Antarctic Science 11 (4): 451–460 (1999) © British Antarctic Survey Printed in the United Kingdom

Post Permian tectono-thermal evolution of western Dronning Maud Land, East Antarctica: an apatite fission-track approach

JOACHIM JACOBS* and FRANK LISKER

Universität Bremen, FB Geowissenschaften, PF 330440, D-28334 Bremen, Germany
**jojacobs@uni-bremen.de*

Abstract: New apatite fission-track (AFT) ages from Heimefrontfjella and Mannefallknausane indicate that the Mesoproterozoic basement and Permian sedimentary cover rocks were heated to *c.* 100°C during the Mesozoic. Heating was due to the burial by up to 2000 m of Jurassic lavas at *c.* 180 Ma, when the area was affected by the Bouvet/Karoo hot spot. Near the developing coastline, the lava pile was quickly eroded and in part deposited on the continental shelf as pebbly and coarse-grained volcaniclastic sandstones. The AFT data indicate that farther inland the lava pile was not eroded until *c.* 100 Ma, and the Palaeozoic unconformity between the Mesoproterozoic basement and Permo–Carboniferous sedimentary rocks as a reference plane remained at temperatures of *c.* 80°C. Formation of an up to 800 m b.s.l. deep graben in front of Heimefrontfjella as well as flexural uplift and rapid denudational cooling of the not extended crust from Heimefrontfjella southwards occurred at *c.* 100 Ma. It is speculated that a period of major plate reorganisation and new rifting at *c.* 100 Ma is responsible for affecting a much wider continental margin as far inland as Heimefrontfjella and producing a total relief in excess of 3500 m.

Received 20 October 1988, accepted 1 September 1999

Key words: apatite, denudation, Dronning Maud Land, East Antarctica, fission-track, rifting

Introduction

Heimefrontfjella is a *c.* 130 km long mountain range between 9° and 13°W, which is situated *c.* 350 km inland from the eastern margin of the Weddell Sea in East Antarctica. The mountain range is exposed between *c.* 1200 and 2700 m a.s.l. and lay within the area affected by the Karoo (White & McKenzie 1989) or Bouvet mantle plume (Storey 1995, Fig. 1). It was intruded by a large number of mafic dikes and sills and was covered by an unknown thickness of continental flood basalts at *c.* 180 Ma (Spaeth & Schüll 1987). A very irregular relief characterizes the area between Heimefrontfjella and the continental margin, with basement cropping out only in a few small nunataks at Mannfallknausane. Mapping of the subice topography reveals a steep graben that extends down to 800 m b.s.l. between Heimefrontfjella and Mannfallknausane (cf. Hoppe & Thyssen 1988). This graben most probably joins the Pencksökket–Jutulstraum graben farther to the north-east (Fig. 1). This graben system was interpreted as a possible southern continuation of the Western Rift System (East African graben system) into Antarctica or a failed Gondwana rift (Grantham & Hunter 1991).

Here, we try to quantify the tectono-thermal effects that Heimefrontfjella and Mannefallknausane underwent during Gondwana break-up by using apatite fission-track analyses. We analysed 37 apatite samples from basement and cover rocks using the external detector method. Twenty-two of these samples had previously been dated using the population technique (Jacobs 1991, Schnellbach 1991). Fourteen of the 15 newly dated samples come from a vertical profile in the northern part of Heimefrontfjella where the basement is unconformably overlain by Permo–Carboniferous sedimentary rocks.

Geological setting and previous fission-track work

Heimefrontfjella and Mannefallknausane are composed of medium to high-grade metamorphic basement rocks. The lithology, structure and geochronology are described in detail in Arndt *et al.* (1991), Jacobs *et al.* (1995) and Jacobs *et al.* (1996). Crust formation and the first major metamorphism occurred between *c.* 1300 and 1050 Ma. Large areas of Heimefrontfjella were overprinted at *c.* 500 Ma during the Pan-African/Ross event, as revealed by numerous K–Ar and Ar–Ar mineral analyses (Jacobs *et al.* 1995, 1997). In the northern part of Heimefrontfjella a pronounced Palaeozoic peneplain is developed, which is exposed at an elevation of *c.* 2100 m. There, the basement is overlain by Permo–Carboniferous sedimentary rocks of the Beacon Supergroup. During the Jurassic, the basement was intruded by many dykes and sills (Rex 1972, Spaeth & Schüll 1987). Large quantities of Jurassic mafic lavas are exposed in Vestfjella farther north (cf. Peters *et al.* 1991). Such lava flows probably covered large parts of Heimefrontfjella during the Jurassic but are mostly eroded now and are only preserved in one small locality at Bjørnnutane (Fig. 2). The Jurassic sills caused contact metamorphism within the sandstones. However, coal seams more than *c.* 60 m away from Jurassic sills show

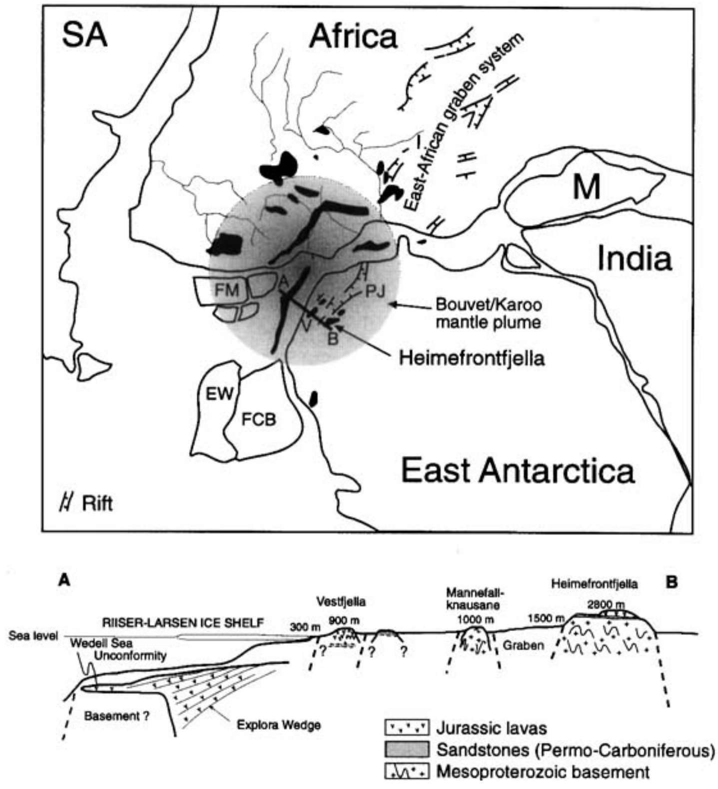

Fig. 1. Gondwana reconstruction with indication of the Bouvet/Karoo mantle plume and associated Jurassic volcanism (after White & McKenzie 1989, Storey 1995, Jacobs *et al.* 1996. Profile after Spaeth & Schüll (1987). Falkland microplate (FM) after Marshall (1994), Ellsworth Whitmore (EW) and Filchner crustal block (FCB) after Curtis & Storey (1996). Note possible continuation of the Western Rift System (East African graben system) into East Antarctica. Abbreviations: M = Madagascar, PJ = Pencksökket–Jutulstraumen, SA = South America, V = Vestfjella.

vitrinite reflectance values of *c.* 0.5 Rr, indicating that temperatures did not exceed 70 to 80°C during the Mesozoic and Cenozoic (Bauer *et al.* 1997). The cover sequence dips at 1–3° to the south-east. Seismic data indicate that the crust north-west of Heimefrontfjella was thinned from *c.* 50 km at Heimefrontfjella and its hinterland to *c.* 35 km north-west of it (Heinz Miller, personal communication 1997). Thus, the crust north-west of Heimefrontfjella represents extended continental crust that was strongly overprinted during the rifting of Gondwana.

