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Phanerozoic exhumation history of northern Prince Charles Mountains (East Antarctica)

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Abstract: Apatite fission-track data from samples of Precambrian basement, Late Permian–Triassic sedimentary rocks and inferred Cretaceous intrusive bodies are used to constrain the low-temperature (i.e. sub ~110°C) thermal history of the northern Prince Charles Mountains, East Antarctica. Two discrete phases of cooling have been identified, both of which are attributed to regional exhumation associated with rifting episodes. A phase of late Palaeozoic cooling, that began during the Carboniferous, is inferred to have been associated with the initial formation of the Lambert Graben. A more recent phase of cooling was initiated during the Early Cretaceous and is estimated to have locally involved the removal of at least 2 km of material using an assumed palaeotemperature gradient of ~25°C km^{-1} at the time of cooling. This latter phase of exhumation was closely accompanied by the emplacement of a variety of mafic alkaline rocks at ambient palaeotemperatures less than ~60°C and was probably related to renewed extension of the Lambert Graben during the break-up of eastern Gondwana. The results of this study suggest that final exhumation of high-grade Precambrian basement of the northern Prince Charles Mountains was largely controlled by Phanerozoic rifting events.

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Introduction

East Antarctica is a region dominated by Precambrian crystalline basement rocks containing only a fragmentary record of Phanerozoic geological events. Given the general absence of Phanerozoic rocks, it is extremely difficult to reconstruct the geological history of East Antarctica since the Precambrian. One indirect approach to deciphering the Phanerozoic geological record of Precambrian basement terranes is to use low-temperature thermochronological techniques that reveal information on the recent cooling history of a particular area. Where sufficient data are obtained, it is then possible to place constraints on the later geological history of these regions.

The results of a reconnaissance apatite fission-track study suggested that the East Antarctic Shield had undergone several discrete phases of cooling during the Phanerozoic, with distinct differences in thermal history on either side of the Lambert Graben (Arne *et al.* 1993). In order to provide better constraints on the low-temperature (i.e. sub ~110°C) thermal history to the west of the Lambert Graben, samples of Precambrian basement, Late Permian–Triassic sedimentary rock and post-Triassic intrusions were collected for apatite fission-track analysis during the 1989/90 ANARE (Australian National Antarctic Research Expedition) field programme in the northern Prince Charles Mountains. Thermal history data from these samples are interpreted in terms of exhumation in the present study and place new constraints on the tectonic evolution of the East Antarctic Shield west of the Lambert Graben during the Phanerozoic.

Geological background

The largest glacial drainage system in Antarctica, the Lambert Glacier and its tributaries, flows northward through the Prince Charles Mountains (Allison 1979) where it follows the Lambert Graben, a major crustal structure orientated perpendicular to the coastline (Fig. 1). Seismic and gravity surveys indicate that the Lambert Graben is underlain by thinned continental crust (Fedorov *et al.* 1982, Wellman & Tingey 1976), while the interpretation of seismic data both onshore (Fedorov *et al.* 1982) and offshore (Stagg 1985) further suggests that the Lambert Graben contains up to several kilometres of Phanerozoic sedimentary rock. The geology of the region was summarized by Tingey (1982) and the main geological features of the northern Prince Charles Mountains are illustrated in Fig. 2.

Areas adjacent to the Lambert Graben are dominated by Precambrian metamorphic rocks ranging from low-grade Archaean to Early Proterozoic supercrustal rocks in the south, to high-grade Late Proterozoic granulite and charnockite to the north. High-grade metamorphic rocks west of Beaver Lake have recently been described by McKelvey & Stephenson (1990) whereas those directly to the east have been described by Hofmann (1991). Most pertinent to the

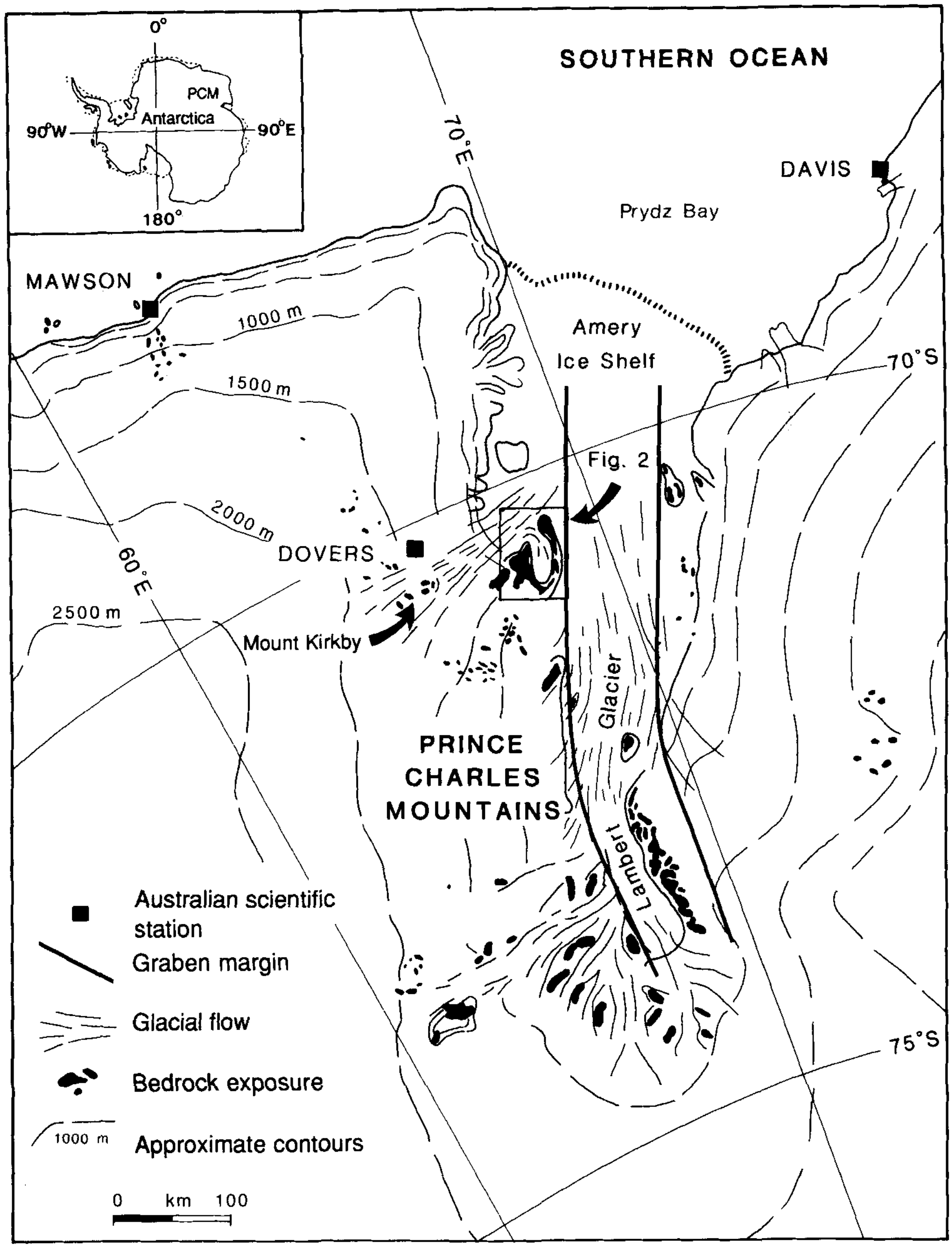

Fig. 1. Location of the main study area (Fig. 2) and Mount Kirkby in the Prince Charles Mountains, East Antarctica. The approximate margins of the Lambert Graben are also shown (thick lines), after Fedorov *et al.* (1982).

Phanerozoic thermotectonic evolution of the Prince Charles Mountains is the observation that Rb-Sr isotopic ages from basement rocks over much of the region have been affected by "widespread retrogression and minor intrusion" at about 500 Ma (Tingey 1982), which is the last metamorphic event recognized over much of East Antarctica.

An isolated inlier of Late Permian coal-bearing sedimentary rocks is preserved in the Beaver Lake area of northern Prince Charles Mountains (Fig. 2). These strata comprise the Amery Group (Fig. 3) and have been described by Mond (1972), McKelvey & Stephenson (1990) and Webb & Fielding (1993). Approximately 2500 m of conglomerate, sandstone and minor shale are preserved in the region, although precise stratigraphical reconstructions are complicated by surficial glacial till and post-Amery Group faulting. These strata generally dip gently to the east (Fig. 2). Mond (1972) divided the Amery Group into three major formations, the basal Radok Conglomerate, the intermediate Bainmedart Coal Measures, and the upper Flagstone Bench Formation. Recent investigations indicate that the uppermost portion of the Amery Group is Late Triassic in age (Webb & Fielding 1993).

A faulted contact between Precambrian basement and the Amery Group in the Radok Lake area is inferred, although the contact is not exposed (Fig. 2). Crohn (1959) considered the Amery Group to be faulted against Precambrian basement, although Mond (1972) concluded that there was no evidence for this interpretation. Recent investigations in the Radok Lake area led McKelvey & Stephenson (1990) to support

