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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

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Fission track analysis of apatites from basement rocks of the Wright Valley in southern Victoria Land provides information about the timing, the amount and hence the rate of uplift of the Transantarctic Mountains in this area. Apatite ages increase systematically with elevation, and a pronounced break in the age versus elevation profile has been recognised at about 800 m on Mt. Doorly near the mouth of Wright Valley. The apatite age of about 50 Ma at this point approximates the time at which uplift of the mountain range began. Samples lying above the break in slope lay within the apatite fission track annealing zone prior to uplift, during a Cretaceous to Early Cenozoic period of relative thermal and tectonic stability. At the lower elevations samples had a zero apatite fission track age before the onset of rapid uplift and have track length distributions indicating rapid cooling. Some 4.8–5.3 km of uplift are estimated to have occurred at an average rate of about 100 ± 5 m/Ma since uplift began. From the total stratigraphic thickness known above the uplifted apatite annealing zone it can be estimated that the Late Cretaceous/Early Cenozoic thermal gradient in the area was about 25–30°C/km.

The occurrence and pattern of differential uplift across the Transantarctic Mountains can be estimated from the vertical offsets of different apatite fission track age profiles sampled across the range. These show the structure of the mountain range to be that of a large tilt block, dipping gently to the west under the polar ice-cap and bounded by a major fault zone on its eastern side. Offset dolerite sills at Mt. Doorly show the mountain front to be step-faulted by 1000 m or more down to the McMurdo Sound coast from an axis of maximum uplift just inland from Mt. Doorly.

1. Introduction

The Transantarctic Mountains (TAM) form one of the great mountain ranges of the world. They extend some 3500 km across Antarctica from northern Victoria Land to the Weddell Sea, and lie along the length of an old Palaeozoic mobile belt. They also mark the boundary between the Precambrian East Antarctic craton and the dominantly Mesozoic/Cenozoic terrains of West Antarctica. The geological setting of the range has recently been discussed by Fitzgerald et al. [1], and placed in context with regard to the geological evolution of Antarctica by Elliot [2]. The regional geology of south Victoria Land is relatively simple. Basement metamorphic and granitic rocks of Precambrian to early Palaeozoic age were eroded to a subdued relief in the Silurian and early Devonian to form the Kukri Peneplain [3]. A thick sequence (2–3 km) of shallow marine and alluvial plain sediments, the Beacon Supergroup, were deposited from the Devonian to Triassic [4]. Beacon sedimentation ended in the mid-Jurassic with the intrusion and extrusion of tholeiitic magma to form the sills and dykes of the Ferrar Dolerite and the flows of the Kirkpatrick Basalt [3]. In south Victoria Land the sills of the Ferrar Dolerite are remarkable for their sub-horizontal and sub-parallel nature. This is particularly evident for the two lowermost sills, here referred to as the "basement" and "peneplain" sills, after Gunn and Warren [5], because of their positions in the sequence. A gap of 160 Ma follows in the on-land geological record in the Dry Valleys area, until the eruption of alkaline basalts in the early Miocene, volcanic activity that still continues today on Ross Island in McMurdo Sound [6].

Uplift in the TAM has been substantial, pro-

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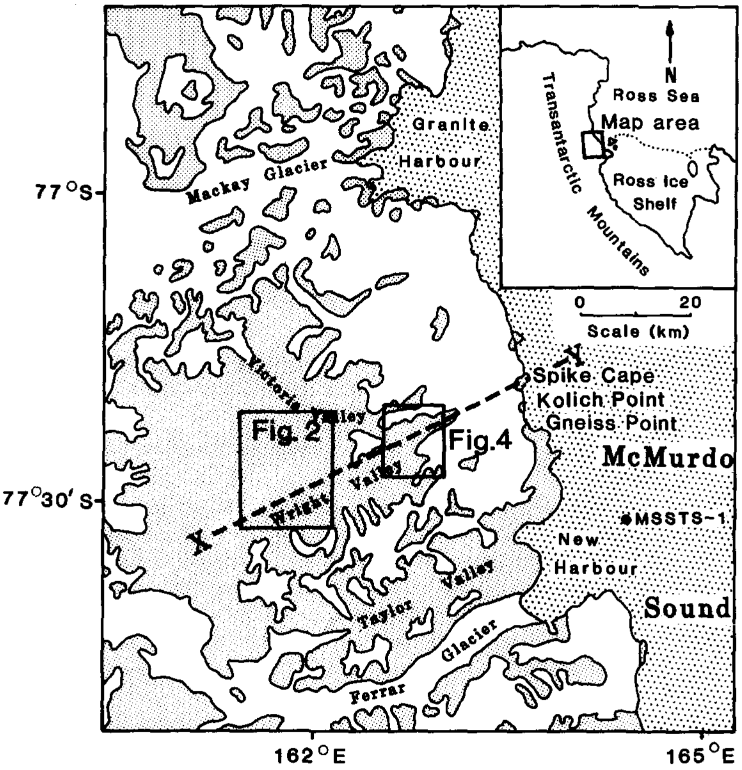

Fig. 1. Index map of south Victoria Land showing localities mentioned in the text, positions of Figs. 2 and 4, and the MSSTS-1 drillhole in McMurdo Sound. The line X-Y marks the location of the cross-section in Fig. 9.

ducing peaks that locally exceed 4500 m above sea level, with large areas above 1500 m. The 100–300 km wide range is remarkable in that it has been formed in an apparently extensional environment, in contrast to most of the world's major mountain belts that have resulted from compressional plate interactions. Consequently, the uplift of the TAM is characterised by block faulting and an absence of thrust deformation, regional metamorphism and intrusive igneous activity so typical of many other orogenic belts.