First apatite fission-track studies using the population technique were carried out by Jacobs (1991) and Schnellbach (1991). Those data revealed ages between *c.* 75 and 230 Ma. Based on mean confined track length measurements the higher ages were interpreted as representing mixed ages, whereas the lower ages were interpreted as cooling ages. The data show a positive correlation between age and elevation as well as age and distance from the coast. The mixed ages around 180 Ma were interpreted as representing partial resetting during a thermal event at the beginning of Gondwana break-up, which was most likely associated with the Jurassic magmatism. The data also imply differential uplift and cooling of three different blocks within Heimefrontfjella, with the highest uplift rates having been concentrated in the now topographically highest regions. Thus, the 2700 m high mountains in Sivorgfjella (Fig. 2) were not interpreted as reflecting a steep Palaeozoic relief but Cretaceous differential uplift during the break-up of Gondwana.

In this study we try to constrain further the major Mesozoic to Cenozoic tectono-thermal events of the wider eastern margin of the Weddell Sea.

Samples and method

Thirty-seven apatite samples were analysed using the external detector method, as described by Green *et al.* (1989). This method yields similar results to the grain population technique when the apatites have homogenous U-concentrations and constant chlorine–fluorine ratios. The latter have an effect on the track-retention temperature of individual apatite grains. Thus, single grain dating is better suitable for apatites with changing composition and complex cooling path. Therefore, we have reanalysed most of the original samples from the study of Jacobs (1991) and Schnellbach (1991) using the external detector method. We also selected 15 new samples, most from a vertical profile at Buråsbotnen (Fig. 2), below and close to the pre- Permo–Carboniferous peneplain defined by the overlying Beacon sedimentary rocks. Apatites from the new samples were separated using standard techniques as recommended by Gleadow (1981). Apatite grains were embedded in epoxy resin, and were then ground and polished. Internal apatite surfaces were etched for 60 seconds at 21°C in 5% HNO_3. Samples were mounted with mica detectors and irradiated in the graphite reflector facility of Risø (Denmark). Thermal neutron fluence was monitored by using standard glasses CN5 (Corning Glass) and apatite standards, Fish Canyon and Durango. Fossil and spontaneous tracks were counted at 1000 x, and horizontal track lengths were measured

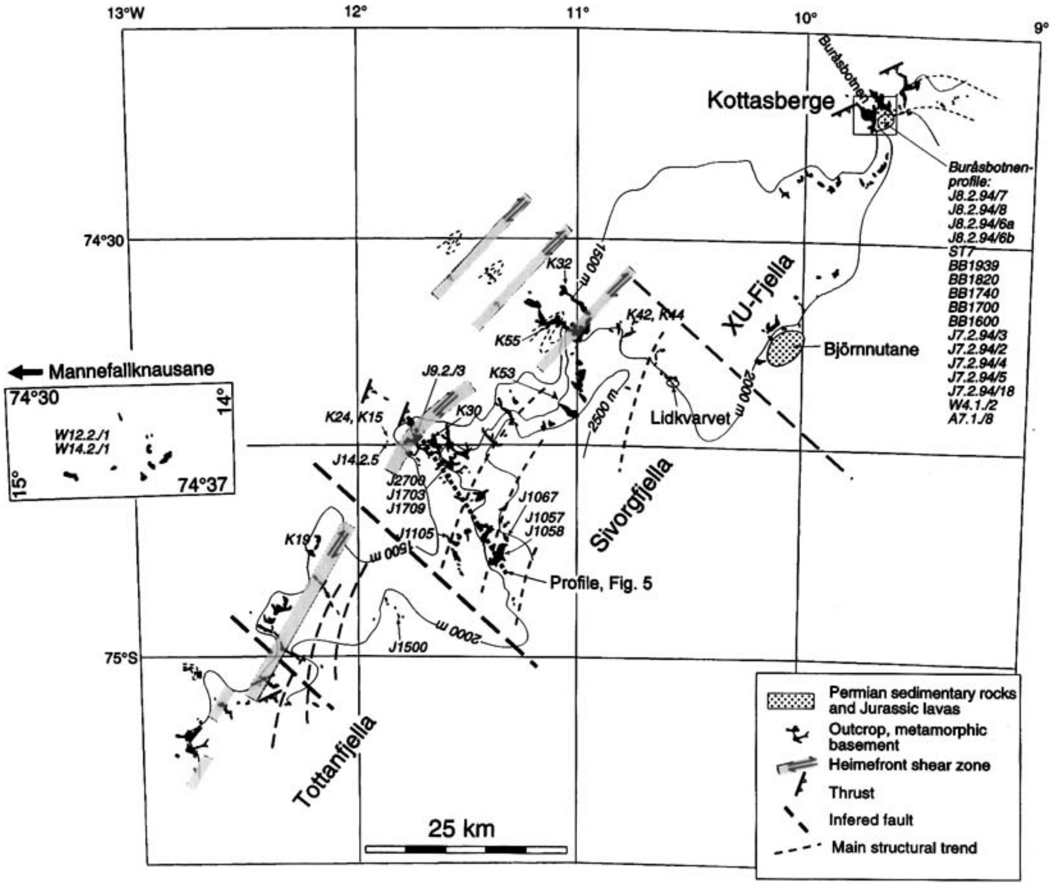

Fig. 2. Geological overview map of Heimefrontfjella with location of samples.

at 1250 x magnification (air lens). Whilst in the study of Jacobs (1991) track lengths were measured in a separate sample which was etched for an additional 20 sec in 20% HNO_3, in our study track lengths were measured in the actual sample on which the age determination was carried out. Thus, the track lengths are generally shorter than in the study of Jacobs (1991) and more compatible to current international procedures when applying the external detector method. We used a Kintec stage with FT-stage program of Dumitru (1993). Ages were determined using the zeta calibration method (Hurford & Green 1983, Green 1985) with a $\zeta = 361 \pm 6$ for J. Jacobs. Errors were calculated using conventional methods (Green 1981) and are quoted with $\pm$ 1 σ errors. The distribution of single grain ages were then characterized using a mixture modelling program (Sambridge & Compston 1994). From this, forward modelling by MonteTrax (Gallagher 1995) was used to constrain the low-temperature cooling history consistent with all measured track length distributions and ages.

Results and interpretation

The AFT data are summarized in Table I, sample locations are indicated in Fig. 2. Thirty-two of the analysed samples were taken from igneous or metamorphic crystalline basement rocks of Palaeozoic age or older, two samples are Permian sandstones, and three samples are granite-gneiss dropstones from the base of the Permo–Carboniferous sequence. The AFT ages range from 172 ± 17 to 81 ± 8 Ma and display a trend towards higher AFT ages at higher elevations (Fig. 3). Generally, the new determined apatite ages were similar to those that had been determined by the population technique (Jacobs 1991, Schnellbach 1991). All apatite ages are significantly younger than their stratigraphical ages, indicating that all samples have experienced major post-Permian thermal annealing.

Northern Tottanfjella/ Sivorgfjella

In northern Tottanfjella and Sivorgfjella, 18 AFT samples were collected between elevations of 1200 and 2710 m. The AFT ages range from 172 ± 17 to 87 ± 7 Ma (Table I), with the higher ages occurring at higher elevations and farther inland. The mean confined track lengths vary between 13.3 and 12.0 μm with corresponding standard deviations between 1.4 and 2.1 μm (Figs 3 & 4). The χ^2 values range from 0 to 99%. Although most χ^2 values are low (<40%), only five samples fail the χ^2-test. The oldest and the youngest samples, i.e. the samples closest to the graben and the samples farthest inland, have both the highest χ^2 values and the longest mean track lengths. A more detailed analysis of the latter samples reveals, that they are characterized by one dominant age group. Samples near the graben show one major age component

https://doi.org/10.1017/S0954102099000589 Published online by Cambridge University Press

Table I. AFT analyses.

