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Apatite Fission Track Ages Associated with the Altered Igneous Intrusive in Beacon Sandstone near the Base of CRP-3, Victoria Land Basin, Antarctica

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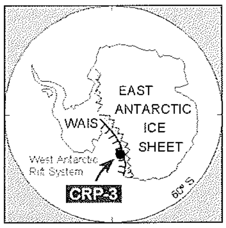

Abstract - The Cape Roberts drillhole 3 (CRP-3) on the western edge of the Victoria Land Basin, Antarctica cored through a highly altered igneous intrusion intruded into Paleozoic sedimentary basement. This intrusion was regarded as highly enigmatic as its origin could represent volcanism associated with early rifting of the Victoria Land Basin, later renewed rifting within the Terror rift, or Jurassic tholeiitic magmatism. Direct methods to date the intrusion by U-Pb dating of zircon or fission track analysis failed due to insufficient quantities of these minerals. Apatite fission track (AFT) analysis on the adjacent sedimentary basement, the Devonian Beacon Supergroup sandstone, yielded an age of 101 ±6 Ma and a mean track length of 12.3 µm with a 1.9 µm standard deviation. The fission tracks were not annealed in the Cenozoic and thus the intrusion must be older than this. This observation, plus trace element chemistry of the intrusion suggest it is most likely the same age and original composition as the middle Jurassic sills and dykes of the Transantarctic Mountains. The AFT age is similar to the onshore regional AFT stratigraphy and reflects complete thermal overprinting in the Jurassic, residence in an apatite partial annealing zone, followed by exhumation in the early Cenozoic and down-faulting at least 3 km to its present position. However, the sample of Beacon sandstone has an AFT age "too young" and a confined track length distribution "too short" relative to the results a sample from an onland equivalent stratigraphic position should yield in the simplest scenario. This is possibly due to the position of the CRP-3 basement on the western edge of the West Antarctic rift system, where it underwent periods of rifting and elevated thermal gradients in the Jurassic, Cretaceous, Eocene and Oligocene causing annealing of the sample. Alternatively, this sample reflects a more complex thermal history involving Cretaceous as well as Cenozoic denudation, prior to being down faulted to its present position.

INTRODUCTION

Cape Roberts drill-hole 3 (CRP-3) was the third of three holes drilled off Cape Roberts on the western edge of the Victoria Land Basin (Fig. 1). The scientific objectives of the Cape Roberts drilling included: (1) investigation of the history of the East Antarctic Ice Sheet and the climate record associated with ice sheet inception at *c.* 34 Ma, (2) constraining the early history of the West Antarctic rift system and uplift of the Transantarctic Mountains (TAM). These objectives, the geological setting and the results of CRP-3 are well discussed in previous papers (Barrett et al., 1995) and initial reports from earlier drill-holes (Cape Roberts Science Team, 1998, 1999, 2000). For this paper, it is sufficient to say only that CRP-3 lies on the Roberts Ridge on the edge of the Victoria Land Basin and is separated from the uplifted TAM, to the west, by the Transantarctic Mountains Front (TMF), a zone of steeply dipping normal faults.

CRP-3 drilled through Early Oligocene to Late Eocene (*c.* 34 Ma) glacial sediments that represent a cold polar climate (Cape Roberts Science Team, 2000). The transition to a warmer pre-ice sheet climate was not found. Near the base of CRP-3 the sediments are cut by a (steeply dipping?) shear zone. Just below this shear zone, glacial sediments sit unconformably on well-cemented quartz sandstone belonging to the Beacon Supergroup (Fig. 2). The quartzose composition and rounded grains are characteristic of several formations in the lower (Devonian) part of the Beacon Supergroup, and of these the Arena Sandstone was considered most likely correlative (Cape Roberts Science Team, 2000). However further sampling has shown a higher proportion of feldspar than is typical of the Arena Sandstone, and present judgement is that the sandstone is from lower in the section and is best described stratigraphically as "lower Taylor Group". Further work is being carried out for a better judgement on the stratigraphic equivalence of this sandstone with onshore stratigraphy (P.J. Barrett, personal communication).

