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Geochronology of Cretaceous granites and metasedimentary basement on Edward VII Peninsula, Marie Byrd Land, West Antarctica

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Abstract: Rb-Sr ages of Swanson Formation on Edward VII Peninsula, West Antarctica, indicate a late Ordovician age, 421–432 Ma for regional metamorphism. K-Ar ages of 113–440 Ma, reflect a second thermal metamorphism during emplacement of widespread Cretaceous granites. Rb-Sr ages of five monzogranite/syenogranitic plutons of Byrd Coast Granite are in the range 95–105 Ma (initial $^{87}Sr/^{86}Sr$ ratios 0.710–0.715) and represent stages of crystallization of anorogenic granite (A subtype). These correlate with Byrd Coast Granite (100–110 Ma) farther east in Marie Byrd Land, and with Cretaceous granitoids on the Campbell Plateau and in southern New Zealand. K-Ar mica/hornblende and fission-track apatite/zircon ages indicate that regional cooling began *c.* 90–100 M.y. ago immediately after granite emplacement. Uplift continued throughout the peninsula during the period 55–100 Ma (late Cretaceous–early Tertiary), associated with regional uplift in the rift-drift stages of Gondwana break-up at the South-west Pacific spreading centre. Apatite fission track ages show that during late Cretaceous-early Tertiary time the peninsula behaved as two blocks. The Alexandra Mountains were exhumed 20 m.y. before the Rockefeller Mountains and are possibly separated by a fault active initially in the mid-Cretaceous or earlier, and later reactivated in the late Cretaceous-early Tertiary. An averaged uplift rate (50–100 Ma) of 0.025 mm yr^{-1} is characteristic of the inferred intra-plate tectonic setting.

Key words: West Antarctica, K-Ar dating, Rb-Sr dating, fission-track dating, granites, Palaeozoic, Cretaceous, Cenozoic

Introduction

Edward VII Peninsula is the western-most part of Marie Byrd Land which extends from the Ross Sea to the Antarctica Peninsula (Fig. 1). It was close to a former junction of four continental fragments at the Pacific margin of Gondwana, i.e. southern New Zealand/Campbell Plateau; south-east Australia (Tasmania); northern Victoria Land (East Antarctica) and Marie Byrd Land (West Antarctica) (see Grindley & Davey 1982, figs 2.1, 2.2). Geochronological studies of granites and metamorphic basement are reported here:

i) to establish the history of metamorphism, plutonism and subsequent uplift on Edward VII Peninsula,

ii) to compare this with those regions formerly adjacent, and

iii) to examine the nature and timing of Mesozoic/Cenozoic continental break-up and drift.

Geological outline

Early geological mapping of Edward VII Peninsula by American expeditions (1933–1935), recognized a division into unfossiliferous metasediments and leucogranites that invade them (Wade 1945, Wade *et al.* 1977a). K-Ar biotite ages of 92–104 Ma (Wade 1969) (94–107 Ma when recalculated using modern constants) indicate a mid-

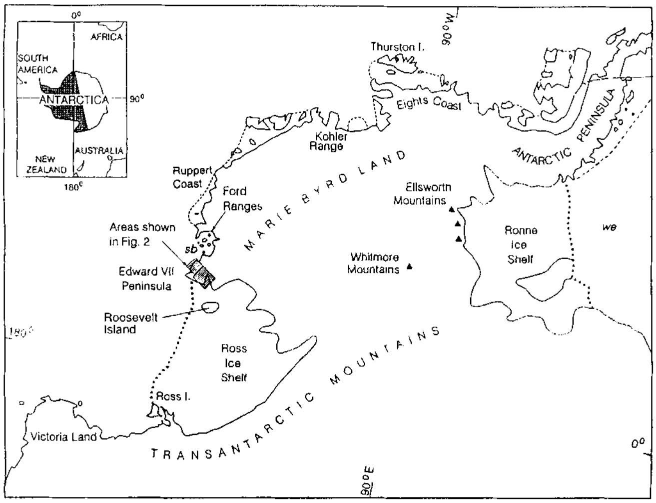

Fig. 1. Schematic map of West Antarctica, showing location of the study area and some localities mentioned in text, sb = Sulzberger Bay, we = Weddell Sea.

