisegga. These are generally subordinate to felsic metavolcanics. (D): Amongst the metasedimentary rocks, paragneisses (SMS1) occur in large quantities. Here, complexly folded paragneisses at Gerhardsenuten (sheet Scharffenbergbotnen). (E): Type 3 refolding structures with paragneisses at Boyesenuten (sheet Scharffenbergbotnen). (F): Quartzites (SMS3) make up subordinate quantities of the metasupracrustal succession. This quartzite at Ristinghortane (sheet Rhygnuten) was used for detrital U-Pb zircon studies.

Abb. 2 A-F: Eine breite Vielfalt von suprakrustalen Gesteinen steht in der Heimefrontfjella an. (A): Metavulkanite sind ein bedeutender Bestandteil der suprakrustalen Abfolge im Sivorg-Terrane. Hier eine typische Abfolge dominant felsischer Metavulkanite (SMV1) am Hansenveggen (Blatt Hanssonhorna). (B): Dominant felsische Metavulkanite (SMV1) am Flisegga (Blatt Cottontoppen). (C): Überwiegend mafische Abfolgen innerhalb der Metavulkanit-Sequenz treten untergeordnet auf. Hier eine dominant mafische Metavulkanitfolge am Flisegga. (D): Bei den Metasedimenten treten Paragneise in großen Mengen auf. Hier komplex verfaltete Paragneise am Gerhardsenuten (Blatt Scharffenbergbotnen). (E): Typ 3 Überfaltung in Paragneisen am Boyesenuten (Blatt Scharffenbergbotnen). (F): Quarzite (SMS3) treten untergeordnet innerhalb der Metasedimente auf. Dieser Quarzit am Risinghortane (Blatt Rhygnuten) wurde für detritsche U-Pb Zirkon-Analysen herangezogen.

together with the metavolcanic rocks. Alternatively, if both groups are volcanic, then volcanism was protracted, lasting at least 80 Ma.

The mafic layers (SMV2) consist of fine- to medium-grained amphibolites and hornblende-biotite gneisses (Fig. 2C), that are volumetrically subordinate to the felsic gneisses. The mineralogy includes green hornblende, plagioclase and biotite with minor amounts of quartz, epidote, titanite, garnet and other accessory minerals. Geochemically, these rocks classify as basaltic andesite and subalkaline basalt. The mafic metavolcanic rocks are difficult to date directly, due to lack of zircon or baddelyite, but one sample gave an imprecise U-Pb zircon age of 1129 ±31 Ma (BAUER et al. 2003), broadly within error of both age groups of felsic gneiss.

In XU-Fjella (sheets Hanssonhorna and Northern XU-Fjella), subordinate layers of grey gneiss with intermediate, rhyodacitic to dacitic compositions occur within the bimodal gneiss sequence. The grey gneisses, which are interpreted to be intermediate metavolcanic rocks, consist of plagioclase, quartz, biotite and hornblende.

In summary, the bimodal sequence of felsic and mafic gneisses is interpreted as a thick volcanic succession, possibly intruded by high-level granite intrusions of similar composition to the acid volcanics. This interpretation is largely supported by zircon morphology studies and their geochemical compositions (e.g. ARNDT et al. 1991, BÜCKSTEEG et al. 1995, SCHMIDT 2001, BAUER et al. 2003).

Heterogeneously layered gneisses (SMS1, SMS2, SMS3)

The bimodal gneisses are in part interlayered with a variegated sequence of heterogeneously layered gneisses. These gneisses are dominated by interlayered paragneisses, schists, quartzites, calcsilicate rocks and marbles, and thus represent a typical metasedimentary sequence. They crop out throughout the Sivorg Terrane, but are concentrated in the SE part. The total exposed thickness is difficult to estimate due to polyphase intense deformation.

Paragneisses (SMS1) form the most voluminous unit of the heterogeneously layered gneisses (Fig. 2D, 2E). Primary layering in the paragneisses is strongly transposed. They are fine- to medium-grained and are composed of quartz, plagioclase, K-feldspar, biotite, ± muscovite, garnet, hornblende, and sillimanite. The paragneisses show very low magnetic susceptibilities.

