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A fission track thermochronological study of King George and Livingston islands, South Shetland Islands (West Antarctica)

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Abstract: This paper reports the dating of apatite fission tracks in eleven rock samples from the South Shetland Archipelago, an island arc located to the north-west of the Antarctic Peninsula. Apatites from Livingston Island were dated as belonging to the Oligocene (25.8 Ma: metasediments, Miers Bluff Formation, Hurd Peninsula) through to the Miocene (18.8 Ma: tonalites, Barnard Point). Those from King George Island were slightly older, belonging to the Early Oligocene (32.5 Ma: granodiorites, Barton Peninsula). Towards the back-arc basin (Bransfield Basin), the apatite appears to be younger. This allows an opening rate of approximately 1.1 km Ma^{-1} (during the Miocene–Oligocene interval) to be calculated for Bransfield Basin. Optimization of the apatite data suggests cooling to 100 ± 10ºC was coeval with the end of the main magmatic event in the South Shetland Arc (Oligocene), and indicates slightly different tectonic-exhumation histories for the different tectonic blocks.

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Introduction

The South Shetland Archipelago lies to the north-west of the Antarctic Peninsula, between Drake Passage and Bransfield Strait (Fig. 1). These islands belong to a volcanic arc associated with subduction below the northern end of the Antarctic Peninsula continental margin during the Mesozoic and Cenozoic, which allowed convergence between the Phoenix and Antarctic plates (for detailed reviews of the region's development see Barker 1982, 2001, Dalziel 1984, Barker *et al.* 1991, Larter & Barker 1991, Livermore *et al.* 2000, Larter *et al.* 2002). Convergence along this tectonic margin appears to have ended 4 Ma ago when the spreading centre of the Phoenix Plate (the Aluk Ridge) became inactive (magnetic chron C2A, 3.3 ± 0.2 Ma: Livermore *et al.* 2000). Roll-back and migration of the subduction zone to the northwest produced the opening of a back-arc basin, Bransfield Basin. Inside this narrow basin an incipient central spreading ridge developed, marked by several Quaternary submarine and subaerial volcanic edifices (e.g. the Deception, Bridgeman and Penguin islands). Earthquake focal mechanism data (Giner-Robles *et al.* 2003) as well as geodetic (Dietrich *et al.* 2001) and fault palaeostress analyses (Gonzalez-Casado *et al.* 2000) suggest that Bransfield Basin opening is associated with two coeval tectonic processes – a sinistral simple-shear couple between the Scotia and the Antarctic plates, and Phoenix plate roll-back.

The islands of this archipelago are mainly composed of

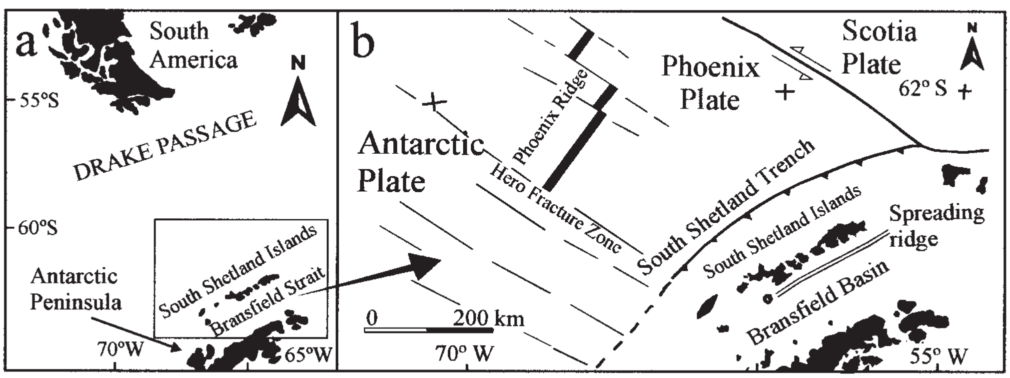

Fig. 1. The northern Antarctic Peninsula and South Shetland Islands, **a.** geographical setting, **b.** tectonic setting.