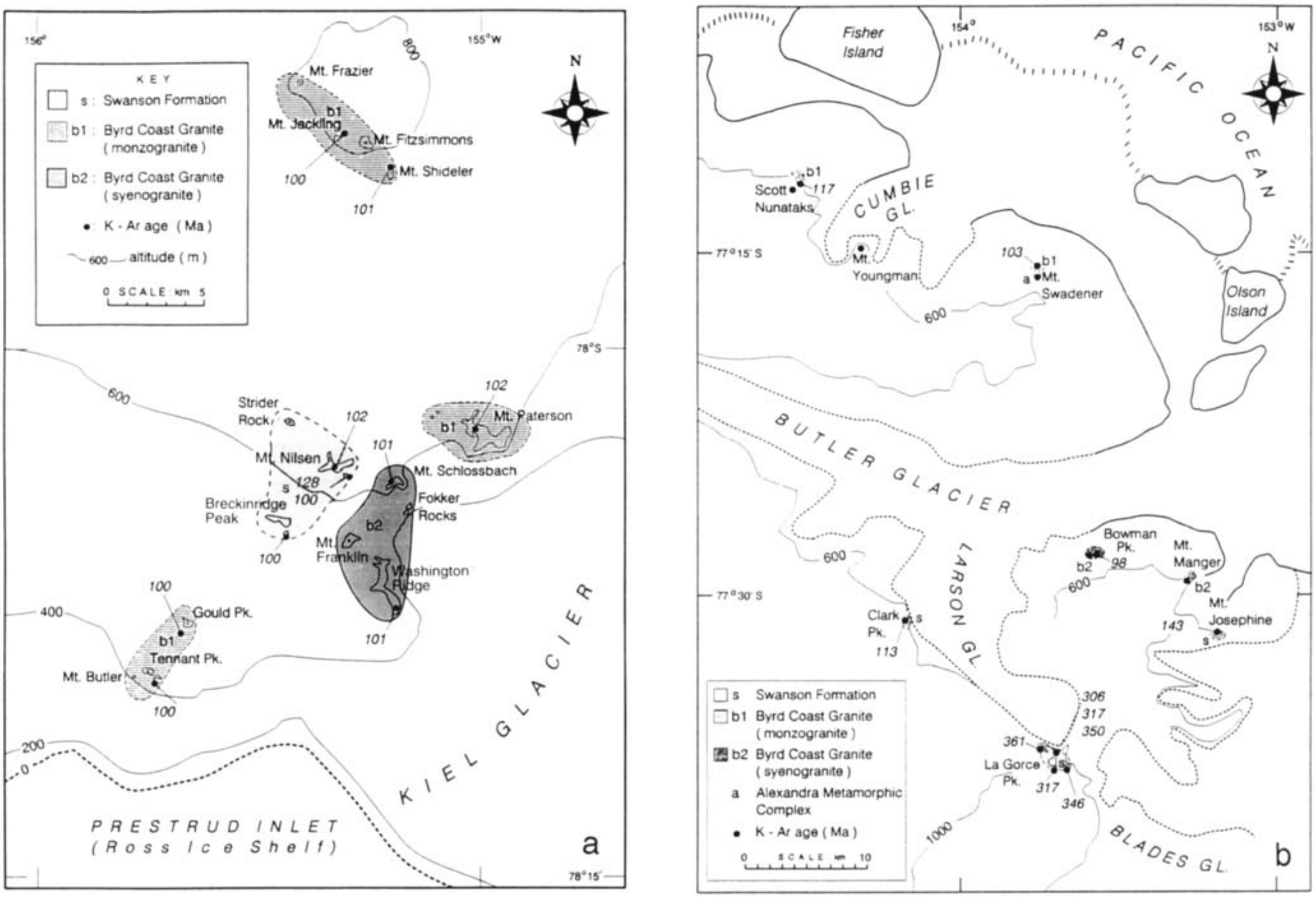

Fig. 2. Geological maps of **a.** Rockefeller Mountains, and **b.** Alexandra Mountains, Edward VII Peninsula, Marie Byrd Land.

Cretaceous age for this plutonism and associated contact metamorphism.

A New Zealand Antarctic Research Programme expedition revisited the peninsula in 1987–88, amended some of the mapping of the Rockefeller Mountains (Fig. 2a) and, in particular, made new observations of migmatite in the Alexandra Mountains (Fig. 2b). The distribution of granitoids/ metasediments/migmatites are shown in Fig. 2a & b and discussed in Adams *et al.* (1989). Laboratory studies have concentrated on the granitoid geochemistry in a regional tectonic setting (Weaver *et al.* 1991, 1992) and geochronological comparisons with high-grade migmatites and low-grade metasedimentary equivalents (Adams & Weaver 1990).

The low-grade (sub-greenschist facies) greywacke/ siltstone/ argillite meta-turbidites are very similar to those of the widespread Swanson Formation in the Ford Ranges, 250 km to the east. Swanson Formation is everywhere unfossiliferous, with the exception of trace fossil which suggest a possible post-Cambrian age (Bradshaw *et al.* 1983). These and *c.* 450 Ma ages for low-grade metamorphism place a younger mid-late Ordovician age limit for sedimentation (Adams 1986). The highest grade (greenschist facies) psammitic metasediments occur at Mount Nilsen (Fig. 2a).

The granites, with few exceptions, are similar to Byrd Coast Granite in the Ford Ranges (Wade *et al.* 1977b, Adams 1987, Weaver *et al.* 1991) and occur across Edward VII Peninsula as two groups of plutons of two types, i.e. coarse, leucocratic monzogranite (b1) and syenogranite (b2). Where seen, the contacts are sharp, with biotite hornfels in Swanson Formation metasediments.

At Scott Nunataks and Mount Swadener (Fig. 2a & b) there is a unique high-grade paragneiss-migmatite complex (Alexandra Metamorphic Complex), which in local steep outcrops shows a mixture of paragneiss (possibly Swanson Formation) with heterogeneous biotite-granitoids, probably variants of Byrd Coast Granite (Adams *et al.* 1989). This shows petrographic/structural similarities with the Fosdick Metamorphic Complex in the Ford Ranges (Wilbanks 1972).

The lower grade of metasediments at Drummond Peak and textural characteristics (sharp contacts) of the Rockefeller Mountains granites indicate a high structural level for the central/south-west sector of the peninsula. This contrasts with more deep-seated high-grade equivalents limited to a horst-like block between Butler Glacier and the north-east coast (Fig. 2b). A significant bathymetric depression (>1000m) may imply an important boundary between this and the Ford Ranges to the west.

Geochronological studies

Sampling was done from *c.* 50 m, outcrop areas from which 15–20, 1–2 kg representative samples were collected.

Technical details of Rb-Sr, K-Ar and fission-track dating methods are given in Adams (1975, 1986, 1987) and Seward (1989). K was determined (±1%) by an ion-exchange separation/flame spectrophotometric technique. Ar measurements were made on a stainless steel UHV preparation system and an automated AEI MS10 mass spectrometer. Rb and Sr were determined by an XRF technique on powdered pellets against international standards, except where concentrations were less than 10–20 when isotope dilution (using ^{87}Sr, ^{85}Rb tracers) analysis was preferred. Sr isotopic compositions were measured on a modified VG MM30B mass spectrometer. Relevant analytical data, with notes on sample type, location and altitude are given in Tables I–III. Decay constants used throughout are those recommended by Steiger & Jäger. (1977), and Rb-Sr isochron ages were calculated according to York (1966). For Rb-Sr age calculations, uniform one-sigma errors of ±1% in Rb/Sr ratios and ±0.07% for $^{87}Sr/^{86}Sr$ ratios are applied. All age errors are quoted at the 95% confidence level. The zeta approach recommended by Hurford & Green (1983) was used for all fission track determinations and all apatite track length measurements are of horizontal confined tracks (Green 1981). The interpreted ages are referred to the time-scale of Harland *et al.* (1990).

Table I. Rb-Sr whole-rock isochron age data, Swanson Formation.