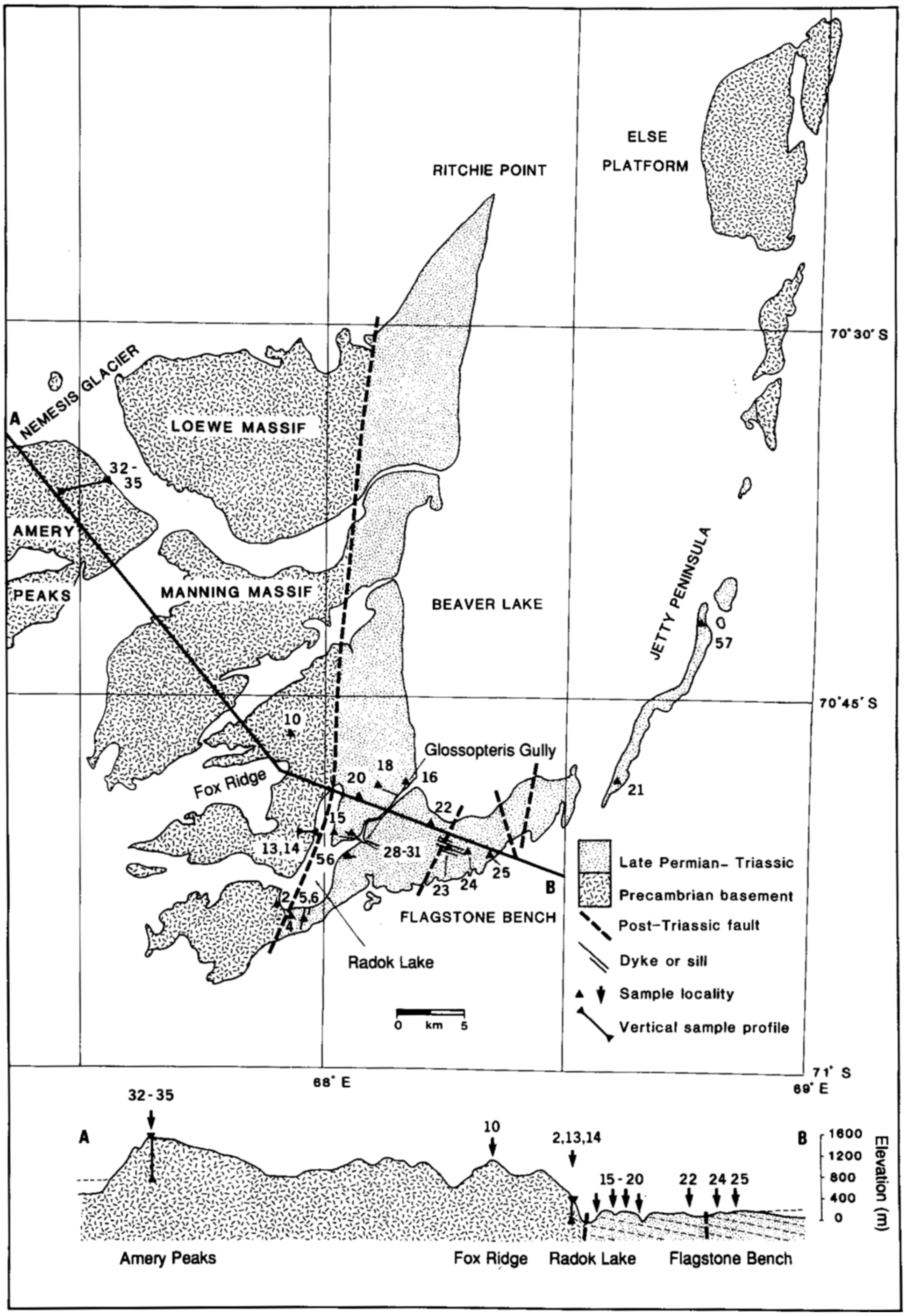

Fig. 2. Simplified geological map of the Amery Oasis area, northern Prince Charles Mountains, after Mond (1972). Sample localities and the positions of vertical profiles are shown. All sample numbers should be prefixed by 9063. The topographic profile from Flagstone Bench to Amery Peaks shows the positions of individual samples and vertical sections.

Crohn's initial suggestion although they concluded that it appears unlikely that faulting in the area was active during Late Permian sedimentation in the region.

Of particular significance for the interpretation of Amery Group thermal history is the presence of approximately 65 seams of high volatile bituminous coal, 8–350 cm thick, which occur in the Bainmedart Coal Measures (Bennett & Taylor 1972). Vitrinite reflectance determinations from 13 samples show a range in mean $R_o$max of 0.55–0.89% and suggest that the sequence was deeply buried in the past. The approximate stratigraphical positions of these samples are shown on Fig. 3, along with values of mean $R_o$max. In general, the highest values occur in the Lower Bainmedart Coal Measures suggesting that maximum palaeotemperatures in the Amery Group were attained prior to tilting of the sequence.

A variety of mafic bodies intrudes the Amery Group in the Beaver Lake area (Tingey 1982, McKelvey & Stephenson

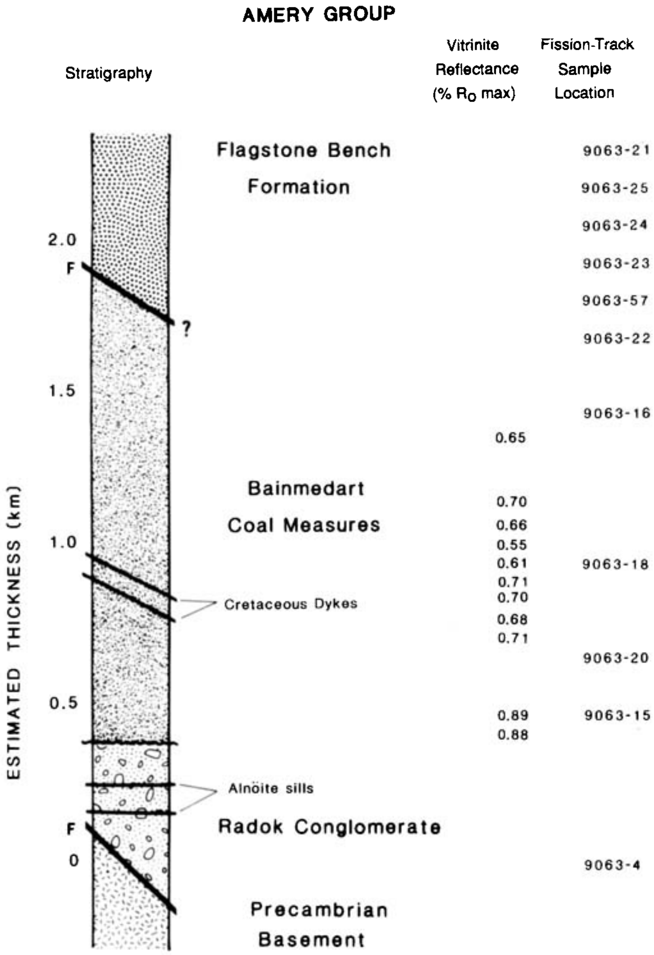

Fig. 3. Schematic stratigraphy for the Amery Group, modified from Mond (1972). Also shown are the approximate positions of vitrinite reflectance samples reported in Bennett & Taylor (1972) and apatite fission track samples reported in this study. Heavy diagonal lines show the positions of inferred faults (F). Samples collected near post-Amery intrusive rocks are not shown.

1990, Mond 1972, Ravich *et al.* 1984, Sheraton 1983, Andronikov 1990). These intrusive bodies include alkaline mafic sills, dykes and plugs, as well as tholeiitic dolerite dykes. A relatively fresh alnöite (lamprophyre) sill in the Radok Conglomerate at the south end of Radok Lake gave a K-Ar mica (phlogophite) age of 110 ± 3 Ma (Walker & Mond 1971), while a suite of alkaline mafic dykes and plugs from Jetty Peninsula gave whole rock K-Ar ages of between 132 ± 9 Ma and 103 ± 5 Ma (Hofmann 1991).

Relief in the Prince Charles Mountains varies from sea level at Beaver Lake to over 1000 m immediately to the west of Radok Lake (Fig. 2). Farther inland, isolated massifs occur at elevations over 2000 m above sea level, and Mount Menzies in the southern Prince Charles Mountains has an elevation of ~3,300 m. The bedrock surface beneath many of the glaciers which flow through the northern Prince Charles Mountains is estimated to be as much as 1500 m below sea level (Allison 1979), indicating a total bedrock relief of over 4,000 m. These tributary glaciers dissect the Prince Charles Mountains into a series of isolated massifs and nunataks, many of which have flat tops at elevations of 1500–2000 m suggestive of former erosional surfaces (Wellman & Tingey 1981). The ages of these surfaces, or whether they once formed a continuous peneplain are not known, although Wellman & Tingey (1981) proposed uplift of a single surface in response to isostatic unloading during pronounced Tertiary glacial erosion.

Apatite fission-track analysis

Introduction

Apatite fission-track analysis is a radiometric method of thermal history determination at temperatures in the range 20–150°C over geological time intervals of between 0.1 and 100 Ma (e.g. Green *et al.* 1989). In sedimentary basins the technique is most useful over the more restricted range of 60–110°C, often referred to as the partial annealing zone, as this is the range over which pronounced partial annealing of fission-tracks occurs. At temperatures greater than ~110°C, depending on the chemical composition and heating rate of the apatite, fission-tracks will totally anneal over geological time intervals on the order of 10^6 to 10^7 years, resulting in a "zero" apatite fission-track age. Track retention will begin following cooling to temperatures below ~110°C, and the style of cooling to near-surface temperatures (i.e. rapid, stepwise or gradual) will be reflected by the distribution of individual track lengths in each sample, since each track records a unique time–temperature history. Alternatively, tracks may not be totally annealed prior to final cooling and so various degrees of partial annealing, as well as the time that final cooling began, will be reflected in the observed distribution of track lengths for a particular sample (Green *et al.* 1989, Gleadow *et al.* 1986). Therefore in most cases, the apatite fission-track age of a sample reflects not its true age, but the subsequent thermal history of that sample as a function of track length reduction (Green 1988).

Apatite fission-track analysis has been used to evaluate the thermal history of basement samples adjacent to rifted continental margins in a variety of geological settings (southeast Australia, Moore *et al.* 1986; Transantarctic Mountains, Gleadow & Fitzgerald 1987; Red Sea, Bohannon *et al.* 1989; Atlantic margin, Miller & Duddy 1989; Gulf of Suez, Omar *et al.* 1989; southwest Africa, Brown *et al.* 1990). In several of these studies, the apatite fission-track age of outcrop samples from low elevations immediately adjacent to the continental margin approximates the time of rifting determined by other methods. While many of these investigations have demonstrated evidence for cooling along rifted continental margins, it is often unclear as to what degree cooling was due to a reduction in heat flow following rifting, or to exhumation of the rifted margin during tectonic uplift because independent estimates of the palaeotemperature gradient prior to cooling are generally not available. An exception to this general observation is provided by the study of Gleadow & Fitzgerald (1987) in the Transantarctic Mountains where an independent estimate of the amount of section removed through erosion was obtained.

Methodology

Details and analytical results for all samples processed for apatite fission-track analysis from northern Prince Charles Mountains are given in Table I. Sample elevations were measured with an altimeter calibrated against a GPS receiver based at Dovers base camp and against sea level at Beaver Lake (Fig.1). All outcrop samples were first broken up in a jaw crusher and then ground to fine sand size in a disk crushing mill. The crushed material was then washed to remove fines and processed by conventional heavy liquid and magnetic separation techniques to concentrate heavy minerals.

A total of 34 samples were processed. Apatite yields were generally excellent, with the exception of three samples for which no apatite was recovered. The apatite separates were prepared for fission-track analysis by the external detector method, following the procedure outlined by Green (1986). Neutron irradiations were carried out in a well thermalized neutron flux at the X-7 facility of the Australian Nuclear Science and Technology Organization's HIFAR reactor, Lucas Heights. This facility has a Cd ratio for Au of ~125. A nominal fluence of 10^{16} ncm^{-2} was employed for the irradiations and this was monitored using NBS standard glass SRM 612 included at either end of the irradiation canister. Where possible, 20 apatite grains were analysed in each mount to determine a fission-track age, and 100 horizontal confined track lengths were measured.

Fission-track ages were calculated following the zeta calibration method described by Hurford & Green (1983) and as recommended to the I.U.G.S. Subcommission on Geochronology by the Fission-track Working Group (Hurford 1990). Details of the author's personal zeta calibration as well as track length data for induced fission-tracks and for age standards are given in Appendix 1. Uncertainties in the fission-track ages were calculated following the "conventional" method for pooled fission-track ages described by Green (1981) and are quoted at 2σ throughout. Where single-grain age data fail the χ^2 statistical test at 5%, real differences in fission-track age are considered to exist between individual apatite grains (Galbraith 1981), either due to the inherited effects of different provenance areas for detrital apatite grains or due to variations in the rate of track length reduction during extreme partial annealing because of compositional differences (Green *et al.* 1986). In these cases calculation of a pooled fission-track age is not strictly valid and instead a mean age was calculated with an uncertainty taken as the standard deviation of the individual grain ages.