Cretaceous to Tertiary calc–alkaline volcanic and plutonic rocks (130 to 20 Ma; Willan & Kelley 1999) which intruded a probably Permo–Triassic basement of sedimentary and low grade metamorphic rocks (Smellie & Millar 1995, Willan *et al.* 1994). These metasedimentary rocks belong to the basement of the Antarctic Peninsula, traditionally considered to be a magmatic arc that records Mesozoic–Cenozoic episodes of deformation, magmatic intrusions and metamorphism associated with the subduction of the palaeo-Pacific plate (Phoenix Plate). New geological evidence suggests, however, that some Antarctic Peninsula segments may represent suspect terranes (Vaughan & Storey 2000) that probably docked during the Cretaceous (Vaughan *et al.* 2002a, 2002b).

Apatite fission track (FT) analysis was performed to investigate the denudation and cooling history (T–t) below 120ºC of the metamorphic basement and plutonic rocks of the South Shetland Islands. Apatite grains for fission track analysis were obtained from the metasediments and granites cropping out on two islands in the central part of the archipelago. Two distinct lithologies were sampled on Livingston Island. The first comprised sediments of the Miers Bluff Formation on the Hurd Peninsula (> 1600 m of feldspar greywackes, shales, arkosic arenites, siltstones and minor conglomerates; Smellie *et al.* 1984). These sediments are affected by advanced diagenesis, and in some cases by incipient metamorphism (Arche *et al.* 1992, Tokarski *et al.* 1997). The Miers Bluff Formation is thought to be analogous to the Trinity Peninsula Group (Antarctic Peninsula) and the Greywacke-Shale Formation (South Orkney Islands). Despite some uncertainty, its age is generally accepted as early Triassic–Permian (Thomson

Table I. Apatite fission track analytical data.

Location Sample	N	ρ_f 10^5 t cm^{-2} (N_f)	ρ_i 10^5 t cm^{-2} (N_i)	Dispersion P(χ^2) %	Dispersion s.e. %	ρ_m 10^5 t cm^{-2} (N_m)	FT Age t ± 1σ Ma	L ± 1σ µm
Barton Peninsula HA-8	32	8.07 (239)	2.95 (875)	> 99	< 1	7.460 (17265)	31.8 ± 2.6	13.41 ± 1.76
	6	1.45 (53)	4.27 (156)	98	< 1	7.460 (17265)	36.0 ± 5.7	
							32.5 ± 2.4 (average)	
Hurd Peninsula HA-17	22	4.65 (622)	1.07 (1435)	81	< 1	3.767 (9964)	27.5 ± 1.4	13.11 ± 1.7
Barnard Point HA-18	49	6.82 (283)	2.18 (904)	> 99	< 1	3.767 (9964)	19.6 ± 1.1	- - - -
Barnard Point HA-19	42	6.89 (245)	2.55 (908)	> 99	< 1	3.767 (9964)	16.9 ± 1.0	11.99 ± 2.11
Barnard Point HA-20	36	1.14 (347)	3.15 (960)	> 99	< 1	3.767 (9964)	22.6 ± 1.2	12.21 ± 1.77
Barnard Point HA-21	45	7.82 (298)	3.03 (1155)	> 95	< 1	3.767 (9964)	16.2 ± 1.0	- - - -
Hurd Peninsula HA-2425	40	1.89 (639)	4.63 (1566)	31	11	3.767 (9964)	25.6 ± 0.9	14.27 ± 1.30
	34	0.722 (746)	1.78 (1834)	14	15	3.767 (9964)	26.2 ± 1.0*	
							25.9 ± 0.7 (average)	
Hurd Peninsula HA-26	26	5.15 (815)	1.16 (1835)	52		3.767 (9964)	28.2 ± 1.3	13.00 ± 1.93
Hurd Peninsula HA-27	28	3.22 (510)	7.91 (1251)	82		3.767 (9964)	25.9 ± 1.4	13.07 ± 1.69
Hurd Peninsula (Binn Point) HA-32	23	2.74 (384)	1.02 (1427)	32		3.767 (9964)	17.1 ± 1.0	12.74 ± 1.99
Hurd Peninsula (Binn Point) HA-33	25	5.07 (1054)	1.08 (2237)	42		3.767 (9964)	30.4 ± 1.2	13.64 ± 1.25

N = number of grains dated, ρf = fossil track density, Nf = number of fossil tracks counted, ρi = induced track density, Ni = number of induced tracks counted, ρ(χ^2) = Galbraith Chi squared probability (1981), s.e. = standard error of the central age, ρm = standard track density, Nm = standard number of tracks, FT = apatite fission track age, L = mean value and standard deviation of the confined track length distribution.