Another striking feature of the TAM in Victoria Land (Fig. 1) is the abrupt transition between the mountain range and the depressed area of the Ross Embayment (comprising the Ross Ice Shelf and Ross Sea) where subsidence of up to 6 km or more has occurred in a number of different basins [7–9]. Uplift and subsidence in these adjacent areas appears to have been broadly synchronous and are therefore probably genetically related. This juxtaposition of major belts of uplift and subsidence requires the existence of a significant structural discontinuity between the two areas. A major boundary fault between these two adjacent areas has been inferred since the earliest days of geological exploration in Antarctica [10,11]. This fault, with a throw estimated by Priestley and David [10] to be about 1000–2000 m, was also seen as forming the eastern boundary of an enormous horst making up the present mountain range. More recent workers have generally supported the idea of a major fault along the present coastline of the Ross Sea which is essentially straight for some 250 km north from the southern end of McMurdo Sound. The first direct evidence for the existence of such a fault in the McMurdo Sound region was obtained from gravity data [12] which confirmed a strong regional gradient parallel to the mountains and the coast. Gunn and Warren [5], however, suggested that the structure of the mountain range was more complex than the "great horst" of David and Priestley [11], preferring a block faulted structure involving many horsts and graben. They defined this block uplift responsible for the TAM, as the Victoria Orogeny, and estimated it to be late Cenozoic in age. The frontal escarpment and fault zone that marks the transition from the uplifted mountains to the Ross Sea has been defined as the Transantarctic Mountain Front [13].

The uplift history of the TAM has more than just structural and tectonic importance, it also bears on the inception of the Antarctic ice sheet. Drewry [14] first suggested that the ice sheet may have originated from a local ice cap on the mountain range during the early stages of uplift. Denton [15], however, suggested that most of the morphological features of the range in the Byrd-Darwin glacier and McMurdo Sound regions can be explained by uplift of the mountains through a pre-existing ice sheet, although these views were later modified [16]. The onset of uplift in the TAM thus has important implications for the glacial and climatic evolution of Antarctica as a whole. Furthermore, the uplift and glacial history of the mountain range have together undoubtedly exerted an influential control on the depositional history of the Ross Sea area (e.g. [17]), currently an important focal area for research in Antarctic earth sciences. The diverse evidence relating to the uplift history of the Transantarctic Mountains has been recently reviewed [18–20].

In an earlier fission track study Gleadow et al. [20] used the variation in apparent fission track age of apatites with sample elevation to infer the uplift history of basement rocks from southern Victoria Land. Results were reported in that study for samples from the central Wright and Victoria Valleys in the Dry Valleys area. A strong correlation was found between apatite age and sample elevation in this area with a gradient of about 15 m/Ma over an apparent age range of about 65–155 Ma. These results were interpreted to indicate that no significant uplift had occurred in the TAM prior to the beginning of the Cenozoic but no direct indication of the time at which uplift began was obtained. A minimum estimate of 55 m/Ma for the average uplift rate during the Tertiary was calculated by assuming that the thermal gradient has remained roughly constant over that period.

The apatite age gradient observed in the basement rocks means that a particular apatite age will be associated with a particular depth in the pre-uplift crust. In effect, an apatite age "isochron" can be used as an artificial reference plane for determining tectonic movement. The present elevation of particular apatite ages from the Dry Valleys area can therefore be used as a form of palaeo-depth marker to gain insight into the regional structure of the mountain range. This can be combined with other indications of structure in the local geology obtained from the elevation and offset of more visible features such as the Kukri Peneplain and the various Ferrar Dolerite sills. As a first approximation, these features may be assumed to have been initially horizontal.

In this study we present new fission track data from the Dry Valleys area and the coast of McMurdo Sound, which extend the earlier work of Gleadow et al. [20] and establish the initiation of uplift of the TAM in southern Victoria Land for the first time. The results also give new information on uplift rates, the structure of the range and the nature of its faulted boundary with the Ross Embayment.

2. Samples and results

Basement rocks from five localities in the Dry Valleys area of southern Victoria Land were collected for fission track dating. At three of these localities, samples were taken at various elevations from vertical profiles up the sides of Wright Valley. Collections were also made from two localities near sea level on the coast of McMurdo Sound. Sample elevations were measured barometrically as described by Gleadow et al. [20] and the study areas are shown in the locality map, Fig. 1. Apatites were separated from these rocks using conventional heavy liquid and magnetic techniques, and analysed using the external detector method as described in detail elsewhere [21]. The results are shown in Table 1 and errors are quoted at the level of one standard deviation throughout.

2.1. Upper Wright Valley

The first area studied was in the Upper Wright Valley and extends the coverage of the Mt. Jason section reported by Gleadow et al. [20]. The samples described from here previously [20] were collected together with the additional ones presented here and were taken at approximately 100 m vertical intervals up a spur between the main valley and Bull Pass, as shown in the geological sketch map, Fig. 2. The sampling profile extended from about 250 m above sea level, near the floor

TABLE 1

Analytical results—fission track dating of basement granites, Wright Valley area

Sample No.	Sample elevation (m)	Number of grains	Standard track density $\times10^6$ (cm^{-2})	Fossil track density $\times10^5$ (cm^{-2})	Induced track density $\times10^6$ (cm^{-2})	Correlation coefficient	Age (Ma)	Uranium (ppm)	$P(\chi^2)$ %
Mount Jason									
R29068A	1395	10	1.213 (2139)	26.71 (1257)	3.905 (1838)	0.915	148 ± 6	43	40
R29068B	1395	8	1.230 (2139)	27.66 (1136)	3.912 (1607)	0.986	155 ± 7	42	97
R29069	1295	9	1.247 (2139)	19.54 (896)	4.435 (2034)	0.826	98 ± 5	47	8
R29070	1195	10	1.268 (2407)	22.89 (1280)	5.178 (2896)	0.822	100 ± 4	54	40
R29071	1095	11	1.292 (2407)	17.94 (1104)	4.153 (2555)	0.795	100 ± 4	42	35
R29072	995	9	1.304 (2407)	20.90 (1052)	3.935 (1981)	0.975	124 ± 5	40	80
R29073	895	11	1.317 (2407)	18.76 (1028)	3.609 (1978)	0.880	122 ± 5	36	25
R29074	805	4	1.330 (2407)	19.97 (393)	4.136 (814)	0.801	115 ± 7 114 ± 14 [a]	41	<1
R29076	445	7	1.357 (2407)	3.985 (156)	0.999 (391)	0.701	97 ± 9	10	10
R29077	345	11	1.370 (2407)	8.880 (596)	2.508 (1683)	0.867	87 ± 5 90 ± 6 [a]	24	3
R29078	245	6	1.383 (2407)	9.107 (413)	2.811 (1275)	0.823	80 ± 5	30	40
Mt. Doorly									
R31735	1113	8	1.293 (1800)	5.652 (196)	1.572 (545)	0.963	83 ± 7	16	95
R31736	1034	15	1.244 (3488)	5.389 (434)	1.810 (1458)	0.959	66 ± 4	19	50
R31737	1041	8	1.350 (5386)	2.312 (75)	0.817 (286)	0.862	64 ± 8	9	98
R31738	949	9	1.336 (5386)	9.958 (479)	3.437 (1653)	0.973	69 ± 4	34	40
R31739	856	9	1.323 (5386)	7.380 (355)	3.478 (1673)	0.980	50 ± 3	35	35
R31740	763	14	1.309 (5386)	4.227 (208)	2.242 (1103)	0.978	44 ± 4	23	95
R31741	671	5	1.295 (5386)	8.290 (204)	4.045 (998)	0.939	48 ± 4 49 ± 7 [a]	41	4
R31742	578	7	1.281 (5386)	4.700 (280)	2.528 (1506)	0.987	43 ± 3	26	60
R31743	485	10	1.267 (5386)	7.268 (374)	3.490 (1796)	0.956	47 ± 3	36	20
R31744	393	18	1.244 (3488)	2.538 (247)	1.179 (1147)	0.973	48 ± 4	13	85
Mt. Newall									
R31745	780	16	1.244 (3488)	2.505 (213)	0.886 (753)	0.886	63 ± 5	9	15
R31746	687	13	1.244 (3488)	5.041 (344)	2.055 (1402)	0.991	55 ± 3	22	60
R31747	595	16	1.244 (3488)	3.065 (264)	1.420 (1223)	0.899	48 ± 3	15	50