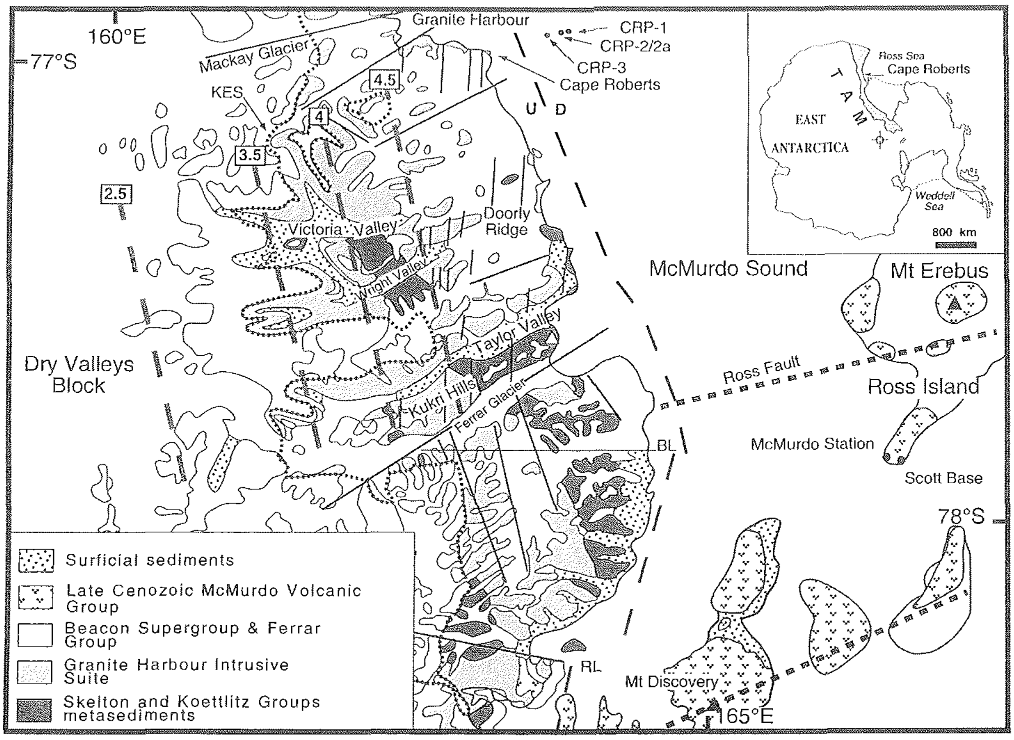

Fig. 1 - Generalized geological map of southern Victoria Land. Modified from (Fitzgerald, 2001). Geology and location of faults and lineaments is after Gunn and Warren (1962), Warren (1969), McKelvey and Webb (1962), Findlay et al. (1984), Gleadow and Fitzgerald (1987), Fitzgerald (1992) and Wilson (1995, 1999). Offshore faults are from McGinnis et al. (1985), Damaske et al. (1994), Barrett et al. (1995). Approximate Cenozoic «rock uplift» contours (marked by black dashed lines with rock uplift amount in km from 4.5 to 2.5) for the Dry Valleys block are modified from Fitzgerald (1992). KES = Kukri erosion surface. RL = Radian lineament. BL = Blue lineament.

Intruded into the lower Taylor Group sandstone from 900 to 920 mbsf (m below sea-floor) is a ~16 m thick body of highly altered magmatic rock. Constraining the age of this intrusive body of rock is the focus of this paper as its presence in the base of the hole was regarded as highly enigmatic by the on-site scientific team (Cape Roberts Science Team, 2000, p. 7). Does this intrusion represent volcanism associated with early rifting of the Victoria Land Basin (part of the volcanic rocks of unit V6), or is it a part of later renewed rifting within the Terror rift? Alternatively, is this intrusion simply a dyke of Ferrar Dolerite intruded into Devonian sandstone in the mid-Jurassic (Heimann et al., 1994)? Under this last scenario, the intrusion and surrounding basement were subsequently down-faulted into its present location in the Cenozoic following the initiation of the main phase of uplift and denudation of the TAM (Fitzgerald, 1992).

The texture of the igneous intrusive and its geochemistry (Cape Roberts Science Team, 2000, p. 130-131) suggest the intrusive may simply be highly altered Ferrar Dolerite, especially as the trace element geochemistry indicate a tholeiitic affinity. However, lack of graphic intergrowths, severe alteration in contrast to dolerite seen onland (Hamilton et al., 1965), and its importance if it was Cenozoic in age given its position near the base of CRP-3, meant constraining the age of this intrusion was important.