Interpretation of thermal history

Forward modelling

Palaeotemperatures, and the time of cooling from those palaeotemperatures, have been estimated for selected samples following the predictive forward modelling procedures described by Green *et al.* (1989). Their model is based on a quantitative description of track annealing in Durango apatite (Laslett *et al.* 1987). Palaeotemperature estimates assume heating for 1–10 Ma and an intrinsic uncertainty of ±10°C based on the extrapolation of laboratory annealing data to geological time scales for palaeotemperature estimates in the range 60–110°C (Green *et al.* 1989). Uncertainties in visually matching predicted and observed track length distributions through trial and error are assumed to be less than the inherent uncertainties in the palaeotemperature estimates (i.e. ±10°C). Predicted ages were matched to within the 2σ uncertainties of the measured ages during forward modelling runs.

Since the annealing behaviour of fission-tracks in apatite is known to be sensitive to Cl content (Green *et al.* 1986), the Cl content of 20 randomly selected apatite grains from a single representative sample each of Precambrian basement and Amery Group sandstone, and from two post-Amery Group intrusives were determined by microprobe analysis. Apatite from sample 9063–45 of Precambrian basement has a Cl content identical to that of Durango apatite while apatite grains in sample 9063–22 of Amery Group sandstone show a significant spread in Cl content between Durango composition and pure fluorapatite, with one grain having a Cl content greater than 1%. Thus palaeotemperatures estimated for the Amery Group samples should be interpreted as maximum estimates. Apatite from the alnöite sill from the southern end of Radok Lake (9063–6) is dominantly fluorapatite, while two populations of apatite occur in a sample from a post-Amery Group dyke (9063–56). These two populations of apatite have average Cl contents of ~0.55 wt.% and 1.13 wt. %, with the high-Cl population etching much more easily than the low-Cl population.

Precambrian basement samples

Fission-track data were obtained for 13 Precambrian basement samples from three separate vertical sections (Mount Kirkby, Amery Peaks, Radok Lake; Figs 1 & 2). The apatite ages of these samples range between 91 ± 12 Ma and 307 ± 25 Ma (Table I). They are not only considerably younger than the inferred Proterozoic metamorphic age of the samples, they are also significantly less than age of the last metamorphic event recognized to have affected the Prince Charles Mountains region at ~500 Ma (e.g. Tingey 1982). Thus Precambrian basement samples show consistent evidence of severe track annealing during the Phanerozoic. The large amount of age reduction shown by these samples suggests that they have cooled from palaeotemperatures in excess of

Table I. Fission track analytical results.

Sample number	Approximate location	Elevation (m a.s.l)	Number of grains	ρ_d	(N_d)	ρ_s	(N_s)	ρ_i	(N_i)	$P(\chi^2)$ (%)	Fission track age (Ma)	Mean track length (μm)	Number of lengths measured	Standard deviation (μm)
Precambrian basement														
Radok Lake														
9063–2	67°53 'E 70°54 'S	10	20	1.479	(4654)	0.947	(357)	2.576	(971)	19.5	91 ± 12	13.7 ± 0.8	(36)	2.5
9063–10	67°55 'E 70°47 'S	1020	20	1.221	(1921)	0.560	(511)	0.979	(893)	1.0	124 ± 16*	13.9 ± 0.4	(51)	1.5
9063–13	67°58 'E 70°15 'S	330	20	1.221	(1921)	4.717	(3681)	8.305	(6481)	0.2	118 ± 11*	14.0 ± 0.3	(100)	1.7
9063–14	67°58 'E 70°51 'S	190	8	1.221	(1921)	1.172	(351)	2.354	(705)	3.7	96 ± 23*	14.0 ± 1.3	(9)	1.9
Amery Peaks														
9063–32	67°29 'E 70°36 'S	1430	20	1.221	(1921)	1.810	(1976)	1.468	(1603)	34.3	248 ± 22	13.6 ± 0.4	(95)	1.9
9063–33	67°29 'E 70°36 'S	1270	20	1.221	(1921)	2.397	(1952)	2.639	(2149)	<0.1	202 ± 32*	13.1 ± 0.5	(100)	2.3
9063–34	67°30 'E 70°36 'S	1070	20	1.221	(1921)	3.344	(928)	3.474	(964)	<0.1	227 ±23.1*	12.9 ± 0.5	(84)	2.3
9063–35	67°31 'E 70°36 'S	910	20	1.221	(1921)	1.984	(1663)	2.014	(1688)	0.1	202 ± 24*	12.7 ± 0.4	(100)	2.6
9063–36	67°32 'E 70°36 'S	690	20	1.221	(1921)	3.780	(2224)	3.970	(2336)	<0.1	192 ± 32*	12.6 ± 0.5	(100)	2.3
Mount Kirkby														
9063–43	65°14 'E 70°26 'S	1900	20	1.221	(1921)	3.863	(2961)	2.523	(1934)	29.2	307 ± 25	13.6 ± 0.5	(99)	2.3
9063–44	65°14 'E 70°26 'S	1760	13	1.221	(1921)	3.039	(1421)	2.258	(1056)	0.3	290 ± 55*	13.3 ± 0.4	(74)	1.9
9063–45	65°14 'E 70°26 'S	1650	20	1.221	(1921)	1.388	(671)	1.014	(490)	59.0	275 ± 36	13.6 ± 0.3	(100)	1.6
9063–48	65°14 'E 70°27 'S	2144	20	1.221	(1921)	6.664	(5242)	4.664	(3669)	0.3	296 ± 30*	13.7 ± 0.3	(99)	1.6
Amery Group														
Radok Conglomerate														
9063–4	67°56' E70°55 'S	100	20	1.479	(4654)	1.244	(965)	2.959	(2296)	0.3	107 ± 13*	13.8 ± 0.4	(101)	1.8
Bainmedart Coal Measures														
9063–15	86°02' E70°51 'S	20	20	1.345	(2116)	1.221	(1063)	2.658	(2313)	<0.1	118 ± 20*	13.6 ± 0.4	(102)	2.0
9063–16	68°10' E70°49 'S	5	20	1.345	(2116)	1.206	(774)	1.820	(1168)	<0.1	137 ± 25*	14.2 ± 0.2	(101)	1.2
9063–18	68°06 'E 70°49 'S	105	20	1.345	(2116)	1.981	(1001)	2.838	(1434)	<0.1	143 ± 26*	13.1 ± 0.6	(100)	2.9
9063–20	68°05 'E 70°49 'S	140	20	1.345	(2116)	0.691	(692)	1.334	(1336)	28.7	116 ± 13	13.6 ± 0.4	(101)	2.0
9063–22	68°15 'E 70°51 'S	180	20	1.345	(2116)	2.644	(1268)	2.594	(1244)	<0.1	260 ± 60*	12.6 ± 0.5	(100)	2.4
Flagstone Bench Formation														
9063–21	68°35 'E 70°50 'S	170	20	1.345	(2116)	1.987	(1357)	1.993	(1361)	<0.1	252 ± 52*	13.0 ± 0.4	(100)	1.9
9063–23	68°17 'E 70°52 'S	180	15	1.345	(2116)	1.853	(822)	1.528	(678)	0.2	273 ± 41*	12.8 ± 0.5	(70)	2.1
9063–24	68°19 'E 70°52 'S	180	20	1.345	(2116)	2.746	(1882)	2.247	(1540)	<0.1	314 ± 49	12.4 ± 0.5	(100)	2.5
9063–25	68°21 'E 70°53 'S	160	20	1.345	(2116)	0.360	(381)	3.541	(3744)	<0.1	25 ± 13*	10.6 ± 0.4	(101)	2.1
9063–25^r	68°21 'E 70°53 'S	160	20	1.296	(4079)	0.708	(770)	2.278	(2471)	<0.1	52 ± 23*	9.9 ± 0.9	(32)	2.5
9063–57	68°45 'E 70°42 'S	120	20	1.345	(2116)	1.379	(956)	2.208	(1531)	<0.1	160 ± 28*	13.1 ± 0.4	(100)	2.3
Intrusive rocks and contact suite														
Intrusions														
9063–6	67°56 'E 70°55 'S	165	20	1.345	(2116)	0.997	(847)	1.816	(1591)	28.9	119 ± 12	14.7 ± 0.2	(100)	1.1
9063–28	68°03 'E 70°52 'S	100	18	1.345	(2116)	0.179	(203)	0.413	(468)	61.8	97 ± 17	15.0 ± 0.3	(81)	1.3
9063–56	68°03 'E 70°52 'S	100	21	1.479	(4654)	1.676	(969)	3.512	(2031)	28.8	118 ± 11	14.4 ± 0.7	(36)	2.0
Amery Group														
9063–5	67°56' E70°55 'S	(5 m)	17	1.479	(4654)	0.631	(329)	1.570	(819)	36.1	99 ± 14	14.2 ± 0.9	(24)	2.1
9063–29	68°03' E70°52 'S	(10 cm)	20	1.345	(2116)	1.903	(1219)	5.335	(3418)	<0.1	82 ± 18*	14.3 ± 0.3	(100)	1.7
9063–30	68°03' E70°52 'S	(15 m)	20	1.345	(2116)	1.328	(722)	2.514	(1367)	97.6	118 ± 13	13.6 ± 0.4	(66)	1.8
9063–31	68°03' E70°52 'S	(50 m)	20	1.345	(2116)	1.287	(841)	2.145	(1401)	0.2	151 ± 26*	13.9 ± 0.3	(100)	1.6

All track densities are 10^6/cm^2. Number of tracks counted and lengths measured are shown in parentheses. Ages calculated using ζ=336 ± 12 for dosimeter glass SRM612 (see text for a discussion of calibration). * Mean age used where pooled data fail the χ^2 test at 5%. ^{r} Repeat analysis. Elevations in parentheses are distances from an intrusive contact. All errors are quoted at 2σ. Full analytical results are available from the author on request.

