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# Thermal history of the Vestfold Hills (East Antarctica) between Lambert rifting and Gondwana break-up, evidence from apatite fission track data

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**Abstract:** Analysis of five basement samples from the Vestfold Hills (East Antarctica) reveals pooled apatite fission track (FT) ages ranging from 188 to 264 Ma and mean lengths of 13.7 to 14.9 µm. Quantitative thermal histories derived from these data give consistent results indicating onset of cooling/denudation began sometime prior to 240 Ma, with final cooling below 105°–125°C occurring between 240 and 220 Ma (Triassic). A Cretaceous denudation phase can be inferred from the sedimentary record of the Prydz Bay offshore the Vestfold Hills. The two denudational episodes are likely associated with Palaeozoic large-scale rifting processes that led to the formation of the adjacent Lambert Graben, and to the Cretaceous Gondwana break-up between Antarctica and India. Subsequent evolution of the East Antarctic passive continental margin likely occurred throughout the Cenozoic based on the depositional record in Prydz Bay and constraints (though tentative) from FT data.

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## Introduction

The Vestfold Hills form an Antarctic oasis (i.e. a permanently snow and ice free area: cf. Shumskiy 1957, Pickard 1986a) occupying a roughly triangular area of approximately 400 km$^2$ along the eastern margin of Prydz Bay between ~78° and ~78°30'E at ~68°30'S (Fig. 1). In this position, they are the most easterly of a series of rocky coastal outcrops that extend north-east from the Amery Ice Shelf towards the West Antarctic Ice Shelf. The Vestfold Hills have attracted the attention of geologists since the first visit of an Australian ANARE expedition some fifty years ago. Since then, particular interest has been dedicated to the unique network of Archean to Mesoproterozoic mafic dykes transecting the predominantly Archaean basement, to the extensive Cenozoic marine fossil deposits, and also to the physiography and morphology of the Vestfold Hills (cf. Pickard 1986b, Hoek & Seitz 1995). Accordingly, both the evolution of the Precambrian basement as well as the Cenozoic history of the Vestfold Hills have been intensely studied.

Despite these attentions, little work to date has addressed the wider geological significance of the exceptional situation of the Vestfold Hills, positioned at the junction between two major crustal features: the Lambert Graben and the East Antarctic passive continental margin. Previous work has revealed that the shoulders of the Lambert Graben experienced at least two major episodes of denudation (each presumably kilometre scale) during rifting in the late Palaeozoic and Cretaceous (Lisker *et al.* 2003). Geophysical data and stratigraphic observation from the ODP Legs 119 and 188 (Barron *et al.* 1991, O'Brien *et al.* 2001) also suggest denudation occurring at similar times across the present passive margin of Mac.Robertson and Princess Elisabeth Land.

With the aid of apatite fission track (FT) data, this study considers the particular setting of the Vestfold Hills within the Prydz Bay region, and aims to

1) provide direct constraints on the post-orogenic thermal history of the Vestfold Hills,
2) constrain the timing and magnitude of denudation at the margins of the Lambert Graben based on thermochronology,
3) evaluate the relative influences and interplays between regional landscape-shaping processes dominating the Phanerozoic history of the border region between Mac.Robertson and Princess Elisabeth Land (e.g. Graben formation, rift reactivation and Gondwana break-up), and
4) compare and contrast the long-term landscape evolution of the Vestfold Hills with that of other previously studied passive margin fragments of East Antarctica.