IGNS No.	Field No.	Sample(1)	Rb ppm	Sr ppm	87Rb/86Sr	87Sr/86Sr	e(2)
1) Drummond Peak 77°37'S; 153°58'W at alt 780m							
13150	E7A1	gw	97.90	170.6	1.664	0.72547	7
13151	E7A2	phyll	307.3	75.50	11.86	0.77453	5
13152	E7A3	sl	184.3	80.20	6.683	0.75738	5
13153	E7A4	sl	452.2	82.50	5.361	0.74957	6
13154	E7A5	sl	219.8	53.40	12.01	0.78842	6
13155	E7A6	sl/zst	189.9	95.60	5.772	0.74940	6
13156	E7A7	phyll	46.40	186.4	0.721	0.72189	6
13157	E7A8	sl	164.2	71.10	6.718	0.75818	9
13158	E7A9	phyll	122.7	126.4	2.817	0.73483	7
13159	E7A10	sl	235.3	109.4	6.252	0.75357	6
13160	E7A11	gw	88.90	185.2	1.392	0.72422	5
13161	E7A12	sl/zst	165.6	90.10	5.341	0.74765	6
2) La Gorce Peak 77°37'S; 153°41'W at alt 1030m							
13162	E7A13	phyll	122.4	105.3	3.376	0.74077	9
13163	E7A14	gw	115.8	117.1	2.870	0.73636	4
13164	E7A15	sl	276.8	60.30	13.40	0.79294	4
13166	E7A17	sl	308.1	29.10	31.22	0.90270	9
13168	E7A19	sl	171.3	107.7	4.622	0.75044	5
13169	E7A19A	sl	274.3	37.90	21.23	0.84525	11
13170	E7A20	sl	239.6	40.80	17.19	0.82655	3
13171	E7A21	sl	281.0	82.70	9.905	0.77858	5
13174	E7A24	gw	109.1	123.4	2.567	0.73671	4
13175	E7A25	gw	112.8	138.1	2.371	0.73682	4
13176	E7A26	gw	218.6	56.50	11.29	0.78863	6
13178	E7A27A	sl	187.4	53.80	10.16	0.78505	8
3) Mount Nilsen 78°03'S; 155°18'W at alt 620m							
13228	E7A76	sch	89.30	152.4	1.702	0.72984	7
13229	E7A77	bi-gn	147.4	165.7	2.582	0.73624	6
13230	E7A78	bi-gn	173.3	159.8	3.148	0.73868	5
13231	E7A79	bi-gn	154.4	161.1	2.782	0.73731	6
13236	E7A84	bi-gn	124.2	122.1	2.953	0.73874	6
13237	E7A85	sch	242.2	173.7	4.051	0.74443	8
13238	E7A86	sch	153.3	146.2	3.044	0.73939	7
13244	E7A92	gw	73.50	102.8	2.074	0.73204	6
13245	E7A93	sch	193.8	254.8	2.206	0.73220	3
13248	E7A96	sch	175.9	134.4	3.802	0.74420	4
13249	E7A97	ca-hf	20.80	107.7	0.560	0.72283	6
13250	E7A98	ca-hf	5.000	100.6	0.144	0.72110	6

1) gw = metagreywacke; zst = metasiltstone; sl = slate; sch = schist; phyll = phyllite bi-gn = biotite-gneiss; ca-hf = calc-silicate hornfel. 2) e = 87Sr/86Sr precision (95% confidence level), x10E+5.

Metamorphic age of the Swanson Formation

Swanson Formation metasediments are best exposed in the Alexandra Mountains, where there are several ridges around La Gorce Peak (Fig. 2b) and to the north at Clark Peak adjacent to the Bowman Peak pluton. They also occur on the isolated Drummond Peak nunatak near the centre of Edward VIII Peninsula. At their lowest metamorphic grade, they are sub-greenschist facies metagreywacke (dominant), phyllite and slate. Metasiltstone horizons commonly contain ovoid concretions of impure carbonate. There is rare incipient (thermal metamorphic) spotting in some slates. At Clark Peak, adjacent to microgranite, meta-siltstones and calcareous carbonate concretions are recrystallizsed to biotite-hornfels and amphibole ± diopside-calc-silicate hornfels.

At Mount Nilsen in the Rockefeller Mountains, Swanson Formation is at a higher greenschist facies grade, with meta-psammite (dominant), quartzo-feldspathic-biotite schist and paragneissic variations showing significant metamorphic segregation (1–5 mm) of micaceous and quartz-feldspar laminae and zoned biotite/epidote/amphibole/diopside/anorthite/calc-silicate assemblages in calcareous concretions.

K-Ar total rock (slate), biotite/hornblende (schist) ages from the Swanson Formation (Table III) vary widely from 113–440 Ma reflecting, in part, the pervasive thermal influence of Cretaceous granitoids. The Clark Peak sample E7A38 is within the thermal aureole of the granites, and has an age of 113 ± 3 Ma. More generally, samples below an altitude of 600 m yield younger ages, e.g. Mount Nilsen E7A135bi, (100 ± 2) Ma and Breckinridge Peak E7A119bi, (100 ± 2) Ma. Outside the thermal aureoles, the ages increase, e.g. Mount Josephine E7A28, (143 ± 2) Ma, and at higher altitude at Drummond and La Gorce Peaks (770/1100 m), there are older ages of 350–440 Ma and 306–361 Ma, respectively. At Drummond Peak, which represents perhaps the highest structural level, there are ages of 440 ± 6, 429 ± 5 (E7A11), similar to the Rb-Sr whole-rock age of metamorphism (see below).

Table II. Rb-Sr whole-rock age data; Byrd Coast Granite.

IGNS No.	Field No.	Sample(1)	Rb ppm	Sr ppm	87Rb/86Sr	87Sr/86Sr	e(2)
1) Mount Butler, 78°09'S 155°47'W; Mount Tennant, 78°09'S 155°44'W; Gould Peak, 78°08' 155°40'W							
13274	E7A122	bi-gte (TP)	296.9	92.30	9.324	0.72529	6
13275	E7A123	l-gte (TP)	293.3	16.80	50.90	0.78220	11
13276	E7A124	bi-gte (MB)	268.5	117.7	6.611	0.72130	7
13277	E7A125	l-gte (MB)	307.6	93.50	9.539	0.72597	6
13278	E7A126	bi-gte (TP)	294.9	68.10	12.56	0.73027	8
13281	E7A129	bi-gte (GP)	365.2	33.80	31.42	0.75558	9
13282	E7A130	bi-gte (GP)	424.1	55.70	22.11	0.74268	10
2) Washington Ridge, 78°08'S 155°11'W ; Mount Franklin 78°05'S 155°18'W; Mount Schlossbach, 78°04'S 155°12'W							
13251	E7A99	m-gte (MF)	574.6	8.56	199.4	0.97906	7
13252	E7A100	m-gte (MF)	552.4	8.99	182.1	0.95427	30
13254	E7A102	l-gte (MF)	551.7	6.94	237.4	1.02902	11
13255	E7A103	m-gte (MF)	625.4	3.82	504.0	1.38672	9
13256	E7A104	m-gte (MS)	826.7	2.02	1404	2.63567	15
13257	E7A105	l-gte (MS)	259.6	3.33	232.9	1.02774	20
13258	E7A106	l-gte (MS)	685.8	3.91	546.4	1.44769	15
13259	E7A107	l-gte (MS)	869.7	1.66	1898	3.29090	50
13261	E7A109	bi-gte (FR)	897.5	3.79	756.9	1.75738	11
13262	E7A110	l-gte (WR)	659.6	5.57	359.6	1.20127	11
13263	E7A111	l-gte (WR)	719.9	3.14	728.1	1.68290	12
13264	E7A112	m-gte (WR)	676.7	3.75	561.0	1.47291	22
13265	E7A113	l-gte (WR)	664.7	5.3	381.6	1.22960	22
13266	E7A114	l-gte (WR)	617.5	9.72	189.0	0.99166	21
3) Mount Paterson 78°02'S 155°00'W							
13288	E7A136	l-gte	220.1	84.30	7.575	0.72246	6
13289	E7A137	l-gte	261.8	108.8	6.975	0.72141	7
13290	E7A138	l-gte	336.2	134.7	7.238	0.72205	8
13291*	E7A139	peg.dyke	1109	16.71	197.2	0.98333	16
13292	E7A140	l-gte	256.4	80.60	9.231	0.72541	7
13293	E7A141	l-gte	326.3	54.00	17.54	0.73664	6
13293'	E7W92	l-gte	280.0	89.00	9.124	0.72567	7
13294	E7A142	bi-gte	289.9	62.10	13.54	0.73112	7
13294'	E7W93	bi-gte	330.0	51.46	18.62	0.73934	5