1992, Willan *et al.* 1994). The second lithology sampled was the Barnard Point granite intrusion on the southern margin of False Bay. This Late Eocene granite (Willan & Kelley 1999) is one of the magmatic arc intrusions generated by the subduction process (Andean plutons, 130 to 20 Ma, Willan & Kelley 1999). On King George Island, only Late Eocene diorites and granodiorites from the Barton Peninsula were sampled. These granites intruded a complex suite of volcanic and volcano-sedimentary rocks with ages ranging from Palaeocene to Cretaceous (Smellie *et al.* 1984).

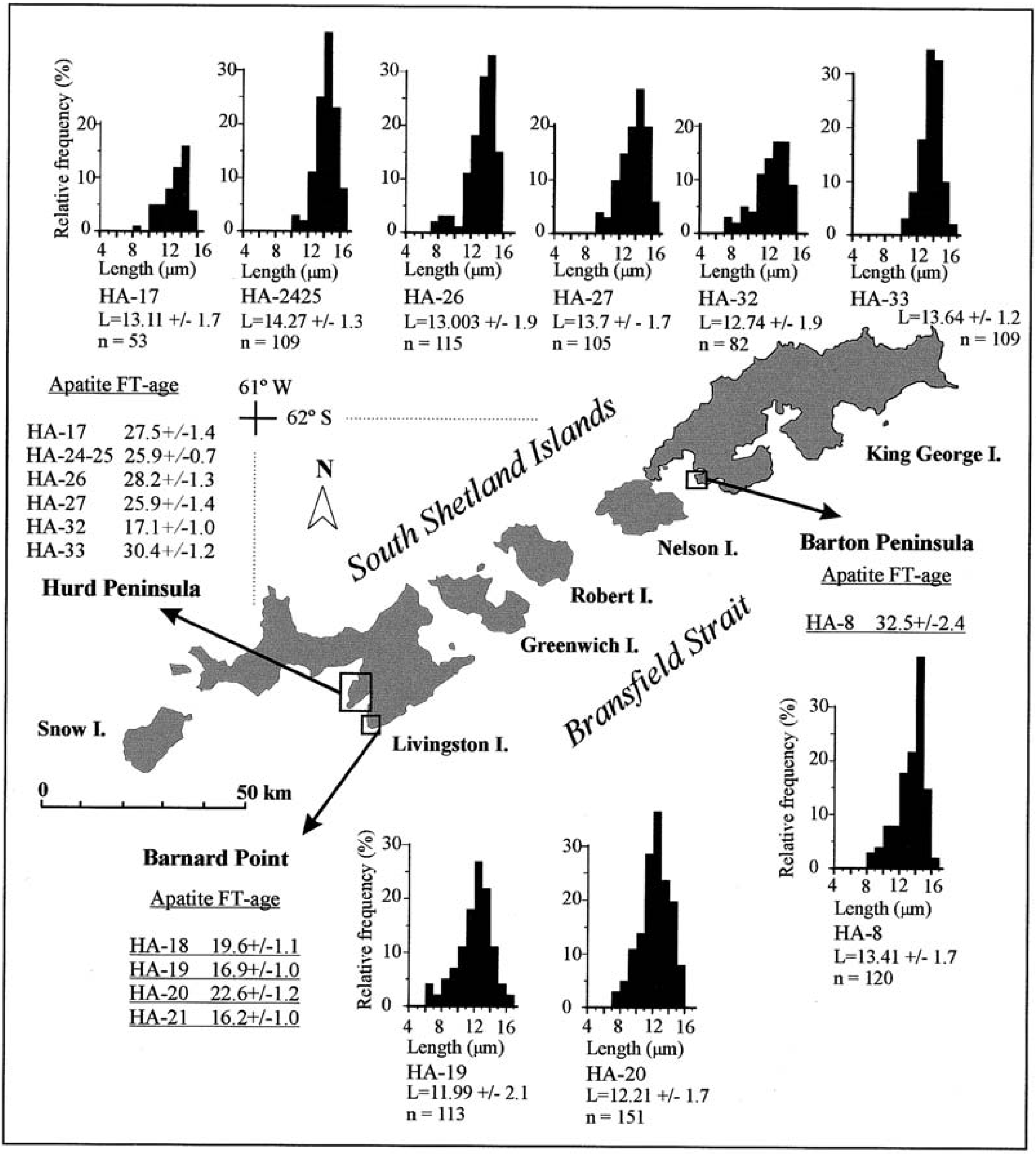

Fig. 2. Apatite fission track ages (Ma ± 1σ) determined in samples from Livingston (Barnard Point and Hurd Peninsula) and King George Islands (Barton Peninsula). Histograms of confined track length distributions are also shown.