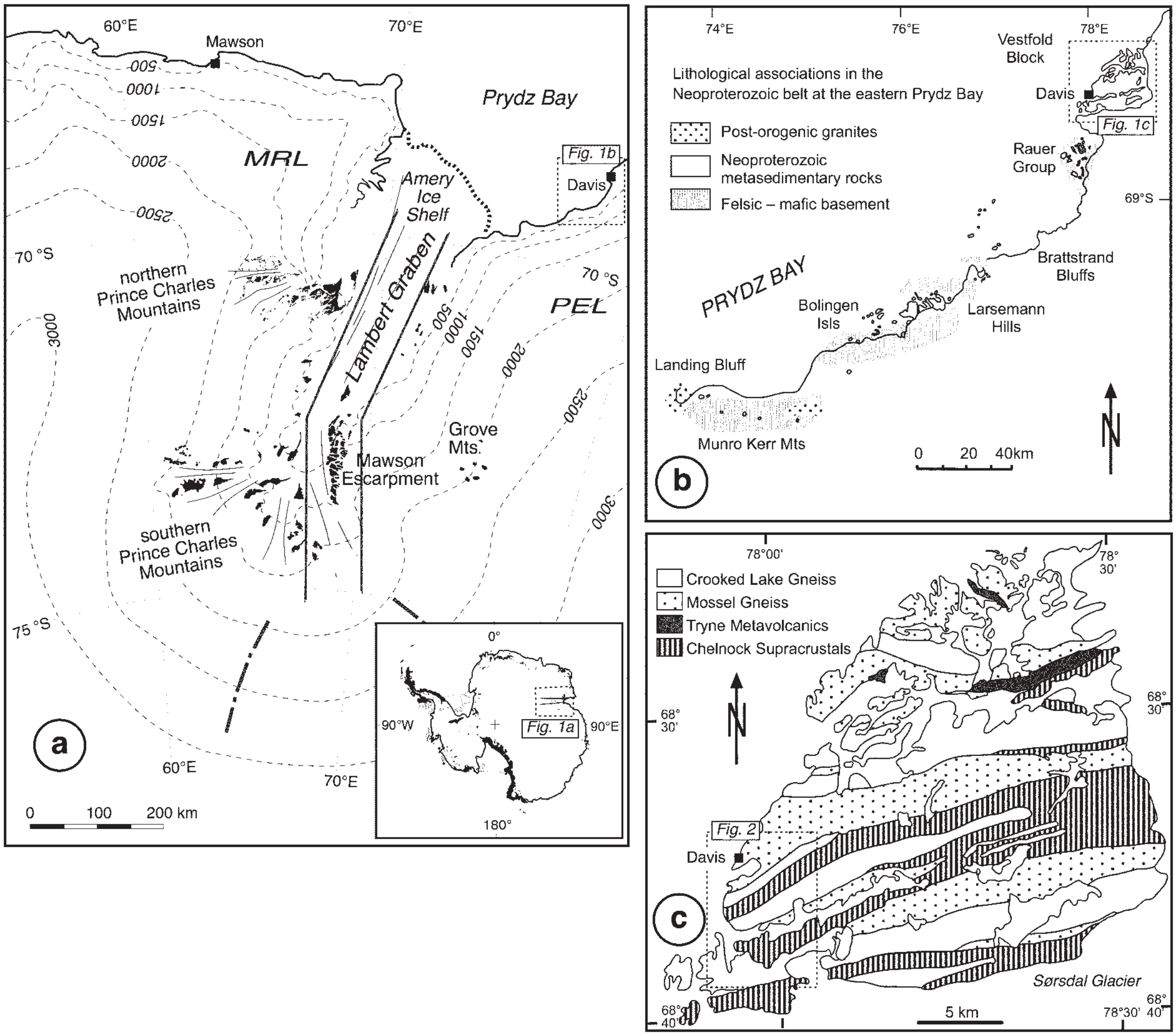

**Fig. 1.** Sketch maps showing **a.** the position of the Vestfold Hills in East Antarctica at **b.** the eastern margin of Prydz Bay, and **c.** the basement geology of the Vestfold Hills (after Hoek & Seitz 1995, Lisker *et al.* 2003). MRL = Mac.Robertson Land, PEL = Princess Elisabeth Land. Dotted insets display the position of the respective maps.

## Geological setting

The Vestfold Hills represent one of several known Archaean crustal fragments in the East Antarctic Craton. Their oldest basement rocks are comprised of Archean Chelneck Supracrustals and the volumetrically minor Tryne Metavolcanics (Fig. 1) (Sheraton & Collerson 1983). The main basement units, the Mossel Gneiss and the Crooked Lake Gneiss, were formed at high temperature/high pressure conditions during a 2.5 Ga tectono-metamorphic event (Collerson & Sheraton 1986). The subsequent Proterozoic evolution of the Vestfold Hills is characterized by the emplacement of several mafic dyke swarms and repeated brittle and ductile deformation on isolated shear zones (e.g. Passchier *et al.* 1991). Hoek & Seitz (1995) identified a first Palaeoproterozoic episode of bimodal magmatism, followed by Mesoproterozoic dyke intrusions at 1.4–1.2 Ga. Two major metamorphic events of amphibolite to granulite facies conditions, involving intense ductile deformation, and felsic magmatism, occurred around 1.0 and 0.5 Ga. Both events are related to the regional scale Grenville and Pan-African events (e.g. Sims *et al.* 1994), which are associated with the emplacement of predominantly tholeiitic dyke swarms.

During the whole Phanerozoic, the Mac.Robertson–Princess Elisabeth Land sector of Antarctica was incorporated into a stable, cratonic evolution of East Gondwana with no significant tectonic or magmatic activities being detected. The regional geological history was dominated by the development of the Lambert Graben to the east, a 700 km long failed rift (Stagg 1985) that transects the craton perpendicular to the continental margin. Therein, a > 10 km thick sedimentary sequence was deposited during two rifting stages between the

Carboniferous and Triassic, and in the Cretaceous, respectively (e.g. Kurinin & Grikurov 1982). In contrast, no Palaeozoic or Mesozoic sedimentary deposits are known from the Vestfold Hills. Only the presence of a variety of yet undated alkaline dykes with petrological and geochemical characteristics similar to the ones from the northern Prince Charles Mountains/Lambert Graben may indicate a link with the rifting of the Lambert Graben where both rifting episodes were accompanied by mafic igneous activities (Collerson & Sheraton 1986). The second rifting stage of the Lambert Graben was probably associated with Gondwana break-up between Antarctica and India commencing in Early Cretaceous times (Lisker *et al.* 2003, Harrowfield *et al.* 2005). Accordingly, two Pre-Cenozoic sedimentary sequences are known from the ODP Sites (Legs 119 and 188: Barron *et al.* 1991, O'Brien *et al.* 2001) in the Prydz Bay adjacent to the Vestfold Hills, a (Permo–Triassic?) red bed unit and an overlying, Aptian coal-bearing sequence. Turner (1991) interprets the underlying unit as deposits of floodplains, whereas the overlying, Aptian sequence was deposited in crevasse splay deposits in swampy, vegetated floodplains including low-sinuosity fluvial channels (Turner & Padley 1991). There are no indications of pre-Cenozoic marine deposition. Brittle structures merely consist of eroded shear zones perpendicular to the coast either filled with till or forming glacial drainages and underwater canyons (e.g. Sørsdal Glacier, Adamson & Pickard 1986a), and kinematic indications are scarce.