TABLE 1 (continued)

Sample No.	Sample elevation (m)	Number of grains	Standard track density $\times 10^6$ (cm^{-2})	Fossil track density $\times 10^5$ (cm^{-2})	Induced track density $\times 10^6$ (cm^{-2})	Correlation coefficient	Age (Ma)	Uranium (ppm)	$P(\chi^2)$ %
R31748	502	15	1.244 (3488)	3.914 (324)	1.831 (1516)	0.967	48 ± 3 45 ± 5 [a]	19	3
Gneiss Point									
R31752	15	7	1.239 (5386)	10.871 (400)	2.574 (947)	0.962	93 ± 6	27	45
Spike Cape									
R31754	4	9	1.225 (5386)	9.238 (310)	2.104 (706)	0.996	96 ± 7	23	50
R22505	5	20	1.460 (12801)	13.43 (586)	3.546 (1547)	0.953	99 ± 5	32	55

Brackets show number of tracks counted. Induced track densities as measured ($g = 0.5$). Ages calculated using Zeta = 360 ± 10 for dosimeter glass SRM612 [48], $\lambda_D = 1.551 \times 10^{-10}$ yr^{-1}. $P(\chi^2)$ = probability of obtaining the observed value of Galbraith's [49] χ^2 parameter, for n degrees of freedom, where n = number of crystals − 1, quoted to the nearest 5 or 10%.
[a] Age calculated from the mean crystal age, used where pooled data fail Chi square test at 5%.

of Wright Valley to the base of the peneplain sill at about 1400 m. The lithologies of the additional samples are very similar to those already described from the same traverse [20], consisting of gneissic, biotite-hornblende granodiorites belonging to the Olympus Granite Gneiss. Results on the additional seven samples from this traverse are given in Table 1 and shown against sample elevation in Fig. 3a. The four apatite ages reported previously are also included for comparison. The new results all lie between the extreme values found in the earlier study and, for the most part, define the same apatite age gradient of about 15 m/Ma.

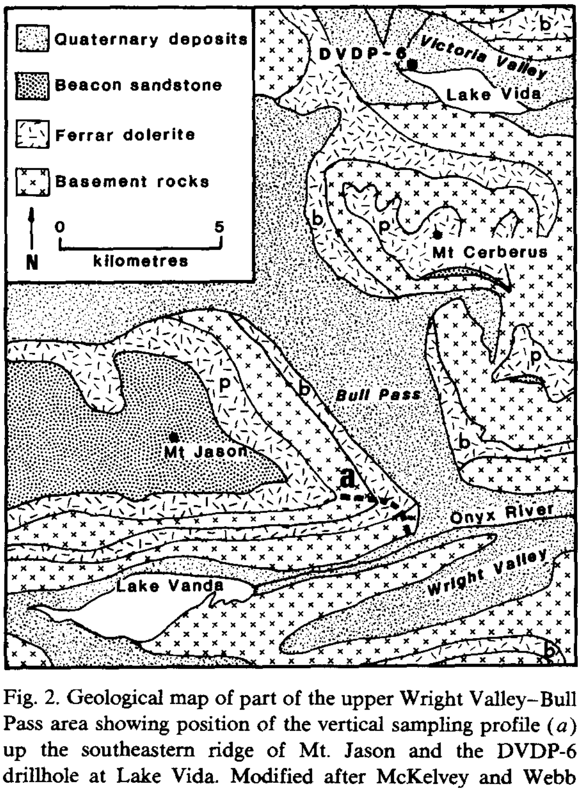

Fig. 2. Geological map of part of the upper Wright Valley–Bull Pass area showing position of the vertical sampling profile (a) up the southeastern ridge of Mt. Jason and the DVDP-6 drillhole at Lake Vida. Modified after McKelvey and Webb [22]. b indicates the basement dolerite sill and p, the peneplain dolerite sill.

Three samples from about 1100–1300 m on the Mt. Jason section gave almost the same age of close to 100 Ma, and lie clearly off the main trend. No satisfactory explanation for these anomalous results is apparent at this stage. A tectonic offset, as was inferred for part of the apatite age profile near Lake Vida [20] in Victoria Valley to the north, seems quite unlikely in this case due to the similarity of apparent ages for the three samples and the fact that immediately underneath them is a flat, laterally continuous dolerite sill of Jurassic age. It is possible that these apatites have slightly different annealing properties to others in the same profile, but this would probably not explain the similarity of their fission track ages. Notwithstanding these three anomalous results, the remaining eight ages from the Mt. Jason section are all highly correlated with elevation and confirm the previously reported gradient of about 15 m/Ma [20].