Sample #	Elev. [m]	Locality	Lithology	n	ρs [xE6cm^{-2}]	Ns	ρi [xE6cm^{-2}]	Ni	ρd [xE6cm^{-2}]	Nd %	χ^2	Cc [ppm]	U [Ma]	Age [Ma]	± 1σ [µm]	MTL [µm]	± 1σ [µm]	s d	nl
J8.2.94/7	2100	Schivestolen	Sandstone	20	0.673	450	1.191	797	1.147	174	58	0.952	13	116	11	13.11	0.23	1.54	49
J8.2.94/8	2130	Schivestolen	Sandstone	20	1.481	588	2.158	857	1.147	174	14	0.864	24	141	8	–	–	–	–
J8.2.94/6a	2100	Schivestolen	Granite dropstone	20	0.873	592	1.299	881	1.147	174	30	0.772	14	138	13	13.43	0.15	1.51	100
J8.2.94/6b	2100	Schivestolen	Granite dropstone	20	0.921	224	1.543	375	1.147	174	20	0.918	17	123	14	13.1	0.19	1.87	99
ST7	2100	Schivestolen	Granite dropstone	20	0.2898	1422	4.534	2225	1.147	174	60	0.969	49	131	11	12.08	0.2	2	100
BB1930	1930	Burasbotnen	granitic orthogneiss	20	1.839	922	3.21	1609	1.147	174	32	0.915	35	118	10	12.69	0.17	1.77	97
BB1820	1820	Burasbotnen	granitic orthogneiss	20	2.398	898	4.088	1531	1.147	174	44	0.929	45	120	11	11.96	0.17	1.69	100
BB1740	1740	Burasbotnen	granitic orthogneiss	20	0.97	435	1.844	827	1.147	174	25	0.881	20	108	10	12.59	0.17	1.74	100
BB1700	1700	Burasbotnen	granitic orthogneiss	20	1.178	706	2.003	1201	1.147	174	95	0.957	22	121	11	13.48	0.16	1.6	99
BB1600	1600	Burasbotnen	granitic orthogneiss	20	1.558	727	2.488	1161	1.147	174	40	0.849	27	128	12	13.01	0.17	1.71	100
J7.2.94/3	1300	Burasbotnen	Leuco-tonalite	20	0.972	499	2.135	1096	1.147	174	7	0.908	23	94	9	12.82	0.19	1.91	100
J7.2.94/2	1300	Burasbotnen	Tonalite	20	0.932	474	1.792	912	1.147	174	69	0.909	20	107	10	13.25	0.19	1.89	100
J7.2.94/4	1300	Burasbotnen	Trondhjemite	20	0.977	506	2.469	1279	1.147	174	50	0.893	27	81	8	13.13	0.25	1.99	66
J7.2.94/5	1300	Burasbotnen	Tonalite	20	0.975	618	2.247	1425	1.147	174	60	0.920	25	89	8	12.75	0.3	1.78	36
J7.2.94/18	1300	Burasbotnen	Tonalite	20	1.243	563	2.914	1320	1.147	174	9	0.838	32	88	8	13.55	0.18	1.83	100
W4.1./2	1300	Burasbotnen	Bio-Hbl-Plag gneiss	20	2.709	896	5.286	1748	1.147	174	1	0.874	58	106	10	12.51	0.18	1.82	100
A7.1./8	1300	Burasbotnen	Felsic gneiss	20	1.496	558	2.796	1043	1.147	174	30	0.879	31	110	10	13	0.16	1.62	100
J2700	2700	Sivorgfjella	Augen gneiss	20	0.17	554	0.227	742	1.147	174	27	0.889	3	153	15	13.16	0.27	1.62	36
J1703	2710	Sivorgfjella	Augen gneiss	11	1.659	511	2.087	643	1.147	174	10	0.863	23	163	16	–	–	–	–
J1709	2620	Sivorgfjella	Mafic augen gneiss	20	2.051	1542	2.936	2208	1.147	174	32	0.931	32	143	12	12.56	0.18	1.77	100
J1057	2420	Sivorgfjella	Pegmatite	6	0.616	228	0.768	284	1.147	174	19	0.806	8	164	19	–	–	–	–
J1058	2300	Sivorgfjella	Pegmatite	20	0.23	485	0.274	578	1.147	174	99	0.958	3	172	17	–	–	–	–
J1500	2280	Tottanfjella	Pegmatite	8	0.191	154	0.314	253	1.147	174	1	0.125	3	164	28	13.57	0.17	1.68	100
J9.2./3	1900	Sivorgfjella	Felsic gneiss	19	0.496	542	0.989	1080	1.147	174	14	0.860	11	103	10	13.29	0.16	1.52	90
J1105	1750	Sivorgfjella	Felsic gneiss	20	0.303	521	0.56	963	1.147	174	22	0.850	6	111	10	–	–	–	–
J14.2./5	1350	Sivorgfjella	Augen gneiss	20	1.283	1085	3.039	2570	1.147	174	70	0.976	33	87	7	13.21	0.14	1.41	100
K55	1200	Sivorgfjella	Metasediment	20	1.273	1109	2.398	2089	1.147	174	34	0.981	26	96	8	12.33	0.19	1.94	100
K44	1855	Sivorgfjella	Amphibolite	20	0.397	473	0.608	724	1.147	174	0	0.889	7	134	17	12	0.33	2.01	37
K42	1860	Sivorgfjella	Orthogneiss	20	1.048	1324	1.659	2097	1.147	174	0	0.832	18	116	12	12.19	0.19	1.95	100
K53	1530	Sivorgfjella	Orthogneiss	20	1.987	1080	3.574	1943	1.147	174	17	0.920	39	100	9	12.11	0.18	1.83	100
K30	1740	Sivorgfjella	Orthogneiss	20	0.434	778	0.861	1544	1.147	174	0	0.908	9	90	9	12.07	0.27	1.74	42
K19	1200	Tottanfjella	Orthogneiss	20	0.581	1217	1.117	2339	1.147	174	39	0.939	12	94	8	12.28	0.19	1.87	99
K24	1740	Sivorgfjella	Orthogneiss	20	0.837	737	1.447	1274	1.147	174	65	0.908	16	104	9	–	–	–	–
K32	1200	Sivorgfjella	Felsic gneiss	20	1.384	763	2.48	1367	1.147	174	1	0.916	27	102	10	–	–	–	–
K15		Sivorgfjella	Orthogneiss	20	0.428	830	0.81	1570	1.147	174	20	0.905	9	95	8	–	–	–	–
W12.2./1	900	Mannefalk.	Charnockite	16	1.071	637	1.773	1055	1.147	174	92	0.981	19	124	11	12.34	0.23	1.9	68
W14.2./1	900	Mannefalk.	Charnockite	18	0.948	657	1.88	1303	1.147	174	83	0.690	21	104	9	12.58	0.22	2	82

Elev. = elevation; Ns and Ni = number of spontaneous and induced tracks; Nd = number of tracks counted in glass dosimetre; ρs, ρi = spontaneous and induced track density; ρs/ρi = ratio between spontaneous and induced track density; χ^2 = text for discussion; Cc = Correlation coefficient, n = number of grains analysed; nl = number of track lengths
Age calculations by using decay constants of Steiger & Jäger (1977)