Mica schists (SMS2) are interlayered with the paragneisses and occur in approximately equal amount. They are fine- to coarse-grained and consist of biotite, plagioclase, K-feldspar, quartz, ± garnet, kyanite, and staurolite. At Sumnerkammen (sheet Kvitebotnen) these metapelites contain kyanite, garnet, and staurolite assemblages. Scapolite + tourmaline are found in metapelites at Sumnerkammen, in contact aureoles around pegmatites.

Quartzites (SMS3) form mappable units at Ristinghortane (sheet Rhygnuten) and Ustvedhorten (single nunatak N of sheet Furubotnnaben). Otherwise, quartzite is locally found as thin (up to about 1 m thick) layers within mica schists and paragneisses. The quartzite at Ristinghortane (Fig. 2F) contains more than 98 % quartz with accessory muscovite, biotite, K-feldspar, garnet and titanite. It is intercalated with thin layers of calc-silicate rocks and kyanite-staurolite schist. The quartzite at Ustvedhorten is less pure and contains porphyroblasts of K-feldspar rimmed by porphyroblastic muscovite. This muscovite gave an Ar-Ar date of ~970 Ma (JACOBS et al. 1995).

Marbles (SMS4) occur as thin layers interbedded with paragneiss and mica schist. They occur as mappable units at Hauglandkleppen (sheet Bjørnnutane), Scharffenbergbotnen (sheet Scharffenbergbotnen) and Mygehenget (sheet Rhygnuten). At Mygehenget, the marbles form lenses up to 20 m in length, composed of calcite with accessory muscovite, titanite and opaque minerals. They are closely associated with calc-silicate rocks.

At Juckeskammen (sheet Juckeskammen), a about 10 m thick, matrix supported meta-conglomerate/diamictite layer is interlayered with mica schists. Three types of clasts were recognized in this lithotype: quartzite, quartz-feldspar gneiss and garnet-biotite-muscovite gneiss.

Intrusive rocks

The supracrustal rocks of the Sivorg Terrane are intruded by a varied assemblage of igneous rocks. Some form mappable units, whereas others were dismembered and strongly transposed with the supracrustal rocks during polyphase tectonometamorphism. Seven meta-igneous units were mapped, varying in composition from monzonite to granite and diorite. Many of the granitoids are garnet-bearing.

The medium-grained, equigranular Cottontoppen Granodiorite (SG1), which has not been dated, crops out along three sections at Cottontoppen (sheet Cottontoppen). It is composed of plagioclase, quartz, biotite, garnet and accessory apatite and zircon. Quartz ocelli, up to 5 mm in size, suggest that this intrusion has a hybrid nature.

The coarse-grained Juckeskammen Orthogneiss (SG2) makes up large parts of Juckeskammen and Bowrakammen (sheet Juckeskammen). It is a relatively felsic granitic augen gneiss, in which large K-feldspar phenocrysts (up to 5 cm in length) are set in a medium- to coarse-grained matrix of biotite, quartz and recrystallised plagioclase, with accessory apatite, zircon and opaque minerals. Although this orthogneiss is undated and its contacts with other granitoids are not exposed, its consistently highly deformed nature, relative to the other granitoids in the terrane, suggests that it is one of the older intrusive units.

The porphyritic Månesigden Granite Gneiss (SG3) is the most voluminous granitoid intrusion in the Heimefrontfjella (Fig. 2G) and is exposed over large parts of Tottanfjella and Sivorgfjella. Impressive outcrops of SG3 appear at Johsonhogna (sheet Juckeskammen), at Månesigden (sheet Kvitebotnen) and at Wrighthamaren (sheet Scharffenbergbotnen). Mylonitic equivalents of the Månesigden Granite Gneiss can be seen at Bieringmulen (sheet Norumnuten), where it is caught up within the Heimfront Shear Zone. The porphyritic Månesigden Granitic Gneiss contains K-feldspar megacrysts up to 15 cm in length, set in a coarse-grained matrix of variably saussuritised plagioclase, quartz, biotite, garnet and accessory hornblende, titanite, apatite and zircon. The K-feldspar megacrysts are sometimes rounded and show hourglass twinning and some display rapakivi-like overgrowths. A sample from Månesigden provided a U-Pb zircon age (TIMS) of 1048 +36-31Ma, which was interpreted as a crystallization age (JACOBS et al. 1999). A sample from Wrighthamaren gave a U-Pb SHRIMP zircon age of 1104 ±10 Ma (ARNDT et al. 1991). The error ranges of these two ages do not overlap, suggesting that granitoid generation must have taken place over a protracted period of time.