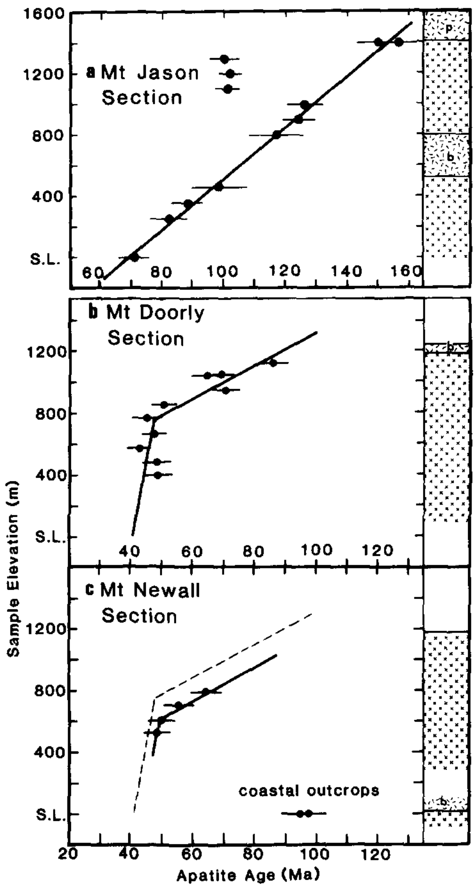

Fig. 3. Apatite fission track age versus elevation plots for the three vertical sampling profiles: (a) Mt. Jason, (b) Mt. Doorly and (c) Mt. Newall. A simplified geological column is shown to the right of each profile using the same symbols as Fig. 2. Note that the age scale for Mt. Jason (a) is different to the lower two parts of the diagram. (a) The Mt. Jason profile is essentially the same as that shown by Gleadow et al. [20], but it has additional results as well as three anomalous ages of about 100 Ma, which are discussed in the text. (b) The Mt. Doorly profile showing the "break in slope" in the apatite age-sample elevation graph at about 50 Ma. Samples above this point lay in the partial annealing zone prior to uplift and now have mixed ages comprising an earlier set of partially annealed tracks and a later set of tracks accumulated during uplift. Samples lying below this point had zero ages prior to uplift and only started accumulating tracks once they were uplifted past the base of the partial annealing zone. The break in slope marks the initiation of uplift of the mountains at this locality. (c) The Mt. Newall profile showing a similar although not as complete pattern to Mt. Doorly. The Mt. Doorly uplift curve is marked by the dotted line, and the relative offset between the two is equivalent to a slope of about 1°, indicating that these two profiles lie on the same tectonic block which probably has a slight tilt to the south. The lower elevations of the coastal outcrops are due to faulting across the mountain front, the apatite age of the gneiss adjacent to the dolerite having a very similar age to what we would expect from a sample directly under the basement sill in (b). Note that the dolerite marked here at the base of the geological column refers only to the coastal outcrops and not to the profile from Mt. Newall.

2.2. The Lower Wright Valley

The second and major area of interest in this study is at the mouth of the Wright Valley where samples of basement granite were collected along two vertical profiles. This area was chosen for further study because of the presence of an elongated spur extending some 10 km eastwards towards the McMurdo Sound coast from Mt. Doorly. This spur provides the most continuous exposure of basement granitic rocks in the Wright Valley area within the Transantarctic Mountain Front. Another reason for sampling in this area was that earlier mapping [22] showed the presence of only a single dolerite sheet at the top of a considerable thickness of basement granite. It is reasonable to correlate this dolerite with the lowest of the three major sills in the Upper Wright Valley (the basement sill) so that sampling to a relatively deeper level in the mountain block could be anticipated.

Samples were taken between elevations of 250 m above sea level on the northern side of the valley near the snout of the Lower Wright Glacier and 1100 m just below the summit of Mt. Doorly, which is capped by a dolerite sill. A second, more limited profile was collected on the southern side of the valley below Mt. Newall and samples were again collected at approximately 100 m vertical intervals on both traverses.

The Lower Wright Valley has not been mapped in detail, since early reconnaissance geological mapping by McKelvey and Webb [22]. A new sketch map of the geology in this area is shown in Fig. 4 illustrating especially the distribution of Ferrar Dolerite and a number of important faults along the Mt. Doorly spur. The locations of the two sampling traverses are also indicated. A cross-section along the Mt. Doorly spur based on our field observations is shown in Fig. 5. It shows a series of normal faults stepping down through the Transantarctic Mountain Front towards the McMurdo Sound to the east. The maximum throw on any one of the faults at Mt. Doorly is about 300 m and the cumulative displacement is over 500 m.

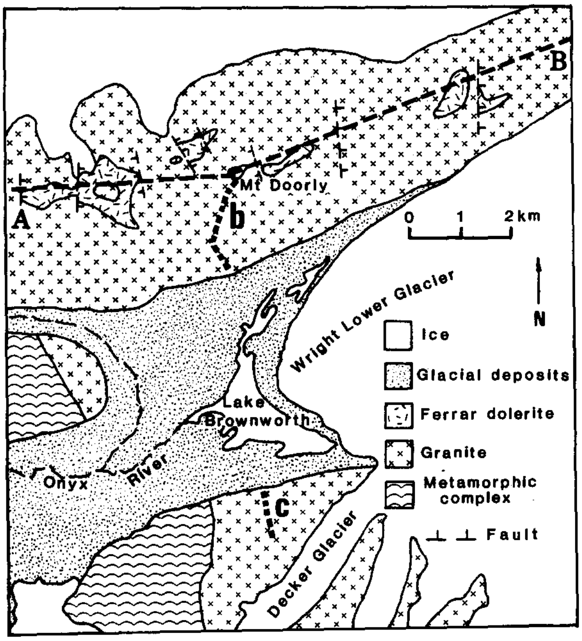

Fig. 4. Geological sketch map of the lower Wright Valley and part of the Mt. Doorly spur. Modified after McKelvey and Webb [22]. The vertical sampling profile up Mt. Doorly (*b*) and that up Mt. Newall (*c*) which lies just off the map to the south, are indicated, as well as the projection line of the cross-section *A-B* which is shown in Fig. 5.