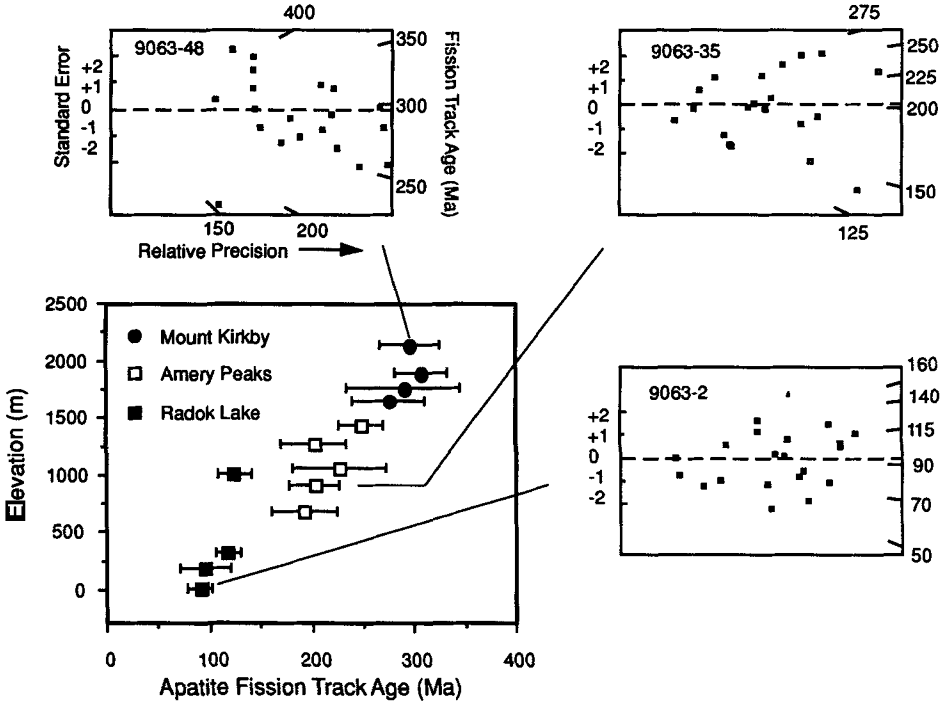

Fig. 4. Relationship between apatite age and sample elevation for Precambrian basement samples. Error bars are plotted at 2σ. Also shown are examples of radial plots illustrating the variation in fission track age between individual apatite grains for three samples. The relative precision of apatite ages increases from left to right in each diagram. Standard error bars on left of radial plots apply to each individual grain age (see Galbraith 1988 for details). Apatite ages for each sample are shown by the horizontal dashed lines.

~110°C at some time during the Phanerozoic.

Apatite ages show a strong correlation with sample elevation (Fig. 4), with the youngest ages occurring near Radok Lake close to sea level. A striking relationship, whereby mean track length increases with increasing elevation, also exists for samples from Amery Peaks and Mount Kirkby (Fig. 5). By contrast, samples from immediately west of Radok Lake consistently have relatively long mean track lengths, although track length distributions for all samples are typically broad. This pattern of variation in apatite age and mean track length with sample elevation is interpreted to reflect an exhumed partial annealing profile at Mount Kirkby and Amery Peaks, similar to that identified by Gleadow & Fitzgerald (1987) from outcrop samples in the Dry Valleys area of the Transantarctic Mountains. Fission-tracks in samples from the Radok Lake section were totally annealed prior to cooling

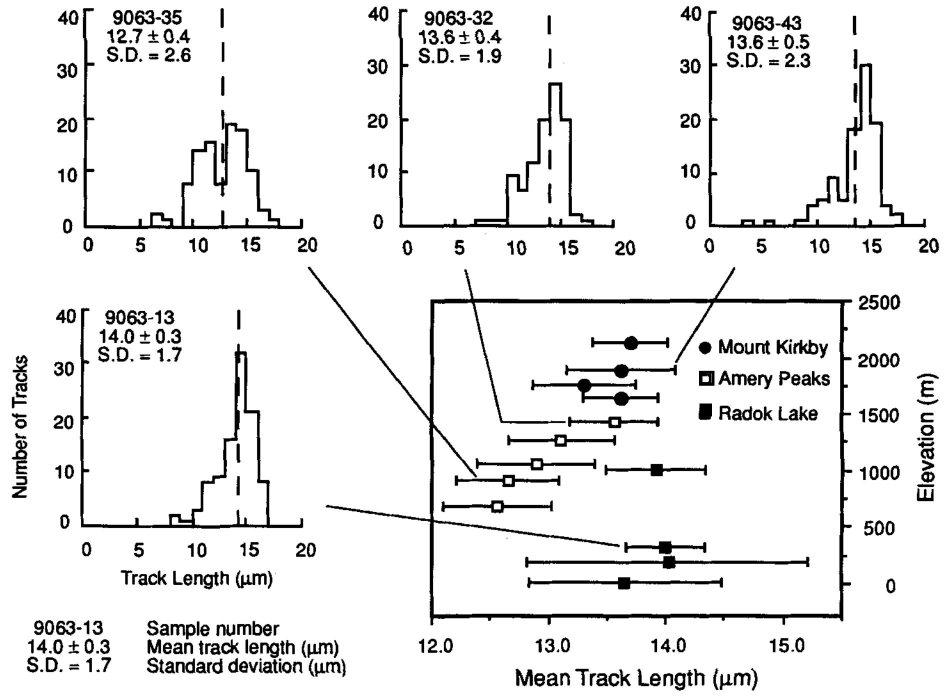

Fig. 5. Relationship between mean length and sample elevation for Precambrian basement samples. Error bars are plotted at 2σ. Also shown are examples of track length distributions for selected samples, normalized to 100 track lengths. Mean lengths are shown by the vertical dashed lines.

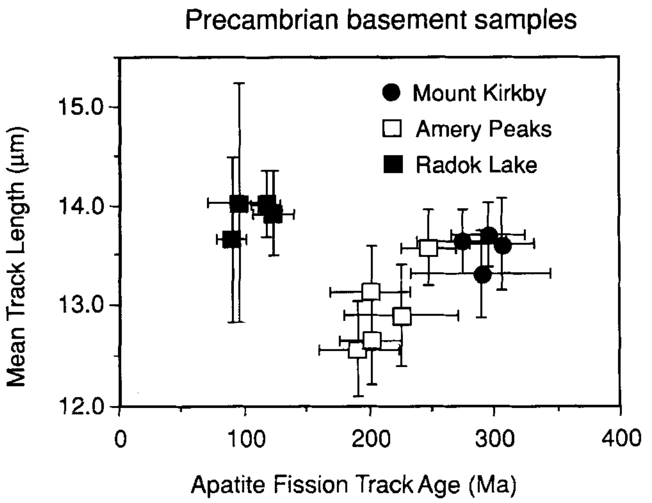

Fig. 6. Relationship between apatite fission track age and mean track length for all Precambrian basement samples. Error bars are plotted at 2σ.

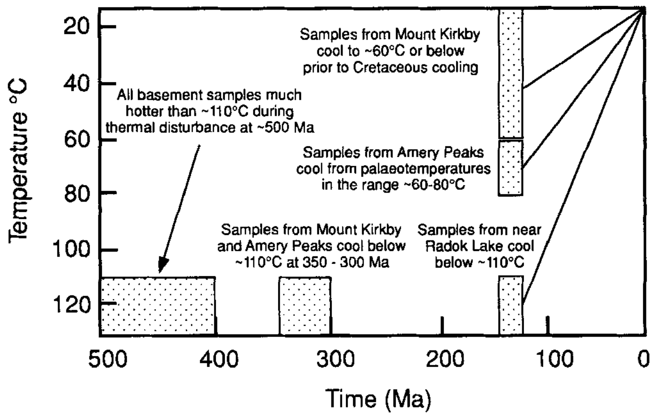

Fig. 7. Schematic summary of thermal history for Precambrian basement samples, northern Prince Charles Mountains, inferred from apatite fission track analysis.

below temperatures of ~110°C at some time in the Cretaceous.

Forward modelling for each of the three vertical profiles indicates that during the Early Cretaceous, between ~140 and 120 Ma, the Mount Kirkby section cooled from temperatures less than 60°C, the Amery Peaks section cooled from temperatures in the range 60–80°C, and the Radok Lake section cooled from temperatures of ~110°C or greater. Partial annealing of fission-tracks in samples from Amery Peaks immediately prior to Early Cretaceous cooling is also indicated by an examination of fission-track age data from individual apatite grains (Fig. 4). For example, apatite grains in sample 9063–35 show a significant spread in fission-track age, with some individual apatite grains giving relatively precise fission-track ages of ~130 Ma, probably due to slight variations in chemical composition.

Various degrees of track annealing displayed by samples from different elevations, representing different levels in the near-surface crust prior to inferred exhumation, are also reflected in a plot of apatite fission-track age against mean track length (Fig. 6). The data show a pattern similar to that obtained by Green (1986) for a suite of outcrop samples from northern England interpreted to have undergone various degrees of annealing prior to cooling. Precambrian basement rocks in northern Prince Charles Mountains are interpreted initially to have cooled below temperatures of ~110°C in the Carboniferous, between 350 and 300 Ma, and this is also supported by modelling the onset of track retention for samples from Mount Kirkby.

An interpretation of thermal history for the Precambrian basement samples is illustrated schematically in Fig. 7.

Amery Group

Fission-track data were obtained from detrital apatite grains in 10 samples of sedimentary rock from the Late Permian–Triassic Amery Group in areas not directly affected by post-Amery Group intrusive activity (Table I; Figs 2 & 3). Apatite fission-track ages of the samples generally range between 107 ± 13 Ma and 314 ± 49 Ma and thus vary from older than the stratigraphical age of the Amery Group (260–230 Ma) to significantly younger (Fig. 8). With the exception of samples 9063–57 and 25, the latter of which is not shown in Fig. 8, there is a good correlation between apatite age and the approximate stratigraphical position of the sample, whereby the youngest apatite ages typically occur at the base of the Amery Group in samples from the Radok Conglomerate and lower Bainmedart Coal Measures.

With the exception of sample 9063–25, mean track lengths for these samples vary between 12.4 ± 0.5 μm and 14.3 ± 0.3 μm and also show a broad correlation with stratigraphical position, with the longest mean track lengths generally found in samples near the base of the preserved sequence, in samples from the Radok Conglomerate and Bainmedart Coal Measures, and the shortest mean track lengths generally found near the top, in samples from the Flagstone Bench Formation.

Also shown in Fig. 8 are examples of track length distributions and radial plots showing the observed spread in fission-track age for apatite grains from two samples. Individual apatite grains from samples of Flagstone Bench Formation and upper Bainmedart Coal Measures characteristically show an appreciable spread in fission-track age, with some grains giving fission-track ages significantly less than the estimated stratigraphical age of the samples (i.e. 260–230 Ma). Thus fission-track age data from these samples show clear evidence for an appreciable degree of post-depositional track annealing, a conclusion also supported by forward modelling to match the observed fission-track data.