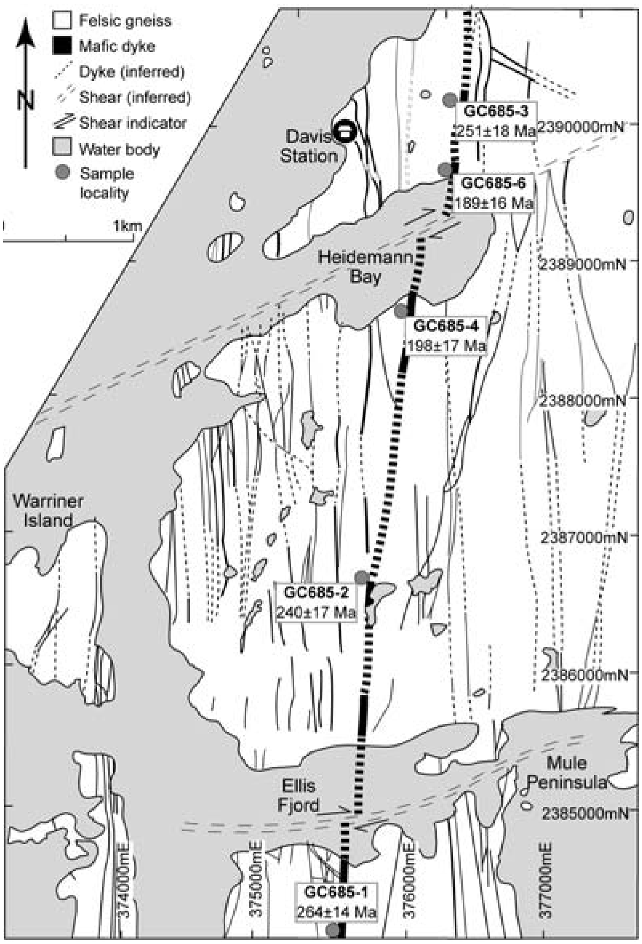

**Fig. 2.** Location map of the study area showing sample locations (bold numbers) and apatite fission track ages. The position of this sketch is indicated in Fig. 1c. Grid line numbers are intervals of the Australian Map Grid, zone 44.

The Cenozoic geological record preserved in the Vestfold Hills is generally typical for an Antarctic oasis: very old basement rocks thinly covered by Pleistocene and Holocene glacial and marine sediments. The only exception is that the Vestfold Hills host a Pliocene marine deposit which is unique in East Antarctica (Adamson & Pickard 1986b). These Cenozoic sediments marginally modify the present geomorphological appearance of the Vestfold Hills as a flat landscape of low islands and flat-topped hills, generally below ~150 m a.s.l., with only ~1% of the total area rising over 100 m a.s.l. and less than 15% above 60 m (Adamson & Pickard 1986a). The subglacial topography inland from the Vestfold Hills is also subdued.

## Sample details

Five basement samples of similar elevation were collected for apatite fission track analysis from a 6 km long transect near to Davis Station in the Vestfold Hills, East Antarctica (Fig. 2). As detailed in Fig. 2, all samples are from within several metres of a mafic dyke which is at least 5 m wide. Two Pan African age (~500 Ma) shear zones crosscut the sample transect, thus post-dating the mafic dyke. All apatite fission track samples comprise granulite facies, felsic gneisses (Snape & Harley 1996), and are of Palaeoproterozoic age.

## Apatite fission track results

### *Introduction*

Apatite FT thermochronology is one of the most powerful methods for documenting low temperature thermal histories. From FT parameters –FT age and length data, and apatite chlorine content– one can constrain the timing of cooling to, and below, temperatures of ~105° to ~125°C (depending on apatite Cl% content). If cooling is produced by denudation, then exhumation amounts (i.e. total depth of previous burial) can also be estimated by assuming or directly measuring the past geothermal gradient (if possible, via analysis of a vertical sequence of samples). In context with the geological record, the regional denudation pattern can then be used to discriminate between the applicability of different models of landscape development, such as orogenic mountain building, cratonic intraplate processes, or passive continental margin development (e.g. Brown *et al.* 1994, Gallagher *et al.* 1998).

**Table I.** Apatite fission track data from the Vestfold Hills (East Antarctica).

| Sample No<br>Lithology | $\rho_D$ [$10^6$ cm$^{-2}$] ($N_D$) | $\rho_S$ [$10^6$ cm$^{-2}$] ($N_S$) | $\rho_i$ [$10^6$ cm$^{-2}$] ($N_i$) | AD [%] (U) [ppm] | P $(\chi)^2$ [%] | FTA [Ma] (#) | MTL [μm] (n) | SD [μm] (Cl) [wt%] | $T_{max1}$ [°C] ($T_{max2}$) [°C] | $t(T_{max1})$ [Ma] ($t(T_{max2})$) [Ma] |
|---|---|---|---|---|---|---|---|---|---|---|
| GC685-1 | 1.274 | 3.592 | 3.280 | 10 | 7 | 264 ± 13 | 14.93 ± 0.14 | 1.38 | > 125 | 290–220 |
| Felsic gneiss | (1944) | (1449) | (1323) | (29) | | (20) | (103) | (1.58 ± 0.09) | (< 65) | (220–present) |
| GC685-2 | 1.266 | 1.076 | 1.078 | 3 | 65 | 240 ± 17 | 14.10 ± 0.15 | 1.31 | > 105 | 295–210 |
| Felsic gneiss | (1944) | (457) | (458) | (10) | | (20) | (74) | (0.12 ± 0.03) | (40–65) | (~200–10) |
| GC685-3 | 1.259 | 1.093 | 1.040 | 3 | 49 | 251 ± 18 | 13.99 ± 0.12 | 1.16 | > 105 | 305–205 |
| Felsic gneiss | (1944) | (494) | (470) | (9) | | (20) | (101) | (0.05 ± 0.03) | (35–55) | (~200–present) |
| GC685-4 | 1.393 | 1.116 | 1.494 | 22 | 17 | 198 ± 17 | 13.73 ± 0.16 | 1.66 | > 110 | 250–160 |
| Felsic gneiss | (2190) | (271) | (363) | (12) | | (20) | (102) | (0.17 ± 0.09) | (40–65) | (110–present) |
| GC685-6 | 1.393 | 1.209 | 1.706 | 25 | 7 | 188 ± 16 | 13.76 ± 0.16 | 1.50 | > 110 | 240–170 |
| Felsic gneiss | (2190) | (280) | (395) | (14) | | (20) | (87) | (0.16 ± 0.09) | (40–55) | (55–present) |