The principal evidence for these faults lies in offsets produced in the dolerite sill which is repeated at various levels down the spur. This sill is identified as the basement sill and not the peneplain sill, as previously mapped [22], for a number of reasons. Firstly, granitic rocks are observed both above and below the dolerite in a peak about 3 km west of Mt. Doorly (Figs. 4 and 5), although the peneplain sill is known in places to dip beneath the Kukri Peneplain and hence have granite slivers above it. The main reason the dolerite capping Mt. Doorly belongs to the basement sill is because apatite ages from just below it are close to 100 Ma, of similar age to those from just below the clearly defined basement sill from the Mt. Jason profile (Fig. 3). It is assumed that the sill was emplaced without major offsets, similar to the situation in the Upper Wright Valley where the dolerite is laterally continuous over about 20 km of outcrop. Dips measured on the base of the dolerite sill increase from less than 1° westwards in the Upper Wright Valley to about 3° on some of the more easterly fault blocks on the Mt. Doorly spur. This indicates minor rotation of the fault blocks suggesting the fault planes may be listric at depth.

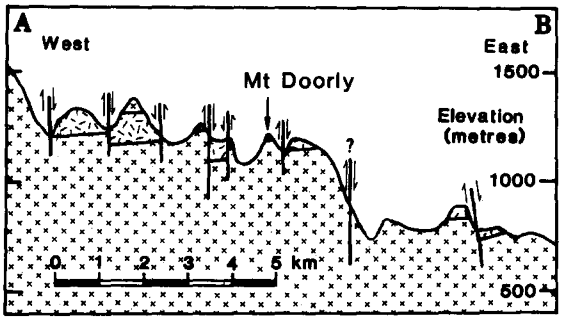

Fig. 5. Geological cross-section through the Mt. Doorly spur showing the offset dolerite sills due to normal step-faulting across the mountain front. The projection line of the cross-section *A-B* is marked in Fig. 4. The question mark indicates that the exact position, not the existence of the fault is in doubt.

The basement rock at Mt. Doorly and on the opposing Mt. Newall traverse is a uniform pale grey to pale pink biotite-granite, porphyritic in places. Sufficient apatite for fission track dating was obtained from all samples and the results are shown in Table 1 for both traverses in this area. Above an elevation of 800 m on Mt. Doorly the apparent ages (Fig. 3b) define a 15 m/Ma gradient similar to that determined from the Mt. Jason section. The ages on this upper part of the profile extend down to about 50 Ma, significantly less than the approximately 60 Ma reported from Mt. Jason and Lake Vida [20]. Below 800 m, however, the apatite ages on Mt. Doorly remain essentially constant with no apparent change over about 400 m of vertical section. This "break in slope" is most important and signifies that a phase of uplift began in this area about 50 Ma ago, as will be discussed in more detail below. Similar, although limited results from the flanks of Mt. Newall (Fig. 3c) on the southern side of the valley follow this trend without any significant difference in elevation for the "break in slope", suggesting that it lies on the same fault block as Mt. Doorly.

2.3. McMurdo Sound coastal outcrops

To the east of the Mt. Doorly spur lie a number of low relief coastal outcrops (Fig. 1). These include gneisses, metadiorites, granodiorites and marbles. Samples of feldspar-quartz-biotite gneiss were collected from Gneiss Point and Spike Cape. Samples at both localities were collected within a few metres of sea level. Outcrops of dolerite, assumed to belong to the Ferrar Group, also occur at sea level at Kolich Point between these two localities, adjacent to the basement gneisses. This association suggests that the dolerite at Kolich Point belongs to the "basement sill" identified at various localities inland. This is confirmed by similar 100 Ma apatite ages (Table 1 and Fig. 3) for the coastal outcrops and adjacent to the basement sills on Mt. Doorly and Mt. Jason. The elevation of the coastal rocks indicates that they have been considerably downthrown relative to the Mt. Doorly area where dolerite occurs at an elevation of about 1200 m. Furthermore, the similarity of apatite ages near this sill at these widely separated localities suggests that all were originally at a similar crustal level when the apatite ages were set. The dolerite at Kolich Point was not apatite-bearing, nor for that matter have any samples of Ferrar Dolerite so far attempted contained sufficient apatite for dating.

3. Discussion

The apatite fission track ages reported here indicate a cooling history which entirely postdates the major thermal event accompanying emplacement of the Jurassic Ferrar Dolerite and extrusion of the Kirkpatrick Basalt, as was found previously [20] for parts of the Wright and Victoria Valleys. Tracks were entirely erased from apatites over the whole region during this thermal event and the present pattern of ages represents a new thermal regime probably established during Cretaceous time. The new results also confirm that above about 800 m in the Lower Wright Valley, apatite ages vary with elevation on a similar shallow gradient (about 15 m/Ma) to that reported in the previous study from localities further inland. At Mt. Doorly an important break in slope occurs on this apatite age profile at an age of about 50 Ma below which no significant change in apparent age can be seen over about 400 m of section. This break in slope was predicted but not observed in the earlier fission track study as representative of a two-stage tectonic history for the region.

The upper portion of the age-elevation profile was thought by Gleadow et al. [20] to represent either a period of extremely slow uplift and erosion during the Cretaceous, or the gradual downward relaxation of isotherms after the Jurassic thermal event. These interpretations were based on the concept that fission track ages date the time of cooling below some effective annealing temperature, below which fission tracks were regarded as stable over geological time. Under either interpretation, the rate of denudation during this period was inferred to be very slow. It was then suggested that this interval was followed by a period of much more rapid uplift beginning some time after the then youngest observed apatite age of around 60 Ma, and maintained at an average uplift rate in the range 55–135 m/Ma, depending on exactly when uplift began.

Here we suggest that the apatite age profile is much better explained by a third model which depends on recent advances in understanding the nature of the fission track annealing process in the upper few kilometres of the earth's crust [23–26]. The previously used concept of an effective annealing temperature is a simplification of the real situation where fission track annealing actually takes place over a range of temperatures, called a partial annealing zone. This previous approach is probably still useful in areas of very high uplift rates, but is of questionable value for extremely low uplift rates as were inferred for the pre-Eocene history of the Dry Valleys region. Such annealing zones can be observed today in deep boreholes where the apparent fission track age of apatites gradually decreases to zero between depths of approximately 2 and 4 km as the temperature increases from about 70 to 130°C [24,27]. Such an annealing zone will have an apparent gradient of apatite age with elevation in an area of little or no uplift which will approximate the pattern observed. We consider then, that above the break in slope the shallow apatite age gradient (Fig. 3b) actually represents a former track annealing zone established under a stable thermal regime prior to the onset of uplift at about 50 Ma. The "fossil" partial annealing zone is now uplifted and preserved at higher elevations in the TAM.