The porphyritic Worsfoldfjellet Monzonite (SG4) crops out in large volumes on sheets Worsfoldfjellet and Cottontoppen. The monzonite (Fig. 2H) has white K-feldspar phenocrysts, up to 5 cm in size, set in a very dark grey matrix of plagioclase, biotite, garnet, and accessory apatite and zircon. Plagioclase is commonly totally saussuritised with carbonate occurring as a retrograde phase. Some early biotite flakes display sagenitic texture, but biotite of a second generation lacks such exsolution features. The Worsfoldfjellet Monzonite contains xenoliths of SG1 and SG3. A U-Pb TIMS zircon age of 1077^{+18}_{-11} Ma is interpreted as the crystallization age of this granitoid (Jacobs et al. 1999). Zircons from the same sample were also dated by the SHRIMP method, which gave a significantly younger age of 1045 ±8 Ma (Arndt et al. 1991), suggesting that early SHRIMP analytical technique may have led to an underestimation of the true age.

The Refsdahlbrekka Granodiorite (SG5) crops out on sheet Rhygnuten and Sirinuten where it appears to have a partly refolded contact with felsic metavolcanic rocks. At Rhygnuten, the marginal zone of the intrusion contains numerous mafic xenoliths (Fig. 2I). This granitoid is undated, but at Malmrusta (sheet Sirinuten), this granodiorite intrudes both the Månesigden Granite Gneiss and the Juckeskammen Orthogneiss. Cuspate-lobate contact relationships between the granodiorite and the Månesigden Granite Gneiss indicate that the SG5 granodiorite intrusion was intruded before the Månesigden granite intrusion had completely solidified.

The Fish Gneiss (SG6) is a medium-grained foliated granodiorite that crops out at Haldorsentoppen (sheet Scharffenbergbotnen). The large abundance of xenoliths (amphibolites, diorites, layered gneisses) is a characteristic feature of this granitoid. This gneiss provided a conventional U-Pb zircon age of 1078 ±30 Ma (Arndt et al. 1991).

The Cottontoppen Granite (SG7) represents the youngest mappable plutonic rock in the Sivorg Terrane. It crops out on sheets Cottontoppen, Worsfoldfjellet, Rhygnuten and Sirinuten. The granite is a leucocratic, fine- to medium-grained muscovite and garnet-bearing granite that is commonly associated with pegmatites. Plagioclase is strongly saussuritised. Late muscovite appears to overgrow the fabric. At Cottontoppen the intrusive contact crosscuts the metamorphic fabrics in the country rock gneisses. The granite itself shows only a weak fabric, and in some parts is better described as a foliated granite (Fig. 2H). Porphyroblastic muscovite from this granite was dated by the K-Ar method at 886 ±19 Ma (Jacobs et al. 1996), but there are no U-Pb zircon data available.

Apart from these mappable units, the basement is intruded by a wide range of small igneous bodies, including a porphyritic gabbro in SE Flisegga (sheet Cottontoppen), various suites of mafic dykes (s.a. Bauer et al., Spaeth 2009 this vol.) as well as numerous aplite and pegmatite veins and sheets. At Wrighthamaren (sheet Scharffenbergbotnen) the Månesigden Granite Gneiss is intruded by a suite of subhorizontal mafic dykes, which are impressively transposed into the Heimfront Shear Zone (Fig. 2J).