Analytical procedures

Apatites in the 80–160 µm range were obtained by conventional separation methods including crushing, the use of heavy liquids, and magnetic separation. Apatite grains were prepared for fission track dating by the external detector method (Hurford & Carter 1991) using the zeta technique (Fleischer & Hart 1972). Mounted grains were irradiated in the Orphée nuclear reactor at the "Centre d'Etudes Nucléaires", Saclay, France. Two to three neutron dosimeters (NIST glass wafers) were irradiated with the samples each time to take into account possible flux gradients in the irradiation rabbit (a polyethylene capsule). External detectors (kapton foils) were fixed on each side of the wafers. Tracks were etched with a HNO_3 molar solution at 20°C for 30–60 s for dating, and for 50–80 s for track length measurements and in kapton within a boiling solution of potassium hypochlorite. At least 2500 induced tracks were counted by each detector. All observations were made with 100x oil objective and 10x eyepiece lenses. Eleven samples were dated (Fig. 2, Table I).

Results

Zone I, Miers Bluff metasediments from the Hurd Peninsula (Livingston Island)

The studied materials were medium to fine-grained detrital Miers Bluff metasediments. The samples were collected from six locations on Hurd Peninsula (Fig. 2) at altitudes of 30–50 m. The apatite grains obtained from these metasediments are slightly rounded due to abrasion during transport, which is consistent with their detrital origin. They are also characterized by large variations in size and low transparency. They are thought to come from the same source area as the Miers Bluff materials, a continental margin essentially formed by metamorphic and magmatic rocks (Smellie 1991, Arche *et al.* 1992, Marfil *et al.* 1994, Tokarski *et al.* 1997). The U–Pb age of detrital euhedral zircons from the Miers Bluff formation and Trinity Peninsula Group rocks (*c.* 320 Ma) probably represents the crystallization age of the source granitoids (Loske *et al.* 1988, Hervé *et al.* 1991). Therefore, the apatite crystallization age would also be close to 320 Ma. Post-depositional development in Miers Bluff materials have been studied by illite crystallinity (Arche *et al.* 1992, Tokarski *et al.* 1997). These observation, plus those of Smellie (1991), Kelm & Hervé (1994) and Willan *et al.* (1994) allow the conclusion that the Miers Bluff sediments were affected by advanced diagenesis or anchimetamorphism. This thermal episode has been tentatively dated as Late Triassic–Early Jurassic (Thomson 1992). Thus, these rocks reached the apatite annealing temperature (> 100ºC), and the apatite fission track record is probably associated with post-anchimetamorphism thermal changes.

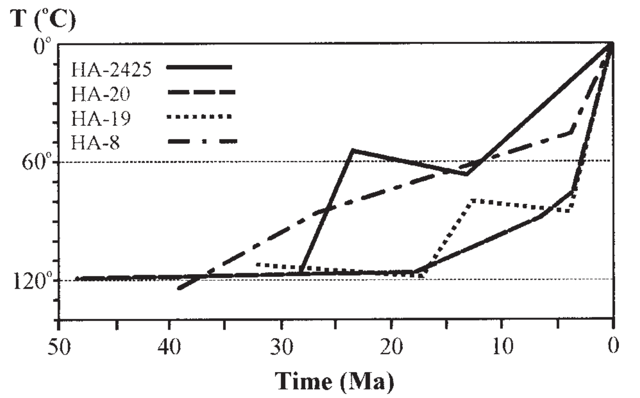

Fig. 3. T–t trajectories for samples from Barnard Point (HA19 & HA20), Hurd Peninsula (HA2425) and Barton Peninsula (HA-8) after Monte-Trax modelling.