Using this model, apatite ages on the steep part of the age profile (Fig. 3b) represent samples which were too hot to record stable tracks before the onset of uplift, having an apparent age of zero up to that time. Such apatites would only begin to

TABLE 2

Analytical results—confined fission track lengths, Dry Valleys area

Sample No.	Age (Ma)	Track length (μm)	Standard deviation	Number of tracks measured
Mt. Jason				
R29068A	148±6	12.50±0.30	2.10	50
R29068B	155±7	12.89±0.26	1.83	50
R29070	100±4	12.79±0.19	1.96	106
R29071	100±4	12.70±0.23	2.34	100
R29072	124±5	13.26±0.24	1.69	50
R29077	90±6	12.27±0.30	2.14	50
R29078	80±5	13.17±0.26	1.86	50
Mt. Doorly				
R31735	83±7	13.21±0.23	1.81	60
R31737	64±8	12.92±0.27	2.51	90
R31739	50±3	13.34±0.23	1.45	40
R31741	49±7	14.14±0.20	2.01	106
R31743	47±3	14.36±0.17	1.20	50
R31744	48±4	14.14±0.23	1.69	56

record a fission track age during cooling accompanying the uplift and associated denudation. The "break in slope" now observed at about 800 m in the apatite age profile on Mt. Doorly may thus be interpreted as the bottom of the partial annealing zone (approximately the 130°C isotherm) prior to about 50 Ma. Samples above the "break in slope" have "mixed ages", with a contribution of tracks from the pre-uplift partial annealing zone and from a later set of post-uplift tracks.

Confirmation of this interpretation of the age profile is given by the distribution of fission track lengths in various samples. Results of length determinations on horizontal confined tracks from the Mt. Jason and Mt. Doorly apatites are given in Table 2. Measurement techniques are described elsewhere [26,28]. Length distributions are shown in Fig. 6 in relation to their corresponding apatite ages on a generalised age-elevation profile using elevations from Mt. Doorly.

Confined track lengths in apatites contain an extremely important record of thermal history and provide valuable assistance in interpreting fission track ages [26]. A clear difference in track length can be observed in Fig. 6 between the samples occurring above and below the "break in slope", those above the break having significantly shorter mean lengths and much broader distributions than

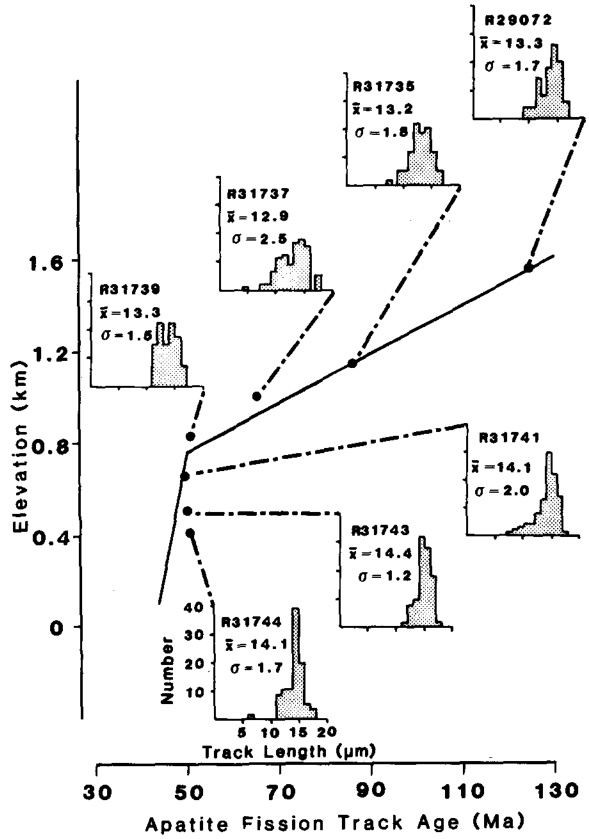

Fig. 6. Fission track length distributions plotted with respect to apatite ages on a generalised age-elevation profile using elevations from Mt. Doorly. Plots are normalised to 100 tracks. Samples occurring above the break in slope have significantly shorter lengths with larger standard deviations reflecting considerable time spent in the partial annealing zone where tracks are shortened. Mean lengths of tracks from samples below the break in slope are longer, with smaller standard deviations, reflecting rapid cooling from temperatures above the track retention zone with only a relatively short residence in the partial annealing zone.

those below. The mean lengths between 14.1 and 14.4 μm for the Mt. Doorly samples from below the break in slope (Table 2) are similar to those considered to be characteristic of undisturbed surficial volcanic rocks [24], although with somewhat larger standard deviations of 1.2–2.0 μm. This pattern suggests very rapid cooling from temperatures above the track stability range for apatite with only a relatively short residence time within the partial annealing zone. In contrast, the broader, shorter distributions above the break in slope (mean lengths of 12.3–13.3 μm with standard

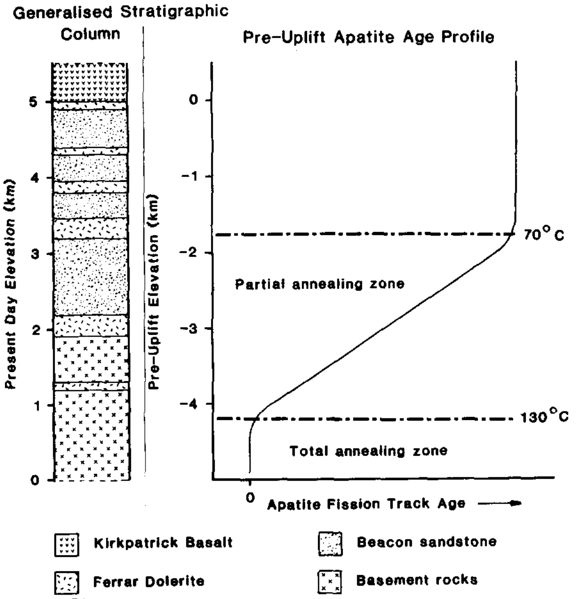

Fig. 7. Generalised stratigraphic column for south Victoria Land [27–31] and reconstructed pre-uplift apatite age profile at Mt. Doorly. The "break in slope" which represents the base of the partial annealing zone then lay at a depth of 4–4.5 km. It now lies at an elevation of about 800 m, inferring an uplift of 4.8–5.3 km.

deviations of 1.45–2.5 μm, Table 2) indicate that many tracks are present in these apatites which have undergone extensive shortening through prolonged exposure to temperatures in the partial annealing zone.