The relationship between mean track length and fission-track age for all Amery Group samples, excluding those in

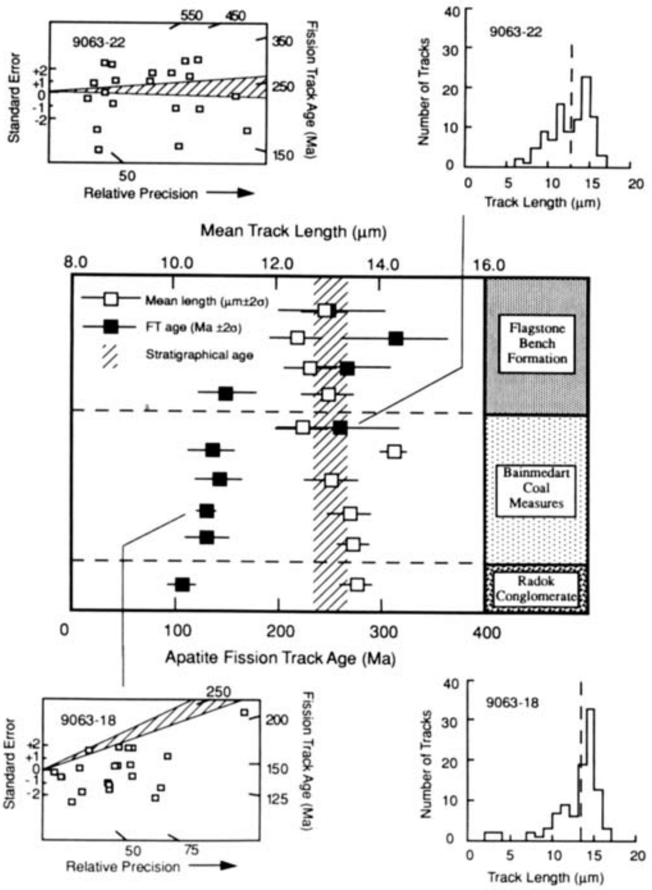

Fig. 8. Relationship between apatite age and approximate stratigraphical position for Amery Group samples. Error bars are plotted at 2σ. The stratigraphical age of the Amery Group is estimated to be 230–260 Ma and is indicated by the diagonal line pattern. Also shown are track length distributions and radial plots illustrating the variation in fission track age between individual apatite grains relative to the stratigraphical age (diagonal line pattern) for selected samples. Not shown are samples from near post-Amery Group intrusives and sample 9063–25, which has undergone a unique thermal history.

close proximity to alkaline mafic intrusions (9063–5, 29–31) and sample 9063–25, is summarized in Fig. 9. The data define a trend of increasing mean track length with decreasing fission-track age indicating increasing degrees of heating during post-depositional burial, followed by cooling during the Early Cretaceous. Forward modelling to match the observed fission-track data in Amery Group samples indicates that the preserved Amery Group cooled from temperatures of between ~80°C at the top of the section and greater than ~110°C near the base beginning in the Early Cretaceous, between 140 and 120 Ma.

Sample 9063–57 from the lower Flagstone Bench Formation on the eastern side of Beaver Lake (Fig. 2) gave a mean apatite age of 160 ± 28 Ma that is significantly less than the stratigraphical age of the sample. Thus this sample shows a degree of age reduction more typical of samples from the Bainmedart Coal Measures, rather than other samples of the Flagstone Bench Formation. The presence of this sample on the eastern side of Beaver Lake suggests that either there are previously unrecognized structural complexities in the area or this sample has been affected by a source of heating other than that which occurred during burial.

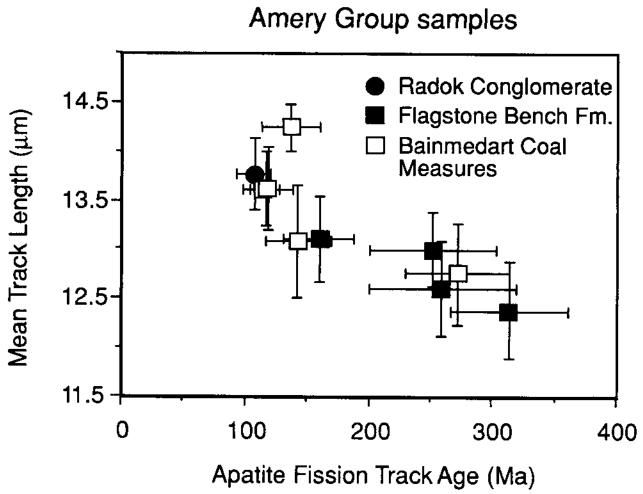

Fig. 9. Relationship between apatite fission track age and mean track length for Amery Group samples. Error bars are plotted at 2σ. Not shown are data from samples near post-Amery Group intrusions and sample 9063-25, which has undergone a unique thermal history.

The interpretation of data from sample 9063–25 is problematical. This sample gives mean fission-track ages of 25 ± 13 Ma and 52 ± 23 Ma with mean track lengths of 10.6 ± 0.2 and 9.9 ± 0.4 µm, respectively, for repeat analyses (Table I) which indicate a degree of recent annealing not seen in any other samples analysed from the area. The presence of individual grains in this sample with appreciable uranium but zero fission-track ages indicates that cooling from elevated palaeotemperatures occurred recently, within the last ~15 Ma. No explanation for these data is immediately obvious, and further analyses of nearby samples is required to confirm them.

An interpretation of the thermal history for the Amery Group samples, excluding samples 9063–57, 25 and those samples directly adjacent to intrusive rocks (9063–5, 29, 30 and 31), is shown schematically in Fig. 10.

Post-Amery Group intrusive rocks and contact suite

Apatite fission-track data were obtained from three tabular mafic igneous bodies up to 12 m in thickness that intrude the Late Permian-Triassic Amery Group (Table I). These include the thickest of two alnöite sills from the south end of Radok Lake (McKelvey & Stephenson 1990), a poorly exposed NW-trending dyke immediately to the west of Glossopteris Gully, and an E-trending dyke on the east side of Radok Lake south-

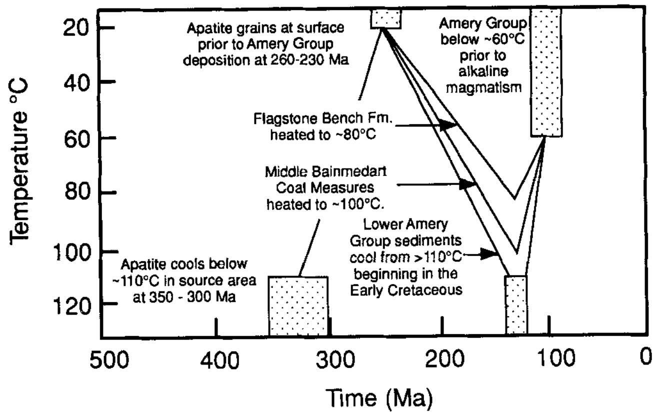

Fig. 10. Schematic summary of thermal history for Amery Group samples, northern Prince Charles Mountains, inferred from apatite fission track analysis and vitrinite reflectance data from Bennett & Taylor (1972).

west of Glossopteris Gully (Fig. 2). In addition to these samples, a suite of sandstone samples from the Bainmedart Coal Measures at distances of 10 cm, 15 m and 50 m away from the contact of the NW-trending dyke (samples 9063–29, 30 and 31, respectively), and a sample of Radok Conglomerate 5 m beneath the lower alnöite sill (9063–5) were collected to examine the thermal effects of igneous activity.

A sample from the alnöite sill (9063–6) gave a pooled apatite age of 119 ± 12 Ma (Table I). The mean track length of this sample is 14.7 ± 0.2 μm and the track length distribution contains no tracks less than 10 μm in length. Therefore the fission-track age of the sample can be interpreted as the time of rapid cooling below ~110°C to a palaeotemperature of less than ~60°C. The apatite fission-track age of this sample agrees within error with a K-Ar mica age of 110 ± 3 Ma for the same sill (Walker & Mond 1971), indicating that the apatite age records the time of intrusion and that sill emplacement occurred during or shortly after regional cooling in the Early Cretaceous. A sample of Radok Conglomerate (9063–5) gave an apatite age of 99 ± 14 Ma that is also statistically indistinguishable from the K-Ar mica age for the sill, at 2σ errors. While this sample gave a relatively long mean track length of 14.2 ± 0.8 μm, its track length distribution is broad, suggesting a more complicated cooling history than that inferred for the sill itself.

A sample of the NW-trending dyke (9063–28) gave a pooled age of 97 ± 17 Ma and a mean track length of 15.0 ± 0.3 μm that can also be interpreted as the time of cooling below ~110°C to a palaeotemperature less than ~60°C. A sample of Bainmedart Coal Measures sandstone 10 cm away from this dyke (9063–29) gave an age of 82 ± 18 Ma that is statistically indistinguishable from that obtained for the dyke itself. The mean track length of sample 9063–29 is 14.3 ± 0.3 μm, similar to that obtained for the dyke, indicating that this sample cooled rapidly below a palaeotemperature of ~110°C at the same time as the dyke. A sample of Bainmedart Coal Measure sandstone 15 m away from the dyke contact (9063–30) also gave an apatite fission-track age of 118 ± 13 Ma that is statistically indistinguishable from the age obtained for the dyke, although it is significantly older than the apatite age obtained for sample 9063–29. A sample 50 m away from the dyke contact gave an apatite age of 151 ± 26 Ma that is significantly older than the fission-track age of the dyke and similar to other samples of Bainmedart Coal Measures sandstone in the area. The mean track lengths for these latter two samples are slightly less than 14 μm and they are interpreted to have been largely unaffected by dyke emplacement, although they were heated prior to regional cooling in the Early Cretaceous.

A sample of the E-trending dyke (9063–56) gave a pooled fission-track age of 118 ± 11 Ma that may also be interpreted as the time of cooling below ~110°C, as this sample gave a mean track length of 14.4 ± 0.7 μm. This sample contains a few tracks with lengths less than 10 μm that suggest cooling below ~110°C was not as rapid as in the previous two cases. This sample has fission-track characteristics similar to those in samples of Bainmedart Coal Measures nearby that when taken together with the presence of tracks with lengths less than 10 μm, suggest that this dyke may have been emplaced either prior to or during the later stages of regional cooling in the Early Cretaceous. In light of data from the two intrusive bodies previously discussed, the latter interpretation is preferred.

Relationship between cooling and exhumation

The recent review of surface uplift, uplift of rocks, and exhumation of rocks by England & Molnar (1990) is particularly pertinent to fission-track studies in general. Of these processes, exhumation is by far the most significant process as a mechanism for cooling. Exhumation alone can produce cooling, while uplift of rocks without exhumation produces none, excluding slight variations in surface temperatures. However, since these processes are linked through isostasy, the phrase "uplift and erosion" has commonly been invoked to explain cooling. Furthermore, surface uplift in response to crustal forces may accelerate erosional processes and therefore provide the impetus for rapid exhumation.