Footnote 1: Apatite mineral concentrates from the samples were obtained using conventional crushing, grinding, heavy liquid, and magnetic separation techniques. Apatite grains were mounted in epoxy resin on glass slides, polished, and etched for 20 s in 5M $HNO_3$ at 20°C. Neutron irradiations were carried out in the well thermalised X-7 graphite reflector facility in the HIFAR research reactor, Sydney, Australia. Fission track ages were determined by the external detector method (Gleadow 1981) applying the zeta calibration technique described by Hurford & Green (1983). $\zeta = 386.9 \pm 6.9$ (H. Gibson) for dosimeter glass CN5. Errors are quoted as $\pm 1\sigma$ (conventional method/ Green 1981). For dating, an Autoscan$^{TM}$ automatic stage system (Smith & Leigh-Jones 1985) was used. Apatite fission tracks were counted and measured using a Zeiss Axioplan microscope with an overall linear magnification of 1068× under dry objectives. If possible, at least 20 grains were counted, and 100 or more confined tracks were measured for each sample. Confined fission tracks were measured following the recommendations of Laslett *et al.* (1987).

Footnote 2: $\rho_D$, $\rho_S$, $\rho_i$, $N_D$, $N_S$, $N_i$ = Density (ρ) and number (N) respectively of counted dosimeter ($_D$), spontaneous ($_S$) and induced tracks ($_i$), AD = age dispersion, U = apatite uranium content, $P(\chi^2)$ = Chi square probability, FTA = fission track age (pooled ages in all cases, because all samples pass $\chi^2$ test at >5%), # = number of counted grains, MTL = mean track length, n = number of measured tracks, SD = standard deviation, $T_{max1}$, $t(T_{max1})$ = maximum palaeotemperature and cooling time of the first revealed cooling episode, $T_{max2}$, $t(T_{max2})$ = peak palaeotemperature and cooling time of the second revealed cooling episode. Brackets indicate events allowed, but not required by the FT data. The timing constraints of both cooling episodes overlap at 240–220 Ma, and 55–10 Ma, respectively. All palaeotemperature and timing estimates are derived assuming a heating rate of 1°C Ma$^{-1}$ and a cooling rate of 10°C Ma$^{-1}$, and an assumed constant paleo-surface temperature of 10°C. For further explanation see text.

The apatite FT method adopted for this study bases on standard procedures which are well covered in the literature (e.g. Hurford & Green 1982, Gleadow *et al.* 1983, 1986, Miller & Duddy 1989) and hence not repeated here. Methodological aspects crucial for this study are given in footnote 1 of Table I.

### *Results*

Apatite FT data from the five Vestfold Hills samples are listed in Table I and illustrated in Figs 3 & 4. The apatite FT ages obtained from all samples range from 188 ± 16 to 264 ± 13 Ma, and are thus considerably younger than the inferred Palaeoproterozoic ages of the host rocks, and younger than the last potential metamorphic overprint during the Pan-African orogeny (~500 Ma). They are also among the youngest apatite FT ages reported from coastal Mac.Robertson and Princess Elisabeth Land about 100 km west and east of the Prydz Bay (Arne *et al*. 1993: 200–350 Ma). There is no correlation between the FT ages and the positions of the samples within the transect, and there is also no correlation between FT age and sample distance from the coast. All sample ages pass the $\chi^2$ test with moderate probabilities between 7 and 65%, indicating that all grains within each sample belong to one homogeneous age population.

The mean track lengths vary from 13.7 to 14.9 μm with standard deviations between 1.7 and 1.2 μm (Table I). Overall, the FT ages and lengths of all five samples are similar. Slightly older FT ages and longer mean track lengths are observed in sample GC685-1, but these reflect higher mean chlorine contents of the apatites in this sample rather than indicating a different thermal history, as further revealed by the thermal history modelling results explained below.

### *Apatite compositions*

The annealing kinetics of fission tracks in apatite are affected by chemical composition, specifically the chlorine content (Gleadow & Duddy 1981, Green *et al.* 1986). Using the thermal history modelling procedure described below, it is possible to predict specific "threshold temperatures" at which tracks begin to be retained according to the Cl content of the individual apatite grains. Therefore, in all samples collected for this study, Cl contents were measured by microprobe analysis, in all apatite grains analysed. The apatite chlorine contents of all samples except one have Cl contents between 0 and 0.2 wt%: Only sample GC685-1 contains apatites with Cl contents between 1.4 and 1.7 wt% (Fig. 3). This suggests threshold temperatures of ~125°C for sample GC685-1, ~110°C for GC685-4 and -6, and ~105°C

