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A Review of Two Decades (1986 – 2008) of Geochronological Work in Heimefrontfjella, and Geotectonic Interpretation of Western Dronning Maud Land, East Antarctica

by Joachim Jacobs[1]

Abstract: During two decades (1986 – 2008) of geochronological work in Heimefrontfjella, nearly 130 geochronological ages were produced using a wide range of geochronological techniques. The ages fall into four broad age groups from Archaean to Cenozoic times, revealing a long and complex geological history. In general, Heimefrontfjella consists of Mesoproterozoic high grade basement related to the ~1100 Ma Maud Belt. This basement is overlain by Permo-Carboniferous sedimentary rocks and Jurassic lavas. Archaean and Palaeoproterozoic detrital zircon ages are recorded from metasedimentary rocks probably characterizing the foreland of the Maud Belt. The protolith and metamorphic ages of the Mesoproterozoic Maud Belt fall into two groups. An older age group from ~1200-1100 Ma is related to back-arc and island arc volcanism. High-grade metamorphism in the Maud Belt is dated between 1090-1060 Ma and is thought to reflect continent-continent collision, possibly related to the formation of Rodinia. Regional cooling to below 500-300 ºC at ~1010-960 Ma in part of the mountain range might indicate rifting of Rodinia. The eastern part of the mountain range is overprinted by the ~600-500 Ma East African-Antarctic Orogen. The orogenic front of this major mobile belt is exposed in the study area as the Heimefront Shear Zone. East of this major lineament all Ar-Ar, K-Ar and Rb-Sr mineral ages are reset to ~500 Ma. Initial Gondwana rifting affected the area at c. 180 Ma, when the Bouvet/Karroo mantle plume caused dynamic uplift of the area, followed by burial underneath up to 2 km of Jurassic lava. This led to tempering of the basement up to about 100 ºC, as indicated by apatite fission track data. The lava pile underwent erosion in Cretaceous time, when renewed rifting affected the region. Latest tectonic movements might be related to Cenozoic ice loading related to the built up of the Antarctic ice sheet.

Zusammenfassung: Während zweier Dekaden (1986 – 2008) geochronologischer Arbeiten in der Heimefrontfjella, entstanden mit Hilfe unterschiedlicher geochronologischer Methoden nahezu 130 Altersdaten. Die Alter fallen in vier breite Altersgruppen vom Archaikum bis Känozoikum und belegen eine lange und komplexe geologische Geschichte. Generell wird die Heimefrontfjella aus mesoproterozoischem Grundgebirge aufgebaut und ist Teil des ~1100 Ma alten Maud-Gebirgsgürtels. Dieses Grundgebirge wird von permo-karbonen sedimentären Gesteinen sowie jurassischen Laven überlagert. Metasedimentäre Gesteine ergaben archäische und paläoproterozoische detritische Zirkonalter und charakterisieren wahrscheinlich das Vorland des Maud-Gebirgsgürtels. Die Protolith- und Metamorphosealter des mesoproterozoischen Maud-Gebirgsgürtels fallen in zwei Altersgruppen. Eine ältere Altersgruppe zwischen ~1200-1100 Ma steht in Verbindung mit back-arc und Inselbogen-Vulkanismus. Die hochgradige Metamorphose im Maud-Gebirgsgürtel wird zwischen 1090-1060 Ma datiert und dokumentiert wahrscheinlich eine Kontinent-Kontinent-Kollision, die mit der Bildung Rodinias korreliert. Eine regionale Abkühlung unter 500-300 ºC um ~1010-960 Ma in Teilen des Gebirges könnte ein Hinweis auf den Aufbruch Rodinias sein. Der östliche Gebirgsteil ist vom ~600-500 Ma *East African – Antarctic Orogen* überprägt. Die orogene Front dieses großen Mobilgürtels ist im Arbeitsgebiet als die Heimefront-Scherzone aufgeschlossen. Östlich dieser Struktur sind alle Ar-Ar, K-Ar und Rb-Sr Mineralalter auf ~500 Ma zurückgesetzt. Der initiale Gondwanaaufbruch beeinflusste das Arbeitsgebiet um ~180 Ma, als der Bouvet/Karoo-Mantel-Plume zu dynamischer Hebung führte und das Arbeitsgebiet unter einer bis zu 2 km dicken Lavadecke begraben wurde. Dies führte zur Erwärmung des Grundgebirges bis zu etwa 100 ºC, wie Apatit-Spaltspurendaten belegen. Die Lavadecke wurde erst in der Kreide erodiert, als erneutes Rifting einsetzte. Die letzten tektonischen Bewegungen entstanden vermutlich als Resultat der känozoischen Eislast.

INTRODUCTION

During the German research activities in Heimefrontfjella between 1985 and 2008, nearly 130 geochronological ages were produced. This major dataset formed a significant basis for the deciphering of the complex and protracted geological history of the area and helped to establish the current geotectonic model.

The dataset (Tab. 1A, 1B, 1C) consists of 29 conventional and SHRIMP U-Pb zircon dates, 11 Ar-Ar hornblende dates, 11 Rb-Sr whole rock and mineral dates, 39 K-Ar mica dates, 37 apatite fission-track ages and 4 (U-Th)/He ages (Arndt et al. 1991, Jacobs et al. 1995, 1996, 1997, 1999, Jacobs & Lisker 1999, Bauer et al. 2003a,b, Jacobs et al. 2003a,b, 2009 (this volume), Emmel et al. 2008). In this review, only fission-track data were considered that were generated using the external detector method. The analytical work was carried out at the following institutions: Max Planck Institute for Chemistry (Mainz, Germany), Institute for Geology und Dynamic of the Lithosphere (University Göttingen, Germany), RWTH (Aachen, Germany), Dept. of Geosciences (University Bremen, Germany), Australian National University Canberra (Australia), CSIRO (Perth, Australia).

Heimefrontfjella (Fig. 1) mainly consists of juvenile Mesoproterozoic basement rocks that underwent medium- to high-grade metamorphism at ~1090-1060 Ma related to the formation of the ~1.2-1.0 Ga Maud Belt. Part of this mobile belt underwent tectono-metamorphic overprint at ~500 Ma when it was situated on the western margin of the Late Neoproterozoic/Early Palaeozoic East African – Antarctic Orogen (Fig. 2). Heimefrontfjella is subdivided into three distinct tectono-stratigraphic terranes, the Kottas, Sivorg and Vardeklettane terranes. The basement is overlain by Permo-Carboniferous sedimentary rocks and is intruded and overlain by basaltic Jurassic dykes, sills and flows.