In the following discussion, evidence for cooling from apatite fission-track analysis is interpreted largely in terms of exhumation. Such an interpretation is generally compatible with the available fission-track data and is supported by the recent discovery of Early Cretaceous sediment in Prydz Bay (Turner & Padley 1991). Palaeotemperature estimates, and thus estimates of the amount of section removed by erosion, assume apatite compositions similar to that of Durango apatite (e.g. Laslett *et al.* 1987). Estimation of the amount of section removed is based on the extrapolation of an assumed linear palaeotemperature gradient of 25°C km^{-1} to an Early Cretaceous surface temperature of 10°C. Regional comparisons of exhumation estimates for different areas do not allow for significant lateral variations in the

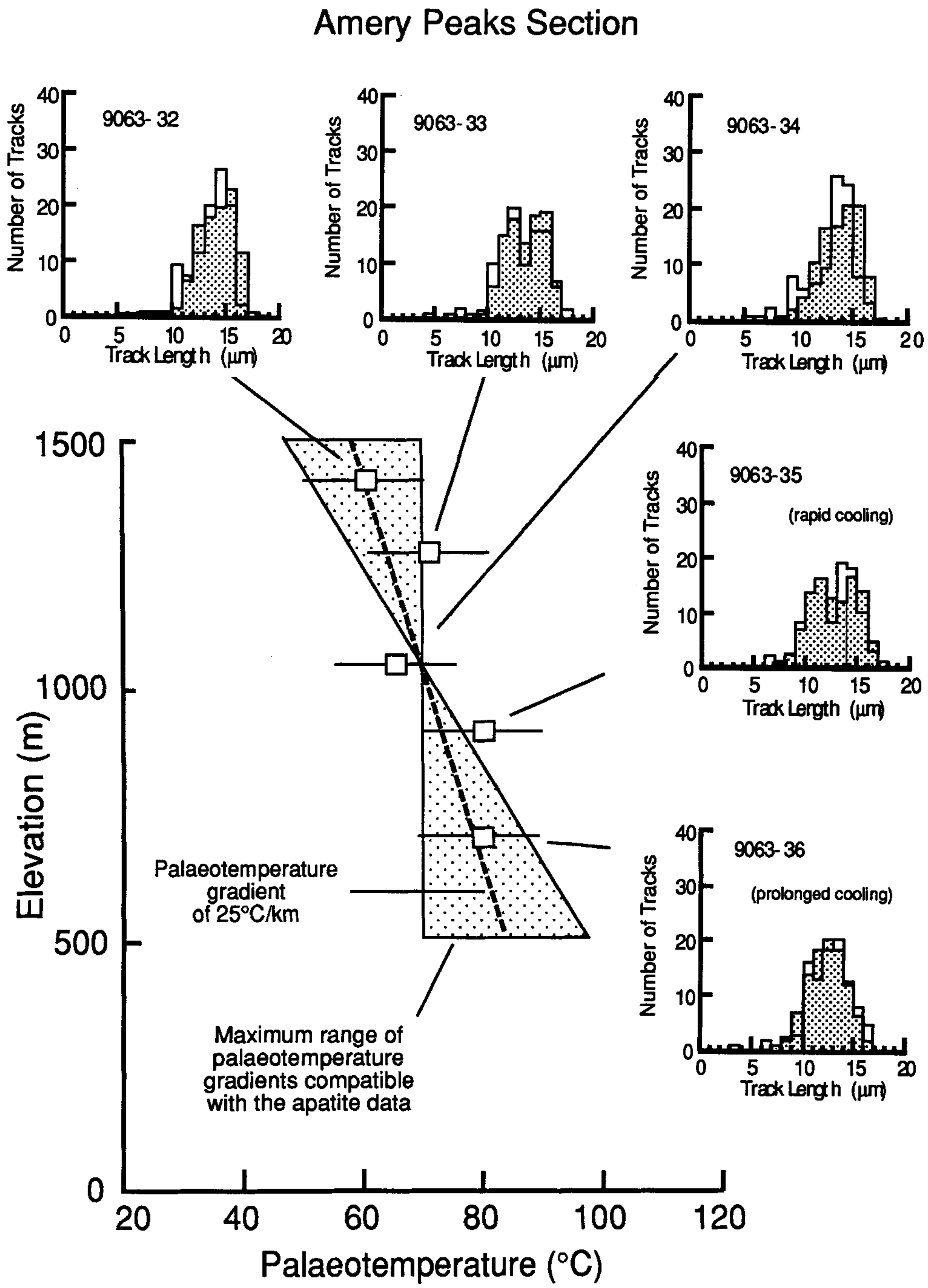

Fig. 11. Palaeotemperature estimates inferred for each sample from the Amery Peaks section prior to cooling at 120 Ma, based on the forward modelling approach of Green *et al.* (1989) using the kinetic annealing description of Laslett *et al.* (1987). The predicted track length distribution is shaded while the measured distribution is shown as an outline. The palaeotemperature estimates are broadly compatible with an assumed palaeotemperature gradient of 25°C km^{-1}.

palaeotemperature gradient prior to cooling. The timing of exhumation inferred from the fission-track data also assumes that the uplift of rocks was not so rapid as to disturb the isotherms during cooling (e.g. Parrish 1983).

For an assumed palaeotemperature gradient of 25°C km^{-1}, it is estimated that ~2 km of material has been removed from the top of the Amery Peaks section since the Early Cretaceous. Palaeotemperature estimates derived from forward modelling fission-track data from the Amery Peaks samples for a preferred time of cooling at 120 Ma are compatible with those predicted for an average linear temperature gradient prior to cooling of 25°C km-1 (Fig. 11), although the constraints provided by the data are rather broad if the intrinsic uncertainty of ±10°C is taken into consideration. Palaeotemperature gradients prior to cooling in the Early Cretaceous cannot be estimated for the Mount Kirkby or Radok Lake sections because, by that time, the former had cooled to palaeotemperatures below ~60°C, where the resolution of palaeotemperatures using apatite fission-track analysis is relatively poor, while the latter cooled from palaeotemperatures greater than ~110°C. However, based on assumptions similar to those used for the Amery Peaks section, it is estimated that at least 4 km of material must have been removed from the top of the Radok Lake section.

Since samples from the Flagstone Bench Formation are inferred to have cooled from palaeotemperatures of ~80°C in the Early Cretaceous, it is therefore suggested that the Amery Group was previously overlain by approximately 3 km of section prior to exhumation. Although the nature of this missing section must necessarily remain speculative, it is presumably Late Triassic or younger in age (Webb & Fielding 1993) and may be preserved in the Lambert Graben to the east (Fedorov *et al.* 1982, Stagg 1985).

An assumed palaeotemperature gradient of 25°C km^{-1} appears reasonable for the middle to upper portion of the Amery Group in light of the available fission-track data. Samples from the Flagstone Bench Formation and upper Bainmedart Coal Measures are inferred to have been heated to maximum palaeotemperatures of ~80°C, while samples from the middle Bainmedart Coal Measures are inferred to have been heated to maximum palaeotemperatures of 100–110°C. For an estimated stratigraphical separation of 1 km, a palaeotemperature gradient of 20–30°C km^{-1} can be inferred. Given that apatite grains from the Amery Group show a significant variation in Cl content compared to Durango apatite and that the stratigraphical positions of the samples in Fig. 3 are approximations only, more rigorous constraints on the palaeotemperature gradient prior to cooling using the available fission-track data are not warranted.

Vitrinite reflectance measurements from coal seams in the Bainmedart Coal Measures generally support the thermal history interpretation proposed for the Amery Group on the basis of apatite fission-track analysis. $R_o$max values of 0.55–0.89% (Bennett & Taylor 1972) correspond to burial temperatures of 85–130°C for heating at maximum palaeotemperatures for ~10 Ma using the distributed activation energy model of Burnham & Sweeney (1989; equation 2). The estimates obtained using this model are in good agreement with the range of palaeotemperatures inferred from apatite fission-track analysis (i.e. ~80 to >~110°C). Values of mean $R_o$max of 0.89 and 0.88% from the lower Bainmedart Coal Measures (Fig. 3) were obtained from strata in which fission-tracks in apatite were totally annealed prior to cooling in the Early Cretaceous, implying palaeotemperatures greater than ~110°C.

However, the amount of variation in $R_o$max values shown by samples collected over a stratigraphical thickness of ~1 km suggests that the palaeotemperature gradient prior to cooling in the Early Cretaceous was higher than the ~20–30°C km^{-1} previously inferred on the basis of apatite fission-track data from slightly higher in the section. Either the amount of section lost during exhumation was less than previously estimated (i.e. ~3 km), or the palaeotemperature gradient at the base of the Amery Group was higher than that inferred for the upper part of the Amery Group, possibly due to the emplacement of alkaline mafic sills. A detailed vitrinite reflectance investigation with careful stratigraphical control would help to resolve these two possibilities.

Exhumation since the Early Cretaceous was greatest near the boundary between the Amery Group and Precambrian basement in the Radok Lake area (Fig. 2). The amount of material removed from the top of the Amery Peaks and Radok Lake sections is inferred to be ~2 km and greater than 4 km, respectively, assuming similar palaeotemperature gradients prior to Early Cretaceous cooling. The tops of the Amery Peaks and Radok Lakes sections are at present day elevations of 1430 and 1020 m, respectively, indicating that the inferred contrast in the amounts of exhumation can not be accounted for by present day elevation differences and that differential uplift of rocks has occurred between the two sites. Tilting of the Amery Group away from Radok Lake into its present orientation must have post-dated or accompanied cooling from maximum palaeotemperatures, or else consistent differences in fission-track data with stratigraphical position would not have been preserved. Thus titling of the Amery Group is interpreted to have been initiated during the Early Cretaceous, either due to structural doming centred on Radok Lake, or to differential movement across some unidentified structure directly to the west.

Samples from relatively high elevations in the northern Prince Charles Mountains preserve evidence for a phase of late Palaeozoic cooling initiated during the Carboniferous, prior to the deposition of the Amery Group in the Beaver Lake area. While no independent constraints can be placed on the palaeotemperature gradient prior to the initiation of cooling, it is suggested that cooling involved some degree of exhumation. For an assumed geothermal gradient of 25°C km^{-1} immediately prior to cooling, it can be estimated that at least 2 km of material was removed beginning in the late Palaeozoic (equivalent to a minimum of 50°C of cooling for samples from Mount Kirkby) but prior to the initiation of cooling during the Early Cretaceous. Similar evidence for late Palaeozoic to early Mesozoic cooling has also been obtained from apatite fission-track analysis of Precambrian basement samples collected to the east of the Lambert Graben (Arne *et al.* 1993).

Samples of Flagstone Bench Formation give apatite fission-track ages similar to or significantly greater than the stratigraphical age of the unit, and thus preserve information concerning the thermal history of the provenance area from which the apatite gains were derived. Forward modelling for these samples suggests that detrital apatite in the Flagstone Bench Formation was derived from a source area that cooled below ~110°C in the Carboniferous, between ~350 and 300 Ma. This observation indicates that Precambrian basement in the region, which cooled below ~110°C in the Carboniferous, ultimately provided a source of detrital apatite grains for the Amery Group.

Discussion

Because the relationship between uplift of rocks and exhumation is not well constrained in the region, the amount of surface uplift and its relationship to the present-day elevation of the Prince Charles Mountains must necessarily remain speculative. It has been suggested that the plateau surfaces preserved locally at elevations of 1500–2000 m represent a pre-glacial peneplain that was formerly located close to sea level (Wellman & Tingey 1981). Although the age of this surface is not known, it is tempting to suggest that this peneplain surface was uplifted to its present elevation beginning in the Early Cretaceous. However, it may also have developed subsequently as samples from the Mount Kirkby section which directly underlie this surface are constrained only to have cooled from palaeotemperatures of ~60°C or less at some time in the Early Cretaceous, leaving considerable scope for further exhumation.

The emplacement of mafic intrusions either coincided with or post-dated the initiation of regional cooling of the Amery Group between ~140 and 120 Ma. Apatite fission-track data from some of these mafic intrusions further suggest that regional cooling to palaeotemperatures below ~60°C must have been largely completed by the mid-Cretaceous. A similar situation involving the emplacement of alkaline intrusions associated with regional cooling of the upper crust, presumably related to uplift and erosion, has also been noted in the southern U.S. (e.g. Arne 1992), further supporting a genetic link between lithospheric uplift and alkaline magmatism (Sykes 1978, Wernicke 1985).

