Polarforschung 72 (1), 41 - 48, 2002 (erschienen 2004)

Magnetic Susceptibilities of the different Tectono-Stratigraphic Terranes of Heimefrontfjella, Western Dronning Maud Land, East Antarctica

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Abstract: In Heimefrontfjella, western Dronning Maud Land, Grenville-age gneisses are exposed, that are part of the extensive Namaqua-Natal-Maud Belt, fringing the Zimbabwe-Kaapvaal-Grunehogna craton. The eastern portion of Heimefrontfjella was intensely reworked during Late Neoproterozoic / Early Paleozoic times. The up to 20 km wide Heimefront Shear Zone marks the western front of the Late Neoproterozoic/Early Paleozoic East African/Antarctic Orogen. It also separates distinct tectono-stratigraphic terranes and thus is an important structure in East Antarctica. The Heimefront Shear Zone is associated with a particular aeromagnetic anomaly pattern.

This study presents susceptibility data from different rock tpyes across this shear zone, in order to give a better understanding of available aeromagnetic data of this mostly ice-covered region. The surprisingly highest susceptibilities of up to 70 x 10^{-3} SI units were measured in felsic gneisses which are part of a metamorphosed bimodal volcanic sequence. The highly oxidised stage of these felsic rocks is typical for magmatic protolith, originating from a lower crustal source without supracrustal involvement.

Zusammenfassung: In der Heimefrontfjella (westliches Dronning Maud-Land) sind Gneise mit spät-mesoproterozoischem („grenvillischem") Deformationsalter aufgeschlossen, die zum langgestreckten Namaqua-Natal-Maud-Orogengürtel gehören Dieser bildet die südliche bis südöstliche Umrandung des archaischen Zimbabwe-Kaapvaal-Grunehogna-Kraton. Der östliche Teil der Heimefrontfjella wurde in spät-neoproterozoischer/früh-paläozoischer Zeit („panafrikanisch") intensiv tektonometamorph überprägt. Die bis zu 20 km breite Heimefront-Scherzone markiert die westliche Front des an der Wende Neoproterozoikum/Paläozoikum entstandenen „East African/Antarctic Orogen". Die Scherzone trennt auch verschiedene spät-mesoproterozoische tektonostratigraphische Terranes und ist deshalb eine wichtige Strukturgrenze innerhalb der Ostantarktis. Sie wird auch durch eine auffällige aeromagnetische Anomalie abgebildet.

Die vorliegende Arbeit präsentiert Suszeptibilitäts-Daten von verschiedenen Gesteinstypen, die innerhalb und auf beiden Seiten der Scherzone analysiert wurden. Ziel dieser Arbeit war es, eine bessere Interpretation von aeromagnetischen Daten in dieser überwiegend eisbedeckten Region zu ermöglichen. Überraschenderweise lieferten felsische Gneise einer bimodalen Sequenz die höchsten Suszeptibilitäten mit bis zu 70 x 10^{-3} SI-Einheiten. Diese felsischen Gneise entstanden aus magmatischen Vorläufergesteinen die unter hohen Sauerstoffpartialdrücken kristallisierten. Dies ist typisch für Magmatite, die durch Aufschmelzung kontinentaler Unterkruste ohne Beimengungen suprakrustaler Komponenten entstanden.

INTRODUCTION

Heimefrontfjella in western Dronning Maud Land forms part of the several thousand kilometres long Namaqua-Natal-Maud Belt (Fig. 1). This c. 1100 Ma orogenic belt fringes the southern and eastern margin of the Zimbabwe-Kaapvaal-Grunehogna Craton (e.g. JACOBS et al. 1993). The high-grade Namaqua-Natal-Maud Belt is interpreted to have resulted from continent-continent collision with an unknown counterpart, possibly Laurentia (DALZIEL et al. 2000). The eastern part of the orogen was intensely overprinted during the collision of East and West Gondwana, along the c. 550 Ma East African/Antarctic Orogen (JACOBS et al. 1998). The western orogenic front of this orogen is thought to be exposed in Heimefrontfjella (GOLYNSKY & JACOBS 2001).

The Namaqua-Natal-Maud Belt is fragmentarily exposed along its length. In southern Africa, it is widely covered by sedi-mentary rocks of the Karoo Supergroup; in Antarctica, it is mostly hidden under the ice and is only exposed in a few places such as Heimefrontfjella. However, the orogen is characterised by a distinct anomaly pattern, so that the structure of the orogen can easily be traced under the various cover. It also makes it distinguishable from the Zimbabwe-Kaapvaal-Grunehogna craton to the north (DE BEER & MEYER 1983, CORNER & GROENEWALD 1991). The anomaly pattern of the orogen is characterised by craton-parallel, very elongate high-amplitude positive and negative anomalies, with long wavelength. The largest of these anomalies is the Beattie anomaly in southern Africa (Fig. 1). This anomaly could represent a Grenville-age suture. The characteristic anomalies can be traced into East Antarctica, where they sharply terminate at the Heimefront Shear Zone (Fig. 2). East of the Heimefront Shear Zone, these anomalies are not existent since the Namaqua-Natal-Maud Belt has been intensely reworked by the c. 550 Ma East African/Antarctic Orogen. In Heimefrontfjella, Grenville-age and Pan-African structures trend at almost right angles, so that the temporally different magnetic anomalies can readily be differentiated. This is different further to the NE, such as in Sverdrupfjella, where Grenville-age and Pan-African structures are co-linear and are often indistinguishably superimposed. Pan-African structures east of the Heimefront Shear Zone are represented by low-amplitude and short wavelength magnetic anomalies.

In this study we measured the magnetic susceptibilities of the different lithologies east, west and within the Heimefront Shear Zone in order to understand which rock types and/or structures are the main sources of the magnetisation at the surface. It is thought that this would lead to a better understanding of the magnetic anomaly pattern seen in the different terranes, and would help to understand ongoing and future aeromagnetic studies in the large ice covered areas of East Antarctica.