Rb-Sr whole-rock isochron data for the Swanson Formation are shown in Fig. 3. The Drummond Peak data set exclude three phyllitic samples (E7A2, E7A7, E7A9) which have young, *c.* 350 Ma, K-Ar ages nearby and do not fall close to the main data array (Fig. 3 isochron 2). The isochron age, 432 ± 14 Ma (initial $^{87}Sr/^{86}Sr$ ratio = 0.7155 ± 6), has an MSWD = 8.5, which denotes an errorchron rather than isochron and implies incomplete Sr isotopic homogenization at the time of metamorphism or variable degree of closed system behaviour subsequently.

Similar data for La Gorce Peak (north-east ridge) (Fig. 3, isochron 1) yield an isochron age of 421 ± 23 (initial ^{87}Sr ^{86}Sr = 0.7214 ± 22) but with an MSWD = 19.0. (This excludes data point E7A15 which clearly does not lie within the main array. The reason for this is unclear, but the lowest parts of this ridge yield the minimum, *c.* 306 Ma, K-Ar ages.) Data for La Gorce (north-west ridge) are shown on the same isochron diagram (Fig. 3, isochron 1) but, although approximately co-linear with north-east ridge data, they are not included in the isochron age calculation. Like Drummond Peak, the MSWD is considerably lower (11.6), and the age slightly reduced (to 416 ± 16 Ma (initial $^{87}Sr/^{86}Sr$ = 0.7215 ± 12)), if sample E7A14 is excluded from the isochron age calculation. The rock is a fine, weakly foliated metagreywacke, which may have incompletely homogenized isotopically with adjacent finer lithologies.

Finally, Rb-Sr whole-rock data for Mount Nilsen (Fig. 3, isochron 3) have a considerably smaller Rb-Sr range and increased analytical scatter; the isochron age is 430 ± 21 Ma (initial $^{87}Sr/^{86}Sr$ ratio = 0.7198 ± 5) and MSWD = 31.3. Part

Table II. Cont.

IGNS No.	Field No.	Sample(1)	Rb ppm	Sr ppm	87Rb/86Sr	87Sr/86Sr	e(2)
4) Mount Frazier, 77°53'S 155°25'W; Mount Jackling, 77°54'S 155°19'W; Mount Fitzsimmons 77°54'S 155°17'W ; Mount Shideler 77°55'S 155°12'W							
13296	E7A144	bi-gte(SH)	409.5	51.5	23.11	0.74457	6
13297	E7A145	bi-gte(SH)	361.8	56.7	18.53	0.73889	7
13298	E7A146	bi-gte(FZ)	396.3	79.4	14.50	0.73241	11
13299	E7A147	bi-gte(FZ)	441.8	49.6	24.28	0.74622	6
13300	E7A148	bi-gte(FZ)	405.6	63.5	18.56	0.73827	6
13301	E7A149	bi-gte(FZ)	435.1	65.8	19.19	0.73864	6
13302	E7A150	l-gte(FZ)	455.3	60.5	21.86	0.74247	7
13303	E7A151	bi-gte(MJ)	357.3	93.6	11.03	0.72798	7
13304**	E7A152	bi-gte(MJ)	379.4	74.9	14.74	0.73196	10
13305	E7A153	bi-gte(MJ)	258.4	56.9	13.68	0.73210	6
13306	E7A154	bi-gte(FR)	326.3	72.7	13.02	0.73042	7
5) Bowman Peak 77°28'S 153°30'W; Clark Peak 77°32'S 154°11'W							
13181	E7A30	l-gte(BP)	483.1	24.12	58.46	0.79405	9
13181'	E7W10	l-gte(BP)	415.8	24.35	49.78	0.78199	37
13182	E7A31	l-gte(BP)	396.3	9.440	123.7	0.89253	20
13182'	E7W12	l-gte(BP)	465.2	7.100	194.7	0.98063	20
13183	E7A13A	l-gte(BP)	398.8	9.570	122.8	0.88950	8
13183'	E7W13	l-gte(BP)	433.2	11.14	114.4	0.87226	20
13184	E7A32	l-gte(BP)	480.7	12.30	115.1	0.88207	6
13185	E7A33	l-gte(BP)	453.0	17.28	76.73	0.82195	10
13185'	E7W14	l-gte(BP)	486.1	17.47	81.53	0.83159	6
13191	E7A39	m-gte(CP)	508.1	13.54	110.4	0.87476	6
6) Mount Nilsen 78°03'S 155°21'W; Breckinridge Peak 78°05'S 155°29'W (Minor Intrusives)							
13225	E7A73	g-di(MN)	252.1	199.9	3.655	0.71663	6
13225'	E7W36	g-di(MN)	240.0	198.0	3.510	0.71620	1
13234	E7A82	l-gte(MN)	222.2	271.4	2.371	0.71202	6
13234'	E7W40	l-gte(MN)	206.0	194.0	3.075	0.71443	2
13443	E7W52	l-gte(MN)	199.0	135.0	4.272	0.71850	2
13267	E7A115	g-di(BR)	266.5	114.1	6.822	0.72265	6
13267'	E7W77	g-di(BR)	278.0	115.0	7.008	0.72315	2
13268	E7A116	g-di(BR)	271.7	106.2	7.417	0.72369	5
13269'	E7W80	l-gte(BR)	232.0	231.0	2.909	0.71265	1
13273'	E7W81	l-gte(BR)	186.0	188.0	2.865	0.71400	5

1) Sample Types : bi-gte = biotite-granite; g-di = granodiorite ; l-gte = leuco-granite m-gte = micro-granite; peg = pegmatite. Locations: BP = Bowman Pk.; BK = breckinridge Pk. ; CP = Clark Pk. ; FR = Mt. Frazier ; FZ = Mt Fitzsimmons ; GP = Gould Pk ; MB = Mt Butler ; MF = Mt Franklin ; MJ = Mt. Jackling; MN = Mt. Nilsen ; MS = Mt. Schlossbach ; TP = Tennant Pk .; WR = Washington Ridge. 2) Precision error 87Sr/86Sr (two standard deviations), x1.0E+5.
* R13291 is cross-cutting dyke; data not included in isochron age calculation. Single Rb/Sr age is 97±2Ma (assuming initial 87Sr/86Sr = 0.700) **R13304 is crosscutting dyke; data not included in isochron age calculation.