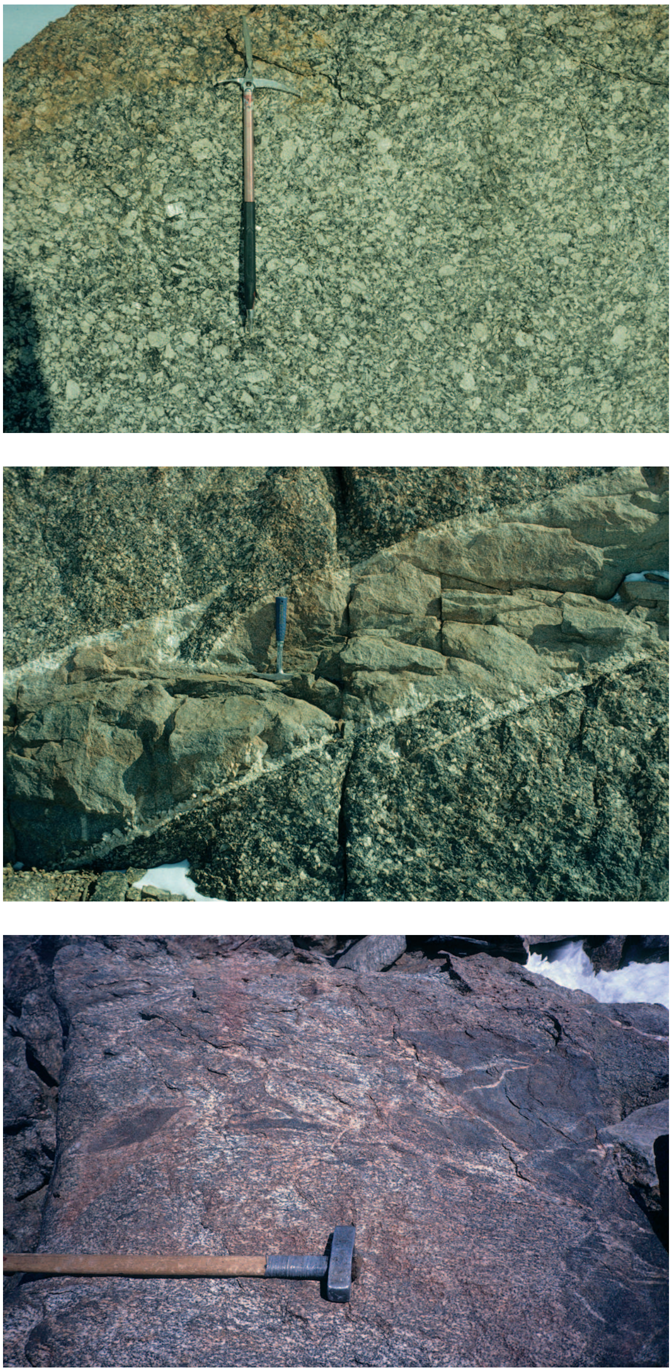

Fig. 2 G-I: Various granitoids intrude the supracrustal rocks. (G): Weakly deformed variety of Månesigden Granite Gneiss (SG3) at Johnsonhogna (sheet Juckeskammen). (H): Intrusion of Cottontoppen Granite (SG7) into Worsfoldfjellet Monzonite (SG4) at Worsfoldfjellet (sheet Worsfoldfjellet). (I): Refsdalbrekka Granodiorite (SG5) with xenolith-rich marginal zone, at Refsdalbrekka (sheet Rhygnuten).

Abb. 2 G-I: Sehr unterschiedliche granitische Gesteine intrudieren die suprakrustalen Einheiten. (G): Nahezu undeformierter Månesigden Granitgneiss (SG3) am Johnsonhogna (Blatt Juckeskammen). (H): Intrusion von Cottontoppen Granit (SG7) in Worsfoldfjellet Monzonit (SG4) am Worsfoldfjellet (Blatt Worsfoldfjellet). (I): Refsdalbrekka Granodiorit (SG5) mit Xenolith-reicher Randzone am Refsdalbrekka (Blatt Rhygnuten).