GEOLOGICAL SETTING

Heimefrontfjella is characterised by three distinct tectono-stratigraphic terranes, the Kottas, Sivorg and Vardeklettane terranes (Fig. 3), the geology of which is summarised in JACOBS et al. (1996). The Kottas and Vardeklettane terranes are separated from the Sivorg terrane by the up to 20 km wide

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Manuscript received 03 March 2003; accepted 13 October 2003

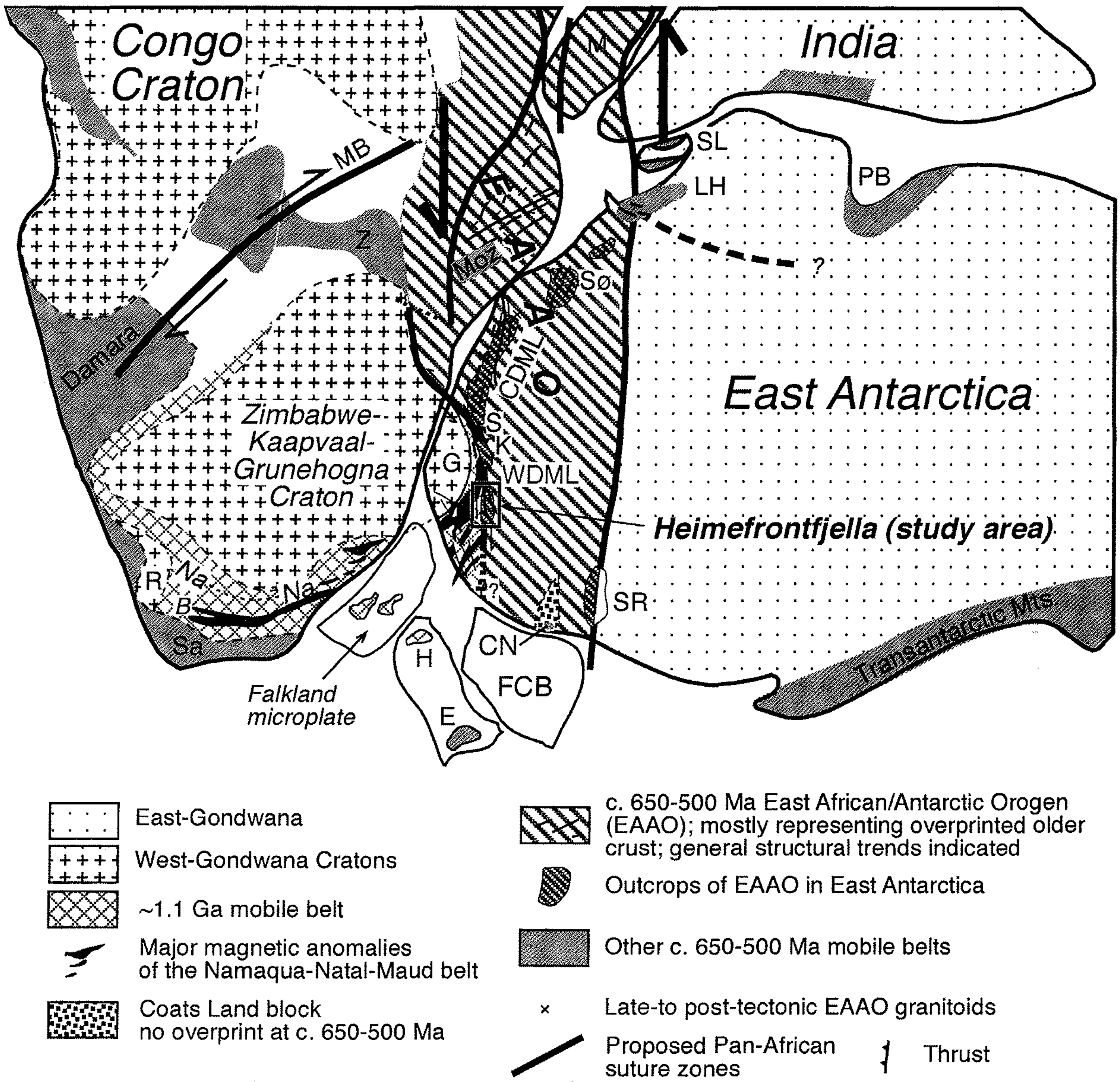


Fig. 1: Location of the study area in a Gondwana reconstruction after GRUNOW et al. (1996), SHACKLETON (1996) and JACOBS et al. (1998, 2003) with major Late Neoproterozoic/Early Palaeozoic belts indicated. The study area Heimefrontfjella is situated within the c. 1.1 Ga Maud Belt and at the western front of the c. 650-500 Ma East African/Antarctic Orogen (EAAO) in western Dronning Maud Land, East Antarctica. Abbreviations: B - Beattie magnetic anomaly, CDML - central Dronning Maud Land, CN - Coats Nunataka, EM - Ellsworth Mts, FCB - Filchner Crustal Block, G - Grunehogna Archean cratonic fragment, H - Haag Nunatak, K - Kirwanveggen, LH - Lützow Holm Bay, M - Madagascar, MB - Mwembeshi Shear Zone, Moz - Mozambique Belt, Na-Na - Namaqua-Natal Belt, PB - Prydz Bay, R - Richtersveld Craton, S - Sverdrupfjella, Sa - Saldania Belt, SL - Sri Lanka, Sø - Sør Rondane, SR - Shackleton Range, WDML - western Dronning Maud Land, Z - Zambezi Belt.

Abb. 1: Lage des Arbeitsgebiets innerhalb Gondwanas nach Rekonstruktion durch GRUNOW et al. (1996), SHACKLETON (1996) und JACOBS et al. (1998, 2003) in Beziehung zu den dominanten spät-neoproterozoischen/früh-paläozoischen Mobilgürteln. Das Arbeitsgebiet, die Heimefrontfjella, ist Teil des c. 1.1 Ga Maud Orogens und befindet sich an der westlichen orogenen Front des ca. 650-500 Ma alten East African/Antarctic Orogen (EAAO) im westlichen Dronning Maud Land.