Based on this interpretation, Fig. 7 shows a reconstruction of the known stratigraphy in this area prior to the Victoria Orogeny and the corresponding distribution of apparent apatite age with depth at that time. This represents the situation during the period after emplacement of the Ferrar Dolerites and their extrusive equivalents, when the known section was at its thickest, and before later uplift and denudation. The break in slope in the apatite age profile is inferred to lie about 1000–1500 m below the Kukri Peneplain. This thickness consists dominantly of basement rocks, principally granitic in composition but also metamorphic in places, and includes the basement dolerite sill, which in the Upper Wright Valley is about 300 m thick. Above the peneplain in southern Victoria Land is an estimated thickness of 2500 m of sediments of the Beacon Supergroup [3,29–31] and an estimated further 500–700 m of dolerite comprising the peneplain sill and sills within the Beacon [29,30,32]. In the Allan Hills area 90 km to the northwest of the Dry Valleys, is an estimated 500 m of Kirkpatrick Basalt [33] which may have added up to another 500 m of section, to give a total possible stratigraphic thickness of about 4.5–5 km above the apatite age break. Combined with a palaeotemperature of 130°C for the base of the partial annealing zone and an estimated mean surface temperature of 0°C, taking into account that no ice ice-cap was then thought to exist [14,34,35], gives an estimate of some 25–30°C/km for the palaeothermal gradient prior to uplift. It is important to note that this estimate is independent of actual measurements of thermal gradient in the area. However, the estimate appears entirely reasonable and consistent with the approximately 30°C/km present-day thermal gradient [36] for the basement granites in DVDP-6 at Lake Vida in the Victoria Valley, which is well away from the higher gradients related to young volcanic centres in the region.

Using this reconstructed stratigraphic profile it is possible to calculate the amount of uplift this area has undergone assuming a landsurface elevation of 500 m prior to uplift. This elevation is poorly constrained but we have selected an estimate of 500 m because the Kirkpatrick Basalt at Allan Hills was deposited in an alluvial flood-plain setting with ponds and streams [37] and comparable flood basalts in eastern Greenland were erupted onto a land surface originally close to sea level [38]. If this estimate of 500 m is valid, then the "break in slope" (i.e. zero apatite age at that time) would have been at a depth of 4–4.5 km below sea level. As this point is now at an elevation of 800 m above sea level at Mt. Doorly we can infer a total uplift of 4.8–5.3 km for the last 50 Ma at this locality. This total uplift implies an average uplift rate of 95–105 m/Ma for the past 50 Ma.

It is important to realise that this is an average value which could conceal phases of significantly higher and lower uplift rates, and does not imply that uplift was necessarily uniform through time. In fact no significant change in apatite age with elevation can be observed for 400 m below the break in slope on the Mt. Doorly profile which leaves the actual uplift rate unconstrained at this point, except that it was relatively high, from the fission track age gradient alone. It is possible from this evidence and the track length data that there was an early rapid stage to the uplift at rates significantly higher than the average. There is evidence for more than 400 m of uplift in the eastern Taylor Valley block sometime in the early Pliocene [39], suggesting uplift rates as high as 200 m/Ma, as well as evidence just offshore in the MSSTS-1 drillhole (Fig. 1) which suggests 1 km of uplift in the Pliocene [40]. This implies differential uplift between different tectonic blocks, as suggested by Wrenn and Webb [39] who further suggest differential movement between a mosaic of discrete fault blocks. The fission track evidence from Lake Vida in Victoria Valley [20] also provide direct evidence of such differential movement.

A similar figure of approximately 100 m/Ma is obtained for the average uplift rate since 50 Ma using the approach of Gleadow et al. [20], based on the measured surface temperature and thermal gradient from the DVDP-6 drillhole in Victoria Valley. This technique estimates the depth of the present 130°C isotherm below the "break in slope" (i.e. the palaeo-130°C isotherm) from the present thermal gradient. In doing this we have ignored the much higher gradients measured in some drillholes in the area of the Transantarctic Mountain Front which we relate to the effects of extensional tectonics and related volcanism [36]. From the consistency of the rates obtained by these two different methods, we conclude that uplift of the TAM in this area has occurred at an average rate of 100 ± 5 m/Ma since about 50 Ma.

This uplift and erosion rate for the TAM is similar to a rate of 100–200 m/Ma determined by Kohn and Eyal [41] for the Sinai Peninsula bordering the Red Sea, also in an extensional tectonic regime. In contrast, and as one would expect, uplift rates for compressional orogenic environments are commonly an order of magnitude greater. Zeitler et al. [42] determined a Quaternary uplift rate of 1000 m/Ma for the Nanga Parbat region of the Himalayas and similarly Nelson [43] calculated a rate of 500–1500 m/Ma for the major post-Cretaceous uplift phase of the Cordillera Darwin in the southern Andes, although this slowed to a post-tectonic uplift rate of 50–200 m/Ma. In the European Alps, Clark and Jäger [44] calculated a mean uplift rate of 400–1000 m/Ma which compares well to uplift rates determined by Wagner et al. [45] on a number of different tectonic blocks in the Central Alps which ranged from 200 to 1300 m/Ma. In the Lepontine Alps, Hurford [46] determined a late Neogene/Recent mean uplift rate of 500 m/Ma with local rates up to 2200 m/Ma. The Southern Alps of New Zealand lying along an active obliquely-compressive plate boundary have uplift rates calculated to be as high as 10,000 m/Ma [47].