Table III. K-Ar age data ; Edward VII Peninsula.

IGNS R No.	Field No.	Sample(1)	Location	Lat	Long	Kwt%	40Ar(rad)nl/g	40Ar(rad)%	Age(Ma)
1) Swanson Formation									
13151tr	E7A2	phyll	Drummond Pk	77°37'S	153°58'W	4.43	66.49	95	351±6
13154tr	E7A5	sl	Drummond Pk	77°37'S	153°58'W	3.81	73.65	98	440±6
13155tr	E7A6	sl/zst	Drummond Pk	77°37'S	153°58'W	3.27	50.96	98	363±6
13159tr	E7A10	sl	Drummond Pk	77°37'S	153°58'W	3.79	62.80	98	383±7
13160tr	E7A11	sl/zst	Drummond Pk	77°37'S	153°58'W	1.44	27.05	89	429±5
13162tr	E7A13	phyll	La Gorce Pk	77°37'S	153°41'W	2.10	28.25	96	317±4
13166tr	E7A17	sl	La Gorce Pk	77°37'S	153°41'W	4.91	63.55	97	306±4
13169tr	E7A19A	sl/zst	La Gorce Pk	77°37'S	153°41'W	4.35	58.52	94	317±7
13173tr	E7A23	sl	La Gorce Pk	77°37'S	153°41'W	3.09	46.17	98	350±4
13176tr	E7A26	sl	La Gorce Pk	77°37'S	153°41'W	3.61	55.83	88	361±7
13178tr	E7A27A	sl	La Gorce Pk	77°37'S	153°41'W	3.27	48.32	98	346±4
13287hb	E7A135	hb-gn	Mt Nilsen	78°03'S	155°18'W	0.82	4.237	68	128±2
13287bi	E7A135	hb-gn	Mt Nilsen	78°03'S	155°18'W	6.05	24.20	95	100±2
13179tr	E7A28	zst	Mt Josphine	77°32'S	153°06'W	4.10	23.69	58	143±2
13190tr	E7A38	hf	Clark Pk	77°32'S	154°11'W	4.51	20.35	86	113±3
13210bi	E7A58	bi-gn	Scott Nunataks	77°12'S	154°33'W	7.10	33.27	95	117±2
13271bi	E7A119	sch	Breckinridge Pk	78°05'S	155°29'W	7.71	30.74	93	100±2
2) Byrd Coast Granite									
13274bi	E7A122	bi-gte	Tennant Pk	78°09'S	155°44'W	6.08	24.33	96	100±2
13280mu	E7A128	peg	Gould Pk	78°08'S	155°41'W	8.31	33.00	74	100±2
13258bi	E7A106	l-gte	Mt Schlossbach	78°04'S	155°14'W	7.08	281.61	91	101±2
13266bi	E7A114	l-gte	Washington Ridge	78°08'S	155°11'W	6.63	25.22	89	101±2
13289bi	E7A137	l-gte	Mt Paterson	78°02'S	155°03'W	2.83	11.49	85	102±2
13296bi	E7A144	bi-gte	Mt Schideler	77°55'S	155°12'W	7.07	28.46	92	101±2
13300bi	E7A148	bi-gte	Mt Fitzsimmons	77°54'S	155°17'W	7.48	29.91	91	100±2
13181bi	E7A30	l-gte	Bowman Pk	77°28'S	153°30'W	4.94	21.32	89	98±2
13225bi	E7A73	g-di	Mt Nilsen	78°03'S	153°21'W	7.19	29.21	90	102±2
13273bi	E7A121	l-gte	Breckinridge Pk	78°06'S	155°27'W	6.48	26.25	90	102±2
13198bi	E7A46	bi-gte	Mt Swadener	77°16'S	153°47'W	7.29	30.03	93	103±2

Notes: tr = total rock; bi = biotite; hb = hornblende; mu = muscovite. 1) bi-gte = biotite-granite; bi-gneiss = biotite-gneiss; g-di = granodiorite; l-gte = leuco-granite; phyll = phyllite. 2) sch = mica-schist; peg = pegmatite; st = slate; zst = metasiltstone.

of the 'geological' scatter contributing to the isochron precision is the pervasive presence of conspicuous calc-silicate-schists (formerly carbonate concretions) within metapsammites, which may have only partially homogenized isotopically with their host rocks.

The Rb-Sr and K-Ar ages thus both point to a *c.* 430 Ma (late Ordovician) metamorphism for the Swanson Formation, similar to that in the Ford Ranges. Owing to the pervasive later thermal overprinting it is impossible to establish the subsequent early uplift/cooling history. Over 400 km farther to the east, on the Ruppert Coast, shallow-water Devonian sediments and associated volcanic rocks have been reported (Grindley & Mildenhall, 1980) which imply a substantial degree of uplift and erosion, before *c.* 380 Ma, of older basement in this region.

Comparisons with northern Victoria Land

The Swanson Formation is broadly similar to the Robertson Bay Group of northern Victoria Land (Fig. 1) (Bradshaw *et al.* 1983). They are both metaturbidite sequences with similar compositions, geochemistry and structural style. Swanson Formation initial $^{87}Sr/^{86}Sr$ ratios at the time of metamorphism appear to have been quite uniform (0.716–0.720) over large areas and comparable with Robertson Bay Group values, 0.716–0.718 (at 490 Ma) (C.J. Adams, unpublished data). The two sedimentary units clearly had similar source areas. The main distinction is the time at which they underwent low-grade regional metamorphism: the Swanson Formation, like its New Zealand analogue, the Greenland Group (Adams *et al.* 1975), was metamorphosed *c.* 430 M.y. ago (early Silurian), whereas metamorphism of the Robertson Bay Group was everywhere early Ordovician (Adams & Kreuzer 1984). This suggests that the Swanson Formation (and Greenland Group of New Zealand) could be younger than Robertson Bay Group and lie within a younger tectonic belt confined to the outer margin of Gondwana (see Adams 1986, fig. 7) and thus not be direct correlatives. There is also the possibility that Swanson Formation is derived from sedimentary cycling of a Robertson Bay source.