Heimefront Shear Zone. The Kottas and Vardeklettane terrane to the NW of the shear zone lack a Pan-African overprint, whilst the Sivorg terrane to the SE of it is intensely overprinted.

The Kottas terrane is mainly made up of amphibolite facies metamorphic rocks derived from igneous protoliths. They occur as sheet-like augen gneisses, a meta-trondhjemite-tonalite-diorite suite and grey biotite-plagioclase gneisses containing euhedral zircons of possible volcanic origin. Paragneisses and calcsilicate rocks, together with amphibolite slices are known, but are of restricted extent, being only exposed in some isolated nunataks in the NE and in a syncline in the north of the Kottas terrane. The metaigneous rocks have a typical calcalkaline subduction-related signature, whereas the amphibolites in the supracrustal sequence have an oceanic affinity (BAUER 1995).

The Vardeklettane terrane is exposed in SW Heimefrontfjella and Mannefallknausane. It is made up of granulite facies rocks including charnockites, layered cordierite-sillimanite gneisses and two-pyroxene granulites. Inverted pigeonite indicate peak metamorphic temperatures in excess of 900 °C. These rocks have Grenville-age protolith ages (ARNDT et al. 1991) and K-

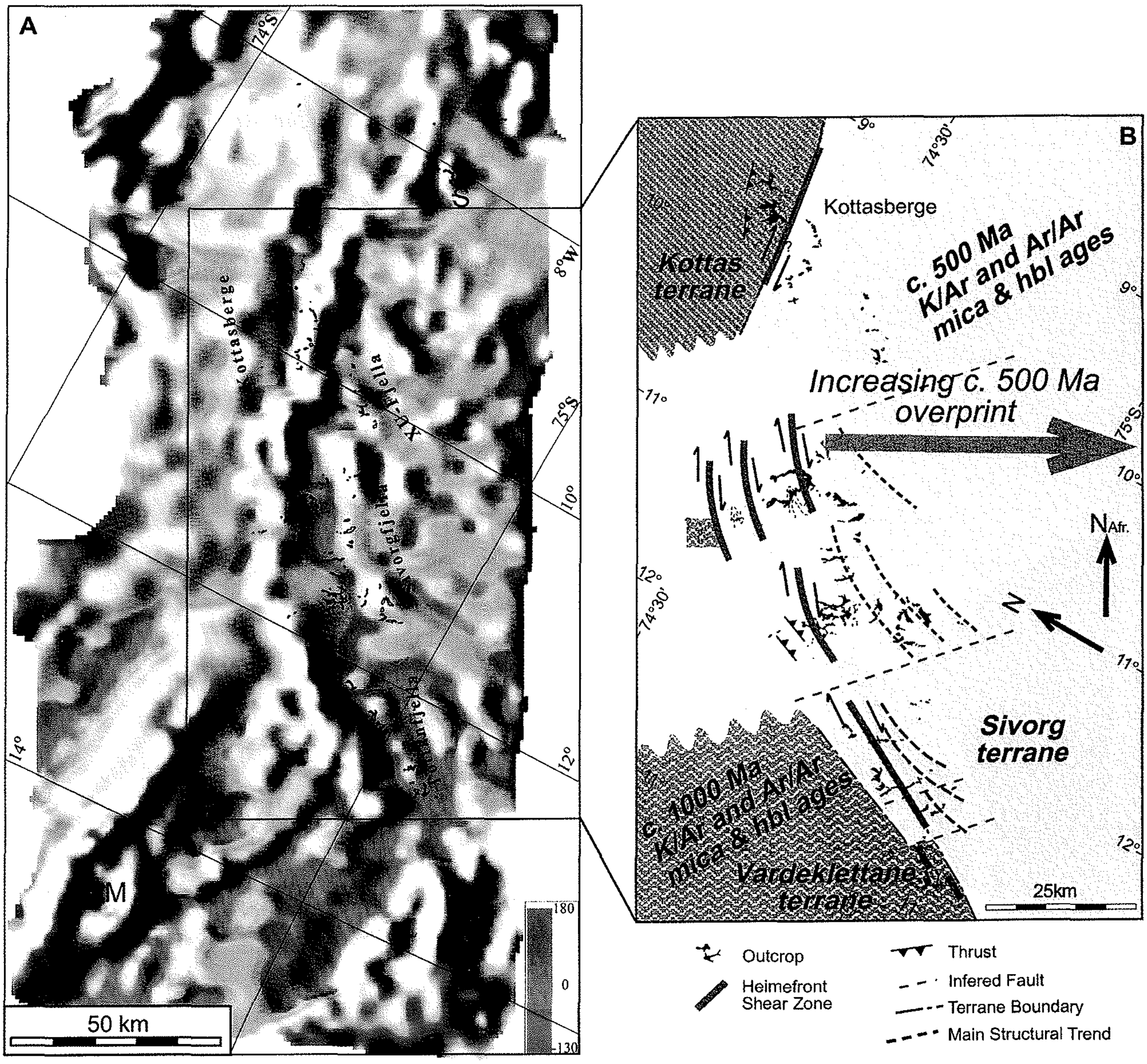


Fig. 2: A) Aeromagnetic shaded relief map (first veritcal derivate) of Heimefrontfjella and adjacent areas (after GOLYNSKY & JACOBS 2001). Abbreviations: M – Mannefallknausane, S – Semberget.
B) Geological overview map of Heimefrontfjella, after rotation into its "African" position in Gondwana (after JACOBS et al. 1996). Heimefrontfjella is separated into three distinct c. 1.1 Ga tectono-metamorphic terranes. Whilst the Kottas and Vardeklettane terranes are characterised by only minor Late Neoproterozoic/Early Palaeozoic overprint in the form of discrete mylonite zones, the Sivorg terrane is typified by strong pervasive Late Neoproterozoic/Early Palaeozoic reworking. The dextral Heimefront transpression zone appears to separate crust with a weak Late Neoproterozoic/Early Palaeozoic overprint to the west from strongly overprinted crust to the east. Also indicated is a succession of mostly felsic metavolcanic rocks that appear to be highly magnetic.