The initiation of exhumation in the Early Cretaceous between 140 and 120 Ma was probably associated with rifting between eastern India and East Antarctica which began at 132.5 Ma (Veevers *et al.* 1991). A direct relationship between cooling of continental margins and Gondwana break-up has previously been demonstrated for south-east Australia (Moore *et al.* 1986) and south-west Africa (Brown *et al.* 1990), and is also suggested for the continental margin of East Antarctica west of Prydz Bay on the basis of reconnaissance apatite fission-track data (Arne *et al.* 1993). The tectonic setting of the Prince Charles Mountains differs from these previous examples in that, rather than being situated along a continental margin, they occur adjacent to the Lambert Graben, which has been interpreted as a failed rift active during the Cretaceous (Stagg 1985).

The direct cause of rapid exhumation and cooling in the northern Prince Charles Mountains during the Early Cretaceous also remains speculative, although a model involving asymmetric extension in the Lambert Graben is attractive (e.g. Wernicke 1985, Fitzgerald *et al.* 1986). In cross section, the average surface elevation on the western margin of the northern Lambert Graben is greater than that on the eastern margin and corresponds to negative Bouger anomalies of up to -120 mGal (Wellman & Tingey 1976) and a depth to the Moho greater than 30 km (Fedorov *et al.* 1982). By contrast, the depth to the Moho beneath the Lambert Glacier decreases to less than 25 km and is associated with positive Bouger anomalies. Alkaline magmatism also appears to be restricted to the Beaver Lake area to the west of the Lambert Graben, although its full extent has probably not been recognized. These lateral variations in topography, Bouger gravity, depth to Moho, and alkaline magmatism are similar to those predicted by Wernicke (1985) for uniform-sense normal simple shear of continental lithosphere. Tectonic uplift of the northern Prince Charles Mountains, in response to asymmetric extension in the Lambert Graben, may therefore have resulted ultimately in rapid exhumation to expose previously buried Precambrian basement and Amery Group strata in the Beaver Lake area.

Reconnaissance apatite fission-track data from the Mawson Coast and Enderby Land, to the north and west of the study area, indicate that Early Cretaceous cooling was not restricted to the northern Prince Charles Mountains but was regional in extent (Arne *et al.* 1993). This cooling was also probably related to the Mesozoic break-up of Gondwana, indicating that the continental margin between the Lambert Graben and Enderby Land was exhumed either immediately prior to or during rifting. It is worth noting that evidence for Early Cretaceous cooling has also been reported from the Vinson Massif in the Ellsworth Mountains, West Antarctica (Fitzgerald & Stump 1991) and in the Scott Glacier region of the Transantarctic Mountains (Stump & Fitzgerald 1992).

Kent (1991) proposed the existence of a long-lived mantle plume in eastern Gondwana at ~250 Ma, and cited evidence from palaeocurrent directions in Permian–Triassic sedimentary rocks from eastern India and the Beaver Lake area to indicate surface uplift. Evidence from the present study for regional cooling during the late Palaeozoic in northern Prince Charles Mountains suggests that the East Antarctic Shield was undergoing some degree of exhumation prior to that time, during the Carboniferous. Evidence for Carboniferous cooling in the northern Prince Charles Mountains is therefore probably related to the earliest stages of rifting in the Lambert Graben.

Detailed apatite fission-track data from northern Prince Charles Mountains, in conjunction with reconnaissance fission-track data from East Antarctica, place important constraints on the exhumation history of the East Antarctic Shield following the last major regional metamorphism at ~500 Ma. Exhumation of the East Antarctic Shield due to basaltic underplating at ~500 Ma has been modelled by Stüwe & Sandiford (1993). Unpublished fission-track ages from sphene and zircon (A.J.W. Gleadow, personal communication, 1989) for Precambrian basement samples from the East Antarctic Shield are ~500 Ma, indicating dramatic cooling to temperatures less than ~300°C shortly after metamorphism at ~500 Ma. Apatite fission-track data from the northern Prince Charles Mountains further indicate that final exhumation of the East Antarctic Shield occurred during at least two discrete pulses in response to rifting (late Palaeozoic) and eventual break-up of Gondwana (Early Cretaceous).

Conclusions

Fission-track analysis of apatite in samples from northern Prince Charles Mountains reveals a thermal history involving at least two distinct phases of cooling during the Phanerozoic. Precambrian basement rocks in the region began cooling below ~110°C in the Carboniferous and these rocks ultimately provided a source of sediment for the late Permian–Triassic Amery Group. Late Palaeozoic exhumation was probably associated with the initiation of rifting in the Lambert Graben. Burial of the preserved Amery Group section by ~3 km of additional sedimentary section is inferred from fission-track analysis of detrital apatite grains, assuming a palaeotemperature gradient of 25°C km^{-1}, and is supported in general by vitrinite reflectance determinations from numerous coal seams in the Bainmedart Coal Measures.

Subsequently, much of the region cooled again beginning in the Early Cretaceous; (140–120 Ma) the best evidence for which is found in the Radok Lake area. The palaeotemperature gradient prior to cooling is assumed to have been ~25°C km^{-1}. This is consistent with the available fission-track data, and suggests the removal of ~2 km of material from the top of the Amery Peaks section and at least 4 km from the top of the Radok Lake section. The Amery Group was exhumed and tilted to the east commencing at that time, possibly due to differential uplift of rocks to the west of Radok Lake.

Early Cretaceous exhumation in the Beaver Lake area was probably related to renewed extension centred in the Lambert Graben and associated uplift of rocks in the northern Prince Charles Mountains, and was accompanied in the later stages by the intrusion of alkaline mafic bodies. Evidence for Early Cretaceous cooling is also found in Precambrian basement samples to the north and west of the Prince Charles Mountains, reflecting the regional nature of cooling at that time.

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References

ALLISON, I. 1979. The mass budget of the Lambert Glacier drainage basin, Antarctica. *Journal of Glaciology*, **22**, 223-235.

ANDRONIKOV, A.V. 1990. Spinel-garnet lherzolite nodules from alkaline-ultrabasic rocks of Jetty Peninsula (East Antarctica). *Antarctic Science*, **1**, 321-330.

ARNE, D.C. 1992. Evidence for regional mid-Cretaceous cooling in the Ouachita Mountain Fold Belt and Arkoma Basin of Arkansa from apatite fission track analysis. *American Association of Petroleum Geologists Bulletin, 76*, 392-402.

ARNE, D.C., KELLY, P.R., BROWN, R.W., & GLEADOW, A.J.W. 1993. Reconnaissance apatite fission-track data from the East-Antarctic Shield, *In* FINDLAY, R.H., BANKS, H.R., VEEVERS, J.J. & UNRUG, R. *eds. Gondwana 8: assembly, evolution and dispersal*, 605-611.

BENNETT, A.J.R. & TAYLOR, G.H. 1972. Coals from the vicinity of the Prince Charles Mountains, Antarctica. *In* ADIE, R.J. *ed. Antarctic geology and geophysics*, Oslo: Universitetsforlaget, 591-598.

BOHANNON, R.G., NAESER, C.W., SCHMIDT, D.L. & ZIMMERMANN, R.A. 1989. The timing of uplift, volcanism, and rifting peripheral to the Red Sea: a case for passive rifting. *Journal of Geophysical Research*, **94**, 1683-1701.

BROWN, R.D., RUST, D.J., SUMMERFIELD, M.A., GLEADOW, A.J.W. & DE WIT, M.C.J. 1990. An Early Cretaceous phase of accelerated erosion on the south-western margin of Africa: evidence from apatite fission track analysis and the offshore sedimentary record. *Nuclear Tracks and Radiation Measurments*, **17**, 339-350.

BURNHAM, A.K. & SWEENEY, J.J. 1989. A chemical kinetic model of vitrinite maturation and reflectance. *Geochimica et Ceosmochimica Acta*, **53**, 2649-2657.

CROHN, P.W. 1959. A contribution to the geology and glaciology of the western part of Australian Antarctic Territory. *Bulletin of the Bureau of Mineral Resources, Geology and Geophysics, Australia*, No.52, 103pp.

ENGLAND, P. & MOLNAR, P. 1990. Surface uplift, uplift of rocks, and exhumation of rocks. *Geology*, **18**, 1173-1177.

FEDOROV, L.V., GRIKUROV, G.E., KURININ, R.G. & MASOLOV, V.N. 1982. Crustal structure of the Lambert Glacier area from geophysical data. *In* CRADDOCK, C. *ed. Antarctic geoscience*, Madison: University of Wisconsin Press, 931-936.

FITZGERALD, P.G., SANDIFORD, M., BARRETT, P.J. & GLEADOW, A.J.W. 1986. Asymmetric extension in the Transarctic Mountains and Ross embayment. *Earth and Planetary Science Letters*, **81**, 67-78.

FITZGERALD, P.G. & STUMP, E. 1991. Early Cretaceous uplift in the Ellsworth Mountains of West Antarctica. *Science*, **254**, 92-94.

GALBRAITH, R.F. 1981. On statistical methods for fission track counts. *Mathematical Geology*, **13**, 471-488.

GALBRAITH, R.F. 1988. Graphical display of estimates having differing standard errors. *Technometrics*, **30**, 271-281.

GLEADOW, A.J.W., DUDDY, I.R., GREEN, P.F. & LOVERING, J.F. 1986. Confined fission track lengths in apatite - a diagnostic tool for thermal history analysis. *Contributions to Mineralogy and Petrology*, **94**, 405-415.

GLEADOW, A.J.W. & FITZGERALD, P.G. 1987. Uplift history and structure of the Transantarctic Mountains: new evidence from fission track dating of basement apatites in the Dry Valleys area, southern Victoria Land. *Earth and Planetary Science Letters*, **82**, 1-14.

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 (Isotope Geoscience Section)*, **58**, 1-22.

GREEN, P.F. 1986. On the thermo-tectonic evolution of Northern England: evidence from fission track analysis. *Geological Magazine*, **123**, 493-506.

Green, P.F. 1988. The relationship between track shortening and fission track age reduction in apatite: combined influences of inherent stability, annealing anisotropy, length bias and system calibration. *Earth and Planetary Science Letters*, **89**, 335-352.

Green, P.F., Duddy, I.R., Gleadow, A.J.W., Tingate, P.R. & Laslett, G.M. 1986. Thermal annealing of fission tracks in apatite: 1 - a qualitiative description. *Chemical Geology (Isotope Geoscience Section)*, **59**, 237-253.

Green, P.F., Duddy, I.R., Gleadow, A.J.W., Hegarty, K.A., Laslett, G.M. & Lovering, J.F. 1989. Thermal annealing of fission tracks in apatite: 4 - quantitative modelling techniques and extension to geologic timesales. *Chemical Geology (Isotope Geoscience Section)*, **79**, 155-182.

Hofmann, J. 1991. Bruchtektonik und magmatismus im Gebiet der Jetty-Oase, McRobertson Land (Ostantarktika). *Frieberger Forschungshefte*, **C438**, 6-38.