DETRITAL ZIRCON PROVENANCE ANALYSIS

New U-Pb SHRIMP detrital zircon analyses were carried out on two metasediment samples from central and southern Sivorgfjella in order to gain a better understanding of the nature and age of the source region (fore/hinterland) of the Maud Belt in Heimefrontfjella. A paragneiss sample was collected from NW Scharffenbergbotnen and a quartzite sample from Ristinghortane in southernmost Sivorgfjella (Fig. 1).

U-Pb SHRIMP zircon analyses were carried out on SHRIMP II at the John de Laeter Centre of Mass Spectrometry, Curtin University of Technology, Perth, Australia. The analyses consisted of five scans through the mass range using a spot size of about 20 μm and otherwise followed the method described by WILLIAMS (1998). A detailed analysis of the data is presented in KZIENSYK et al. (2007).

Paragneiss sample S1-40 was collected from the northern tip of Gerhardsenuten (Fig. 1) in northwestern Sivorgfjella (sheet Scharffenbergbotnen), where paragneisses (SMS 1) are interlayered with metavolcanic rocks. The sample is of a typical medium-grained gneiss containing both muscovite and biotite. It is well-foliated and has undergone polyphase deformation. The sample contains small rounded to elongate, mostly clear and colourless zircons, 30-200 μm in size. Zircons have clear core-rim relations, with high-U rims (low cathodoluminescence), probably representing metamorphic overgrowths. All analyses targeted the zircon cores, many of which seem to be fragments of oscillatory zoned zircons, that appear, at least in part, to have undergone mechanical grain size reduction.

Thirty-eight zircon cores were analyzed from 38 grains (Fig. 3a). Of these, two analyses were more than 10 % discordant. The remaining 36 single grain ages ($^{207}Pb/^{206}Pb$) fall into two broad age groups, one between ~1350 and 1140 Ma and a smaller second group between 1850 and 1650 Ma. The youngest grains dated were ~1140 Ma and are thus significantly older than the timing of inferred Grenville-age metamorphism (1090-1060 Ma). The youngest age is interpreted as the maximum age of deposition, which is thus only a little older than the age of widespread volcanism within the Sivorg Terrane. The pre-Mesoproterozoic ages indicate the existence of a Palaeoproterozoic hinterland to this part of the Maud Belt (see also ARNDT et al. 1991).

Quartzite sample W30.01./4 (SMS 3) was collected from a quartzite, several hundred metres thick, that is interlayered with other metasedimentary rocks at Ristinghortane (sheet Rhygnuten). The quartzite has abundant muscovite and shows intense deformation. Both well-rounded and very elongate zircons with length/width ratios up to 5 occur in this sample.

Seventy-two core analyses produced 66 results, which were less than 10 % discordant (Fig. 3b). Of these, 90 % of the ages fall into a single large group, ranging from ~1320-980 Ma ($^{207}Pb/^{206}Pb$). The remaining 10 % of the ages show a large scatter between 1500 and 3000 Ma. The youngest concordant grains were dated at ~980 Ma and a significant amount of grains have ages around 1100-1000 Ma. This age component is younger than the Late Mesoproterozoic metamorphism of the Maud Belt (~1090-1060 Ma) and indicates that the