Abb. 2: A) Aeromagnetic „shaded relief" Karte (erste vertikale Ableitung) der Heimefrontfjella und angrenzender Gebiete (nach GOLYNSKY & JACOBS 2001).
B) Geologische Übersichtskarte der Heimefrontfjella nach Rotation in ihre Position innerhalb Gondwanas (nach Jacobs et al. 1996). Heimefrontfjella lässt sich in drei verschiedene ca. 1.1 Ga tektono-metamorphe Terranes unterteilen. Während das Kottas und Vardeklettane-Terrane lediglich durch geringe spät-neoproterozoische/früh-paläozoische Überprägung in Form diskreter Mylonitzonen gekennzeichnet ist, zeichnet sich das Sivorg-Terrane durch eine starke spät-neoproterozoische/früh-paläozoische Überprägung aus. Dabei trennt die dextrale Heimefront-Scherzone Kruste mit schwacher spät-neoproterozoischer/früh-paläozoischer Überprägung im Westen von strarker Überprägung im Osten.

Ar mineral ages not younger than 880 Ma (JACOBS et al. 1995), proving the lack of a pervasive Pan-African overprint.

The Sivorg terrane covers the largest area in Heimefrontfjella. It is composed of a thick volcano-sedimentary sequence that is intruded by voluminous granitoids. Metasedimentary rocks consist of metapelites, calcsilicates, marbles, quartzites and paragneisses. Metavolcanic rocks are made up of a bimodal sequence of felsic and mafic rocks, of which ca. 70 % are felsic rocks. Further metaigneous rocks occur as megacrystic augen gneisses, pegmatites, aplites and amphibolites. The metaigneous rocks of the Sivorg terrane have crystallisation ages of c. 1100 Ma and K-Ar and Ar-Ar cooling ages of c. 500 Ma (JACOBS et al. 1995, 1997, 2003).

Within the up to 20 km wide Heimefront Shear Zone, rocks of the three different terranes have been mylonitised to different degrees. The shear zone is steeply inclined and has a pronounced curvilinear outline. It is not clear whether the Heimefront Shear Zone was initiated during Pan-African times or has an older Grenville-age history. However, its Pan-African history is characterised by dextral transpression. In its

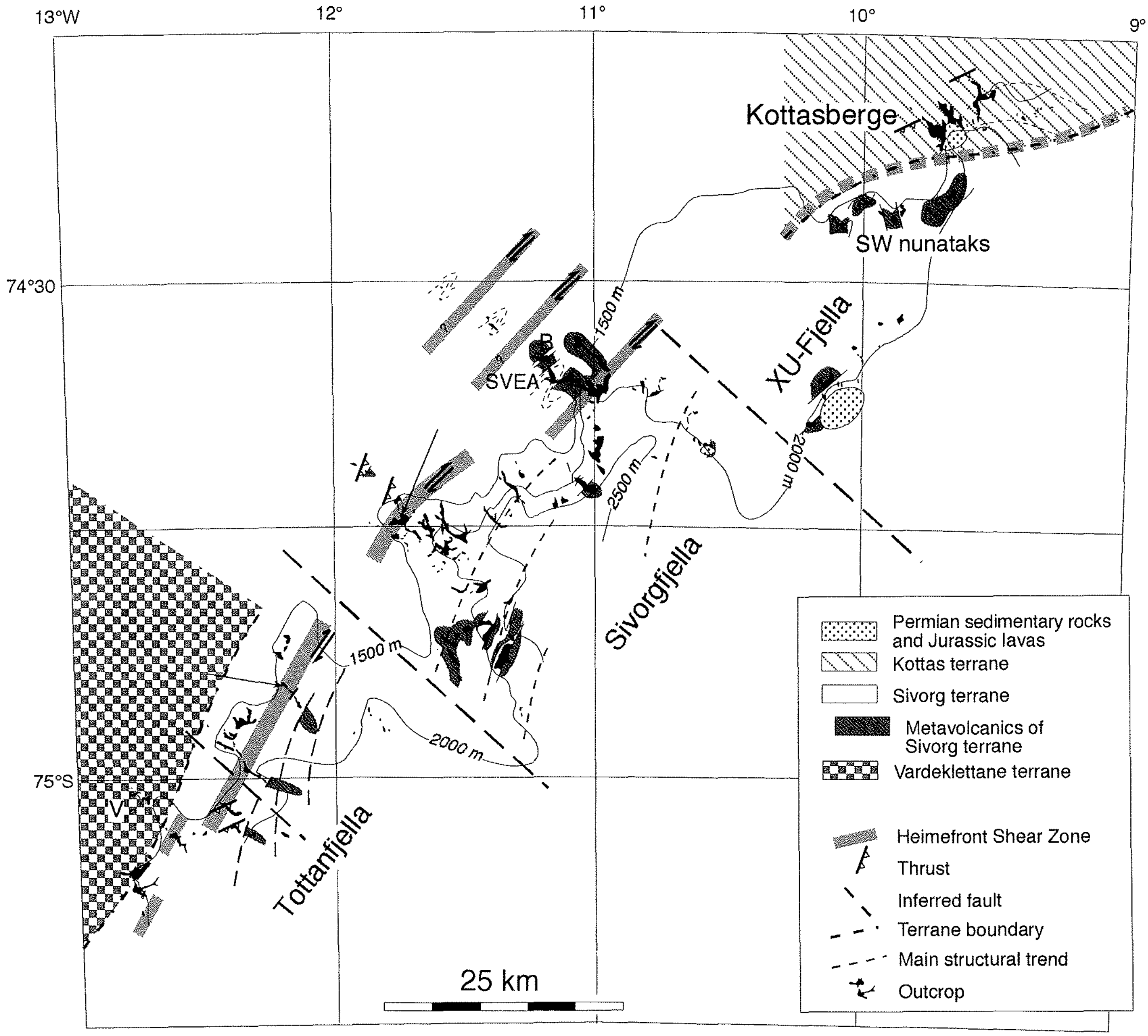


Fig. 3: Geological overview map of Heimefrontfjella with place names and the locations of major, highly magnetic metavolcanic sequences. Abbreviations: B - Boyesenuten, V - Vardeklettane.