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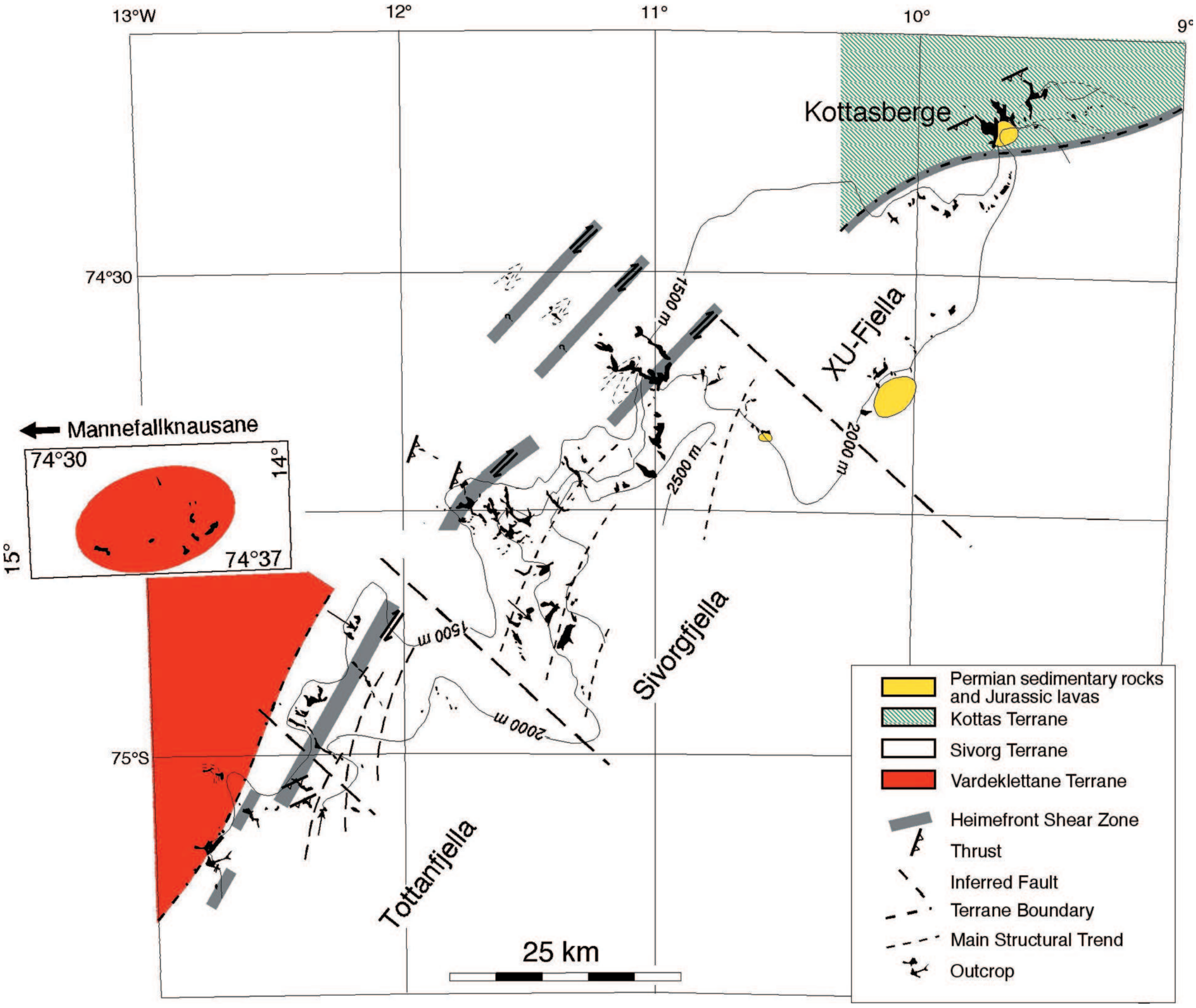

Fig. 1: Overview map of Heimefrontfjella, with major tectono-stratigraphic terranes, and Heimefront Shear Zone (after JACOBS et al. 2003a).

Abb. 1: Übersichtskarte der Heimefrontfjella mit Lage der wichtigsten tektono-stratigraphischen Terranes sowie der Heimefront-Scherzone (nach JACOBS et al. 2003a).

GEOCHRONOLOGICAL DATA AND GEOTECTONIC INTERPRETATION

Archaean to Mesoproterozoic record

The oldest recorded ages are U-Pb data from detrital zircons separated from metasedimentary rocks, both from the Sivorg and Vardeklettane terranes (ARNDT et al. 1991, JACOBS et al. 2009, this vol.). Detrital zircons with ages ranging between 2000-1200 Ma and with a significant peak around 1800 Ma are common. Since there is no Palaeoprotereozoic basement exposed, neither within Heimefrontfjella, nor in the vicinity to the north of it (Grunehogna Craton), it is speculated that the zircons hint at the presence of Palaeoproterozoic basement to the south of the mountain range. One sample from the Sivorg Terrane also records detrital zircons with Archaean ages (JACOBS et al. 2009). The latter sample was interpreted as having been derived from a post-tectonic molasse deposit related to the Grenville-age Maud Belt and could have obtained its Archaean age component when the belt amalgamated with the Zimbabwe-Kaapvaal-Grunehogna Craton at ~1090-1060 Ma (Fig. 2).

The most common protolith ages in the Heimefrontfjella range between 1180-1050 Ma, obtained from pre-, syn- and late-tectonic rocks formed during the evolution of the Maud Belt. The Maud Belt makes the eastern part of the major Namaqua-Natal-Maud Belt of southern Africa and East Antarctica (Fig. 2). The oldest granitic gneisses, interpreted as original metavolcanic rocks, have protolith ages ranging from ~1180 to 1100 Ma, whilst rocks with younger protolith ages between 1100 and 1040 mainly represent syntectonic intrusions. Metavolcanic rocks of the Sivorg Terrane are bimodal in composition. These make up a well-exposed sequence of metamorphosed tholeiitic MORB and high-K metarhyolite. It has been proposed that these rocks were generated in a back-arc setting (BAUER et al. 2003b). In contrast, banded gneisses of the Kottas Terrane have tonalitic to dioritic compositions and associated granitoids have volcanic arc chemistry. The Kottas Terrane therefore represents a typical subduction-related calc-alkaline magmatic arc, which was active at approximately the same time as the Sivorg back-arc was forming (BAUER et al. 2003b). The geotectonic setting of the granulites of the small Vardeklettane Terrane is only poorly studied and understood. The best estimate for the age of the Grenville-age metamorphism within the Heimefrontfjella ranges from 1090