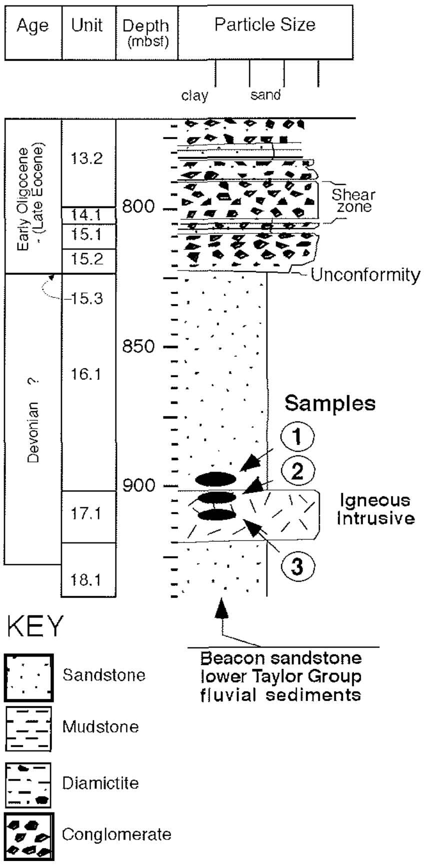

Fig. 2 - Stratigraphic column for the basal part of CRP-3 (modified from Cape Roberts Science Team, 2000).

Tab. 1 - Samples collected for analysis

Informal sample #	*Lithology*	*Box*	*Top of sample interval (m)*	*Bottom of sample interval (m)*
CRP3-1	Quartzose sandstone	246	898.45	898.97
CRP3-2	Intrusive – highly altered	248	906.94	907.45
CRP3-3	Intrusive – severely altered	249	911.82	912.34

To do this, direct means either by U-Pb ion-probe analysis on single crystals of zircon, or fission track analysis of zircon or apatite were considered. If this direct approach failed, an indirect approach using apatite fission track (AFT) thermochronology in the adjacent sandstone to look for an overprinting thermal effect was to be used.

Three samples were collected (Tab. 1), two of the highly altered igneous intrusion and one of the adjacent lower Taylor Group sandstone (Fig. 2). The direct approach to date the intrusion failed, as neither of the two samples of altered igneous rock yielded sufficient amounts or large enough zircon crystals, or any apatite. However, sample CRP3-1 from the Beacon sandstone, yielded relatively abundant amounts of both apatite and zircon. In order to look for thermal overprinting within the sandstone, AFT thermochronology was used because of its relatively low closure temperature (~100°C) and relatively low temperature bounds of the apatite partial annealing zone (PAZ) (~70-110°C). Fission track thermochronology on zircon from the sandstone would be less likely to register a thermal overprint because of its higher closure temperature (~250°C). A basic intrusion of this sort would be expected to have an intrusion temperature in excess of 1000°C (*e.g.* Sparks, 1992) and thus completely anneal fission tracks in apatite. Metamorphic reactions within Beacon sandstone adjacent to Ferrar Dolerite sills in the Taylor Valley indicate temperatures exceeded 500°C following intrusion of the sills (Haskell, 1964). Also in southern Victoria Land, Fitzgerald (1982) examined the thermal effects of dolerite intrusion on a 180 m thick sequence of alluvial plain sediments within the upper part of the Beacon Supergroup. These sediments are bounded by an upper sill ~30 m thick and a lower sill ~60 m thick. Metamorphic reactions requiring temperatures of 310-315°C were estimated for the centre of the sedimentary package, with temperatures close to 550°C adjacent to the chilled margin decreasing to 400-450°C 0.5 m away from the sill contact. Such temperatures would completely anneal fission tracks in apatite. Indeed, throughout the TAM wherever Jurassic dolerite sills are present, the apatite fission track thermochronometer has been reset. As with the Jurassic sills, if the intrusion cored in CRP3 was mid-Cenozoic in age, then the apatite fission track thermochronometer would also be reset at the time of intrusion.

CRP-3 BASAL STRATIGRAPHY AND SAMPLE MATERIAL

An unconformity (at 823.11 mbsf) separates Cenozoic strata (including ~33 m of basal conglomerate) from Devonian Beacon (lower Taylor Group) sandstone (Fig. 2). Apart from the igneous intrusion (from *c.* 902 to *c.* 920 mbsf) Beacon sandstone extends to the bottom of the hole (939.46 mbsf). The basal conglomerate in the Cenozoic section is extensively sheared. Faulting in the Beacon sandstone is more localized, but contains considerable brittle deformation, with breccia within the sandstone forming up to 36% of the core.

The sandstone is a light red/brown medium-grained quartzose sandstone, generally well stratified, mostly with parallel lamination but with some cross-stratification (Cape Roberts Science Team, 2000, p. 67). Strata immediately above and below the igneous intrusion comprises a breccia containing clasts of sandstone and dolerite. Away from the intrusion sandstone decreases in hardness and colour changes from purple to light red/brown. These features are indicative of thermal and mechanical alteration along the boundaries of the intrusion.