Abb. 3: Geologische Übersichtskarte der Heimefrontfjella und Lokation dominanter, stark magnetisierter Metavulkanit-Abfolgen.

northern part the transcurrent component dominates, whilst towards the south compressional elements increase, indicated by the increasingly downdip orientation of the mylonititc stretching lineations towards the south (JACOBS et al. 1996).

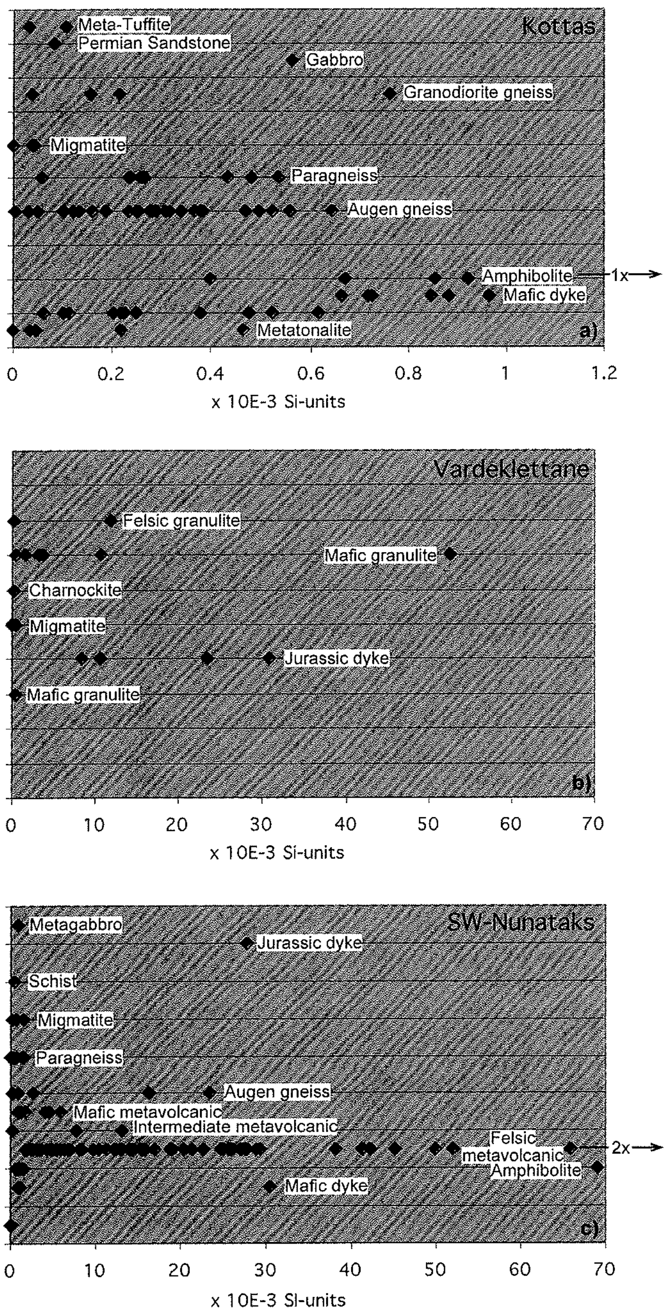
Post-tectonic rocks include Permo-Carboniferous sedimentary rocks of the Beacon Supergroup, that unconformably overly the basement in a few isolated places in the northern and central part of the range. Jurassic dykes and sills intrude these rocks in small quantities locally.

MAGNETIC SUSCEPTIBILITIES

Magnetic susceptibilities were measured using a Kappa metre, Explorarium KT-9, in pin mode. Measurements were carried out at almost 350 localities within the Kottas and Sivorg terranes and the Heimefront Shear Zone. At each locality ten measurements were taken within an area of up to 10 m^2. The means of these ten analyses are plotted in Figures 4a-f. Typical standard deviations are 10-20 %, occasionally higher. Susceptibility measurements were carried out on all major and minor lithologies as well as on different shear zones. From the Vardeklettane terrane no field measurements are available however, representative measurements on 23 rock specimens were carried out in the laboratory with a Kappa metre, Explorarium KT-5, in normal mode. For the latter measurements only rock samples with a volume of 10 cm^3 or larger were analysed. It was attempted to use even rock surfaces.

Kottas terrane

Within the Kottas terrane magnetic susceptibilities were carried out at 79 localities. The analysed lithologies included paragneisses and metatuffites, migmatites, augen gneisses, a