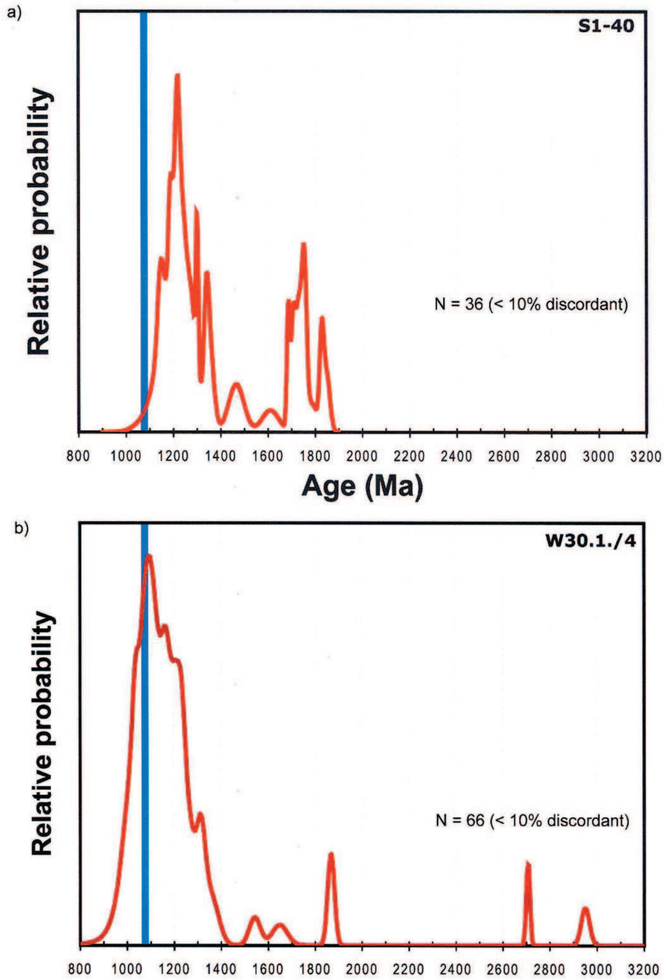

Fig. 3: Probability density diagrams of U-Pb SHRIMP ages of zircons from two metasediment samples from the Sivorg Terrane (see Fig. 1). Blue bar indicates approximate age of Grenville-age metamorphism within the Sivorg Terrane.
(A): A paragneiss sample from Gerhardsenuten shows two major age peaks at ~1140-1350 Ma and at 1650-1850 Ma. The youngest concordant zircon is ~1140 Ma and provides an estimate of the maximum deposition age of this metasediment layer.
(B): A quartzite sample from Ristinghortane is dominated by a broad age peak with ages ranging from 980 to 1320 Ma. A significant proportion of zircon ages is younger than the Grenville-age metamorphism of the Sivorg Terrane and indicates that the analyzed metasediments might represent the unconformably overlying molasse of the Maud Belt.

Fig. 3: *Probability density*-Diagram von U-Pb SHRIMP Zirkon-Altern von zwei Metasediment-Proben aus dem Sivorg-Terrane. Der blaue Balken zeigt das ungefähre Alter der grenvillischen Metamorphose im Sivorg-Terrane.
(A): Eine Paragneissprobe vom Gerhardsenuten zeigt zwei Alters-Häufigkeiten, zwischen 1350-1140 Ma und zwischen 1850-1650 Ma. Die jüngsten konkordanten Zirkone sind ~1140 Ma alt und liefern eine gute Einschätzung für das maximale Ablagerungsalter dieses Metasediments.
(B): Eine Quarzitprobe vom Ristinghortane zeigt eine breite Alters-Häufigkeit zwischen 1320-980 Ma. Eine signifikante Anzahl von Zirkonen ist jünger als die grenvillische Metamorphose des Sivorg Terranes und zeigt, dass die Metasedimente möglicherweise die diskordant das Grundgebirge überlagernde Molasse des Maud-Orogens repräsentieren.

Ristinghortane quartzite is probably part of a sequence which unconformably overlies the metamorphic basement. Unfortunately, the contact with the basement is not exposed, and it therefore uncertain whether it is primary, sedimentary or tectonic. The young, post-metamorphic depositional age suggests that the Ristinghortane quartzite could represent a molasse deposit, containing the erosional detritus of the Maud

Belt. This would explain the dominance of Maud Belt detrital ages within the age spectra. It is uncertain whether the Ristinghortane quartzite differs structurally from the other supracrustal rocks, because of the strong Early Palaeozoic tectono-metamorphic overprint related to the East African – Antarctic Orogen. The full extent of these younger metasedimentary rocks, such as the Ristinghortane quartzite is unknown.

GEOCHEMISTRY

Whole-rock major and trace element geochemistry of all major units of the Sivorg Terrane was performed by a PhD student (M. Tapfer, University of Giessen). Unfortunately, the thesis was never completed and the data were never published. Furthermore, the Geoscience Department of Giessen has closed down and the data are lost.