The intrusion itself is highly altered and the original mineralogy is totally destroyed, although in samples from the upper part (*e.g.* CRP3-2 from 907.45 mbsf) the original texture can be seen. The rock generally consists of a replacement mineralogy of an anastomosing web of carbonates, smectites, serpentine(?), chlorite and haematite.

RESULTS AND DISCUSSION

Sample CRP3-1 of quartzose sandstone gave an AFT age of 101 ±6 Ma (1 σ) with a mean confined length of 12.3 µm and standard deviation of 1.9 µm (Tab. 2). The track length distribution indicates that this sample has not had a simple thermal history, but that the fission track population had been subjected to protracted annealing over geologic time. The sample fails the Chi-square test indicating that greater than one population of single grain ages may be present. This wide distribution of single grain ages can be seen in the radial plot in figure 3. Such a wide spread of single grain ages is likely to be caused by the grains having slightly different compositions, common in a sedimentary rock, as different apatite compositions have slightly different annealing

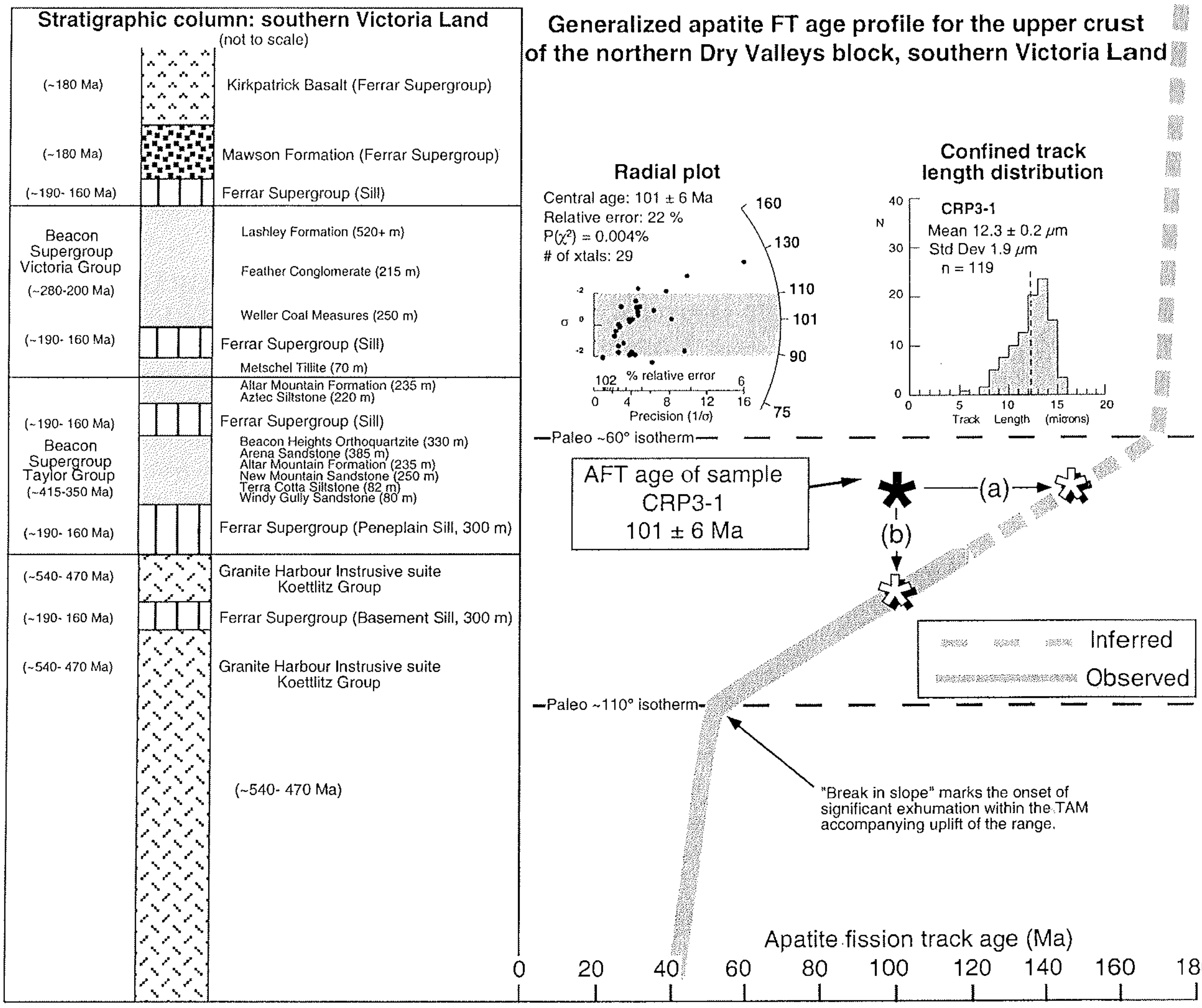

Fig. 3 - Generalized AFT age profile for the upper crustal stratigraphy of the northern portion of the Dry Valleys block. Stratigraphy modified from Fig. 4.4 of the CRP-3 initial report (Cape Roberts Science Team, 2000) and (Barrett, 1991). Thicknesses given for each unit of the Beacon Supergroup are maximums. Note that the stratigraphic column is not to scale. Fission track results generalized from (Gleadow et al., 1984; Gleadow and Fitzgerald, 1987; Fitzgerald, 1992). The apatite age profile represents a pattern formed following complete overprinting by thermal effects accompanying Jurassic tholeiitic magmatism, followed by residence in the upper crust until exhumation accompanying uplift of the TAM began in the early Cenozoic.

characteristics (*e.g.* Green et al., 1986). Thus, long term residence within an apatite PAZ would result in differential annealing on grains with slightly differing compositions, magnifying the statistical spread in single grain ages that would be expected from monocompositional apatites.

The AFT result precludes a Cenozoic age for the intrusion. Given the proximity of the sandstone sample to the igneous intrusion, we would expect that thermal resetting of the sample would have been complete. However, the AFT data appears to reflect the "regional" pattern of AFT ages that is revealed in onshore data for the Dry Valleys block (Gleadow et al., 1984; Gleadow and Fitzgerald, 1987; Fitzgerald, 1992) (Fig. 3). Thus, the intrusion is most likely Jurassic in age, as also suggested by the geochemistry.