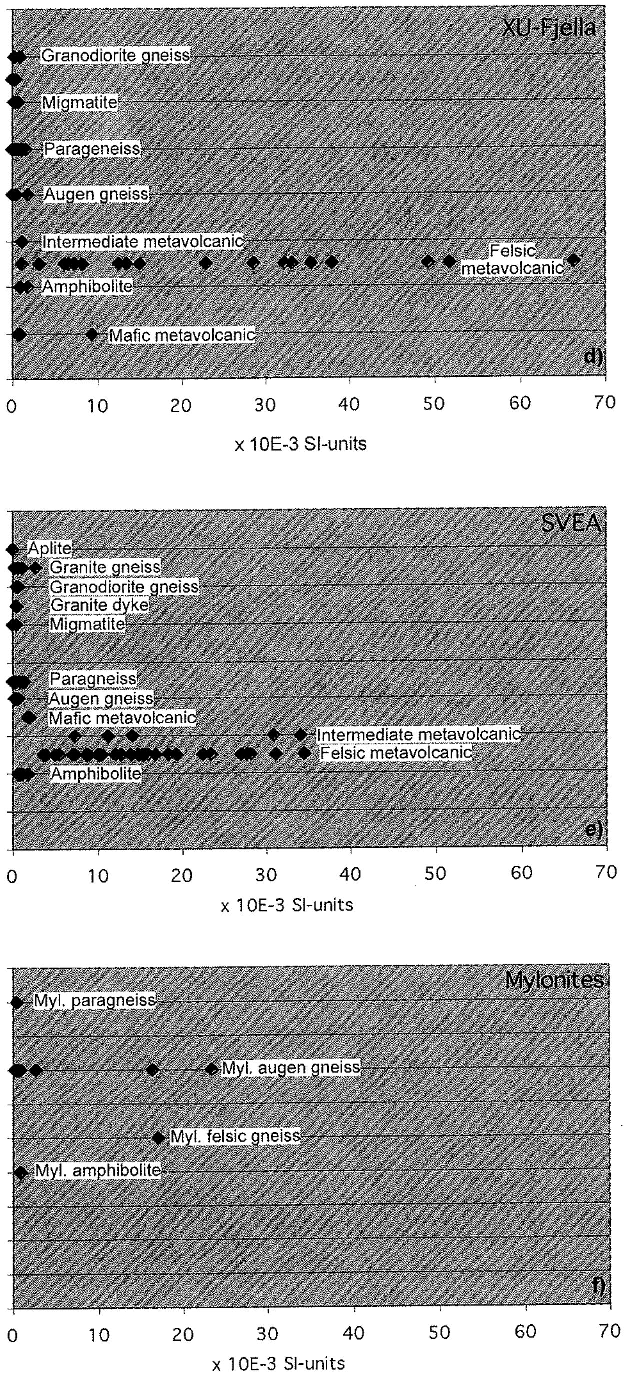


Fig. 4: Magnetic susceptibility measurements for the different regions of Heimefrontfjella. Each data point represents the means of ten measurements. Felsic to medium metavolcanic rocks from the Sivorg terrane gave consistently high susceptibilities.

Abb. 4: Magetische Suszeptibilitätsdaten der verschiedenen Regionen der Heimefrontfjella. Jeder Datenpunkt repräsentiert die Mittelwerte von zehn Einzelanalysen. Felsische bis intermediäre Metavulkanite ergaben konsistent hohe Suzeptibilitäten.

granodiorite gneiss and a distinct metatonalite, pegmatites, mafic dykes (metamorphic), amphibolites, a small gabbro and a Permian sandstone (Fig. 4a). Except for one analysis from an amphibolite, all analyses show very little variations with usually very low susceptibilities, not exceeding 1 x 10^{-3} SI units. As expected, largest susceptibilities were determined from mafic rocks. However, only one small amphibolite had high susceptibilities of c. 130 x 10^{-3} SI units. In general, most rocks showed lower susceptibilities than one would expect from their unmetamorphosed protolith.

Vardeklettane terrane

From the Vardeklettane terrane only a few measurements from granulite rock specimens are available (Fig. 4b). Mafic granulites gave highest susceptibilities of up to 60 x 10^{-3} SI units and show a large variability. Post-tectonic dolerite dykes of probably Jurassic age also gave high susceptibilities of up to 30 x 10^{-3} SI units. Further rocks analysed included felsic granulites, charnockites and migmatites, all of which have relatively low susceptibilities.

Sivorg terrane

Within the Sivorg terrane magnetic susceptibility measurements were carried out at 260 localities. Measurements were carried out on metavolcanic rocks from mafic to felsic composition, metasedimentary rocks, augen gneisses, metagabbros, pegmatites, migmatites, amphibolites and granitic dykes as well as post-tectonic dolerite dykes (Fig. 4c-e).

Magnetic susceptibilities show a much larger range than in the Kottas terrane. A number of lithologies reach susceptibilities of up to 70 x 10^{-3} SI units.

In the SW nunataks, consistent high susceptibilities have been recorded in fine to medium grained intermediate and felsic gneisses, that were interpreted to represent metavolcanic rocks. These rocks have susceptibilities that reach values up to 70 x 10^{-3} SI units. Surprisingly, rocks that were interpreted to represent mafic metavolcanic rocks and amphibolites, have with a few exceptions lower susceptibilities than associated intermediate and felsic counterparts. One Jurassic dyke has susceptibilities of c. 25 x 10^{-3} SI units. As in the Kottas terrane, all other rocks have with a few exceptions susceptibilities smaller than 1 x 10^{-3} SI units. Highest susceptibilities are recorded in one garnet-amphibolite.

A similar distribution of magnetic susceptibilities is recorded in the rocks of XU-Fjella. Again, the felsic volcanic rocks have by far the highest susceptibilities, reaching values up to 70 x 10^{-3} SI units. Apart from the felsic metavolcanic rocks, only one exposure within a mafic volcanic rock showed a value larger than 1 x 10^{-3} SI units.

In Sivorgfjella, intermediate and felsic metavolcanic rocks reach susceptibilities of 35 x 10^{-3} SI units and are again those rocks with the by far highest susceptibilities.

Heimfront Shear Zone

Rocks of all three terranes were mylonitised to different degrees within the Heimefront Shear Zone. Mylonitised rocks were analysed at 23 localities. Their protolith comprise paragneisses, augen gneisses, felsic gneisses and an amphibolite (Fig. 4f). Highest susceptibilities were recorded in a few mylonitic augen gneisses (up to 25 x 10^{-3} SI units). A mylonitised felsic gneiss gave relatively high values of c. 20 x 10^{-3} SI units.

Mineralogy of pink felsic gneisses (metavolcanic rocks)

The suite of pink, fine-grained felsic gneisses that show surprisingly high susceptibilities, were interpreted as metavolcanic rocks (Fig. 5). They are rhyolitic to dacitc in composition, containing quartz (30-65 %), <30 % K-feldspar, 10-40 % plagioclase, <17 % biotite with minor amounts of hornblende, titanite, garnet and accessory zircon and apatite (Bauer et al. 2003). Magnetite occurs mostly as idioblasts, up to 10 mm in diameter. Some magnetite grains however, have resorbed grain boundaries and show oriented exsolution lamellae of ilmenite (Fig. 6). Titaniferous components in magnetite are typical for volcanic rocks, that are characterised by quenched magnetite compositions (Clark 1999), that during metamorphic overprint undergo exsolution. Also, most magnetite grains are surrounded by a reaction zone in which biotite has disappeared (Fig. 7). The most likely reaction is:

$$\underset{\text{annite}}{KFe_3AlSi_3O11\ H_2O} \rightarrow \underset{\text{magnetite}}{Fe_3O_4} + \underset{\text{K-feldspar}}{KAlSi_3O_8} + H_2$$

in which the annite component of biotite reacts to magnetite and K-feldspar (Wones & Eugster 1965, Iishirara et al. 2002).