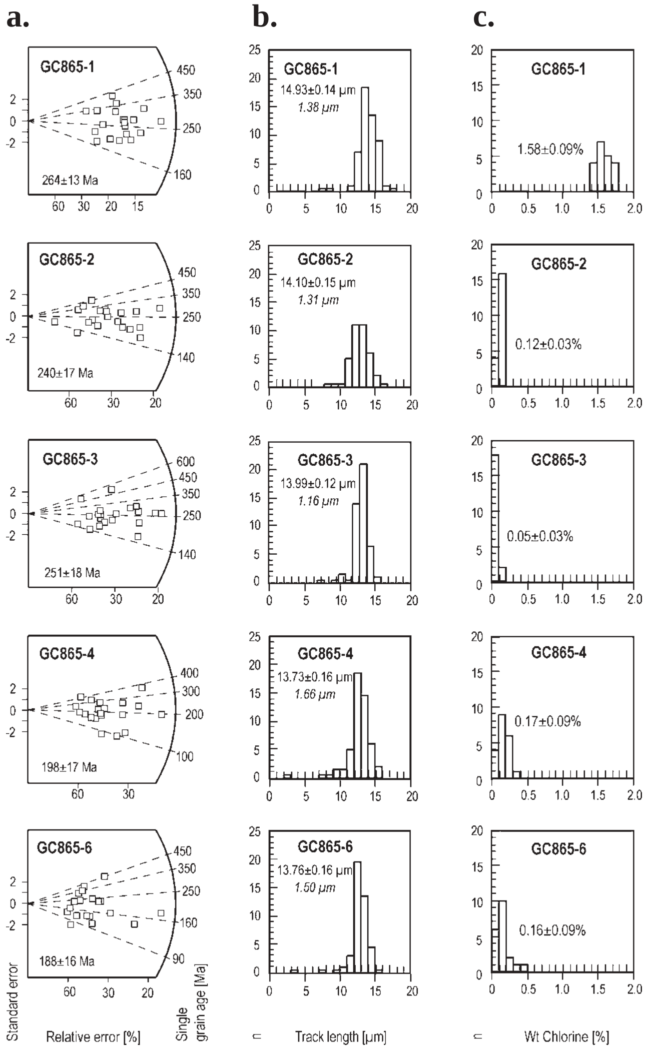

**Fig. 3.** Diagrams of the fission track data from the Vestfold Hills (East Antarctica). **a.** Radial plots, showing the single grain ages. Sample number is given on left top side, sample ages (pooled ages) are on the bottom of the plots. **b.** Length histograms. All data are normalised to 100 confined tracks. The mean track length ± 1σ and standard deviation (in italics) are shown above each plot. **c.** Histograms of the Cl contents of the dated grains.

for samples GC685-2 and -3 (Table I, Fig. 5).

## Thermal history reconstruction

### Qualitative estimates

The close similarity of the apatite FT ages and mean track lengths of all five samples suggests that the timing and magnitude of maximum/peak palaeotemperatures in all samples may overlap. Thus a single thermal history solution could be consistent with the constraints in all FT samples. This is perhaps not surprising given the samples are all from close proximity to each other (< 6 km) and from similar settings within several metres of a mafic dyke.

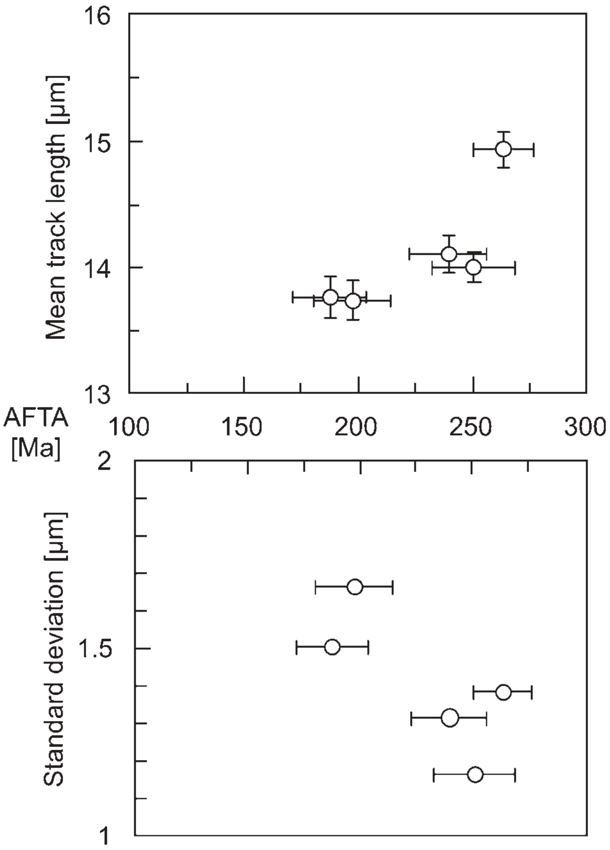

**Fig. 4.** Plots showing the relationship between mean track lengths (MTL), their standard deviation, and apatite fission track ages (AFTA) of the samples from the Vestfold Hills (East Antarctica).

A qualitative interpretation of the data reported in Table I: FT ages between 188 ± 16 and 264 ± 13 Ma, relatively long mean track lengths from 13.7 to 14.9 µm, and moderate $\chi^2$ values suggests that the samples cooled to track retention temperatures of ~125° to ~105°C (depending on apatite Cl content) sometime within the Permo–Carboniferous to Triassic period, but quantitative estimates of the cooling history can only be obtained by thermal history modelling, as reported below.