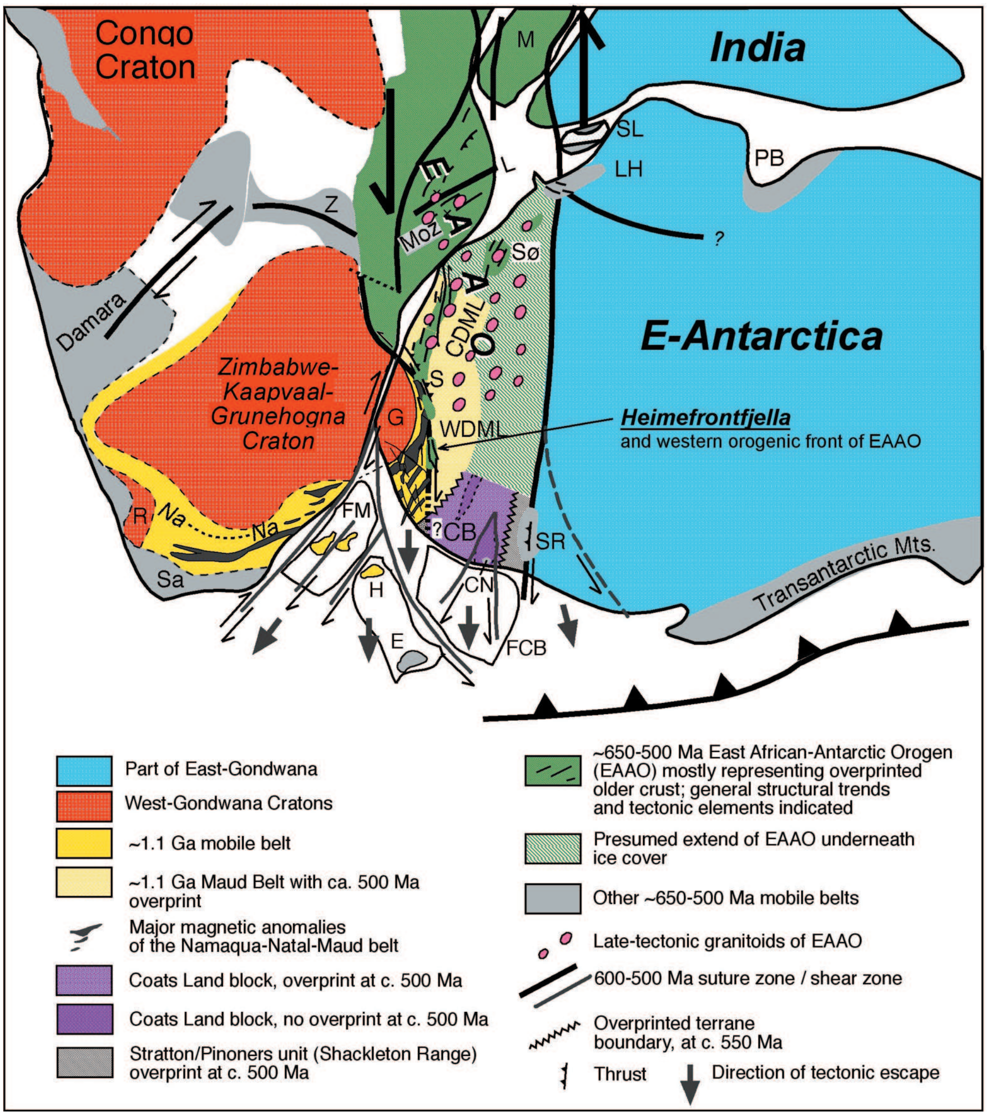

Fig. 2: Location of the study area in a Gondwana reconstruction with major Late Neoproterozoic-Cambrian belts indicated (after Jacobs 2003b, Jacobs & Thomas 2004 and references therein). Heimefrontfjella is situated along the eastern margin of the Archaean Grunehogna craton and along the western margin of the ~500 Ma East African – Antarctic Orogen (EAAO) in western Dronning Maud Land. The southern termination of the EAAO is interpreted in terms of an escape tectonic scenario. Abbreviations: CDML = central Dronning Maud Land, CB = Coats Land block, CN = Coats Nunataks, E = Ellsworth Mts, FCB = Filchner Crustal Block, FM = Falkland microplate, G = Grunehogna Craton fragment, H = Haag Nunatak, L = Lurio Belt, LH = Lützow Holm Bay, M = Madagascar, 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. 2: Lage des Arbeitsgebiets in einer Gondwana-Rekonstruktion mit Lage der wichtigsten spät-neoproterozoisch-kambrischen Mobilgürteln (nach Jacobs 2003b, Jacobs & Thomas 2004 cum lit.). Heimefrontfjella befindet sich am östlichen Rand des archaischen Grunehogna Kratons sowie am Westrand des ~500 Ma alten East African – Antarctic Orogen (EAAO) im westlichen Königin-Maud-Land. Das südliche Ende des EAAO wird als Extrusions-Tektonik interpretiert.

to 1060 Ma, based on SIMS dating of syntectonic granitoids and metamorphic zircon rims of older gneisses (Jacobs et al. 2003b). The Maud Belt was formed from collision of the Zimbabwe-Kaapvaal-Grunehogna Craton (Proto-Kalahari) and the Coats Land block (Fig. 2), (Jacobs et al. 2003a, 2008). By 1050 Ma the main deformation within the Maud Belt was over and the orogen was intruded by voluminous coarse-grained, late to post-tectonic, porphyritic granitoids (e.g. Månesigden granite). Post-tectonic mafic dykes are dated at ~1030 Ma (Bauer et al. 2003a). The post-tectonic Mesoproterozoic cooling history is poorly documented, because of the later resetting of some of the geochronological systems during the ~500 Ma overprint related to the East African – Antarctic Orogeny, especially within the Sivorg Terrane. Nevertheless, the Sivorg Terrane was probably quickly exhumed as indicated by the clastic molasse deposits, which are thought to overlie the basement gneisses of the Sivorg Terrane (Jacobs et al. 2009). The Kottas and Vardeklettane terranes cooled to below 500-300 °C at ~1010-960 Ma, as evidenced by Ar-Ar, Rb-Sr as well as K-Ar mineral cooling ages (Jacobs et al. 1995, 1996, 1999). This cooling period might have been related to rifting of Kalahari from Rodinia; no other obvious evidence for rifting related to the breakup of Rodinia is recorded (e.g. Jacobs et al. 2008).

The ~4000-5000 km long Namaqua-Natal-Maud Belt is thought to be a major segment of a global network of coeval orogens that may have led to the amalgamation of the Rodinia supercontinent at ~1000 Ma (e.g. Li et al. 2008). The belt has a very characteristic aeromagnetic anomaly pattern, defined by very elongate, orogen-parallel anomalies of high amplitude (Figs. 2 & 3). The largest of these anomalies is termed the Beattie Anomaly in southern Africa and has been related to major steep shear zones. This set of anomalies sharply terminates in the east against the Cambrian Heimefront Shear Zone (Golynsky & Jacobs 2001). Within the Maud Belt west of the Heimefront Shear Zone, the mantle anisotropy is co-linear with the orogen, as documented by shear wave splitting analysis (Bayer et al. 2007). This might indicate that the lithospheric mantle has retained its Mesoproterozoic anisotropy until today.

The high-grade Namaqua-Natal-Maud Belt represents a collision orogen, of which only one of the colliding continents is relatively clear: Proto-Kalahari (Jacobs et al. 1993, 2008). The question of what the colliding counterpart could have been remains open. Certainly, no remnant of this counterpart is exposed in southern Africa. In Antarctica, very limited evidence of this crustal block exists, due to the extensive ice