Geochemical analyses of the pink gneisses revealed relatively high potassium contents and low MgO, CaO and $Fe_2O_3^{tot}$. (Bauer et al. 2003). They are metaluminous to mildly peraluminous, have moderately enriched LREE/HREE and a pronounced negative Eu anomaly (Bauer et al. 2003). Therefore, these felsic gneisses are thought to have evolved during partial melting and subsequent fractional crystallisation within an attenuated continental crust, possibly within a back-arc setting.

A number of U-Th-Pb SHRIMP zircon ages on the pink gneisses reveal crystallisation ages ranging from 1160 to 1090 Ma, with a first metamorphic zircon overgrowth under medium to high-grade conditions, dated between c. 1090 and 1060 Ma (Bauer et al. 2003, Jacobs et al. 2003). A second overprint occurred during Early Palaeozoic times at c. 500 Ma.

INTERPRETATION AND DISCUSSION

The magnetic properties of rocks are largely controlled by their amount of ferromagnetic minerals such as magnetite. The amount of magnetite in a rock is a function of the partitioning of iron between silicate and oxide phases, which is controlled by a number of factors, such as oxidation ratio, chemical composition and petrogenetic condition (Clark 1999). A high oxidation stage favours the growth of magnetite rather than silicates and carbonates. Therefore, susceptibility values in general are not diagnostic for a certain lithology, but rather reflect the petro-chemical environment under which the rocks crystallised or underwent metamorphism. In certain circumstances the magnetic properties of magmatic rocks allow some predictions on the tectonic setting under which they crystallised. Ishihara (1981) distinguished a magnetite-series from ilmenite-series granitoids, that crystallised under distinct tectonic environments and can easily be distinguished by their magnetic properties. Magnetite-series granitoids are characterised by the occurrence of magnetite ± ilmenite + haematite, pyrite, titanite and oxidised Mg-rich biotite and are usually I-type in composition (Whalen & Chappell 1988). The ilmenite-series granitoids lack magnetite, but have ilmenite + pyrrhotite, graphite, muscovite and reduced Fe-rich biotite and have often S-type characteristics. The higher oxidation state of the magnetite-series granitoids results in their ferromagnetic properties, whilst ilmenite-series granitoids usually are paramagnetic. Magnetite-series granitoids are thought to have evolved in the lower continental crust or upper mantle with little involvement of carbonaceous material, whereas ilmenite-series rocks probably indicate significant contamination by C-bearing crustal rocks in the middle to lower crust (Clark 1999). The oxidisation state of a granitoid rock is also documented in the colour of the K-feldspar. Pink, rather than white K-feldspar indicate a high oxidation stage and therefore such rocks usually have high susceptibilities (Blevin 1996).

The measured magnetic properties of rocks outcropping in the Heimefrontfjella largely reflect their tectono-metamorphic setting. The pink felsic gneisses of the Sivorg terrane have the highest susceptibilities. Together with their general geochemisty (Bauer et al. 2003), the high susceptibilities indicate highly oxidised melts that were probably generated in the lower continental crust and show no supracrustal involvement. These rocks very likely indicate metavolcanic rocks, that were generated in a back-arc setting.

The metagranodiorites and metatonalites of the Kottas terrane are thought to have evolved along an island arc. They have low magnetic susceptibilites, although they are not typical ilmenite-series granitoids. Minor amounts of carbon that

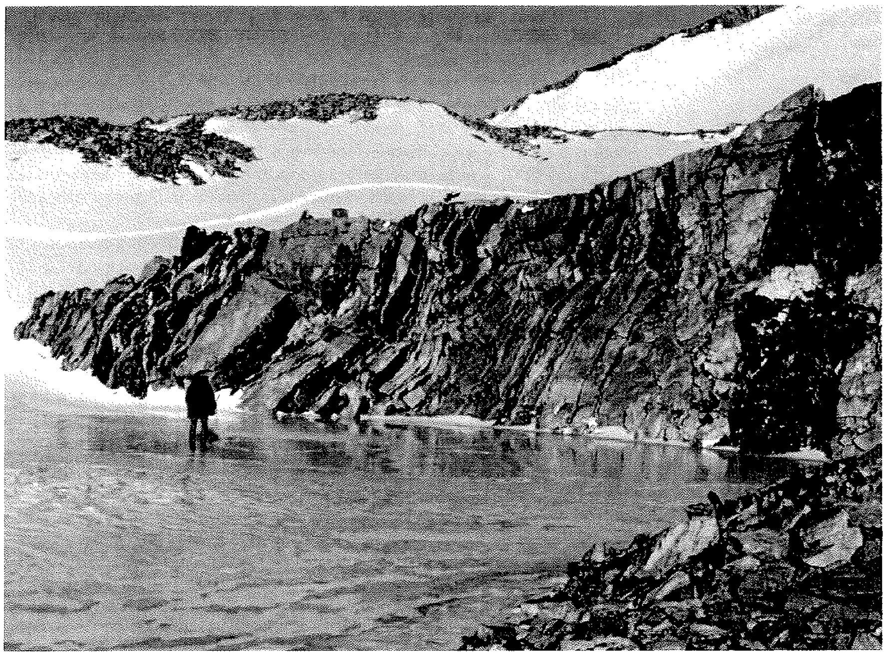


Fig. 5: Typical appearance of a succession of felsic and mafic gneisses interpreted to represent metavolcanic rocks, Boyesenuten, Sivorgfjella.