Dispersion tests such as the Galbraith χ^2 test (Galbraith 1981) and the standard error of the "central ages" (Galbraith & Laslett 1993) showed that, in each sample, only one age population exists among the dated grains. The ages obtained for six samples are in the 31–26 Ma range, and the mean confined track length 13 < L < 14.3 µm (standard deviations 1.2 < σ < 1.9 µm) (Fig. 2, Table I). This suggests rapid cooling through the partial annealing zone. The optimization of sample HA-2425 data by the Monte Trax algorithm (Gallagher 1995) shows that track registration began *c.* 28 Ma and was followed by a two-stages cooling history. The first stage occurred between ~28 Ma and 23 Ma through the > 115 to ~50°C temperature range. After a slight reheating (~60–70°C) at 13 ± 2 Ma, the second cooling stage lasted from this time to present (Fig. 3). The recent exhumation of the Hurd Peninsula therefore probably began around 13 Ma ago.

One sample (HA32), which presents a shorter mean confined track length of 12.7 µm and a significantly younger age of 17 Ma, may have had a different cooling history, possibly linked to local hydrothermal activity or fault-related heating.

Zone II, the Barnard Point intrusion (Livingston Island)

The Barnard Point pluton was sampled at four points close to the Bransfield Basin margin (Fig. 2) at altitudes from 5–390 m. The apatite grains from this region show a prismatic shape suggesting a magmatic origin. They are homogeneous in size and highly transparent. Their crystallization age is thought to be comparable to that of the Barnard Point tonalite intrusion, i.e. 40.9 ± 2.7 Ma (Willan & Kelley 1999). The apatite fission track ages obtained in the present work range from 16.2–22.6 Ma. Since the analysed vertical section comprises only a few hundred metres (< 400 m), a positive relationship between the apatite fission track age and elevation cannot be affirmed (Sell *et al.* 2000). The mean confined fission track lengths varied from 11.9–12.2 µm (Fig. 2, Table I). Optimization of the fission track data using the Monte Trax algorithm of Gallagher (1995), using the Laslett *et al.* (1987) track stability model for Durango apatite algorithm (Fig. 3), suggests continuous cooling took place throughout the 110–60ºC interval between 40–35 and 10–13 Ma ago. A second cooling step would have begun in the Miocene (*c.* 6–4 Ma).

Zone III, Barton Peninsula intrusion (King George Island)

The diorites and granodiorites of the Barton Peninsula intrusion were only sampled at one location at an altitude of 40 m (Fig. 2). Their apatites show morphologies similar to those of the Barnard Point granite, again suggesting a magmatic origin. Crystallization is assumed to have occurred around the time it took place in the Barton intrusions, i.e. 46 ± 1 Ma (K–Ar biotite age; Pankhurst & Smellie 1983). The apatites showed an age of 32.5 Ma (the older of the samples studied) and a mean fission track length of 13.4 µm. Modelling of their thermal history (Fig. 3) shows the beginning of the track record 40 Ma ago and a continuous cooling from 110–46ºC between 40–4 Ma ago. A second step that began in the Miocene (*c.* 4 Ma) can also be deduced. Other apatite fission track age data from the same area (Thomson *et al.* 2001) are quite different (46.1 ± 6.5 to 44.5 ± 4.5 Ma) and difficult to interpret since they are very similar in age to the granodiorite intrusion.

Discussion

The crystallization of the detrital apatite grains of the Miers Bluff Formation probably occurred during the Carboniferous. However, the apparent apatite FT data, as well as the optimized data, show that the last cooling below 120°C occurred at the beginning of the Oligocene. This gives a lower limit to the low-grade metamorphic event of previously unknown age, which affected the Miers Bluff Formation. The beginning of FT recording at around 30 Ma (as obtained by data optimization) coincides approximately with the end of the magmatic intrusion period in the South Shetland magmatic arc (130–20 Ma, Willan & Kelley 1999), and with the age of the younger magmatic dykes dated on Hurd Peninsula (Zheng *et al.* 2003). It may therefore be a thermal anomaly associated with the plutonic intrusions that produced the anchimetamorphism and sporadic epimetamorphism of the Miers Bluff metasediments. The alternative hypothesis that the *c.* 3 km of sedimentary cover was eroded (starting at 30 Ma) can be rejected since these rocks have experienced continuous uplift (accretionary prism). In addition, hydrothermal episodes of vein formation, probably coeval with the thermal anomaly, attest to palaeodepths of around 1–2 km (Willan 1994).