METAMORPHISM

The metamorphic history of the Sivorg Terrane was studied by Schulze (1992) and Bauer (1995). In general, the Sivorg Terrane is characterized by amphibolite facies metamorphism. However, there are significant metamorphic trends recognized across the terrane. The northern part of the Sivorg Terrane, in XU-Fjella and the southernmost Kottas Berge contain metasedimentary rocks in which the garnets show strong zoning. Garnet cores record peak temperatures of 660 ºC, whilst rims indicate retrograde metamorphism with temperatures at ~550 ºC at ~6.0-4.0 kb. In the southern Sivorg Terrane (Tottanfjella), migmatised metasedimentary rocks have kyanite-staurolite-garnet paragenesis and provided PT data of ~610-580 ºC at ~8 kb. The PT data of the Sivorg Terrane are interpreted to represent the conditions during Early Palaeozoic metamorphism associated with the East African – Antarctic Orogeny, since all thermochronological data (~50 Ar-Ar, Rb-Sr and K-Ar mineral data) show cooling ages of ~500 Ma (Jacobs 2009 this vol.).

STRUCTURE

The structural evolution of the Sivorg Terrane was outlined by Jacobs (1991), Bauer (1995) and Jacobs et al. (1995, 1996, 2003). The main structures seen are now believed to be related to the intense overprint of the Late Neoproterozoic-Early Palaeozoic East African-Antarctic Orogeny (e.g. Jacobs & Thomas 2004). Specifically, the northwestern margin of the Sivorg Terrane was strongly affected by the Early Palaeozoic Heimefront Shear Zone, which is thought to represent the western front of the East African – Antarctic Orogen (Fig. 1).

In the southeastern part, away from the Heimefront Shear Zone, tight to open folding on N to NNE trending and mostly shallow northerly-plunging fold axes is observed (e.g. sheet Rhygnuten). Approaching the Heimefront Shear Zone, however, the dominant fold axes and associated mineral stretching lineations are rotated progressively more to the northeast, subparallel to the general trend of the shear zone (e.g. sheet Norumnuten). Away from the shear zone, fold vergence is to the east, but approaching the Heimefront Shear Zone the folds become upright and NW-vergent.

The Heimefront Shear Zone itself is a complex zone of mylonitization, in which various rocks with Mesoproterozoic protolith ages are commonly difficult to differentiate and map (Figs. 2J, 2K, 2L, 2M). The zone is up to 20 km wide (Fig.1) with a curvilinear outline and fabrics indicative of a dextral transpression zone. In its northeastern part, it trends NE and is associated with shallow NE- plunging stretching lineations. In the southwest, the transpression zone trends NNE and stretching lineations have oblique, down-dip orientations. The widest part of the shear zone is exposed in Sivorgfjella. Here, large lensoid bodies of unmylonitized gneiss occur surrounded by wide zones of the anastomosing mylonite. The preserved lenses often show steeply-inclined fold axes with a geometry suggesting that they were probably generated in a dextral transpressional strain regime (“Schlingen”-tectonics) as seen, for example, on the ridge between Gerhardsenuten and Engenhovet (sheet Scharffenbergbotnen). Jacobs et al. (1999) suggested that the Heimefront Shear Zone probably encompasses several generations of mylonite, and a history of repeated movement is supported by the occurrence of pseudotachylites at Sirinuten (sheet Sirinuten). The Heimefront Shear Zone is also prominent on aeromagnetic images (Golynsky & Jacobs 2001) and can be traced beneath the ice cover.

In some parts of the Sivorg Terrane, fold interference refolding structures are recognized at different scales. The question posed by these structures is whether the older deformation is related to earlier, Grenville-age deformation. At Mathiesenskaget (sheet Rhygnuten), isoclinal F1 folds are refolded by F2 folds. At Boyesenuten (sheet Scharffenbergbotnen) Type 3 refolding structures are well developed in metasedimentary rocks (Fig. 2E). At Sumnerkammen (sheet Kvitebotnen), an earlier set of sheath folds (F1) is refolded by F2 folds (Fig. 2N). Commonly, this earlier deformation phase can only be recognized on the microscopic scale and in general it is only rarely preserved. It has not been possible to ascertain whether the earlier deformation is Grenville in age, or if it is related to an early phase of deformation associated with the East African – Antarctic Orogeny.