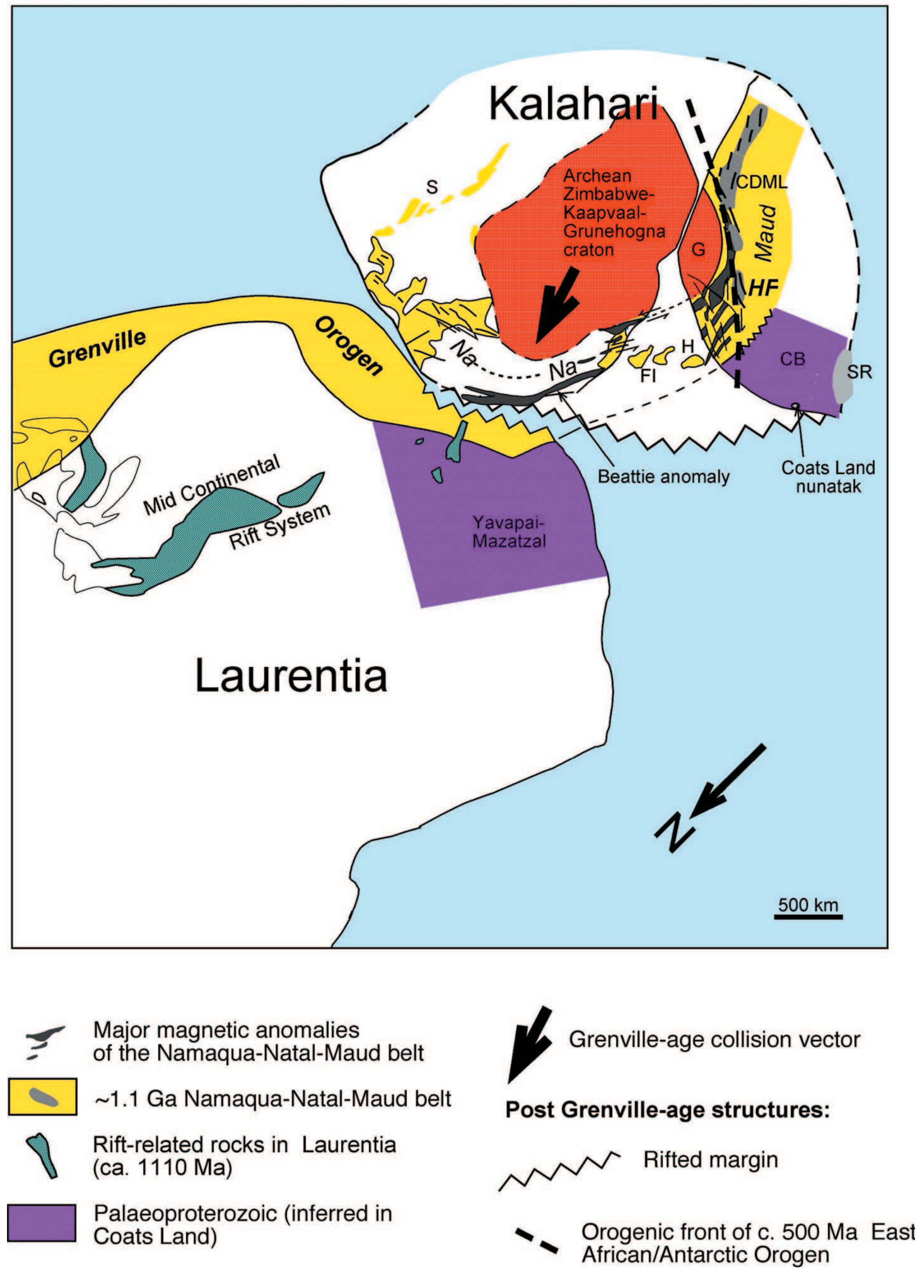

Fig. 3: If Heimefrontfjella in Dronning Maud Land as part of Kalahari was ever part of the Rodinia supercontinent at ~1000 Ma, then the extensive Namaqua-Natal-Maud mobile belt could have its counterpart in the Grenville Orogen of Laurentia (after JACOBS et al. 2003a,b, 2008, and references therein). In this scenario, the Zimbabwe-Kaapvaal-Grunehogna craton would have collided with the Yavapai-Mazatzal – Coats Land block to form the extensive Grenville – Namaqua-Natal-Maud Orogen at 1200-1000 Ma, with major collision and final suturing recorded in DML and parts of the Grenville Orogen at ~1090-1060 Ma. Coats Land could have been part of Proto-Laurentia prior to the collision but rifted away together with Kalahari from Laurentia during Rodinia breakup.
Abbreviations: CB = Coats Land block, CDML = central Dronning Maud Land, G = Grunehogna Craton, SR = Shackleton Range, HF = Heimefrontfjella, H = Haag Nunatak, FI = Falkland Islands, NaNa = Namaqua-Natal Belt, S = Sinclair Suite (~1.1 Ga).

Abb. 3: Wenn Heimefrontfjella in Königin-Maud-Land als Teil von Kalahari je Teil des Rodinia-Superkontinents vor ~1000 Ma war, dann könnte der ausgedehnte Namaqua-Natal-Maud-Mobilgürtel sein Gegenstück im Grenville-Orogen Laurentias haben (nach JACOBS et al. 2003a,b, 2008, cum lit.). In diesem Szenario wäre der Zimbabwe-Kaapvaal-Grunehogna-Kraton mit dem Yavapai-Mazatzal – Coats-Land-Block kollidiert, wobei das extensive Grenville – Namaqua-Natal-Maud-Orogen zwischen 1200-1000 Ma entstanden wäre. Die Hauptkollision wird in Königin-Maud-Land und Teilen des Grenville-Orogens mit ~1090-1060 Ma datiert. Coats-Land könnte Teil von Proto-Laurentia vor der Kollision gewesen sein, wäre aber zusammen mit Kalahari während des Rodinia-Aufbruchs weggeriftet.

cover. One strand of evidence is given by detrital zircons recorded from metasediments from the Heimefrontfjella, which indicate a Palaeoproterozoic source. Since Palaeoproterozoic basement is not known from the Heimefrontfjella, these detrital zircons could characterise the southern foreland of the Maud Belt. Thus, the Maud Belt might be bound by Palaeoproterozoic basement to the south and southeast. The closest outcrops south of the Maud Belt are exposed in Coats Land (Figs. 2 & 3). At the Coats Land nunataks, volcanic rocks dated at ~1110 Ma (GOSE et al. 1997) unconformably overlie basement rocks. However, the basement is unaccessibly exposed beneath the volcanic rocks in an ice cliff and therefore has never been studied. The volcanic rocks have crystallisation ages older than the dated collision of the Maud Belt, and must thus overlie the southern foreland of the orogen. It could be this foreland, which provided the Palaeoproterozoic detrital zircon ages of the Heimfrontfjella metasediments. Palaeoproterozoic rocks are also extensive in the northern Shackleton Range (Fig. 3). After collision of Proto-Kalahari with another continent and the formation of the Maud Belt, Kalahari rifted away together with a fragment of this other continent (Coates Land). Therefore, the extremely poorly exposed Coats Land Block may be the key to the understanding of which continent Proto-Kalahari originally collided with.

Two general positions of the Kalahari continent and the Maud Belt within Rodinia have been recently discussed. Some models place Kalahari along Western Australia (e.g. PISAREVSKY et al. 2003), others have Kalahari in various configurations along eastern Laurentia (e.g. HANSON et al. 2004, JACOBS et al. 2008 and references therein). In the Kalahari – western Australia correlation, the Namaqua-Natal-Maud Belt has no colliding counterpart and the detrital zircon population of metasedimentary rocks of the Maud Belt is difficult to explain (KSIENZYK et al. 2007). Therefore, this correlation is unlikely. There are also problems with the Kalahari-Laurentia fit. However, a correlation with Laurentia is geologically more plausible: The Namaqua-Natal-Maud Belt would have a colliding counterpart (Laurentia), a correlation with the Grenville Orogen, and detrital zircons would indicate a common Palaeoproterozoic foreland, represented by the Coats-Yavapai-Mazatzal block (Fig. 3). A Kalahari-Laurentia correlation is also supported by comparison of palaeomagnetic data from the Coats Land nunataks and from coeval rocks in Laurentia (GOSE et al. 1997, discussion in JACOBS et al. 2003a). The Coats Land block could therefore represent a piece of Laurentia that rifted away together with Kalahari during the break-up of Rodinia. This rifting must have occurred soon after collision in order to not conflict with other palaeomagnetic data. There is little record of this rifting in Dronning Maud Land and southern Africa, apart from a cooling and exhumation episode around ~1010-960 Ma. Although the Coats Land block has a characteristic aeromagnetic signature, the exact extent of this block is unknown at present.

Neoproterozoic to Cambrian record

The boundary between the Kottas, Sivorg and Vardeklettane terranes is a major subvertical dextral transpression zone, the Heimefront Shear Zone that coincides with highly contrasting mineral cooling ages on either side (JACOBS et al. 1995, 1996, 1997, 2003b). Within the Sivorg Terrane and the Heimefront Shear Zone, Ar-Ar, Rb-Sr as well as K-Ar mineral ages are reset to ~500 Ma; igneous rocks with protolith ages of ~500 Ma are absent, apart from a few mafic dykes. Many zircons from the Heimefront Shear Zone have thin metamorphic reaction zones, often too thin to be analysed even by SIMS. However, in two samples such zones around zircon tips were wide enough to reveal ages of ~500 Ma, indicating the pervasive Cambrian overprint of the Mesoproterozoic rocks (JACOBS et al. 2003b). On the western side of the Heimefront Shear Zone, ~500 Ma ductile deformation is limited to narrow local shear zones. Consequently, Ar-Ar, Rb-Sr and K-Ar mineral cooling ages are not reset. The Heimefront Shear Zone is therefore an important structure, separating not only different tectono-metamorphic terranes, but it probably also marks the western orogenic front of the East African – Antarctic Orogen (Fig. 2). In the larger picture, the Heimefront Shear Zone forms part of a N-S trending set of shear zones that is thought to be related to south-directed tectonic escape at the southern termination of the East African – Antarctic Orogen (Fig. 2), (JACOBS & THOMAS 2004).

The characteristic, very elongate, high-magnitude, Mesoproterozoic magnetic anomalies of the Namaqua-Natal-Maud Belt sharply terminate along the Heimefront Shear Zone, providing additional evidence that the Maud Belt East of this shear zone was thoroughly reworked by the East African – Antarctic Orogen (e.g. GOLYNSKY & JACOBS 2001). Furthermore, seismic studies across the Heimefront Shear Zone indicate, that east of the shear zone the fast anisotropy direction of the mantle is not parallel to the Maud Belt any longer (BAYER et al. 2007). This probably also indicates that the lithospheric mantle to the E of the shear zone was reworked during the collision along the East African – Antarctic Orogen and that the Heimefront Shear Zone represents a significant lithosphere-scale shear zone.