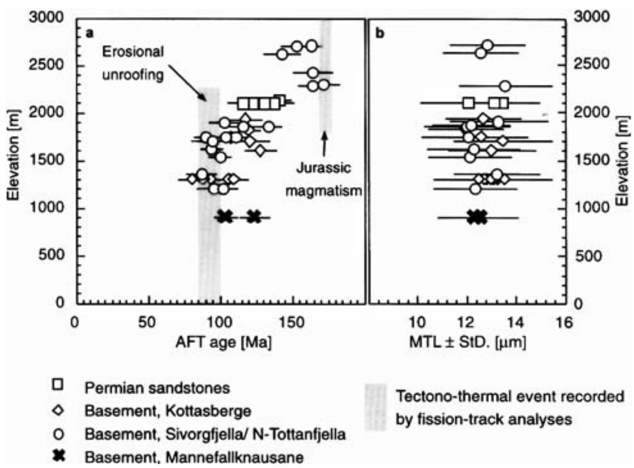

Fig. 3. AFT results: **a.** AFT age vs elevation and elevation vs mean track length (MTL). **b.** There are no ages older than the Jurassic volcanism at *c.* 180 Ma, which is thought to have caused total annealing of pre-Jurassic fission tracks. Erosional unroofing caused cooling during mid-Cretaceous times and is documented in very few single grain ages younger than *c.* 80 Ma.

of *c.* 100 Ma, the samples farthest inland of *c.* 170 Ma; by contrast, samples from between the latter localities show a broad mixture of ages (Fig. 5). The concentration of single grain ages around 170 and 100 Ma in some of the samples most probably reflect discrete tectono-thermal events, the causes of which are discussed later.

AFT ages of similar altitudes increase from north-west to south-east, i.e. further inland (Fig. 3). This trend is approximately perpendicular to the general strike of the graben and the coastline of Dronning Maud Land. The gentle dip of the Palaeozoic sedimentary rocks towards the SE probably indicates that the whole Heimefrontfjella underwent post-Permian tilting or flexural uplift on a NE-trending axis. In Sivorgfjella, this block rotation is documented in the distribution of the AFT ages, in that the AFT ages follow SW inclined paleo-isotherms (Fig. 5).

All samples taken from altitudes >2000 m (J1057, J1058, J1500, J1703, J1709, J2700) have AFT ages between 172 ± 17 and 143 ± 12 Ma. There is a concentration of single grain ages between 160 and 170 Ma with an increasing component of younger ages toward lower altitudes. Because of very low U-concentrations, only some samples revealed satisfactory track length information. The longest mean confined track length (13.57 ± 1.68 µm) came from the oldest sample. Successive younger samples have mean confined track lengths that are up to *c.* 1 µm shorter, indicating that they spent a longer time in the partial annealing zone (PAZ).

Samples with ages from *c.* 140 to *c.* 110 Ma (J1105, K42, K44) display a very broad range in single grain ages and have mean confined track lengths of 12.2 and 12 µm with broad track length distributions. They have a significant component of short tracks with lengths <10 µm. The total number of

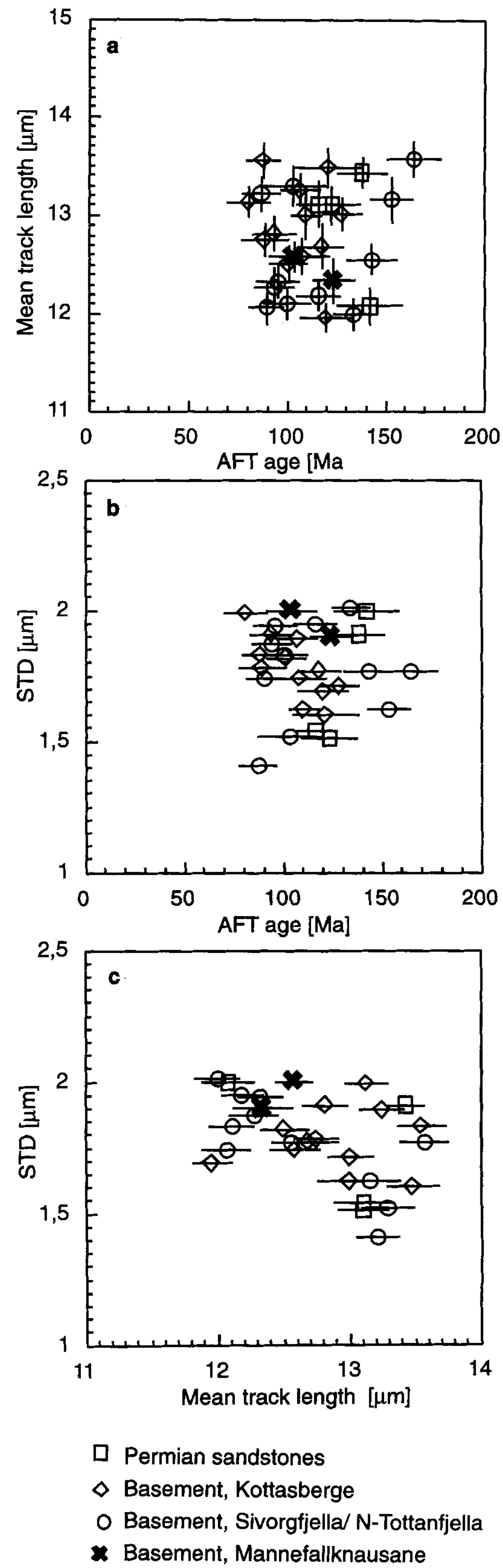

Fig. 4. AFT results: **a.** AFT age vs mean track length, **b.** AFT age vs standard deviation, **c.** mean track length vs standard deviation.

https://doi.org/10.1017/S0954102099000589 Published online by Cambridge University Press