Abb. 5: Typisches Erscheinungsbild einer Abfolge von felsischen und mafischen Gneisen, die als eine Abfolge von Metavulkaniten interpretiert wird (Boyesenuten, Sivorgfjella).

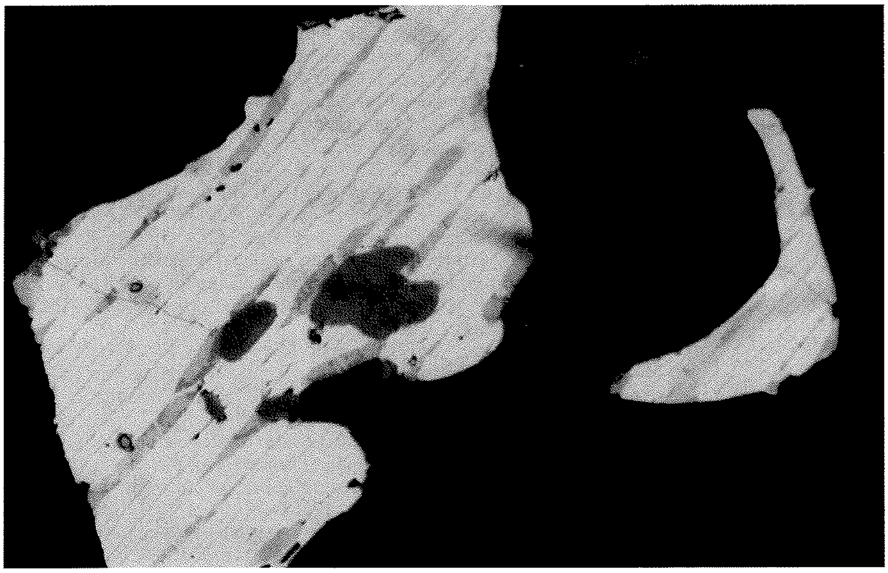


Fig. 6: Magnetite crystal with large exsolution lamellae of ilmenite; reflected polarised light, width of view 0.216 mm.

Abb. 6: Magnetitkristall mit Ilmenit-Entmischungslamellen; reflektiertes polarisiertes Licht, Bildbreite 0,216 mm.

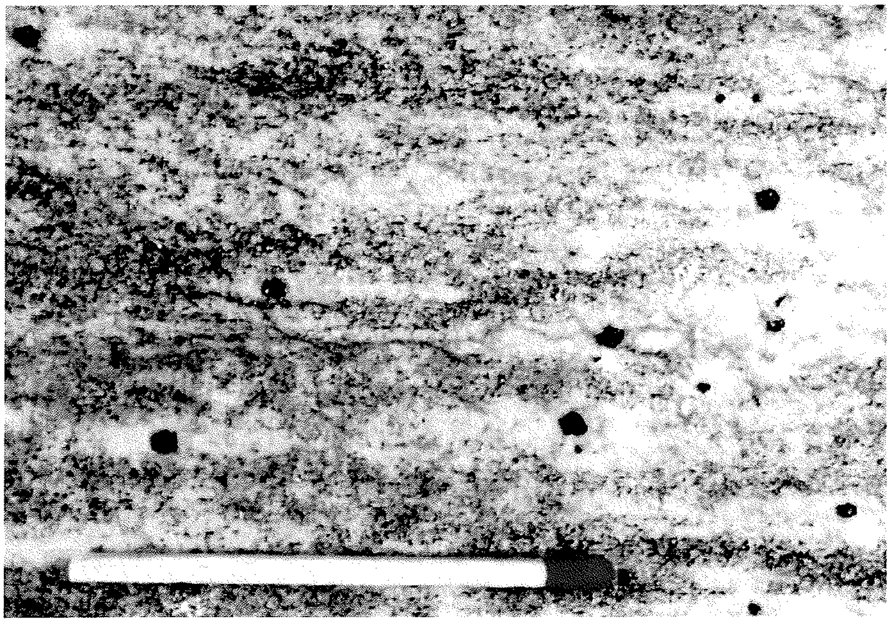


Fig. 7: Pink felsic gneiss interpreted as a felsic metavolcanic rock, with reaction zone around magnetite (polished specimen).

Abb. 7: Rosarote felsische Gneise, die als felsische Metavulkanite interpretiert werden; mit Reaktionszone um Magnetit (polierte Probe).

could have been introduced during subduction could have caused an overall reducing environment for these rocks, resulting in low susceptibilities.

Mylonites from the Heimefront Shear Zone do not show significantly higher susceptibilities, suggesting that mobile elements such as alkalies, silica and LILE were not removed during deformation. Otherwise, immobile elements like Fe and Ti should be relatively enriched in this shear zone.

CONCLUSIONS

The area SE of the Heimefront Shear Zone was intensely reworked during Late Neoproterozoic/Early Palaeozoic times, resulting in an entirely different magnetic anomaly pattern on either side of the shear zone. Highest susceptibilities were measured in felsic metavolcanic rocks SE of the Heimefront Shear Zone. The susceptibilities of the felsic metavolcanic rocks exceed the susceptibilities of associated amphibolites on the order of about one magnitude. In the metavolcanic rocks, magnetite is the main magnetic mineral, formed by metamorphic reactions in excess of annite within oxidised rocks that lack supracrustal involvement. Thus far, these highly magnetised rocks are not clearly recognised in available aeromagnetic surveys, because the flight-line spacing of 5 km is probably too large to resolve these units. A narrower flight line spacing and an appropriate flying altitude would probably decipher the Late Neoproterozoic/Early Palaeozoic structures along the orogenic front of the East African/Antarctic Orogen with good resolution and would significantly help in the understanding of this structurally complex region at the southern extension of the East African/Antarctic Orogen.

ACKNOWLEDGMENT

This project was supported in part by Deutsche Forschungsgemeinschaft grants Ja 617/14+16 to J. Jacobs and Ba 1636/5 to W. Bauer. The field work would have not been possible without the help and logistic support of the Alfred Wegener Institute for Polar and Marine Research. Reviews by Wilfried Jokat and Georg Kleinschmidt are kindly acknowledged.

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