Late Palaeozoic to Cenozoic record

In the northern part of Heimefrontfjella, the metamorphic basement is unconformably overlain by isolated outcrops of Permo-Carboniferous sandstones of the Beacon Supergroup upon a pronounced peneplain. These sandstones, together with the basement, were intruded by Jurassic dykes and sills at ~180 Ma. At Bjørnnutane, up to 130 m of Jurassic lavas are exposed. These lavas are related to the Bouvet/Karoo mantle plume that is thought to have led to dynamic uplift of this area of up to 2 km during the Jurassic (Fig. 4). Thirty-seven apatite fission-track analyses from across Heimefrontfjella indicate ages ranging from ~170 – 80 Ma. The oldest apatite fission-track age is younger than the Jurassic magmatism and indicates that the entire area was probably buried underneath a lava sheet up to 2-3 km in thickness that led to a near-total annealing of apatite fission-tracks at temperatures >100 ºC. The oldest fission-track ages come from the highest peak of central Sivorgfjella, which also indicate the highest amount of tectonic exhumation and the least burial. Many fission-track ages are around 100 Ma, indicating that the basement remained at elevated temperatures for a considerable time and that erosional unroofing took only place during the Cretaceous. The latter was probably associated with intense block tectonics as evidenced by a deep sub ice-sheet graben (800 mbsl) recorded from immediately to the NW of Heimefrontfjella. Since the highest mountains reach 2700 masl, the present total relief is still close to 3500 m.

Heimefrontfjella also coincides with a significant change in crustal thickness as indicated by seismic studies (ECKSTALLER unpubl.). The crustal thickness changes from about 53 km underneath the mountain range, to about 45 km to the NW of it. The crust to the NW of Heimefrontfjella probably represents a rifted, wide, thinned continental margin with thinning probably coeval with rift graben formation during late Mesozoic times.

Apatites of four of the 37 fission-track dated samples were additional analyzed by the (U-Th)/He method (EMMEL et al. 2008). These data indicate rapid Cenozoic exhumation. It was speculated that this late rapid exhumation was related to flexural uplift during the build-up of the East Antarctic ice sheet. This relatively young tectonic event could explain the apparent young topography observed in the mountain range.

SUMMARY AND CONCLUSION

In Heimefrontfjella, Archaean to Cenozoic ages were recorded from a wide range of metamorphic and igneous rocks by various geochronological methods.

(1) The oldest ages recorded in Heimefrontfjella were derived from detrital zircons from possible molasse deposits of the Maud Belt, which revealed Archaean ages. These zircons are probably derived from the Kaapvaal-Grunehogna Craton, after the Sivorg and Kottas terranes had become part of the Proto-Kalahari Craton.

(2) Palaeoproterozoic detrital zircon ages probably record the presence of an old, unexposed block to the south and southeast of the Maud Belt, the Coats Land block. The latter is unacces-

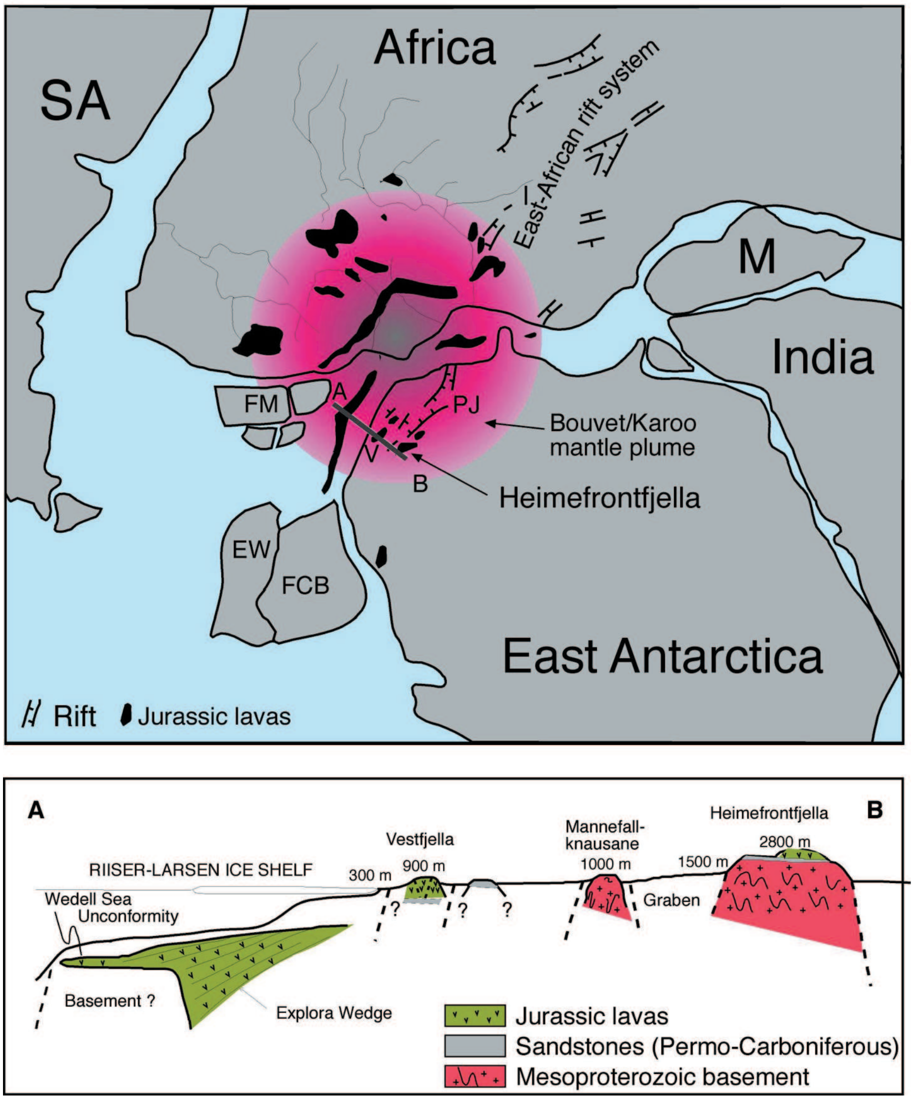

Fig. 4: Gondwana reconstruction with indication of the Bouvet/Karoo mantle plume (red) and the associated Jurassic volcanism (after JACOBS & LISKER 1999 and references therein). Updoming over the mantle plume was associated with a characteristic drainage sytem away from the plume. Note the possible continuation of the East African rift system into East Antarctica. The schematic geological profile indicates intense segmentation of a ~350 wide continental margin. Fault tectonics probably initiated during initial Gondwana break-up and impact of the mantle plume. However, continued fault tectonics is evident by fission-track and (U-Th)-He thermochronological data during Cretaceous and Cenozoic times.
Abbreviations: EW = Ellsworth-Whitmore Mts, FM = Falkland microplate, FCB = Filchner Crustal Block, M = Madagascar, PJ = Pencksökket-Jutulstraumen, SA = South America, V =-Vestfjella.

Abb. 4: Gondwana Rekonstruktion mit Lage des Bouvet/Karoo Mantelplumes und dem damit verbundenen jurassischen Magmatismus (nach JACOBS & LISKER 1999, cum lit.). Die Aufwölbung über dem Mantelplume führte zu einem charakteristischen Entwässerungsnetz, das vom Plume-Zentrum weg zeigte. Das Ostafrikanische Riftsystem setzt sich möglicherweise in die Antarktis fort. Das schematische geologische Profil zeigt eine intensive Segmentierung eines etwa 350 km breiten Kontinentalsaums. Die damit verbundene Störungstektonik entstand zunächst wahrscheinlich während des initialen Gondwana-Aufbruchs und im Zusammenhang mit dem Mantelplume. Jedoch weisen Spaltspuren und (U-Th)/He Thermochronologie auf eine anhaltende Störungstektonik während der Kreide und des Känozoikums hin.

sibly exposed but overlain by undeformed volcanic rocks (~1110 Ma) and might correlate with the Yavapai-Mazatzal Province of Laurentia.

(3) The Sivorg Terrane contains a thick succession of bimodal volcanic rocks that evolved between the Coats Land block and the Kaapvaal-Grunehogna Craton probably within a back-arc setting. The calk-alkaline rocks of the Kottas Terrane on the other hand document the formation of an island arc at approximately the same time.

(4) The best estimate for continent-continent collision within this part of the Maud Belt is ~1090-1060 Ma, recorded by metamorphic zircon overgrowths and the emplacement of syntectonic granitoids.