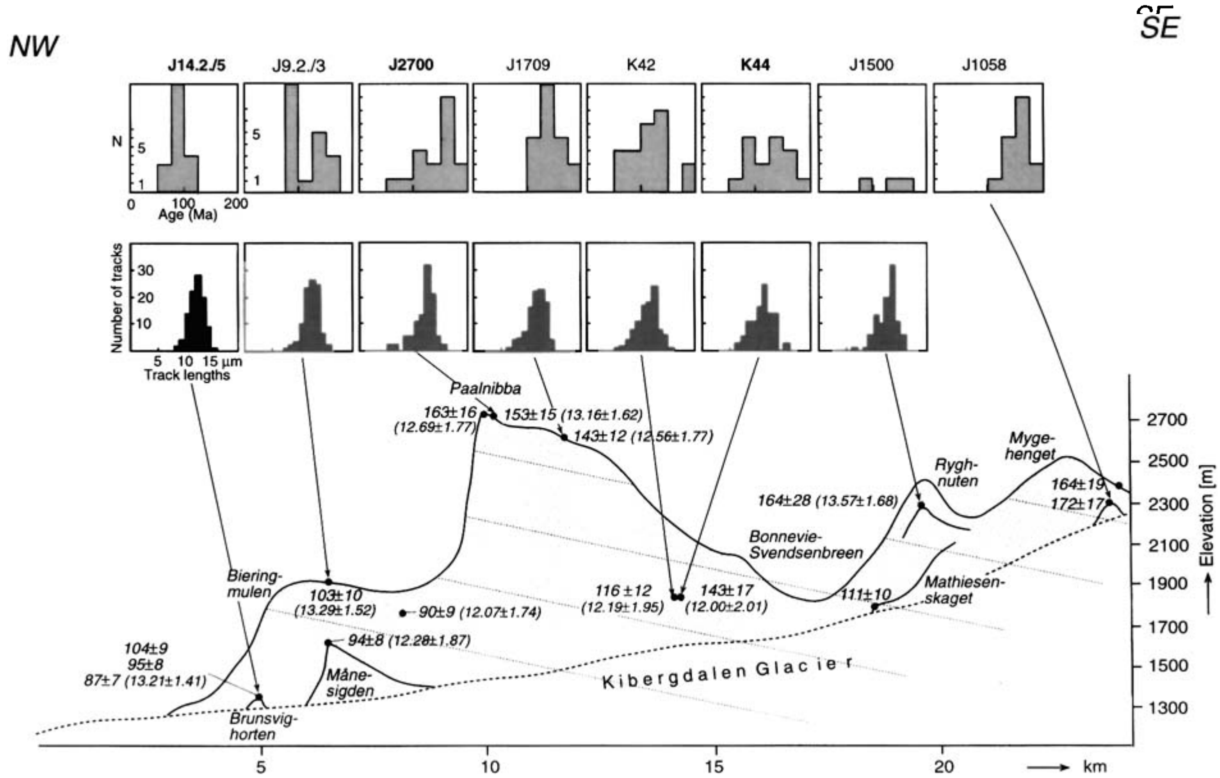

Fig. 5. The regional AFT age distribution indicates increasing ages towards the SE as well as a positive correlation between age and height. Samples farthest south-east show only one age component of *c.* 170 Ma, whilst samples in the very north-west show one age component of *c.* 100 Ma. Samples between show a mixture of these two age components. Mean confined tracks length are longest for the samples with one single age component and shortest for samples with multiple age components. AFT ages can be grouped along palaeo-isotherms (stippled lines). Palaeo-isotherms were derived by projecting the tilted Palaeozoic peneplain of Kottasberge into Sivorgfjella (i.e. tilting of 1–3° toward the SE). Note vertical exaggeration. Bold sample numbers refer to samples that were modelled (cf.Fig. 7).

fission tracks in the samples comprise two distinct populations. An older population of tracks was partially annealed, whilst a younger generation of tracks with longer lengths (> 13 µm) accumulated during and after a second cooling stage.

Nine samples have AFT ages of *c.* 100 Ma or younger (J9.2./3, 14.2./5, K15, K19, K24, K30, K32, K53, K55). Their mean track lengths vary between 13.3 and 12.1 µm with standard deviations between 1.4 and 2 µm. All samples experienced some degree of annealing but there are few tracks <10 µm, which would indicate major annealing.

To constrain the observed pattern of the apatite ages and confined track lengths quantitatively, we applied the principles of interpretation explained by Gleadow *et al.* (1983, 1986) and Green *et al.* (1989). The data show a rapid cooling of the oldest samples from temperatures above *c.* 120–85°C at *c.* 170 Ma. They cooled further to below 60°C at *c.* 100–90 Ma, although this period of cooling is not very well constrained in all samples. The samples with the mixed ages (*c.* 140–110 Ma) also display both cooling events but they spent more time in the upper part of the PAZ, and thus have shorter mean confined track lengths. The youngest samples, close to the graben structure, show the most evidence for the cooling event at 100–90 Ma. These samples indicate another cooling event during the Cenozoic. Cretaceous denudational controlled cooling can be estimated to *c.* 40°C near the graben and *c.* 20°C in the farthest inland area.

Forward modelling with MonteTrax (Gallagher 1995) has been applied to test the thermal history derived from the AFT data by using the Monte Carlo approach for Durango apatite (Laslett *et al.* 1987) by running 200 random thermal histories (Fig. 7). All samples apart from K30 fit the model within ± 1 σ rejectance level.

Kottasberge

The 17 samples from Kottasberge were taken from a near-vertical profile at Buråsbotnen (ten granitoid gneiss samples) and Schivestolen (five sandstones and dropstones samples). The AFT ages vary between 141 ± 8 at the top of the profile and 81 ± 8 Ma at the bottom (Figs 3 & 5b). All but one sample (W14.1./2) passed the χ^2 test.

The five samples above the Palaeozoic unconformity at *c.* 2100 m (Schivestolen: J8.2.94/6a, J8.2.94/6b, J8.2.94/7, J8.2.94/8, ST7) have the oldest ages between 141 ± 8 and 116 ± 11 Ma. The two sandstone samples (J8.2.94/7, J8.2.94/8) mark the upper and lower limit of the age spectrum. They have the broadest range of single grain ages which is thought to reflect the typical broad chemical compositional

https://doi.org/10.1017/S0954102099000589 Published online by Cambridge University Press

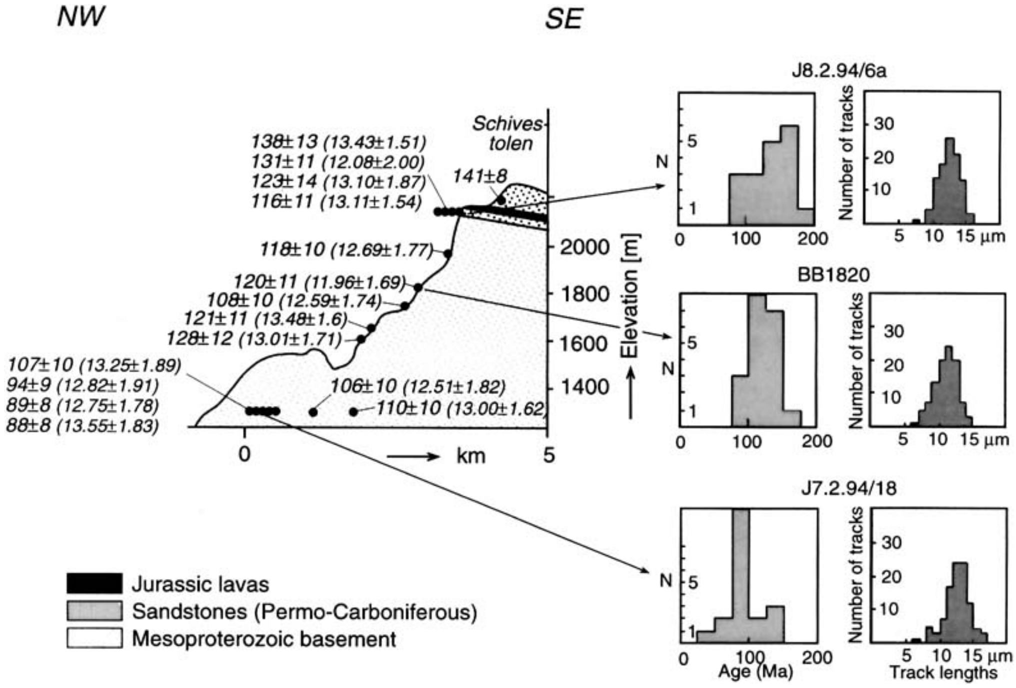

Fig. 6. Buråsbotnen-profile, showing the positive correlation between AFT age and elevation. This profile resolves the two stage thermal history less well than the regionally distributed samples in Sivorgfjella and Tottanfjella.