Emplacement age of the Byrd Coast Granite of Edward VII Peninsula

For the purposes of age, isotopic and geochemical study of the Byrd Coast Granite (Wade *et al.* 1977a), Adams *et al.* (1989) and Weaver *et al.* (1992) grouped the Edward VII Peninsula granitoids into five, small (10–20 km) plutons, i.e. from south to north :

i) Butler (Tennant/Gould)

ii) Washington (Franklin/Schlossbach)

iii) Paterson

iv) Frazier (Jackling/Fitzsimmons/Shideler), and

v) Bowman (Clark).

Minor intrusive granite sheets occur on Mount Nilsen, Breckinridge Peak and Strider Rock (Fig. 2a) and are also intimately associated with migmatite at Mount Swadener and Scott Nunataks (Fig. 2b). The Washington and Bowman plutons are buff equigranular, leucocratic syenogranites, whereas the Frazier/Paterson/Butler plutons are darker, porphyritic biotite-monzogranites. The relationship between the two types is nowhere seen (the only contact of syenogranite is with biotite-hornfels at Mount Franklin). All the plutons are uniform and xenoliths are usually absent. Miarolitic cavities (Mount Schlossbach) and very sharp marginal contacts (Mount Franklin) and the high-degree of geochemical fractionation all suggest a high-level of emplacement and subsequent rapid cooling.

Rb-Sr whole-rock isochron data (Table II) for the five plutons are shown in Fig. 4a & b, with isochron ages as follows: i) Butler, 97 ± 3 Ma (i = 0.7124 ± 5); ii) Washington, 95 ± 3 Ma (i = 0.7150 ± 122); iii) Paterson, 105 ± 7 Ma (i = 0.7113 ± 10); iv) Frazier, 97 ± 4 Ma (i = 0.7128 ± 10); v) Bowman, 102 ± 4 Ma (i = 0.7100 ± 53). The Rb-Sr data sets have high (3–10) to very high (80–300) Rb/Sr ratios which therefore make precise estimation of initial $^{87}Sr/^{86}Sr$ very difficult. In every case (Table III) the K-Ar biotite (and muscovite) ages of granites (and pegmatite) from each pluton are concordant with Rb-Sr whole-rock isochron ages, indicating rapid cooling after emplacement. There are no significant differences between the pluton ages, confirming the general geochemical conclusion that syeno- and monzogranite types simply reflect a co-genetic suite displaying different fractionation stages.

Weaver *et al.* (1992) argued that the geochemical and isotopic characteristics of these plutons point to an A-subtype originating from an I-type source. From the relatively high, $^{87}Sr/^{86}Sr$ initial ratios and consideration of Sm-Nd isotopes, it was inferred that the latter may have been related to the late Devonian–early Carboniferous*c.* 375 Ma) Ford Granodiorite, which is well exposed in the Ford Ranges, 250 km to the east (Adams 1987, Weaver *et al.* 1991). However, no Ford Granodiorite occurs on Edward VII Peninsula. It is also

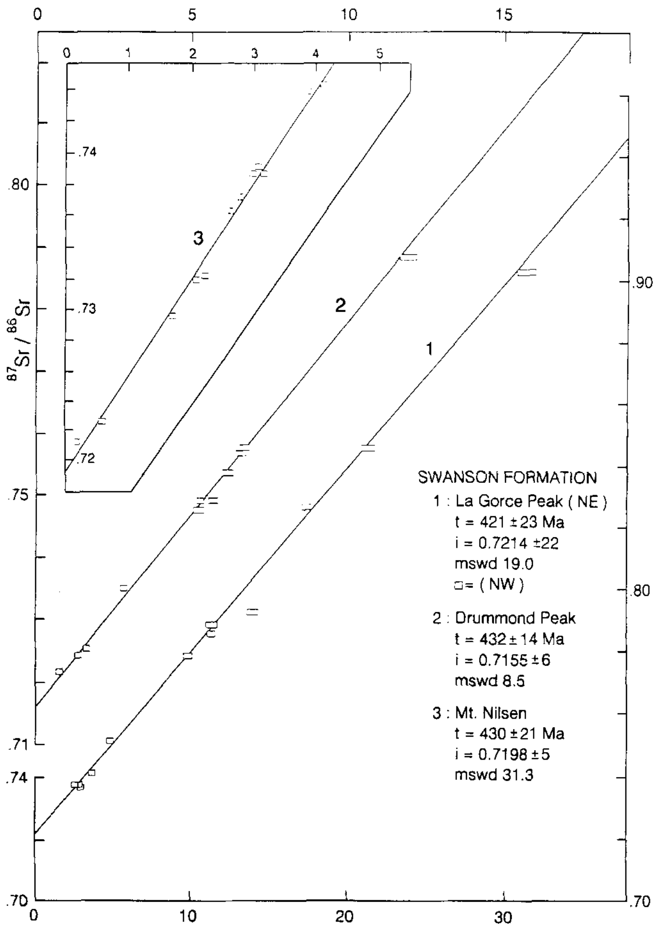

Fig. 3. Rb-Sr whole-rock isochron diagrams for Swanson Formation. Axes for Drummond Peak data are top/left, for La Gorce Peak data are bottom/right. Data for the north-western ridge of La Gorce Peak are not included in isochron calculation.

important to note that Byrd Coast Granite in the Ford Ranges yields slightly older, *c.* 110 Ma, ages and with distinctly more primitive initial ratios, *c.* 0.706 (Adams 1987). There is also no correlative on the peninsula of an older, *c.* 142 Ma, earliest Cretaceous plutonic phase of Byrd Coast Granite, seen in the Clark Mountains, Ford Ranges (Boudette *et al.* 1966, Adams 1987).