(5) An episode of post-orogenic cooling dated at ~1010-960 might be related to rifting of Kalahari from Rodinia. No other evidence for Rodinia rifting is recorded from Dronning Maud Land.

(6) Ar-Ar, Rb-Sr and K-Ar mineral cooling ages between 1010-960 Ma from the Vardeklettane and Kottas terranes indicate that this part of Heimefrontfjella was not effected by the ~500 Ma East African – Antarctic Orogeny and, thus, were part of its western foreland.

(7) The western orogenic front of the East African – Antarctic Orogen is represented by the Heimefront Shear Zone, that, together with the entire Sivorg Terrane, record Ar-Ar, Rb-Sr and K-Ar mineral cooling ages of ~500 Ma. Metamorphic zircon rims from samples of the Heimefront Shear Zone also gave ages of ~500 Ma. The Sivorg Terrane, together with the Heimefront Shear Zone, are interpreted as the immediate orogenic front of the East African – Antarctic Orogen. Furthermore, the Heimefront Shear Zone forms a lithosphere-scale feature that separates areas with different aeromagnetic signatures as well as lithospheric mantle with highly contrasting anisotropy directions.

(8) By Permian times a peneplain had formed, upon which Permo-Carboniferous sediments were deposited. During the Jurassic, the area was affected by the Bouvet-Karoo mantle plume that led to dynamic uplift and was associated with initial Gondwana rifting. The area was also covered by a thick succession of Jurassic lavas, probably up to 2-3 km thick. This lava blanket led to tempering of the basement up to about 100 ºC, as indicated by apatite fission-track ages that are all significantly younger than the emplacement age of the lavas. Differential exhumation and erosion are recorded during Cretaceous

and Cenozoic times, when large rift structures formed. Latest flexural uplift might have occurred due to ice loading, as indicted by (U-Th)/He apatite data. The present total relief is around 3500 m.

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Sample	Lithology	Terrane	Longitude Latitude	Ar-Ar Hbl	Rb-Sr Min	K-Ar Ms	K-Ar Bt, <2 µ	Reference
Kotpeg1	pegmatite	Kottas	9°45.2'W 74°18.1'S			967 ±21		JACOBS et al 1996
W12.1.86/1	amphibolite	Kottas	9°22.9'W 74°18.6'S	1012 ±1.4[I]				JACOBS et al. 1999
W5.1.86/2	sheared mafic gneiss	Kottas	9°46.3'W 74°19.6'S	c. 950				JACOBS et al. 1999
W10.1.86/3	augen gneiss	Kottas	9°45.8'W 74°19.5'S		484.6 ±2.2[B]			JACOBS et al. 1999
W10.1.86/4	grey gneiss	Kottas	9°45.5'W 74°19.6'S		444.1 ±3.9[B]			JACOBS et al. 1999
J29.1.94/1	leucogranite	Sivorg-N	11°46.4'W 74°06.4'S		458.4 ±10.1[B]			JACOBS et al. 1999
J30.1./18	amphibolite mylonite	Sivorg-C	11°06.1'W 74°35.7'S	531 ±6				JACOBS et al. 1997
J27.1./08	amphibolite mylonite	Sivorg-C	11°05.4'W 74°35.8'S	484 ±4				JACOBS et al. 1997
J25.1./14	amphibolite mylonite	Sivorg-C	11°05.6'W 74°35.8'S	499 ±4				JACOBS et al. 1997
W3.2.88/20	amphibolite	Sivorg-C	11°39.5'W 74°46.9'S	500.5 ±3.7[I]				JACOBS et al. 1999
J1145.5	granodiorite	Sivorg-C	11°32.5'W 74°50.3'S	501.1 ±2.1[P]				JACOBS et al. 1999
J1176	felsic gneiss with hornblende garben	Sivorg-C	11°24.0'W 74°49.6'S	502.1 ±2.3[P]			468 ±5	JACOBS et al. 1999
GZ44	biotite-hornblende gneiss	Sivorg-C	11°38.3'W 74°50.8'S				494 ±3	JACOBS et al. 1999
J7.2.88/7	mylonitic augen gneiss	Sivorg-C	11°47.9'W 74°42.2'S		490.2 ±5.2[M]			JACOBS et al. 1999
J10.2.88/9	mylonitic augen gneiss	Sivorg-C	11°52.0'W 74°43.9'S		487.5 ±5.2[B] 455.2 ±4.8[M]			JACOBS et al. 1999
J23.1.94/1	mylonitic amphibolite	Sivorg-S	11°20.2'W 74°03.3'S	565 ±21[I]			498 ±5	JACOBS et al. 1999
J23.1.94/13	porphyritic gabbro	Sivorg-S	12°24.1'W 74°02.6'S	535 ±13[I]			479 ±5	JACOBS et al. 1999
W23.1.94/3	mylonitic amphibolite	Sivorg-S	12°26.0'W 75°01.7'S	506 ±8			509 ±5	JACOBS et al. 1999
W23.1.94/2	Mylonitic gneiss	Sivorg-S	12°27.5'W 74°01.3'S		389.1 ±5.4[B]			JACOBS et al. 1999
W23.1.94/3	Mylonitic gneiss	Sivorg-S	12°26.0'W 75°01.7'S		471.8 ±7.1[B]			JACOBS et al. 1999
J23.1.94/2	mafic boudin	Sivorg-S	11°19.8'W 75°03.3'S		470.7 ±26[B]			JACOBS et al. 1999
J25.1.94/3	monzonite mylonite	Sivorg-S	12°38.5'W 75°03.4'S				495 ±5	JACOBS et al. 1999
J1.2.88/9	mylonitic augen gneiss	Sivorg-S	11°09.0'W 74°35.6'S		487.0 ±5.6[B] 481.7 ±4.9[M]			JACOBS et al. 1999
J1.2.94/1	felsic gneiss	Sivorg-C	10°11.9'W 74°35.3'S				469 ±5	JACOBS et al. 1999
W2.2./1	ultramylonite	Kottas	10°48.0'W 74°19.2'S				473 ±11 <2µ	Jacobs et al. 1995
J1013	muscovite-paragneiss	Sivorg-C	11°26.1'W 74°52.7			508 ±11		Jacobs et al. 1995
J1057	folded pegmatite	Sivorg-C	11°23.5'W 74°51.5'S			510 ±11		Jacobs et al. 1995
W30.01./3	quartzite	Sivorg-C	11°20.2'W 74°55.5'S			493 ±10	476 ±10	Jacobs et al. 1995
J1028	paragneiss	Sivorg-C	11°24.9'W 74°52.3'S				497 ±11	Jacobs et al. 1995
J1102	mafic metavolcanic	Sivorg-C	11°37.9'W 74°50.9'S				477 ±10	Jacobs et al. 1995
J1160	paragneiss	Sivorg-C	11°28.7'W 74°50.1'S					Jacobs et al. 1995
J5.2./3	protomylonitic augen gneiss	Sivorg-C	11°46.2'W 74°45.6'S			478 ±10		Jacobs et al. 1995
J7.2./7	mylonitic augen gneiss	Sivorg-C	11°48.2'W 74°42.8'S			508 ±11		Jacobs et al. 1995
J7.2./7	mylonitic augen gneiss	Sivorg-C	11°48.2'W 74°42.8'S				499 ±10	Jacobs et al. 1995
J9.2./3	paragneiss	Sivorg-C	11°47.1'W 74°43.9'S				486 ±10	Jacobs et al. 1995