POST-OROGENIC TECTONO-THERMAL EVOLUTION OF THE SIVORG TERRANE

The Sivorg Terrane is overlain by Mesozoic sedimentary rocks and basaltic lavas at Lidkvarvet (sheet Gramkroken), and Bjørnnutane (sheet Bjørnnutane). Permian diamictites, sandstones and coals were deposited on a pronounced peneplain, now exposed at an elevation of ~2000 m above sea level. Today, Heimfrontfjella is characterized by pronounced relief. The highest mountain tops reach over 2700 m in southern Sivorgfjella, whilst a deep graben of 800 m below sea-level has been recorded immediately north of the mountain range. Additional fault segmentation occurred along NW-trending faults, now occupied by major glaciers. Since the area was probably a peneplain in Permian times, the mountain range must have undergone a strong post-Permian geomorphic evolution. Apatite fission-track analyses across the mountain range indicate that the entire area was probably covered with a ~2000 m thick lava pile during Jurassic times (~170 Ma), relics of which are still exposed at Bjørnnutane (Jacobs et al.

Fig. 2 J-N: The main structures seen in the mountain range are related to the evolution of the Heimefront Shear Zone. (J): Classic exposure of the Heimefront Shear Zone in SW Scharffenbergbotnen at Wrighthamaren. To the right, the porphyritic Månesigden Granite Gneiss is intruded by numerous mafic dykes. These mafic dykes are strongly transposed into the mylonitic foliation of the Heimefront Shear Zone (central part of the picture). View from ridge between Gerhardsenuten and Engenhovet towards Wrighthamaren (height of wall about 500 m). (K): Fish Gneiss (SG6), here in part highly mylonitic (left) at Haldorsentoppen (sheet Scharffenbergbotnen). (L): Mylonitic variety of the porphyritic Månesigden Granite Gneiss within the Heimefront Shear Zone (SW Scharffenbergbotnen). (M): Shear zone close to the contact between the Kottas and Sivorg terranes at Hasselknippennova (sheet Hanssonhorna). (N): Refolded sheath folds within paragneisses at Sumnerkammen (sheet Kvitebotnen).

Abb. 2 J-N: Die Hauptstrukturen in der Heimefrontfjella sind im Zusammenhang mit der Entstehung der Heimefront Scherzone zu sehen. (J): Klassischer Aufschluss der Heimefront-Scherzone im südwestlichen Scharfenbergbotnen am Wrighthamaren. Rechts erkennt man, dass der porphyrische Månesigden Granitgneiss von zahlreichen mafischen Gängen intrudiert wird. Diese mafischen Gänge sind innerhalb der Heimefront-Scherzone stark eingeschert (zentraler Bildbereich), Blick vom Felskamm zwischen Gerhardsenuten und Engenhovet in Richtung Wrighthamaren (Höhe der Felswand etwa 500 m). (K): Fisch-Gneiss (SG6), hier teilweise stark mylonitisch (links) am Haldorsentoppen (Blatt Scharfenbergbotnen). (L): Mylonitischer Månesigden Granitgneiss innerhalb der Heimefront-Scherzone (südwestlicher Scharfenbergbotnen). (M): Scherzone am Kontakt zwischen Kottas- und Sivorg-Terranen am Hasselknippennova (Blatt Hanssonhorna). (N): Überfaltete *sheath folds* in Paragneisen am Sumnerkammen (Blatt Kvitebotnen).

1992, Jacobs & Lisker 1999). The lavas are related to the Bouvet mantle plume that probably led to dynamic uplift of the mountain range in Jurassic times. The thermochronological studies showed that the lava blanket led to partial to total annealing of apatite fission-tracks until about 100 Ma ago when the mountain range underwent strong block uplift tectonics resulting in rapid erosional exhumation. The highest mountains of southern Sivorgfjella are also those areas that underwent the greatest degree of uplift, and thus differential exhumation probably occurred along NW-trending faults. Surprisingly, the block uplift tectonics is not related to Gondwana break-up at ~170 Ma, but was associated with later plate reorganization, possibly related to the opening of the South Atlantic.

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