The amount of offset between the TAM and the basement (the sandstone) of CRP-3 is at least 3000 m. The sandstone in CRP-3 is 1140 m below present mean sea-level (Cape Roberts Science Team, 2000, Fig. 7.8) and lower Taylor Group sandstone crops out at elevations of ~2000 m in the TAM inland from Cape Roberts. Given the AFT age and confined track length distribution of the sandstone sample (CRP3-1), the simplest interpretation is that this sample was completely reset by the thermal effects of Jurassic magmatism, resided within an apatite partial annealing zone before being exhumed in the early Cenozoic, and down-faulted to its present position off the coast of Cape Roberts. This simple scenario is consistent with regional geology, regional AFT stratigraphy, evidence for faulting within the CRP-3 core, plus the documented faulting across the onland portion of the TMF (Gleadow and Fitzgerald, 1987; Fitzgerald, 1992).

Tab. 2 - Apatite fission track analytical tesults: CRP-3 drill hole, Antarctica.

Drill site & sample number		CPR3-1
Lithology		Quartzose sandstone
Sample depth interval	(m)bsf	898.45 – 898.97
No. of Grains		29
Standard Track Density	$\times 10^6 cm^{-2}$	1.60 (4919)
Fossil Track Density	$\times 10^6 cm^{-2}$	1.861 (1262)
Induced Track Density	$\times 10^5 cm^{-2}$	4.963 (3366)
Chi-Square Probability	%	<0.1
Relative Error	%	22
Central Age $\pm 1\sigma$	Ma	101 ±6
Mean Track Length	μm	12.3 ± 0.2 (119)
Standard Deviation	μm	1.9

Parentheses enclose number of tracks counted (density) or measured (track lengths). Standard and induced track densities were measured on mica external detectors (geometry factor = 0.5), and fossil track densities were measured on internal mineral surfaces. Apatites were mounted in epoxy resin on glass slides, ground and polished to reveal an internal surface, and then etched for 20 s at room temperature in 5N HNO_3 to reveal spontaneous fission tracks. Apatite ages were determined using the external detector method and an automated stage. Samples were irradiated at the Oregon State University Nuclear reactor in the slow soaker position B-3 (Thermal column number 5) that has a Cd for Au ratio of 13.6 at the column face. The mounts were counted at a magnification of 1250x under a dry 100x objective. Ages were calculated using the zeta calibration method (zeta = 361 ± 10 for dosimeter glass CN5) following the procedures of Hurford and Green (1983) and Green (1985). Analytical errors were calculated using the conventional method (Green, 1981). The chi-square test performed on single-grain data (Galbraith, 1981) determines the probability that the counted grains belong to a single age population (within Poissonian variation). If the chi-square value is less than 5%, it is likely that the grains counted represent a mixed-age population with real age differences between single grains. The relative error or age dispersion (spread of the individual grain data) is given by the relative standard deviation of the central age. Where the dispersion is low (<15) the data are consistent with a single population, and the mean/pooled ages and the central age converge. Track lengths were measured using confined fossil fission tracks using only those that were horizontal (Laslett et al., 1984). Tracks were measured under a 100x dry objective using a projection tube and a digitizing tablet attached to a microcomputer.