### Modelling concept

Values of maximum palaeotemperatures and timing of cooling in each sample are determined by predictive forward modelling using the FT annealing characteristics described by Laslett *et al.* (1987) modified by Geotrack International to allow for varying apatite chlorine contents, as determined by microprobe analysis (Fig. 3). Allowing for the Cl contents of the analysed grains (grains used for both age and length data), the modelling approach implements an iterative routine which explores a wide range of possible thermal history solutions that can satisfy the measured age and length data. The result is the possible range of *cooling conditions*, expressed as maximum palaeotemperatures and

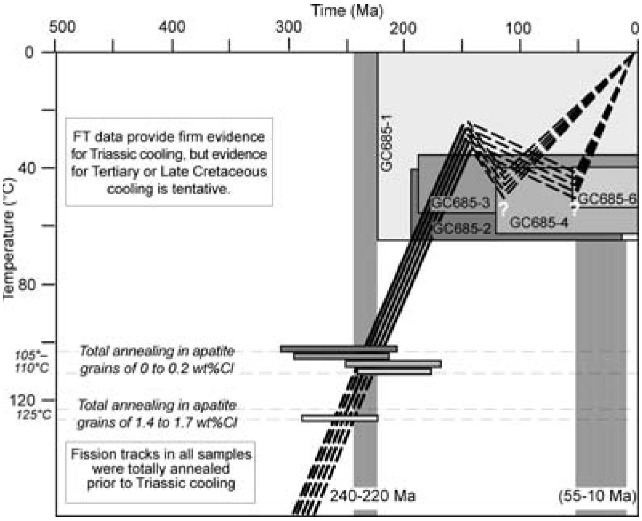

**Fig. 5.** Schematic illustration showing possible thermal history scenarios which can account for the apatite FT parameters from the Vestfold Hills (East Antarctica). The grey shaded boxes represent cooling time intervals according to the thermal history modelling described in the text. Note that a Tertiary cooling episode (commencing at ~50 Ma) is only allowed, but not required, by the FT data. Alternatively, this second event could be reconstructed commencing at ~110 Ma, by disregarding the sample GC685-6 results. Also, a scenario involving both Cretaceous and Tertiary cooling events cannot be ruled out, due to the somewhat broad constraints in this part of the cooling history, from the currently available data.

times. These are reported using conventional maximum likelihood theory. In this way, maximum palaeotemperatures and times of onset of cooling are defined together with ± 95% confidence limits, and have been reported as a range in each case (Table I). Note that for complex thermal histories, definition of two or three cooling episodes is usually at the limit of the resolution of the FT dataset, and this has been the experience with the data in this study. See Gibson & Stüwe (2000) for further details about the modelling method adopted here.

### *Palaeo-surface temperature*

Quantitative thermal history modelling in this study allowed only for the assumption of a single, constant palaeo-surface temperature value, for the period since deposition/emplacement of the samples (in this case ~500 Ma to the present day). Since the modelling seeks to determine the degree of additional palaeo-heating affecting the sample during a relatively long period (500 Ma) the value of the assumed constant surface temperature has a significant bearing on the thermal history interpretations.

The surface temperature of the Vestfold Hills is though to have varied considerably since the late Palaeozoic. Values as low as < 0°C during the Carboniferous are indicated by the occurrence of diagenetically compacted diamictites in the nearby Grove Mountains (observed by F.L.), and the occurrence of tillites in the Talchir Formation of the juxtaposed Indian Mahanadi Graben (e.g. Veevers & Tewari 1995). Considerably higher average annual temperatures, in excess of 15°C, are thought to have prevailed during the Permo-Triassic when dense vegetation provided the base for formation of the coal measures in the northern Prince Charles Mountains (Cantrill *et al.* 1995). A similarly significant climatic change has been proposed since the Cretaceous. Depending on the specific palaeo-position with respect to geographic latitude and vicinity to the coast, and on the method and model used, Cretaceous surface temperatures are predicted to have been ~10°C higher than the present day values at the margin of Antarctica, and as much as 27°C (winter) to 47°C (summer) higher in central Antarctica (Barron *et al.* 1994). Hence, although the present day annual mean temperature of the Vestfold Hills is -10°C (Streten 1986), it appears reasonable to use an average ("constant") palaeo-surface temperature of ~10°C for modelling the thermal histories of the apatite FT samples from the Vestfold Hills since ~500 Ma.

### *Thermal history results for individual samples*

An excellent yield of apatites in all samples, and a high quality of all apatite grains analysed implies that the measured FT ages and lengths are of high precision, and that the thermal history solutions presented here are reliable. Adopting a constant palaeo-surface temperature of 10°C and a "stratigraphic age" > 500 Ma (as initial conditions of the model), the apatite FT parameters clearly require thermal history solutions which include the following key palaeo-temperature results (Table I):

Sample GC685-1 dropped below ~125°C some time in the period from 290 to 220 Ma. The sample probably remained at peak palaeotemperatures < 65°C throughout most of the last 220 Ma.

Sample GC685-2 dropped below ~105°C some time in the period from 295 to 210 Ma, and has remained < 105°C to the present-day. The sample probably began further cooling from temperatures in the range of 40° to 65°C some time between 200 and 10 Ma (tentative constraint).

Sample GC685-3 dropped below ~105°C some time in the period from 305 to 205 Ma, and has remained < 105°C to the present-day. The sample probably began further cooling from temperatures in the range of 35° to 55°C, commencing some time between 200 Ma and the present-day (tentative constraint).

Sample GC685-4 cooled through ~110°C some time between 250 and 160 Ma, and has remained < 110°C to the present-day. The sample probably began further cooling from temperatures in the range of 40° to 65°C some time within the last 110 Ma (tentative constraint).

Sample GC685-6 cooled through ~110°C some time between 240 and 170 Ma, and has remained < 110°C to the present-day. The sample probably began further cooling from temperatures in the range of 40° to 55°C some time within the last 55 Ma (tentative constraint).

### *Thermal history reconstruction*

Combining the results in all five apatite FT samples suggests that one, perhaps two, cooling events affected the 6 km transect in the Vestfold Hills. Assuming the events were regionally synchronous, the overlap of the timing constraints from all five samples indicates that the common time of the initial phase of cooling through respective threshold temperatures was some time between 240 and 220 Ma (Triassic), while common timing for onset of the later cooling pulse is some time between 55 and 10 Ma (Fig. 5). Inclusion of this second cooling event provides an improved fit to the FT data in all samples (compared with a one event-only model), but evidence for the second event is only tentative (i.e. allowed, but not directly required, by the FT data).