Table 1A continued

Sample	Lithology	Terrane	Longitude Latitude	Ar-Ar Hbl	Rb-Sr Min	K-Ar Ms	K-Ar Bt, <2 µ	Reference
J10.2./9	mylonitic augen gneiss	Sivorg-C	11°58.1'W 74°40.2'S			484 ±10		JACOBS et al. 1995
J10.2./9	mylonitic augen gneiss	Sivorg-C	11°58.1'W 74°40.2'S				469 ±10	JACOBS et al. 1995
J14.2./5	mylonitic augen gneiss	Sivorg-C	11°52.0'W 74°43.9'S				498 ±10	JACOBS et al. 1995
J14.2./5	mylonitic augen gneiss	Sivorg-C	11°52.0'W 74°43.9'S				494 ±10	JACOBS et al. 1995
J11.2./21	orthomylonitic augen gneiss	Sivorg-C	11°21.1'W 74°40.9'S				495 ±10	JACOBS et al. 1995
J11.2./24	pseudotachylite	Sivorg-C	11°21.1'W 74°40.9'S				**395 ±9 <2 µ**	JACOBS et al. 1995
J950	folded pegmatite	Sivorg-C	10°37.3'W 74°39.3'S			510 ±11		JACOBS et al. 1995
J965	migmatitic paragneiss	Sivorg-C	10°42.0'W 74°38.1'S				499 ±11	JACOBS et al. 1995
J1.2./9	orthomylonitic augen gneiss	Sivorg-C	11°12.3'W 74°35.4'S			489 ±10		JACOBS et al. 1995
J1.2./9	orthomylonitic augen gneiss	Sivorg-C	11°12.3'W 74°35.4'S				475 ±10	JACOBS et al. 1995
BvS	folded pegmatite	Sivorg-C	11°27.2'W 74°31.6'S				533 ±12	JACOBS et al. 1995
W6.2./4	mylonitic augen gneiss	Sivorg-S	12°38.8'W 75°03.4'S				812 ±17	JACOBS et al. 1995
W7.2./6	ultramylonitic augen gneiss	Sivorg-S	12°45.0'W 75°01.1'S				**470 ±10 <2 µ**	JACOBS et al. 1995
W8.2./3	paragneiss	Sivorg-S	12°25.7'W 75°01.6'S			486 ±6		JACOBS et al. 1995
W8.2./3	paragneiss	Sivorg-S	12°25.7'W 75°01.6'S				488 ±10	JACOBS et al. 1995
GZ27	mylonitic augen gneiss	Sivorg-S	12°10.9'W 74°54.7'S				476 ±10	JACOBS et al. 1995
J1553	paragneiss	Sivorg-S	11°51.7'W 74°55.4'S			530 ±13		JACOBS et al. 1995
Cotbau1	Cottentoppen granite	Sivorg-S	12°34.7'W 75°04.3'S			886 ±19		JACOBS et al. 1996
W23.1./7	quartzite	HSZ	11°36.8'W 74°29.7'S			960 ±20		JACOBS et al. 1995
PvU 1-2	pegmatite	HSZ	11°36.8'W 74°29.7'S			987-960		JACOBS et al. 1995

Tab. 1A: Summary Ar-Ar, Rb-Sr and K-Ar data. Abbreviations: B = biotite, M = muscovite, HSZ = Heimefront Shear Zone, I = integrated age, P = plateau age. Coordinates are not based on GPS measurements, but are approximate values taken from map localities.

Tab. 1A: Zusammenfassung von Ar-Ar, Rb-Sr und K-Ar Daten. Abkürzungen: B = Biotit, M = Muskowit, HSZ = Heimefront Shear Zone, I = integriertes Alter, P = Plateau Alter. Koordinaten basieren nicht auf GPS-Messungen, sondern sind Näherungswerte von Kartenlokationen.

U-Pb data Sample	Lithology	Terrane	Longitude Latitude	Method	Mineral	Age 1 (Ma)	Age 2 (Ma)	Reference
A7.1/8	metavolcanic (KMR)	Kottas	9°40.5'W 74°19.2'S	U-Pb SHRIMP	Zircon	1093^{+35}_{-39}		Arndt et al. 1991
A7.1/1	kater gneiss (KG2)	Kottas	9°43.2'W 74°18.2'S	conv. U-Pb	Zircon	1088 ±10		Arndt et al. 1991
3.1./2	pegmatite	Kottas	9°45.1'W 74°18.1'S	U-Pb SHRIMP	Zircon	1060 ±8		Arndt et al. 1991
KB18	tonalite gneiss (KTT)	Kottas	9°44.9'W 74°18.2'S	U-Pb SHRIMP	Zircon	1130 ±17		Jacobs et al. 1999
W16.1.86/1	leucogranite (KD4)	Kottas	9°37.6'W 74°16.7'S	conv. U-Pb	Zircon	1184^{+326}_{-176}		Jacobs et al. 1999
W8.1.a	granitic gneiss (KG1)	Kottas	9°37.6'W 74°16.7'S	conv. U-Pb	Zircon	1110^{+23}_{-17}		Jacobs et al. 1999
KB 156	mafic dyke (MD)	Kottas	9°19.7'W 74°18.5'S	U-Pb SHRIMP	Zircon	1033 ±7		Bauer et al. 2003a
S1-40	Paragneiss (SMS1)	Sivorg-C	11°08.6'W 74°32.7'S	U-Pb SHRIMP	Zircon	1900-1140 detrital		Jacobs et al. this vol.
W30.01./4	Quartzite (SMS	Sivorg-C	11°20.0'W 74°55.4'S	U-Pb SHRIMP	Zircon	3000-1500 1320-980 detrit.		Jacobs et al. this vol.
17.1./7	garnet-amphibolite (SMV2)	Sivorg-N	9°55.2'W 74°25.3'S	U-Pb SHRIMP	Zircon	1068 ±8		Arndt et al. 1991
S1-3	felsic metavolcanic (SMV1)	Sivorg-N	9°55.8'W 74°25.3'S	U-Pb SHRIMP	Zircon	1171 ±25	1062 ±11	Jacobs et al. 2003a
S1-17	felsic gneiss (SMV1?)	Sivorg-N	10°02.6'W 74°33.9'S	U-Pb SHRIMP	Zircon	1098 ±11	555 ±8	Jacobs et al. 2003a
S1-12	meta-granodiorite	Sivorg-N	10°09.8'W 74°34.7'S	U-Pb SHRIMP	Zircon	1107 ±11	496.5 ±6.5	Jacobs et al. 2003a
S1-49	mafic metavolcanic (SMV2)	Sivorg-N	9°58.2'W 74°24.9'S	U-Pb SHRIMP	Zircon	1129 ±31	1112 ±31	Bauer et al. 2003b
S1-32	felsic metavolcanic (SMV1)	Sivorg-N	11°15.8'W 74°33.7'S	U-Pb SHRIMP	Zircon	1086 ±10		Bauer et al. 2003b
S1-55	felsic metavolcanic (SMV1)	Sivorg-N	9°45.8'W 74°24.8'S	U-Pb SHRIMP	Zircon	1161.2 ±9.5		Bauer et al. 2003b
KB 135	mafic dyke (MD)	Sivorg-N	11°09.1'W 74°34.9'S	U-Pb SHRIMP	Zircon	586 ±7		Bauer et al. 2003a
25.1./9	Wrighthamaren gneiss	Sivorg-C	11°01.4'W 75°35.2'S	U-Pb SHRIMP	Zircon	1104 ±10		Arndt et al. 1991
27.1./1	Fish gneiss (SG6)	Sivorg-C	11°16.2'W 74°33.7'S	conv. U-Pb	Zircon	1078 ±30		Arndt et al. 1991
W23.1.86/1	Leucogranite	Sivorg-C	11°06.0'W 74°35.0'S	conv. U-Pb	Zircon	1079^{+61}_{-53}		Jacobs et al. 1999
W9.2.86/22	granodiorite	Sivorg-S	12°49.7'W 75°05.7'S	conv. U-Pb	Zircon	1077^{+18}_{-11}		Jacobs et al. 1999
W9.2.86/22	granodiorite	Sivorg-S	12°49.7'W 75°05.7'S	U-Pb SHRIMP	Zircon	1045 ±8		Arndt et al. 1991
W1.2.86/17	Månesigden granite (SG3)	Sivorg-S	12°15.5'S 74°52.1'S	conv. U-Pb	Zircon	1048^{+36}_{-31}		Jacobs et al. 2003a
J8.2./1	granite gneiss mylonite	HSZ	11°46.3'W 74°43.6'S	U-Pb SHRIMP	Zircon	1135 ±7		Jacobs et al. 2003a
J10.2./5	granite mylonite	HSZ	11°57.3'W 74°40.4'S	U-Pb SHRIMP	Zircon	1141 ±21		Jacobs et al. 2003a
J1674	ultramylonite	HSZ	12°13.7'W 74°53.8'S	U-Pb SHRIMP	Zircon	1090.8 ±5.8		Jacobs et al. 2003a
12.2./1	charnockite, Mannefall-knausane (Ch)	Vardeklettane	14°22.1'W 74°36.9'S	conv. U-Pb	Zircon	1073^{+15}_{-9}		Arndt et al. 1991
10.2./2	equigranular charnockite (Ch)	Vardeklettane	12°47.5'W 74°00.8'S	conv. U-Pb	Zircon	1135 ±8		Arndt et al. 1991
10.2./1	quartzite	Vardeklettane	12°44.8'W 74°01.1'S	U-Pb SHRIMP	Zircon	2000-1100 detrital		Arndt et al. 1991