Regional extent of Cretaceous granite plutonism

Adams (1987) summarized geochronological data for Cretaceous granitoids in Marie Byrd Land and southern New Zealand/Campbell Plateau. In eastern Marie Byrd Land in particular, good age and isotopic data have not yet been published, but similar Cretaceous granites have been dated on the Campbell Plateau, on Auckland Island (C.J. Adams unpublished data; t *c.* 105 Ma, i *c.* 0.7085) and in oil-exploration wells of the Great South Basin (Fig. 7). K-Ar and Rb-Sr mineral ages for Cretaceous granitoids on Snares Islands (94.7–97.2 Ma, Denison & Coombs (1977)), Stewart

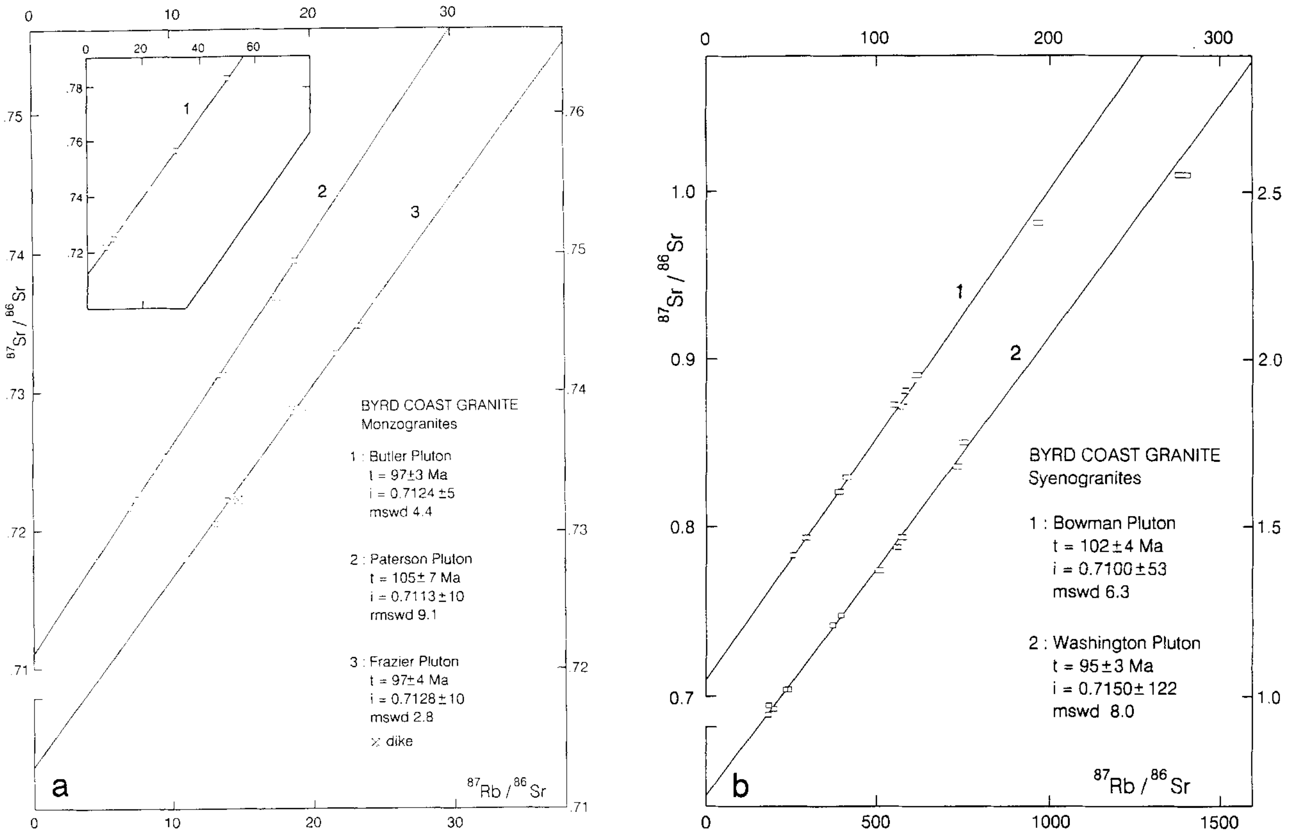

Fig. 4. Rb-Sr whole-rock isochron diagrams for monzogranite plutons of Byrd Coast Granite. Vertical axes are at left for **a.** Paterson pluton and right for Frazier pluton, (Frazier pluton isochron age calculation excludes dyke sample, E7A52) Paterson pluton isochron age calculation excludes pegmatite sample E7A139) **b.** Syenogranite plutons, axes for Bowman pluton are left/top and Washington pluton bottom/right.

Island (98–103 Ma, Aronson (1968)), and southern Fiordland (98–100 Ma, Aronson (1968)) all seem to point to a general connection of western Marie Byrd Land Cretaceous granites with the western edge of the Campbell Plateau and the southwest part of the South Island of New Zealand. For the Ford Range/Edward VII Peninsula suites, Weaver *et al.* (1992) argued for an intra-plate tectonic setting, emplacement being initiated during the rift stage of the south-west Pacific spreading centre, but the geochemical/isotopic data for their northern correlatives remain insufficient to compare precisely their tectonic setting.

A possible Permo-Triassic granite at Mount Nilsen/ Breckinridge Peak

In a geochemical review of Edward VII Peninsula granites, Weaver *et al.* (1992) included analyses of minor intrusive sheets at Mount Nilsen and Breckinridge Peak. These are monzo-granites which generally resemble those at Mount Butler. Several individual isotopic analyses of dykes on the west side of Mount Nilsen and at Breckinridge Peak (Fig. 5, data in Table II) show that at least the western Breckinridge Peak granites almost certainly fall within the Mount Butler isochron array but, unusually, all those of Mount Nilsen appear to define an older, Permo-Triassic isochron age, 246 ± 14 Ma. This Rb-Sr isochron age is considered as tentative evidence for minor Permo-Triassic plutonism, hitherto unrecognized in Marie Byrd Land. The initial $^{87}Sr/^{86}Sr$ ratio, 0.7037 ± 6, is characteristic of I-type granitoids and quite distinct from that of the Byrd Coast Granite in the area. K-Ar biotite ages for minor intrusions at both localities (*c.* 102 Ma) indicate that there is nonetheless a very strong thermal overprint by the Cretaceous granites.