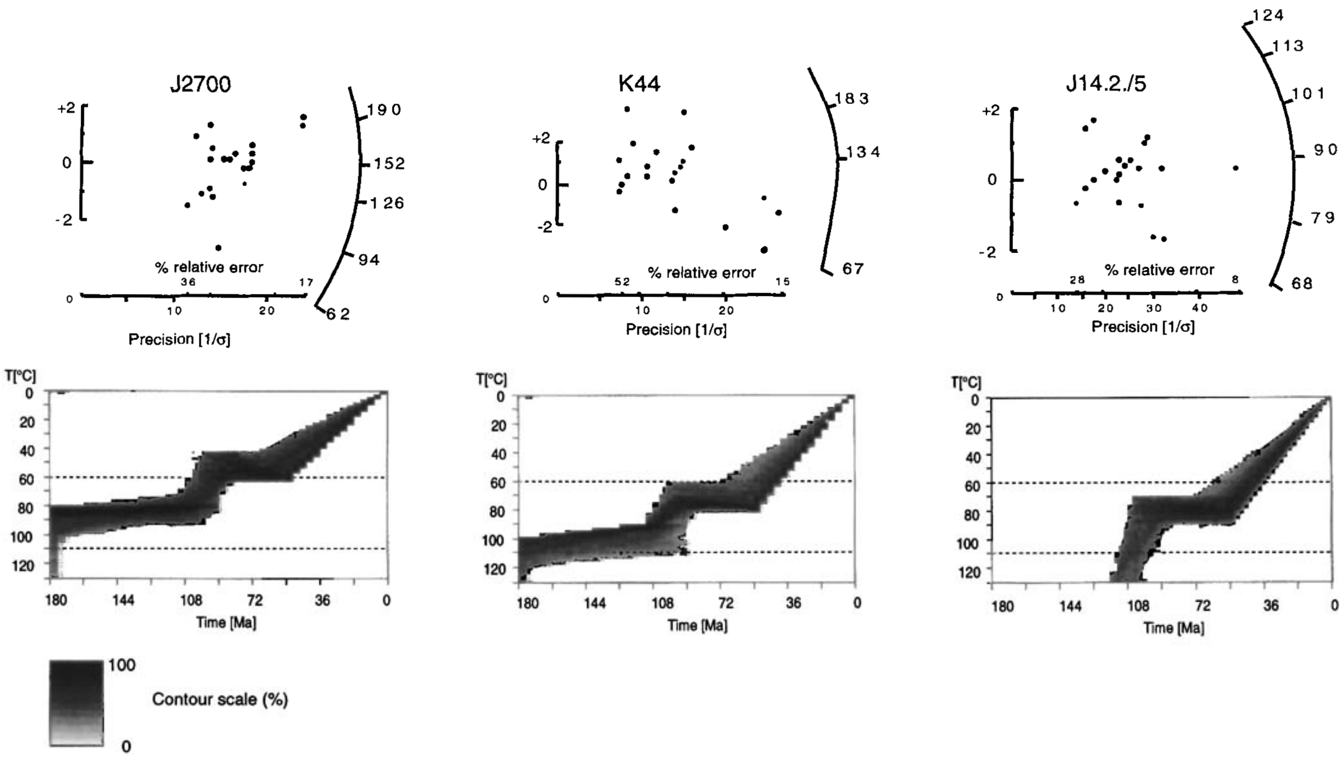

Fig. 7. Radial plots for three selected samples (cf. Fig. 5) and numerical modelling using MonteTrax (Gallagher 1995).
a. The topographically highest sample (J2700) indicates one major cooling event at *c.* 180 Ma, probably dating the cooling after Jurassic volcanism. The sample remained within the partial annealing zone (PAZ) until final exhumation at *c.* 100 Ma. **b.** During most of the Jurassic and Early Cretaceous the sample from middle elevations (K44) remained in the upper part of the PAZ where not many fission-tracks could accumulate. Exhumation at *c.* 100 Ma brought the sample near to the field of total track stability but final cooling was probably not earlier than Early Tertiary times, **c.** The topographically lowest sample (J14.2./5) has no Jurassic record. It only entered the PAZ during the mid-Cretaceous unroofing event.

variation of apatites in sediments. The ages for the granite gneiss dropstone only scatter within the 1σ-error range between 138 ± 13 and 123 ± 14 Ma.

None of the samples shows single grain ages above *c.* 200 Ma, indicating that they were thermally overprinted during the Jurassic and have not retained any detrital information. All pre-Jurassic tracks were entirely annealed during the Jurassic thermal event. However, the duration of heating must have been short, i.e. < 1 Ma, because VR values of coal seams in the sandstones have been determined as low as *c.* 0.5 (Bauer *et al.* 1997). This indicates that temperatures of 80–130°C persisted long enough to anneal apatite fission tracks but the duration of heating was not long enough significantly to mature the coal seams (cf.Burham & Sweeny 1989).

The AFT ages below the Palaeozoic peneplain (12 samples from 1900 to 1300 m) vary between 128 ± 12 and 81 ± 8 Ma. The range in ages of the samples at 1300 m (110 ± 10 to 81 ± 8 Ma) is most probably controlled by differing chemical composition of the samples as is also apparent from the broad spread of the single grain ages between *c.* 180 and 50 Ma. The mean confined track lengths of the Kottasberge samples range from 13.6 to 12 μm with corresponding standard deviations between 1.5 and 2.0 μm. These shortened lengths and the broad standard deviations as well as the broad spread in single grain ages of samples from similar altitudes indicate significant annealing and a longer residence time of the samples in the partial annealing zone.

For Kottasberge we suggest a similar thermal history to that of northern Tottanfjella/ Sivorgfjella, with a late Jurassic episode of rapid cooling and a second cooling stage in the mid-Cretaceous. Numerical modelling of the available fission-track data using MonteTrax confirm this interpretation.

Mannefallknausane

The samples W12.2./1 and W14.2./1 taken from Mannefallknausane at *c.* 900 m altitude have AFT ages of 124 ± 11 and 104 ± 9 Ma. Both mean track lengths of 12.6 and 12.3 μm with standard deviations of 2 and 1.9 μm indicate significant annealing.

Discussion

K–Ar mica data indicate that western Dronning Maud Land cooled to below *c.* 300°C for the last time at *c.* 470 Ma (e.g. Jacobs *et al.* 1995). A stable platform should have been formed during the Palaeozoic, when the basement was buried by an unknown thickness of Permian sandstones. The next major tectono-thermal event was associated with the break-up of Gondwana, when western Dronning Maud Land was affected by the Bouvet mantle plume (White & McKenzie 1989). The broader geological setting, marine geophysical and palaeomagnetic data indicate that, in this part of Gondwana, the Jurassic–Cretaceous break-up history can be differentiated into three distinct stages.

1. At about 180 Ma dynamic uplift above the Bouvet or Karoo mantle plume was accompanied by initial rifting, erosional unroofing of Permian sandstones and volcanism (White & McKenzie 1989). Large quantities of lavas are known from the Explora wedge (Hinz & Krause 1982), Vestfjella (e.g. Peters *et al.* 1991), and in smaller quantities from localities farther inland, such as Heimefrontfjella, Semberget and Kirwanveggen. These volcanic rocks are part of the Karoo volcanic province which was synchronous with the Ferrar magmatism along the Pacific and Transantarctic margin of the East Antarctic craton at *c.* 180 Ma (e.g. Elliot 1992, Encarnacion *et al.* 1996). Initial updoming and volcanism was probably associated with magmatic underplating that caused permanent uplift of the underplated areas (e.g. White & McKenzie 1989, Brown *et al.* 1994).

2. Dextral transpressional/transtensional movements between East and West Gondwana followed from *c.* 170 and 140 Ma (Henriet & Miller 1990). Transpressional/ transtensional movements did not allow the full development of the continental margin until the early Cretaceous.

3. A three-plate drift configuration developed when South America split from Africa at *c.* 140 Ma. This led to a total reorganization of drift configuration, the production of major amounts of ocean floor, and to an extension of the continental margin of Dronning Maud Land up to 350 km wide.