Tab. 1B: Summary of U-Pb data from Heimefrontfjella. Age 1 = ages are interpreted as igneous crystallisation ages. Age 2 = ages are interpreted to represent metamorphic overprint. Abbreviation: C = central, HSZ = Heimefront Shear Zone, N = north, S = south; abbreviations behind lithologies correspond to those used on the 1:25,000 scale geological maps. Coordinates are not based on GPS measurements, but are approximate values taken from map localities.

Tab. 1B: Zusammenfassung von U-Pb-Daten der Heimefrontfjella. Age 1 = Alter werden als magmatische Kristallisationsalter interpretiert. Age 2 = Alter repräsentieren metamorphe Überprägungsalter. Abkürzung: C = zentral, HSZ = Heimefront Shear Zone, N = Nord, S = Süd; Abkürzungen hinter Lithologien entsprechen denen in den 1:25.000 geologischen Karten. Koordinaten basieren nicht auf GPS-Messungen, sondern sind Näherungswerte von Kartenlokationen.

Sample	Lithology	Terrane	Longitude	Latitude	Eleva. (m)	Age (Ma)	± 1σ (Ma)	MTL (µm)	± 1 σ (µm)	ST.D. (µm)
J8.2.94/7	sandstone	Kottas	9°44.4'W	74°20.1'S	2100	116	11	13.11	0.23	1.54
J8.2.94/8	sandstone	Kottas	9°44.4'W	74°20.1'S	2130	141	8	–	–	–
J8.2.94/6a	granite dropstone	Kottas	9°44.4'W	74°20.1'S	2100	138	13	13.43	0.15	1.51
J8.2.94/6b	granite dropstone	Kottas	9°44.4'W	74°20.1'S	2100	123	14	13.10	0.19	1.87
ST7	granite dropstone	Kottas	9°44.4'W	74°20.1'S	2100	131	11	12.08	0.20	2.00
BB1930	granitic orthogneisses	Kottas	9°42.7'W	74°19.7'S	1930	118	10	12.69	0.17	1.77
BB1820	granitic orthogneisses	Kottas	9°42.8'W	74°19.6'S	1820	120	11	11.96	0.17	1.69
BB1740	granitic orthogneisses	Kottas	9°42.8'W	74°19.6'S	1740	108	10	12.59	0.17	1.74
BB1700	granitic orthogneisses	Kottas	9°42.8'W	74°19.5'S	1700	121	11	13.48	0.16	1.60
BB1600	granitic orthogneisses	Kottas	9°43.0'W	74°19.4'S	1600	128	12	13.01	0.17	1.71
J7.2.94/3	leuco-tonalite	Kottas	9°48.8'W	74°19.1'S	1300	94	9	12.82	0.19	1.91
J7.2.94/2	tonalite	Kottas	9°48.7'W	74°19.1'S	1300	107	10	13.25	0.19	1.89
J7.2.94/4	trondhjemite	Kottas	9°48.5'W	74°19.1'S	1300	81	8	13.13	0.25	1.99
J7.2.94/5	tonalite	Kottas	9°48.3'W	74°19.1'S	1300	89	8	12.75	0.30	1.78
J7.2.94/18	tonalite	Kottas	9°48.2'W	74°19.1'S	1300	88	8	13.55	0.18	1.82
W.4.1./2	Bt-Hbl-Plag gneiss	Kottas	9°48.0'W	74°19.2'S	1300	106	10	12.51	0.18	1.82
A7.1./8	felsic gneiss	Kottas	9°40.5'W	74°19.2'S	1300	110	10	13.00	0.16	1.62
J2700	augen gneiss	Sivorg-C	11°35.3'w	74°44.8'S	2700	153	15	13.16	0.27	1.62
J1703	augen gneiss	Sivorg-C	11°37.3'W	74°45.6'S	2710	163	16	–	–	–
J1709	mafic augen gneis	Sivorg-C	11°36.7'W	74°45.7'S	2620	143	12	12.56	0.18	1.77
J1057	pegmatite	Sivorg-C	11°23.5'W	74°51.5'S	2420	164	19	–	–	–
J1058	pegmatite	Sivorg-C	11°24.0'W	74°51.6'S	2300	172	17	–	–	–
J9.2./3	felsic gneiss	Sivorg-C	11°47.1'W	74°43.9'S	1900	103	10	13.29	0.16	1.52
J1105	felsic gneiss	Sivorg-C	11°37.8'W	74°51.1'S	1750	111	10	–	–	–
J14.2./5	augen gneiss	Sivorg-C	11°52.0'W	74°43.9'S	1350	87	7	13.21	0.14	1.41
K55	metasediment	Sivorg-C	11°14.7'W	74°35.2'S	1200	96	8	12.33	0.19	1.94
K44	amphibolite	Sivorg-C	11°51.0'W	74°35.5'S	1855	134	17	12.00	0.33	2.01
K42	orthogneis	Sivorg-C	11°51.0'W	74°35.5'S	1860	116	12	12.19	0.19	1.95
K53	orthogneiss	Sivorg-C	11°09.9'W	74°40.5'S	1530	100	9	12.11	0.18	1.83
K30	orthogneis	Sivorg-C	11°42.3'W	74°43.3'S	1740	90	9	12.07	0.27	1.74
K24	orthogneis	Sivorg-C	11°48.0'W	74°43.8'S	1740	104	9	–	–	–
K32	felsic gneiss	Sivorg-C	11°08.5'W	74°32.7'S	1200	102	10	–	–	–
K15	orthogneiss	Sivorg-C	11°48.0'W	74°43.8'S	1700	95	8	–	–	–
J1500	pegmatite	Sivorg-C	11°50.0'W	74°56.3'S	2280	164	28	13.57	0.17	1.68
K19	orthogneiss	Sivorg-C	12°16.0'W	74°52.1'S	1620	94	8	12.28	0.19	1.87
W12.2./1	charnockite	Mannefal	14°22.1'W	74°36.9'S	900	124	11	12.34	0.23	1.90
W14.2./1	charnockite	Mannefal	14°22.1'W	74°36.9'S	900	104	9	12.58	0.22	2.00

Tab. 1C: Apatite fission track analyses from Heimefrontfjella (JACOBS & LISKER 1999). Abbreviations: Eleva. = elevation, MTL = mean track length, ST.D. = standard deviation. BB1930, J1709, J1058, J14.2./5 = samples from which additionally (U-Th)/He data exist (EMMEL et al. 2008). Coordinates are not based on GPS measurements, but are approximate values taken from map localities.

Tab. 1C: Apatit Spaltspur-Daten from Heimefrontfjella (JACOBS & LISKER 1999). Altersberechnung mit Zerfallskonstanten von STEIGER & JÄGER (1977). Abkürzungen: Eleva. = Höhe, MTL = Mittlere Spurendichte, ST.D. = Standardabweichung. BB1930, J1709, J1058, J14.2./5 = Proben von denen auch (U-Th)/He Daten existieren (EMMEL et al. 2008). Koordinaten basieren nicht auf GPS-Messungen, sondern sind Näherungswerte von Kartenlokationen.