Note that onset of the second cooling episode is alternatively allowed to be as early as ~110 Ma (common timing) for all samples except GC685-6. That is, if the sample GC685-6 results were ignored, onset of the second cooling event could instead be “Late Cretaceous”, say any time between 110 and 65 Ma (Fig. 5).

Importantly, FT analysis only constrains cooling paths - more particularly the time of cooling - and cannot be used to model the approach to maximum palaeotemperatures. Therefore, the lead-up to peak palaeotemperatures in the “Tertiary” (or Late Cretaceous?) palaeo-thermal event is unconstrained by the FT results. We have arbitrarily chosen to reconstruct re-heating prior to Tertiary or Late Cretaceous cooling (Fig. 5), but simple continuation of cooling following protracted cooling from the Triassic event can equally be reconstructed from the thermal history constraints. Alternatively (as mentioned above) no second, “Tertiary” (or Late Cretaceous) event is actually required by the FT data - or both of these events may have occurred - within the resolution of the available data.

## Discussion

### *Late Palaeozoic Lambert rifting*

Previous thinking designates the Pan African Orogeny (around ~500 Ma) as the last major tectonic and metamorphic event to affect the basement of the East Antarctic craton in the Prydz Bay region, and that this was probably accompanied by increased basal heat flow and exhumation of the East Antarctic shield (e.g. Stüwe & Sandiford 1993, Kelsey *et al*. 2003). In the Vestfold Hills, the principal effect of this event is recorded in biotite and muscovite Rb–Sr mineral ages (604–555 Ma) and mafic dykes (~500 Ma) (Collerson & Sheraton 1986). Until now, no later igneous activity has been formally recorded despite the existence of several varieties of potentially younger alkaline dykes of unknown age and genetic relationships (Fig. 2).

New work presented here provides substantial evidence for significant Triassic (or earlier) cooling of basement rocks in the Vestfold Hills. Our thermal history modelling results clearly indicate that all samples along the study transect cooled through threshold temperatures of ~125°C to ~105°C commencing between ~240 and ~220 Ma. Using an estimated mean surface temperature of 10°C (as assumed for this study) at least 115°C of total cooling has occurred within the last 240–220 Ma, and although the exact cooling path is unconstrained by apatite FT analysis, at least 60°C of cooling from at least ~125° to ~65°C is probably confined to late Palaeozoic to early Cretaceous times (Fig. 5). Furthermore, the degree of cooling since the early Palaeozoic could have been as much as ~150°C referring to the difference between an upper temperature limit of 160°C as indicated by the $^{40}$Ar/$^{39}$Ar K-feldspar plateau at ~450 Ma for samples from the neighbouring Larsemann Hills (Zhao *et al.* 1997), and a surface temperature of 10°C (or even more for lower present-day surface temperature).

In general, late Palaeozoic to early Cretaceous cooling observed by FT analysis may have been caused by either the decay of heat added to the upper crust following dyke emplacement and/or denudation. However, radiometric dating and according field relations indicate that the various igneous dykes cropping out within the Vestfold Hills exclusively are of Precambrian age (see above), and there is no evidence of any later hydrothermal or significant tectonic activity. Instead, the Phanerozoic development of the Vestfold Hills can only be understood when correlating the thermal history obtained in this study with offshore stratigraphic information. Drill cores recovered from ODP Legs 119 and 188 combined with geophysical data reveal that the basement of the adjacent eastern Prydz Bay is unconformably overlain by several kilometres of pre-Cenozoic and Cenozoic sediments (Barron *et al.* 1991, O’Brien *et al.* 2001). The pre-Cenozoic sediments comprise a 2–3 km thick lower red bed unit (Turner 1991: Permo-Triassic?), and a similarly thick upper coal-bearing sequence of Aptian age. Turner (1991) interprets the Palaeozoic red bed sediments as deposits of floodplains in an actively subsiding basin where rapid uplift, erosion, and deposition preserved their immature composition. Even if subsequent extension of the Prydz Bay does not allow to calculate a sediment budget for the Palaeozoic denudation/deposition stage, the geologic evidence within the Prydz Bay is an excellent match in timing and magnitude, for at least 60°C of cooling within late Palaeozoic to early

Cretaceous times observed in the Vestfold Hills (surface samples recording minimum cooling from ~125° down to ~65°C). For any geologically reasonable geothermal gradient, kilometre scale denudation is implied by the FT results in this study.

The close spatial vicinity, and similarity in the timing and style of late Palaeozoic denudation/ deposition noted at the Lambert Graben (Lisker *et al.* 2003), the Vestfold Hills (this study), and within Prydz Bay (Fig. 1) suggest that the Lambert Graben and the north-western area of Princess Elisabeth Land may have been part of a single denudational system, at least operating during the late Palaeozoic to Triassic. This suggests either that the Vestfold Hills formed the margin of a flat eastern flank of a Palaeozoic Lambert Graben, or implies the existence of a more diversified rift system similar to the present Basin and Range province. Rifting and late Mesozoic regional uplift maybe related to plume incubation prior to magmatic outpourings in the form of flood basalts as suggested by Kent (1991) or Vaughan & Livermore (2005).

### *Passive margin development since the Cretaceous*

Our apatite FT modelling results allow (but do not directly require) final cooling of the Vestfold Hills samples from palaeotemperatures of ~65°C or less, to surface temperature, commencing some time between ~55 and 10 Ma, or alternatively, commencing some time between ~110 and 55 Ma, if the results from sample GC685-6 are excluded.