While the above scenario is certainly the simplest, there are possible complications. Under that scenario, the ~100 Ma AFT age of the sandstone sample is ~50 my younger than that would typically be found onshore for a similar stratigraphic position (Fig. 3, path a). Onshore, AFT ages of ~100 Ma are usually found near the level of the Ferrar Dolerite basement sill (Gleadow and Fitzgerald, 1987; Fitzgerald, 1992), that is considerably lower in the stratigraphic column than the lower Taylor Group (Fig. 3, path b). In addition, onshore basement samples with AFT ages of ~100 Ma have confined track length distributions with means typically of 12.7-13.3 μm, even up to 13.8 μm along the Mt Doorly spur, and standard deviations of near 2 μm. Thus the CRP-3 sandstone sample has an AFT age "too young" and a confined track length distribution "too short" for its stratigraphic position. This indicates that under this simple scenario, this sample, compared to samples onshore having a similar stratigraphic position, has undergone a greater amount of annealing.

Annealing is caused by residence at higher temperatures. In this case, factors contributing to greater annealing in CRP-3 include [1] CRP-3 lies on the edge of a rift zone adjacent to a rift-flank uplift, and rift zones are areas of elevated heat flow, [2] the basement of CRP-3 has been down-faulted to deeper crustal levels (within a rift zone), and hence hotter temperatures.

Rifting and exhumation events: The age of rifting for this part of the Victoria Land Basin may be represented by the age of the Cenozoic strata (*c.* 34 Ma) just above the unconformity with the at the base of CRP-3 (Cape Roberts Science Team, 2000 - chapter 7). It is likely that this Late Eocene-Oligocene phase of rifting elevated the geotherm. Other phases of rifting, that may also have elevated the geotherm, occurred within the West Antarctic rift system in the Cretaceous (*e.g.* Lawver and Gahagan, 1994; Fitzgerald and Baldwin, 1997), and probably also in the early Eocene, coeval with the onset of exhumation as recorded by AFT profiles along the TAM (*e.g.* Davey and Brancolini, 1995; Fitzgerald, 2001). It should be noted that aside from the main phase of exhumation within the TAM begun in the early Cenozoic, other phases of exhumation also occur in the Early and Late Cretaceous, including a period of Cretaceous exhumation documented in the Kukri Hills of southern Victoria Land (Fig. 1) (Fitzgerald, 1995). Theoretically, sample CRP3-1 could lie just above a ~100 Ma break in slope similar to that seen in the Kukri Hills. As of yet there is no definitive evidence for Cretaceous exhumation in the northern part of the Dry Valleys block, but that possibility should not be discounted. On the other hand, Cretaceous thermal alteration of samples cannot be ruled out either, as a mid-Cretaceous thermal event has been documented from 40Ar/^{39}Ar ages on hydrothermally altered Ferrar Dolerite (*e.g.* Molzahn et al., 1999) in the TAM of northern Victoria Land. In the Dry Valleys block, there is not yet direct evidence for a mid-Cretaceous thermal event, although three samples from the Mt Jason profile gave anomalously young AFT ages of ~100 Ma (Gleadow and Fitzgerald, 1987). These three samples should also have had AFT ages of 140-150 Ma. In addition to the regional elevated heat flow brought about by episodes of rifting, local thermal perturbations due to late Cenozoic alkaline volcanism (McMurdo volcanics) in southern Victoria Land (from *c.* 25 Ma, LeMasurier and Thomson, 1990, and articles within) are likely to have effected the local geotherm.

Faulting: The timing of down-faulting constrains how long the base of CRP-3 has been at depth. As the lowermost Cenozoic glacial sediments (*c.* 34 Ma) are cut by faults and a large shear zone, faulting within the sedimentary package was ongoing after 34 Ma. However, as the depositional level of sediments cored in CRP-3 show a progressive deepening from fluvial to near-shore marine to deltaic (Cape Roberts Science Team, 2000, p. 196-197), faulting to near present levels was probably complete in the Oligocene. As the major part of the Beacon Supergroup section and accompanying Ferrar Dolerite sills must have been eroded off prior to deposition of *c.* 34 Ma old sediments it is also clear that faulting across the TMF must have started earlier than that. Complicating this simple interpretation is the fact that the rake of fault striae on fault surfaces within the CRP-3 core indicate a change from 100% dip-slip faulting in Oligocene sediments above 789.5 mbsf to include a significant component of oblique-slip faulting below that (Cape Roberts Science Team, 2000, p. 22).