Especially the first and last tectonic episodes are reflected in the AFT results of Heimefrontfjella. The Palaeozoic peneplain proves that the basement cooled to surface temperatures during the Palaeozoic. However, neither apatites from the basement nor apatites from the sedimentary rocks show single grain ages greater than 200 Ma. This indicates that the area was affected by a short-lived thermal event of at least 100–120°C during the Mesozoic, most probably caused by the burial of 1500 to 2000 m of Jurassic lavas (depending on the geothermal gradient) which led to rising isotherms. However, as discussed earlier, very low coal maturity within the sedimentary cover indicates that this event was short-lived (Bauer *et al.* 1997). This observation is in agreement with the assumptions that the Ferrar–Karoo magmatism lasted for less than 1 Ma (e.g. Elliot 1992). The Palaeozoic peneplain cooled quickly to temperatures of *c.* 80°C and remained at such temperatures until mid-Cretaceous times.

Near the coast, the initial formation of the continental margin probably caused steep topography which enabled fast erosion of large parts of the continental flood basalts, but not as far inland as Heimefrontfjella, where no major unroofing is recorded until *c.* 100 Ma. In Heimefrontfjella the Palaeozoic peneplain remained at temperatures of *c.* 80°C until mid-Cretaceous time, indicating that a substantial thickness of

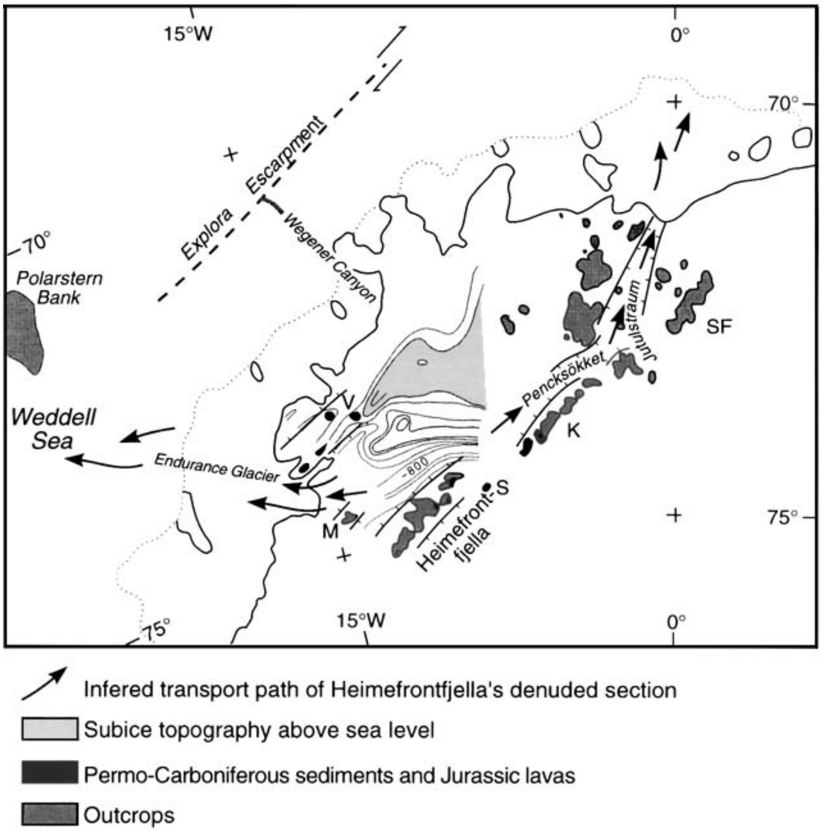

Fig. 8. Regional map of western Dronning Maud Land after Jacobs *et al.* (1996) indicating the sub-ice topography after Hoppe & Thyssen (1988). Note the deep graben in front of Heimefrontfjella that might join the similarly deep Pencksökket. It was speculated that the erosional detritus of Heimefrontfjella during mid-Cretaceous times was not shed onto the shelf but was channelled through the developing graben into the Weddell Sea and the South Atlantic. Abbreviations: K = Kirwanveggen, M = Mannefallknausane, S = Semberget, SF = Sverdrupfjella, V = Vestfjella.

Jurassic lavas must have covered the area for some 80 Ma.

The initial Jurassic rifting near the coast led to rapid denudation of the lavas. The erosional detritus of the lavas was deposited on the continental shelf, where a 2000 m thick pebbly and coarse-grained volcaniclastic sandstone sequence has been recorded that was deposited at minimum sedimentation rates of 60 m Ma^{-1} (Fütterer *et al.* 1990). By contrast, Cretaceous–Cenozoic sediments on the shelf show much lower sedimentation rates of *c.* 15 m Ma^{-1}, when the main erosional unroofing in Heimefrontfjella is recorded at *c.* 100 Ma. The low sedimentation rates on the shelf indicate that the erosional detritus from Heimefrontfjella cannot have been shed directly onto the shelf. The area between the Heimefrontfjella and the coast is characterized by large-scale horsts and grabens (Fig. 8). They probably formed during large-scale crustal thinning from *c.* 140 Ma onwards. The Cretaceous and Cenozoic erosional detritus of Heimefrontfjella was probably channelled through the developing deep graben systems into the Weddell Sea to the west and along the Pencksökket and Jutulstraum into the South Atlantic and was thus not deposited on the immediate shelf (Fig. 8, Jacobs *et al.* 1992). Seismic studies indicate that Heimefrontfjella forms the boundary between thinned continental margin crust about 35 km thick to the north-west, and unaffected continental crust with a thickness of *c.* 50 km at Heimefrontfjella and farther south (Heinz Miller, personal communication 1997). Tilting of Heimefrontfjella, as recorded by the Permo–Carboniferous cover rocks, was probably caused by flexural uplift at the boundary between normal and thinned continental crust. This caused topographic relief in excess of 3500 m. Flexural uplift must have occurred during the Cretaceous cooling event, because the older apatite stratigraphy seems to have been affected by this event.

Acknowledgements

J.J. thanks the Alfred-Wegener-Institut for organisation and logistic support during the 1994 expedition to Heimefrontfjella, when most of the samples were collected for this study. G. Patzelt is thanked for leading up the steep cliffs at Kottasberge. We thank M. Olesch (Bremen) for providing the samples of U. Schnellbach and K. Weber (Göttingen) for supporting this project. The manuscript benefited from reviews by E. Hejl and B.C. Storey. This project was supported in part by Deutsche Forschungsgemeinschaft grant We 488/27 to K. Weber and Ja 617/9 to J.J.

References

Arndt, N.T., Todt, W., Chauvel, M., Tapfer, M. & Weber, K. 1991. U–Pb zircon age and Nd istopic composition of granitoids, charnockites and supracrustal rocks from Heimefrontfjella, Antarctica. *Geologische Rundschau*, **80**, 759–777.

Bauer, W., Hagemann, H.W., Poscher, G., Sachsenhofer, R.F. & Spaeth, G. 1997. Permian coals from western Dronning Maud Land – composition, environment, and influence of Jurassic magmatism on their maturity. *In* Ricci C.A., *ed. The Antarctic region: geological evolution and processes.* Siena: Terra Antartica Publication, 945–951.

Brown, R., Gallagher, K. & Duane, M. 1994. A quantitative assessment of the effects of magmatism on the thermal history of the Karoo sedimentary sequence. *Journal of African Earth Sciences*, **18**, 227–243.

Burham, A.K. & Sweeny, J.J. 1989. A chemical kinetic model of vitrinite maturation and reflectance. *Geochimica et Cosmochimica Acta*, **53**, 2649–2657.

Curtis, M.L. & Storey, B.C. 1996. A review of geological constraints on the pre-break-up position of the Ellsworth Mountains within Gondwana: implications for Weddell Sea evolution. *In* Storey, B.C., King, E.C. & Livermore, R.A., *eds. Weddell Sea tectonics and Gondwana break-up*. Geological Society of London Special Publication, No. 108, 191–199.