Hurford, A.J. 1990. Standardization of fission track dating calibration: recommendation by the Fission Track Working Group of the I.U.G.S. Subcommision on Geochronology. *Chemical Geology (Isotope Geoscience Section)*, **80**, 171-178.

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

Kent, R. 1991. Lithospheric uplift in eastern Gondwana: evidence for a long-lived mantle plume system? *Geology*, **19**, 19-23.

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

McKelvey, B.C. & Stephenson, N.C.N. 1990. A geological reconnaissance of the Radok Lake area, Amery Oasis, Prince Charles Mountains. *Antarctic Science*, **2**, 53-66.

Miller, D.S. & Duddy, I.R. 1989. Early Cretaceous uplift and erosion of the northern Appalachian Basin, New York, based on apatite fission track analysis. *Earth and Planetary Science Letters*, **93**, 35-49.

Mond, A. 1972. Permian sediments of the Beaver Lake area, Prince Charles Mountains. *In* Adie, R.J. *ed. Antarctic geology and geophysics*, Oslo: Universitetsforlaget, 585-589.

Moore, M.E., Gleadow, A.J.W. & Lovering, J.F. 1986. Thermal evolution of rifted continental margins: new evidence from fission tracks in basement apatites from southeastern Australia. *Earth and Planetary Science Letters*, **78**, 255-270.

Omar, G.I., Steckler, M.S., Buck, W.R. & Kohn, B.P. 1989. Fission-track analysis of basement apatites at the western margin of the Gulf of Suez rift: evidence for synchroneity of uplift and subsidence. *Earth and Planetary Science Letters*, **78**, 316-328.

Parrish, R.R. 1983. Cenozoic thermal evolution and tectonics of the Coast Mountains of British Columbia 1. Fission track dating, apparent uplift rates, and patterns of uplift. *Tectonics*, **2**, 601-631.

Ravish, M.G., Soloviev, D.S. & Federov, L.V. 1984. *Geological structure of Mac. Robertson Land (East Antarctica)*. new Delhi: Amerind Publishing, 247pp.

Sheraton, J.W. 1983. Geochemistry of mafic igneous rocks of the northern Prince Charles Mountains, Antarctica. *Journal of the Geological Society of Australia*, **30**, 295-304.

Stagg, H.M.J. 1985. The structure and origin of Prydz Bay and MacRobertson Shelf, East Antarctica. *Tectonophysics*, **114**, 315-340.

Stump, E. & Fitzgerald, P.G. 1992. Episodic uplift of the Transantarctic Mountains. *Geology*, **20**, 161-164.

Stüwe, K. & Sandiford, M. 1993. A preliminary model for the 500 Ma event in the East Antarctic Shield, *In* Findlay, R.H., Banks, H.R., Veevers, J.J. & Unrug, R. *eds. Gondwana 8: assembly, evolution and dispersal*, 125-130.

Sykes, L.R. 1978. Intraplate seismicity, reactivation of pre-existing zones of weakness, alkaline magmatism, and other tectonism postdating continental fragmentation. *Reviews in Geophysics and Space Physics*, **16**, 621-688.

Tingey, R.J. 1982. The geological evolution of the Prince Charles Mountains - an Antarctic Archean cratonic block. *In* Craddock, C. *ed. Antarctic geoscience*, Madison: University of Wisconsin Press, 455-464.

Turner, B.R. & Padley, D. 1991. Lower Cretaceous coal-bearing sediments from Prydz Bay, East Antarctica. *In* Barron, J., Larsen, B. *et al. eds., Proceedings of the Ocean Drilling Program, Scientific Results*, **119**, 57–60.

Veevers, J.J. McA, Powell, C. & Roots, S.R. 1991. Review of seafloor spreading around Australia. I. Synthesis of the patterns of spreading. *Australian Journal of Earth Sciences*, **38**, 373-389.

Walker, K.R. & Mond, A. 1971. Mica lamprophyre (alnöite) from Radok Lake, Prince Charles Mountains, Antarctica. *Bureau of Mineral Resources, Australia, Record*, No.108. 6pp. [Unpublished].

Webb, J.A. & Fielding, C.R. 1993. Permo-Triassic sedimentation within the Lambert Graben, northern Prince Charles Mountains, East Antarctica. *In* Findlay, R.H., Banks, H.R., Veevers, J.J. & Unrug, R. *eds. Gondwana 8: assembly, evolution and dispersal*, 357-369.

Wellman, P. & Tingey, R.J. 1976. Gravity evidence for a major crustal fracture in eastern Antarctica. *Journal of the Bureau of Mineral Resources, Geology and Geophysics, Australia*, **1**, 105-108.

Wellman, P & Tingey, R.J. 1981. Glaciation, erosion and uplift over part of East Antarctica. *Nature*, **291**, 142-144.

Wernicke, B. 1985. Uniform-sense normal simple shear of the continental lithosphere, *Candaian Journal of Earth Sciences*, **22**, 108-125.

Appendix : Personal calibration

Following the recommendations of the Fission-track Working Group of the I.U.G.S. Subcommission on Geochronology (Hurford 1990), data for eight replicate analyses from each of three different age standards used in determining the author's personal zeta calibration factor are presented in Table AI. The age standards selected for analysis were Fish Canyon Tuff (27.8 ± 0.7 Ma), Durango apatite (31.4 ± 0.5 Ma) and Mount Dromedary Banatite (98.7 ± 0.7 Ma), as suggested by Green (1985) and Hurford (1990). Experimental conditions for the determination of individual zeta values were identical to those described in the preceding text.

Weighted mean zetas were calculated for each of the three age standards analysed and then an overall weighted mean zeta of 336 ± 12 was calculated from these values (Green 1985). The analyses presented in Table AI were performed over a 3 1/2 year period from September, 1986 to March, 1990 using standards from two separate irradiations. Note that, with one exception, all analyses agree within 2σ with the mean value of 336 ± 12.

In addition, given the increasing use of track length measurements in apatite as an indicator of thermal history, some consideration should also be given to the standardization and testing of length calibration. As an example, measurements of horizontal confined track lengths determined using the later method described by Gleadow *et al.* (1986) are presented in Table AII for each of the three age standards already discussed and for induced tracks in apatite. Mean track lengths presented in Table AII are generally within error (at 2σ) of mean lengths for the same age standards presented in Gleadow *et al.* (1986), although the two measurements for Mount Dromedary apatite presented in Table AII are slightly lower.

Table AI. Apatite age standard analyses for system calibration

Sample number	Number of crystals	Spontaneous ρs	(N_s)	Induced ρi	(N_i)	$P(\chi^2)$ (%)	$\rho s/\rho i \pm 2\sigma$	Dosimeter ρd	(N_d)	$\zeta \pm 2\sigma$
Fish Canyon Tuff										
72N8-24	20	0.202	(255)	1.745	(2201)	72.4	0.119 ± 0.016	1.455	(2567)	331 ± 48
72N8-24	20	0.203	(278)	1.748	(2390)	93.1	0.118 ± 0.016	1.455	(2567)	329 ± 46
72N8-1	19	0.182	(193)	1.764	(1875)	37.9	0.108 ± 0.016	1.455	(2567)	372 ± 62
72N8-1	16	0.172	(219)	1.576	(2009)	1.3	0.113 ± 0.022	1.455	(2567)	320 ± 72*
72N8-1	19	0.187	(299)	1.899	(3032)	90.6	0.100 ± 0.012	1.455	(2567)	388 ± 54
8424-20a	22	0.199	(245)	1.488	(1826)	12.6	0.135 ± 0.022	1.353	(2129)	307 ± 46
8424-20b	22	0.196	(246)	1.575	(1973)	40.2	0.129 ± 0.018	1.353	(2129)	330 ± 50
8424-20c	20	0.217	(249)	1.651	(1891)	30.3	0.131 ± 0.020	1.353	(2129)	313 ± 48
								Weighted mean ζ		334 ± 20
Durango Apatite										
8122-3b	20	0.194	(293)	1.388	(2099)	11.9	0.144 ± 0.020	1.455	(2567)	310 ± 42
8122-3b	20	0.169	(260)	1.452	(2231)	45.2	0.119 ± 0.016	1.455	(2567)	371 ± 52
8122-3a	20	0.140	(245)	1.324	(2312)	69.8	0.109 ± 0.014	1.455	(2567)	408 ± 58
8122-3a	19	0.154	(252)	1.240	(2034)	44.0	0.128 ± 0.018	1.455	(2567)	349 ± 50
8122-3a	20	0.209	(364)	1.570	(2741)	38.7	0.136 ± 0.016	1.455	(2567)	326 ± 40
DA 2a	20	0.161	(203)	1.430	(1800)	65.5	0.115 ± 0.016	1.353	(2129)	413 ± 66
DA 2a	20	0.193	(243)	1.380	(1737)	84.8	0.140 ± 0.016	1.353	(2129)	333 ± 50
DA 2a	20	0.177	(223)	1.329	(1673)	70.9	0.136 ± 0.018	1.353	(2129)	349 ± 54
								Weighted mean ζ		348 ± 24
Mount Dromedary Banatite										
8322-42	19	0.852	(589)	2.104	(1455)	52.2	0.409 ± 0.040	1.455	(2567)	338 ± 36
8322-39	19	1.001	(468)	2.561	(1197)	76.5	0.394 ± 0.044	1.455	(2567)	350 ± 42
8322-39	14	1.110	(370)	3.000	(1000)	16.1	0.370 ± 0.056	1.455	(2567)	370 ± 48
8322-42	20	1.077	(414)	2.091	(804)	5.7	0.523 ± 0.076	1.455	(2567)	266 ± 34
8322-42	19	0.793	(447)	1.947	(1097)	7.9	0.413 ± 0.054	1.455	(2567)	336 ± 40
8322-158a	19	1.016	(898)	2.319	(2049)	35.8	0.445 ± 0.040	1.353	(2129)	335 ± 30
8322-158b	20	0.943	(553)	2.257	(1324)	1.0	0.454 ± 0.060	1.353	(2129)	324 ± 46*
8322-158c	20	0.874	(824)	1.929	(1820)	63.9	0.459 ± 0.036	1.353	(2129)	325 ± 32
								Weighted mean ζ		327 ± 22
							Overall weighted mean ζ			**336 ± 12**

ρd-standard track density measured for NBS SRM 612. ρs-fossil track density. ρi- induced track density. All tracks x10^6/cm^2. *-Mean ζ, used where pooled data fail χ^2 test at 5%.

Table AII. Measurement of confined track lengths

Sample	Mean track length ± 2σ (μm)	Standard deviation (μm)	Number of tracks
Induced A	15.8 ± 0.2	1.0	100
Induced B	16.4 ± 0.2	0.8	100
Induced E	15.8 ± 0.2	0.9	100
Durango	14.5 ± 0.3	1.1	44
Durango	14.5 ± 0.4	1.1	25
Mt. Dromedary	14.2 ± 0.2	1.0	100
Mt. Dromedary	14.1 ± 0.3	1.3	102
Fish Canyon	14.9 ± 0.3	1.1	46
Fish Canyon	15.1 ± 0.2	1.1	91