CONCLUSIONS

The sample of early Devonian lower Taylor Group sandstone from near the base of the CRP-3 drillhole yielded an AFT age of 101 ±6 Ma (1σ) with a mean confined length of 12.3 μm and standard deviation of 1.9 μm. This age from a sample adjacent to an igneous intrusion does not reflect thermal overprinting in the mid-Cenozoic and so the intrusion is more likely a heavily altered dyke related to intrusion of the Ferrar Dolerite in the mid-Jurassic. However, the sample of sandstone has an AFT age "too young" and a confined track length distribution "too short" relative to the onland equivalent stratigraphic position. This indicates this sandstone sample has undergone a greater amount of annealing compared to its onland stratigraphic equivalent. Annealing may be related to the position of the CRP-3 basement, lying on the western edge of the West Antarctic rift system, a system that has experienced periods of rifting and elevated thermal gradients in the Jurassic, Cretaceous, Eocene and Oligocene. Alternatively, this sample may have experienced exhumation in the Cretaceous or a partial thermal overprint in the Cretaceous before being down faulted to its present level.

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REFERENCES

Barrett P.J., 1991. The Devonian to Triassic Beacon Supergroup of the Transantarctic Mountains and correlatives in other parts of Antarctica. In: Tingey R.J. (ed.), *The Geology of Antarctica*, Volume **17**, Oxford Monographs on Geology and Geophysics: Oxford, Clarendon Press, 120-152.

Barrett P.J., Henrys S.A., Bartek L.R., Brancolini G., Busetti M., Davey F.J., Hannah M.J., and Pyne A.R., 1995. Geology of the margin of the Victoria Land Basin off Cape Roberts, southwest Ross Sea. In: Cooper A.K., Barker P.F. & Brancolini G. (eds.), *Geology and seismic stratigraphy of the Antarctic margin*, Volume **68**, Antarctic Research Series: Washington D.C., American Geophysical Union, 183-207.

Cape Roberts Science Team, 1998. Initial Report on CRP-1, Cape Roberts Project, Antarctica. *Terra Antartica*, **5**, 1-173.

Cape Roberts Science Team, 1999. Studies from the Cape Roberts Project, Ross Sea Antarctica. Initial Report on CRP-2/2A. *Terra Antartica* **6**, 1-173. With supplement, 245 p.

Cape Roberts Science Team, 2000. Studies from the Cape Roberts Project, Ross Sea Antarctica. Initial Report on CRP-3. *Terra Antartica*, **7**, 1-209.

Damaske D., Behrendt J., McCafferty A., Saltus R. & Meyer U., 1994. Transfer faults in the western Ross Sea: new evidence from the McMurdo Sound/Ross Ice Shelf aeromagnetic survey (GANOVEX VI): *Antarctic Science*, **6**, 359-364.

Davey F.J. & Brancolini G., 1995. The Late Mesozoic and Cenozoic structural setting of the Ross Sea region, Geology and stratigraphy of the Antarctic margin. In: Cooper A.K., Barker P.F. & Brancolini G. (eds.), *Geology and seismic stratigraphy of the Antarctic margin*, Volume **68**, Antarctic Research Series: Washington D.C., American Geophysical Union, 167-182.

Findlay R.H., Skinner D.N.B., & Craw D., 1984. Lithostratigraphy and structure of the Koettlitz Group, McMurdo Sound, Antarctica. *New Zealand Journal of Geology and Geophysics*, **27**, 513-536.

Fitzgerald P.G., 1982. Environment of deposition of the Feather Conglomerate at Mt. Bastion, southern Victoria Land, Antarctica [BSc Honours thesis]: Wellington, New Zealand, Victoria University, 89 p.

Fitzgerald P.G., 1992. The Transantarctic Mountains of southern Victoria Land: The application of apatite fission track analysis to a rift shoulder uplift. *Tectonics*, **11**, 634-662.

Fitzgerald P.G., 1995. Cretaceous and Cenozoic exhumation of the Transantarctic Mountains: evidence from the Kukri Hills of southern Victoria Land compared to fission track data from gneiss at DSDP site 270. In: Ricci C.A. (ed.), VII International Symposium on Antartic Earth Sciences, Siena (Italy), Abstracts, 133.