4. Structure of the mountain range

Recognition of the significance of the "break in slope" in this way allows the apatite ages on the shallow upper part of the age-elevation profile to be used as indicators of palaeodepth in the pre-uplift crust (Fig. 8). A particular apatite age of, say, 90 Ma can be taken to indicate a similar palaeocrustal depth wherever it is found. The elevations

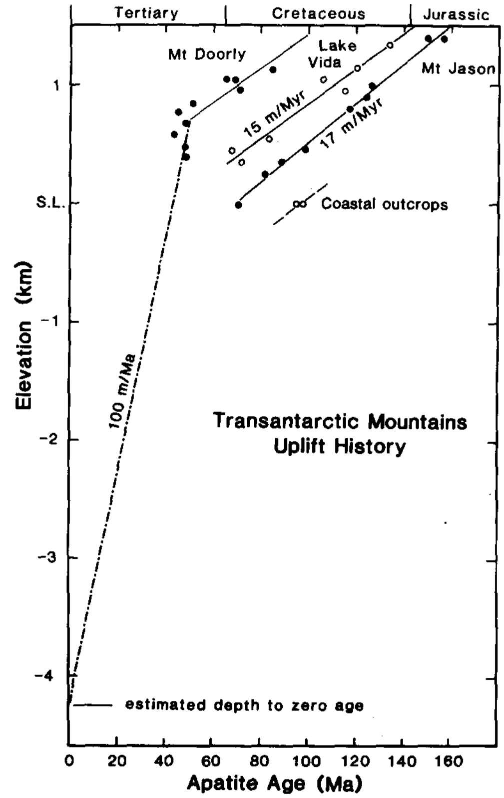

Fig. 8. Apatite fission track ages plotted against sample elevation for all profiles, except Mt. Newall. Results from Lake Vida are from [20]. This shows the relative offset in the profiles due to relative amounts of uplift as well as faulting.

of such points in the present-day mountains can then be used to reconstruct the structural evolution of the range. The much steeper gradient in relation to the uncertainties in measured age below the "break in slope" preclude the precise use of apatite ages for this purpose. In essence we are using the variation in age along a horizontal traverse through the TAM and tied to a reference age to infer the structure of the range. This is illustrated in Fig. 9, and the reference used is that of the coastal samples at sea level which have an average age of 96 Ma. Extrapolation of this reference isochron intersects the various vertical sampling profiles at different elevations which then represent the amount of relative uplift across the mountain range. Profiles well inland lie at a low elevation because they have not been uplifted as much as samples lying closer to the coast. The coastal samples on the other hand lie at a low elevation because they have been down-faulted relative to Mt. Doorly across the mountain front.

The structure of the TAM in this region is therefore that of a large tilt block with the axis of maximum uplift, which although not definitively located, lying some 30 km inland of the Victoria Land coast. This axis is just inland of Mt. Doorly, which lies within the step-faulted frontal zone. From this axis of maximum uplift the mountains dip gently westwards at 1–2° to eventually disappear under the polar ice-cap. Progressively thicker sections of Beacon strata are preserved further inland, so that although the amount of uplift decreases to the west, the elevation of the mountains increases until they pass under the ice-cap some 80–100 km inland at an elevation of about 2000 m.

The time of initiation of uplift of the TAM in the early Cenozoic has a number of significant consequences. If the establishment of an ice-cap on East Antarctica occurred near 25 Ma [34], then it means that valley glaciers forming on an embryonic mountain range before that time were probably the precursors of that ice sheet, as was suggested by Drewry [14]. Another, perhaps more important consequence is that the uplift of the TAM can now be related temporally as well as spatially to the subsidence and formation of sedimentary basins within the Ross Embayment.

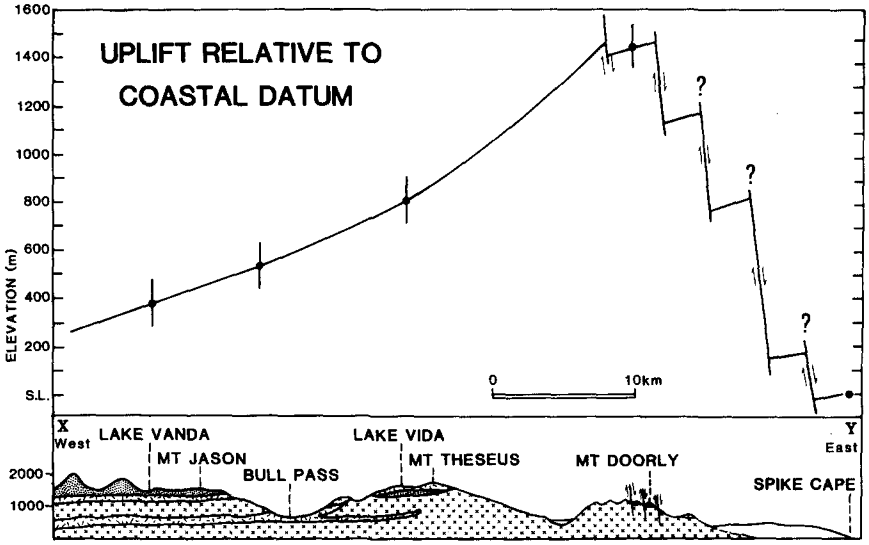

Fig. 9. Diagram showing the structure of the Transantarctic Mountains in the Dry Valley area and uplift relative to a coastal datum. The line *X-Y* is marked in Fig. 1. This diagram is constructed from Fig. 8 by extrapolating an isochron from the coastal samples at sea level and then plotting the elevation of the intersection of the different sampling profiles with lateral position. The resulting profile of relative uplift reflects the structure of the range and gives the total uplift by adding the approximately 4 km of known section above the reference isochron. This structure agrees with that inferred from the geology of the area, especially the attitude of the Kukri Peneplain and the basement and peneplain dolerite sills. The apatite age of the sample near Lake Vanda is from Gleadow et al. [20], but note that this age has not been plotted separately on the apatite age-elevation diagram in Fig. 8 that was used to construct this cross-section.

Combining this with recent advances in the field of extensional tectonics, Fitzgerald et al. [1] have presented a model that can account for the parallel but contrasting geological histories of the TAM and the Ross Embayment. They suggest that the uplift of the TAM and subsidence of the Ross Embayment are a result of passive rifting governed by a shallow crustal penetrative detachment zone that dips westward beneath the Transantarctic Mountain Front. Simply put, there has been crustal thinning and subsidence in the Ross Embayment due to extension at crustal levels, whereas beneath the TAM extension is largely confined to the subcrustal lithosphere resulting in uplift. The detachment fault allows the transfer of strain from crustal levels in the Ross Embayment to deeper levels beneath the mountains.

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