Dumitru, T.A. 1993. A new computer-automated microscope stage system for fission-track analysis. *Nuclear Tracks Radiation Measurements*, **21**, 575–580.

Elliot, D.H. 1992. Jurassic magmatism and tectonism associated with Gondwanaland break-up: an Antarctic perspective. *In* Storey, B.C., Alabaster, T. & Pankhurst, R.J., *eds. Magmatism and the causes of continental break-up*. Geological Society of London Special Publication, No. 68, 165–184.

Encarnacion, J., Fleming, T.H., Elliot, D.H. & Eales, H.V. 1996. Synchronous emplacement of Ferrar and Karoo dolerites and the early breakup of Gondwana. *Geology*, **24**, 535–538.

Fütterer, D.K., Kuhn, G. & Schenke, H.W. 1990. Wegener Canyon bathymetry and results from rock dredging near ODP Sites 691–693 Weddell Sea, Antarctica. *In* Barker, P.F., Kennett, J.P. *et al. Proceedings of the Ocean Drilling Program, Scientific Results*, **113**, 39–48.

Gallagher, K. 1995. Evolving temperature histories from apatite fission-track data. *Earth and Planetary Science Letters*, **136**, 421–435.

Gleadow, A.J.W. 1981. Fission-track dating methods: what are the real alternatives? *Nuclear Tracks*, **5**, 3–14.

Gleadow, A.J.W., Duddy, I.R. & Lovering, J.F. 1983. Fission track analysis: a new tool for the evaluation of thermal histories and hydrocarbon potential. *Australian Petroleum Exploration Association Journal*, **23**, 93–102.

Gleadow, A.J.W., Duddy, I.R., Green, P.F. & Lovering, J.F. 1986. Confined fission track length in apatite: a diagnostic tool for thermal history analysis. *Contributions to Mineralogy and Petrology*, **94**, 405–415.

Grantham, G.H. & Hunter, D.R. 1991. The timing and nature of faulting and jointing adjacent to the Pencksökket, western Dronning Maud Land, Antarctica. *In* Thomson, M.R.A., Crame, J.A. & Thomson, J.W., *eds. Geological evolution of Antarctica*. Cambridge: Cambridge University Press, 47–51.

Green, P.F. 1981. A new look at statistics in fission-track dating. *Nuclear Tracks*, **5**, 77–86.

Green, P.F. 1985. Comparison of zeta calibration baselines for fission-track dating of apatite, zircon and sphene. *Chemical Geology*, **58**, 1–22.

Green, P.F., Duddy, I.R., Laslett, G.M., Hegarty, K.A., Gleadow, A.J.W. & Lovering, J.F. 1989. Thermal annealing of fission tracks in apatite 4. Quantitative modelling techniques and extension to geological timescales. *Chemical Geology*, **79**, 155–182.

Henriet, J.P. & Miller, H. 1990. Some speculations regarding the nature of the Explora–Andenes Escarpment, Weddell Sea. *In* Bleil, U. & Thiede, J., *eds. Geological history of the polar oceans: Arctic versus Antarctic*. Dordrecht: Kluwer, 163–169.

Hinz, K. & Krause, W. 1982. The continental margin of Queen Maud Land, Antarctica: Seismic sequences, structural elements and geological development. *Geologisches Jahrbuch*, **E23**, 17–41.

Hoppe, H. & Thyssen, F. 1988. Ice thickness and bedrock elevation in western Neuschwabenland and Berkner island, Antarctica. *Annals of Glaciology*, **11**, 42–45.

Hurford, A.J. & Green, P.F. 1983. The zeta age calibration of fission-track dating. *Isotope Geoscience*, **1**, 285–317.

Jacobs, J. 1991. Strukturelle Entwicklung und Abkühlungsgeschichte der Heimefrontfjella (Westliches Dronning Maud Land/Antarktika). *Berichte zur Polarforschung*, **97**, 1–141.

Jacobs, J., Hejl, E., Wagner, G.A. & Weber, K. 1992. Apatite fission track evidence for contrasting thermal and uplift histories of metamorphic basement blocks in western Dronning Maud Land. *In* Yoshida, Y., Kaminuma, K. & Shiraishi, K., *eds. Recent progress in Antarctic earth science*. Tokyo: Terra Scientific Publishing Company, 323–330.

Jacobs, J., Arendt, H., Kreutzer, H. & Weber, K. 1995. K–Ar, ^{40}Ar–^{39}Ar and apatite fission-track evidence for Neoproterozoic and Mesozoic basement rejuvenation events in the Heimefrontjella and Mannefallknausane (East Antarctica). *Precambrian Research*, **75**, 251–262.

Jacobs, J., Bauer, W., Spaeth, G., Thomas, R.J. & Weber, K. 1996. Lithology and structure of the Grenville-aged (~1.1 Ga) basement of Heimefrontfjella (East Antarctica). *Geologische Rundschau*, **85**, 800–822.

Jacobs, J., Falter, M., Weber, K. & Jeßberger, E.K. 1997. ^{40}Ar–^{39}Ar evidence for the structural evolution of the Heimefront Shear Zone (Western Dronning Maud Land), East Antarctica. *In* Ricci, C.A., *ed. The Antarctic region: geological evolution and processes*. Siena: Terra Antartica Publication, 37–44.

Laslett, G.M., Green, P.F., Duddy, I.R. & Gleadow, A.J.W. 1987. Thermal annealing of fission tracks in apatite 2. A quantitative analysis. *Chemical Geology (Isotope Geoscience Section)*, **65**, 1–13.

Marshall, J. 1994. The Falkland Islands: a key element in Gondwana palaeogeography. *Tectonics*, **13**, 499–514.

Peters, M., Haverkamp, B., Emmermann, R., Kohnen, H. & Weber, K. 1991. Palaeomagnetism, K–Ar dating and geodynamic setting of igneous rocks in western and central Neuschwabenland, Antarctica. *In* Thomson, M.R.A., Crame, J.A. & Thomson, J.W., *eds. Geological evolution of Antarctica*. Cambridge: Cambridge University Press, 549–555.

Rex, D.C. 1972. K–Ar age determinations on volcanic and associated rocks from the Antarctic Peninsula and Dronning Maud Land. *In* Adie, R.J., *ed. Antarctic geology and geophysics*. Oslo: Universitetsforlaget, 133–136.

Sambridge, M.S. & Compston, W. 1994. Mixture modeling of multi-component data sets with application to ion-probe zircon ages. *Earth and Planetary Science Letters*, **128**, 373–390.

Schnellbach, U. 1991. *Neue Erkenntnisse der Hebungsgeschichte des Transantarktischen Gebirges mittels Spaltspuranalytik*. PhD thesis, Universität Bremen, 175 pp. [Unpublished].

Steiger, R.H. & Jäger, E. 1977. Subcommission on geochronology: convention on the use of decay constants in geo- and cosmochronology. *Earth and Planetary Science Letters*, **36**, 359–362.

Storey, B.C. 1995. The role of mantle plumes in continental break-up: case histories from Gondwanaland. *Nature*, **377**, 301–308.

Spaeth, G. & Schüll, P. 1987. A survey of Mesozoic dolerite dikes from western Neuschwabenland, Antarctica, and their geotectonic setting. *Polarforschung*, **57**, 93–113.

White, R.S. & McKenzie, D.P. 1989. Magmatism at rift zones: the generation of volcanic continental margins and flood basalts. *Journal of Geophysical Research*, **94**, 7685–7729.