The sediment record of Prydz Bay implies that a Cretaceous/Cenozoic denudation phase indeed occurred, producing sedimentary deposits with a total thickness of up to almost 5 km from the Cretaceous onwards. A 2–3 km thick Aptian sequence has been deposited in swampy, vegetated floodplains or low-sinuosity fluvial channels (Turner & Padley 1991). Superimposed Cenozoic sediments vary in thickness between a couple of hundred metres in the vicinity of the coast, and up to 2 km towards the interior of Prydz Bay. They are constituted by three major sequences composed chiefly of diamictites with stratigraphical ages between middle Eocene–Oligocene (lowermost sequence) and late Miocene, Pliocene, and Pleistocene (upper sequence), in places overlain by Holocene siliceous muddy ooze (Barron *et al.* 1991, O'Brien *et al.* 2001).

So again, for any reasonable geothermal gradient value used, kilometre scale denudation is probable, based on total cooling by up to 55°C, which would be allowed by the FT data for event(s) at this time. Cretaceous–Cenozoic denudation of the Vestfold Hills may have provided a major contribution to the Cenozoic sedimentary fill of the Prydz Bay. Such conclusion is supported by the presence of an extensive Palaeocene erosion surface across Mac.Robertson Land (Wellmann & Tingey 1981) and the lack of "significant Cenozoic erosion" of the interior of the juxtaposed Indian Mahanadi area (Lisker & Fachmann 2001), excluding these cratonic areas as main sources for the Cretaceous and Cenozoic deposits within Prydz Bay. Therefore, the bulk of the Prydz Bay sediments must have been derived from the immediate vicinity of the passive continental margin(s), including the Vestfold Hills, and from the interior of the Lambert Graben.

A conservative estimate of maximum Cretaceous –Cenozoic denudation obtained when adopting a low post-Early Cretaceous geothermal gradient of ~20°C km$^{-1}$, as determined uniformly for the East Antarctic craton of Mac.Robertson Land (Lisker *et al.* 2003) and for the juxtaposed Singhbhum Craton (eastern India), does not exceed an order of 3 km. This estimate, the sedimentary record of the Prydz Bay and morphological evidence concordantly show that denudation associated with passive margin formation in the eastern Prydz Bay was of lesser magnitude than the coeval rifting-related denudation across the nearby Lambert Graben (up to > 4 km: Arne 1994, Lisker *et al.* 2003), and less than the break-up-related denudation on the high standing passive East Antarctic margin of Dronning Maud Land (up to > 5 km: Jacobs & Lisker 1999, Meier 1999). Instead, denudation estimates in the Vestfold Hills transect bears a close similarity with the slow and meagre denudation of the low-standing margin segments of the East Antarctic craton between Mac.Robertson Land and Oates Land which show little evidence of Cretaceous cooling, as suggested by congruent apatite FT results reported by Arne *et al.* (1993), Lisker (2002) and Lisker & Olesch (2003).

## Conclusions

1. Apatite FT analysis results from Vestfold Hills samples are consistent with the proposal that initial rifting of the Lambert Graben was associated with cooling/ denudation occurring in the Late Palaeozoic.
2. FT results (this study) are consistent with the observation of significant thicknesses (2–3 km) of Permo-Triassic(?) sediments deposited in Prydz Bay, and reveal firm evidence to suggest that the likely thermal history of the provenance area of these sediments includes cooling through ~125°C, between 240 and 220 Ma (Triassic). The degree of cooling revealed by the FT results (at least 60°C of cooling: ~125°C down to ~65°C) suggests kilometre scale exhumation some time prior to the early Cretaceous (possibly all within the Triassic), for any reasonable value of assumed palaeo-geothermal gradient.
3. Thick sequences (2–3 km) of Aptian age sediments are deposited in Prydz Bay and seem likely to be associated with Cretaceous Gondwana break-up between Antarctica and India. Also, middle Eocene to Pleistocene age sediments (varying from several

hundred metres to two kilometres in the depocentre) are deposited in Prydz Bay, consistent with Cenozoic passive margin development. This geologic record (and implied coincident denudation in the provenance area) is again entirely in agreement with FT results in this study. Our results allow (but do not directly require), total cooling of at least ~55°C (from ~65°C down to surface of 10°C, or less) commencing some time between ~55 and 10 Ma, or alternatively between ~110 and 55 Ma (excluding results from sample GC685-6). Two separate cooling events may have occurred between ~110 and 10 Ma, but resolution of this fact, or differentiation of the degrees of cooling in each phase, is not possible from the currently available FT data.

4. The long-term landscape evolution of the Vestfold Hills since Cretaceous Gondwana break-up does not display any feedback effect of the coeval, second rifting stage of the Lambert Graben. Instead, it merely represents the development of a low-standing passive margin, as elsewhere observed at the East Antarctic Craton, between eastern Dronning Maud Land and Oates Land.

5. Higher standing margins (and therewith significantly larger amounts of post-Cretaceous denudation) compared with the Vestfold Hills, are known only from the West Antarctic rims of the craton, at Dronning Maud Land and northern Victoria Land. Such variation in amount and style of denudation, and in the rheological behaviour of the crust very likely results from fundamentally differences in vector and speed of the extension between the various Gondwana fragments.

6. We further suggest that slow rotation and extension between India/Australia and Antarctica, as interpreted here for the Vestfold Hills, seem to have produced only a relatively minor denudational response, compared to fast crustal rupture and significant denudation observed in the vicinities of Dronning Maud Land and northern Victoria Land (Lisker 2002).

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