On Livingston Island, the Barnard Point intrusion shows Rb–Sr and K–Ar (whole rock and mineral) ages in the 46–40 Ma range. Confined track distribution and optimization of the data (Figs 2 & 3) indicate that track recording started about 27–28 Ma ago, coinciding with the $^{40}Ar/^{39}Ar$ 29.3 ± 0.7 Ma for the biotites of a pegmatitic dyke inside the Barnard Point intrusion (Willan & Kelley 1999). This suggests a mid-Oligocene cooling from > 300ºC to < 120ºC in a few million years. The T–t paths of Fig. 3 suggest also late Oligocene acceleration of the cooling rate, contemporaneous with an extensional tectonic episode and the intrusion of magmatic rocks (dykes and sills, Willan & Kelley 1999). A second episode of fast cooling (up to 80ºC in 5–4 Ma) is also recorded from the mid-Miocene to the present. T–t path models for the Barnard and Hurd peninsulas show some differences (Fig. 3), suggesting tectonic-denudation evolutions were different and that major tectonic structures may separate the peninsulas (González-Casado *et al.* 1999). Recent (< 1 Ma) Bransfield rift volcanism is not apparently recorded in the apatite fission tracks in the basin margin, i.e. at Barnard Point.

Though the Barton Peninsula granite of King George Island may have a different cooling history (< 120°C) to that of Barnard Point, the first fission tracks were recorded at about the same time: *c.* 32 Ma ago, when a continental separation episode took place in the Northern Antarctic Peninsula region (Ashcroft 1972, Barker 1982, Dalziel 1984, Smellie *et al.* 1984). The overall data suggest that this was accompanied by efficient denudation up to about 20–30 Ma ago, coeval with an extensional tectonic episode accompanied by the injection of basic dykes and sills.

Nevertheless, a rough linear correlation exists between apparent apatite age and the distance of samples from the Bransfield Basin ridge (Fig. 4). This allows one to calculate

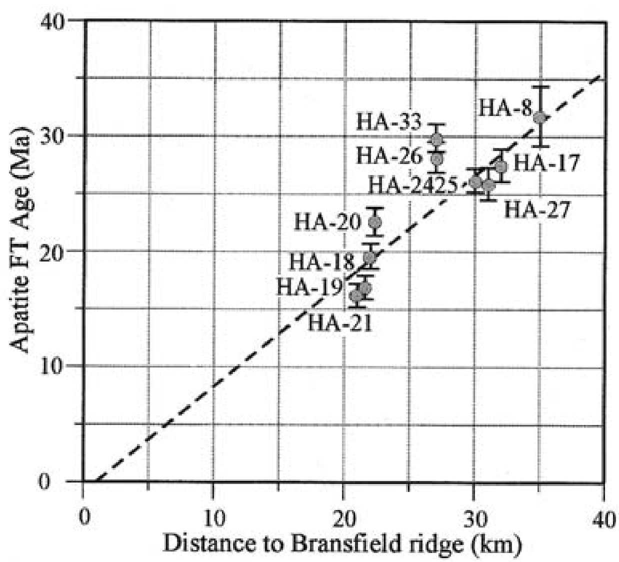

Fig. 4. Relationship between apparent apatite fission track ages (Ma ± 1σ) and distance to the Bransfield opening ridge.

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the migration of the 120ºC isotherm towards the basin edge at 1.1 km Ma^{-1}, and to estimate that this process began (approximately) during the early Miocene. This is coincident with the end of volcanic activity in the arc (lava, dykes, sills and stocks intrusions; Willan & Kelley 1999) and probably also correlates with the end of the rapid subduction of the Phoenix Plate. The linear relationship between fission track age and the distance to the basin edge suggests the process may still be active.

Conclusions

The end of the thermal event associated with the beginning of the apatite fission track record is almost synchronous in the three areas studied. Given that today these zones are geographically relatively far apart, and since the Bransfield Strait opened relatively recently, it is suggested that the beginning of fission track preservation is approximately coeval with the end of the last plutonic pulse (Oligocene). This thermal event probably also produced the anchimetamorphism processes reflected in the Miers Bluff sediments.

The confined track length distributions are different in the three areas considered, with mean values ranging from 11.9–14.3 µm. This means that after ~40 Ma, their cooling histories are somewhat different, as confirmed by optimization of the fission track data (Fig. 3). Since all samples were collected at low altitudes (< 400 m), their distinct cooling paths probably reflect slightly different tectonic and exhumation histories for the different tectonic blocks.

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