Fitzgerald P.G., 2001. Tectonics and landscape evolution of the Antarctic plate since Gondwana breakup, with an emphasis on the West Antarctic rift system and the Transantarctic Mountains. In: Gamble J. et al. (eds.), *Proceedings of the Eighth International Symposium on Antarctic Earth Sciences*, Wellington, New Zealand, The Royal Society of New Zealand.

Fitzgerald P.G., & Baldwin S.L., 1997. Detachment fault model for the evolution of the Ross Embayment. In: Ricci C.A. (ed.), *The Antarctic Region: Geological Evolution and Processes*, Terra Antartica Publication, Siena, 555-564.

Galbraith R.F., 1981. On statistical models for fission track counts: *Journal of the International Association of Mathematical Geologists*, **13**, 471-488.

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.

Gleadow A.J.W., McKelvey B.C., & Ferguson K.U., 1984. Uplift history of the Transantarctic Mountains in the Dry Valleys area, southern Victoria Land, Antarctica, from apatite fission track ages. *New Zealand Journal of Geology and Geophysics*, **27**, 457-464.

Green P.F., 1981. A new look at statistics in fission track dating: *Nuclear Tracks and Radiation Measurements*, **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., Duddy I.R., Gleadow, A.J.W., Tingate P.T., & Laslett G.M., 1986. Thermal annealing of fission tracks in apatite: 1. A qualitative description. *Isotope Geoscience*, **59**, 237-253.

Gunn B.M., & Warren G., 1962. Geology of Victoria Land between the Mawson and Mulock Glaciers, Antarctica: Lower Hutt, *New Zealand Geological Survey Bulletin*, **157**, 157p.

Hamilton W., Hayes P.T., Calvert R., Smith V.C., Elmore S.D., Barnett P.R., & Conklin N., 1965, Diabase sheets of the Taylor Glacier region, Victoria Land, Antarctica. *U.S. Geological Survey Professional Paper*, **456B**, 71p.

Haskell T.R., 1964. Thermal metamorphism of Beacon Group sandstone of the Taylor Valley, Antarctica. *Nature*, **201**, 910

Heimann A., Fleming T.H., Elliot D.H., & Foland K.A., 1994. A short interval of Jurassic continental flood basalt volcanism in Antarctica as demonstrated by ^{40}Ar/^{39}Ar geochronology. *Earth and Planetary Science Letters*, **121**, 19-41.

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

Laslett G.M., Gleadow A.J.W., & Duddy I.R., 1984. The relationship between fission track length and density in apatite. *Nuclear Tracks and Radiation Measurements*, **9**, 29-38.

Lawver L.A., and Gahagan L.M., 1994, Constraints on the timing of extension in the Ross Sea region. *Terra Antartica*, **1**, 545-552.

LeMasurier W.E., & Thomson J.W., 1990. Volcanoes of the Antarctic Plate and Southern Oceans, Antarctic Research Series, Volume 48: Washington, D. C., American Geophysical Union, 487.

McGinnis L.D., Bowen R.H., Erickson J.M., Aldred B.J., & Kreamer J.L., 1985. East-West Antarctic boundary in McMurdo Sound. *Tectonophysics*, **14**, 341-356.

McKelvey B.C., & Webb P.N., 1962. Geological investigations in southern Victoria Land, Antarctica. Part 3: Geology of Wright Valley. *New Zealand Journal of Geology and Geophysics*, **5**, 143-162.

Molzahn M., Wörner G., Henjes-Kunst F., & Rocholl A., 1999. Constraints on the Cretaceous thermal event in the Transantarctic Mountains from alteration processes in Ferrar flood basalts. *Global and Planetary Change*, **23**, 105-12745-60.

Sparks S.J., 1992. Magma generation in the Earth. In: Brown G.C., Hawkesworth C.J. & Wilson R.C.L. (eds.), *Understanding the Earth, a new synthesis*. New York, Cambridge University Press, 91-114.

Warren G., 1969. *Antarctic Map Folio Series, Folio 12 - Geology*. Geologic Map of Antarctica: Sheet 14, Terra Nova Bay - McMurdo Sound area, American Geographical Society.

Wilson T.J., 1995. Cenozoic transtension along the Transantarctic Mountains-West Antarctic rift boundary, southern Victoria Land, Antarctica. *Tectonics*, **14**, 531-545.

Wilson T.J., 1999. Cenozoic structural segmentation of the Transantarctic Mountains rift flank in southern Victoria Land. *Global and Planetary Change*, **23**, 105-127.