Relationship to the Alexandra Metamorphic Complex

The Alexandra Metamorphic Complex is dominantly high-grade paragneiss and orthogneiss similar to the Fosdick Metamorphic Complex (Wilbanks 1972, Smith 1992) with only subordinate and variable granitoid. It is unclear whether the host-rock component of the migmatite, at the time of granitoid intrusion, was originally a low-grade meta-turbidite protolith, or a more metamorphosed equivalent, such as the paragneiss at Mount Nilsen. The limited areas of granitoids within the Alexandra Metamorphic Complex at Mount Swadener and Scott Nunataks show much variation in degree of assimilated metasediment/gneiss and are unsuitable for Rb-Sr whole-rock age determination. In a preliminary study of the possible ancestry of the complex, Adams & Weaver (1990) argued from Rb-Sr data of paragneiss in the migmatites that the sedimentary precursor was Swanson Formation. On an outcrop by outcrop basis, the isochron arrays suggested an intense thermal event at about 100 Ma. They concluded that the complex represented a deep-seated metamorphic unit in which turbidite sediments (or metasediments) were invaded by Cretaceous granites, sufficient to cause formation of migmatite, high-grade paragneiss and in the latter, partial isotopic rehomogenization of Sr. Two Rb-Sr analyses of a garnet-bearing granodiorite at Mount Swadener (E7A46, 47) seem to bear out this model: at *c.*100 Ma their initial ratios would have been very high, *c.*0.733–0.737, quite different from other high level Cretaceous granites, *c.* 0.710–0.712. Adams (1986) suggested a similar situation in the Fosdick Metamorphic Complex, a host protolith of Swanson Formation being migmatized, at least in part, by Cretaceous granitoid.

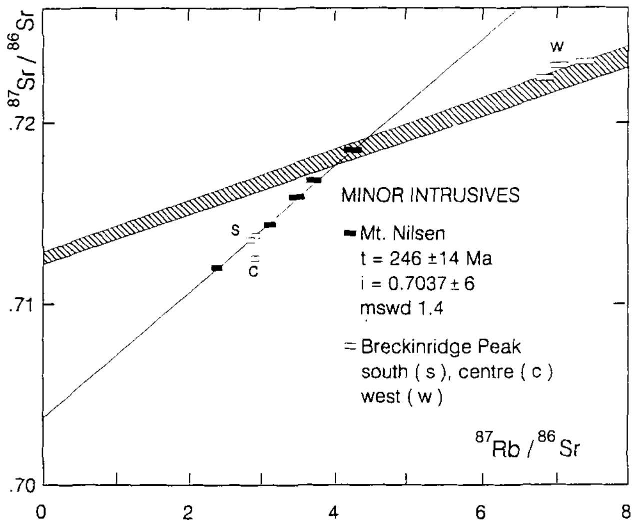

Fig. 5. Rb-Sr whole-rock isochron diagram for minor granitoid intrusives at Mount Nilsen and Breckinridge Peak. Shaded isochron is that of Mount Butler (Fig. 4 inset).

Table IV. Fission track age data: Edward VII Peninsula.

NS R No.	Field No.	Sample type Locality (alt. m)	Crystals counted	Dosimeter track density x 10^4 cm^{-2} (counted)	ρ_s x 10^4 cm^{-2} (counted)	ρ_i x 10^4 cm^{-2} (counted)	$p(\chi^2)$%	Age ±2S(Ma)
13197Z	E7A45	Paragneiss, Mount Swadener; (390)	7	42.8 (1200)	599 (677)	947 (535)	80	90.9±11.7
----A	"	"	8	60.0 (1561)	1281 (1409)	3338 (1836)	85	77.4±6.7
13210Z	E7A58	Paragneiss; Scott Nunataks; (500)	8	42.8 (1200)	720 (792)	1056 (580)	85	98.0±12.1
----A	"	"	17/17*	61.3 (1226)	51.3 (150)	137 (400)	-	77.1±15.4
13219Z	E7A67	Orthogneiss; Scott Nunataks; (240)	10	14.7 (2219)	630 (1238)	488 (480)	<1	82.7±30.6
----A	"	"	10	356 (4348)	230 (1491)	1234 (4007)	82	67.8±4.6
13228A	E7A76	Schist; Mt Nilsen; (600)	9	349 (4348)	67.4 (432)	366 (1170)	17	66.0±7.7
13261A	E7A109	Granite; Mt Schlossbach; (420)	6	52.0 (2669)	52.3 (120)	128 (147)	70	71.3±17.8
13269Z	E7A117	Granite; Breckinridge Peak; (440)	6	42.8 (12000	471 (476)	737 (372)	95	91.9±13.7
----A	"	"	13	60.0 (1561)	385 (666)	1393 (1205)	84	55.8±6.1
13274Z	E7A122	Granite; Tennant Peak; (330)	7	42.8 (1200)	570 (621)	917 (500)	92	89.2±11.9
13290A	E7A138	Granite; Mt Paterson (650)	12	354 (4348)	48.3 (487)	257 (1293)	99	67.8±7.48
13296A	E7A144	Granodiorite; Mt Shideler; (800)	15	60.0 (1561)	396 (823)	1075 (1118)	80	74.3±8.3
13300Z	E7A148	Granodiorite; Mt Fitz-simmons; (875)	8	42.8 (1200)	586 (369)	914 (288)	79	92.0±15.4
----A	"	"	17/11* (1226)	61.3 (146)	59.8 (354)	174	-	71.0±14.5

A = apatite, Z = zircon. * represent samples determined using the population technique; all others determined with external detector and a geometry factor of 2. All samples irradiated at the ANSTO facility, Lucas Heights, Australia. Ages calculated using the zeta approach (Hurford & Green 1983) Zeta = 338 ± 5 for dosimeter glass SRM612 and 103 ± 8 for CN1. Errors are calculated according to Green (1981) and are expressed at the 2σ level. ρ_s and ρ_i represent sample spontaneous and induced track densities; P (χ^2) is the probability of obtaining χ^2 value for v degrees of freedom, where v = number of crystals -1; mean ρ_s/ρ_i ratio used to calculate age and uncertainty when P(χ^2)<5% test (e.g. 13219Z). 1D = 1.55125 x 10^{-10}.

Cretaceous–Cenozoic uplift history

The K-Ar biotite ages for the Rockefeller Mountains are all concordant with Rb-Sr isochron ages of granite emplacement, thus uplift and cooling through the relevant argon retention threshold temperatures (*c.* 350°C) must have rapidly occurred at *c.* 100 Ma. This is supported by the indications for a high level of intrusion mentioned earlier. However, the K-Ar ages of 116.9 Ma and 103.0 ± 1.5 Ma at Scott Nunataks (500 m) and Mount Swadener (390 m), may suggest slightly earlier cooling in the Alexandra Mountains (although it is possible that the former sample, a paragneiss, has undergone only partial resetting).

In order to understand more clearly the later uplift/cooling patterns in the Rockefeller and Alexandra mountains, fission track zircon and apatite ages were determined on representative samples covering the maximum, albeit limited vertical range (300–900 m). Analytical results are given in Table IV and the results shown in the age/altitude diagram (Fig. 6).

Although the zircon age profiles of the Rockefeller and Alexandra mountains may be slightly different (Fig. 6), because of their large errors, their age-altitudinal relationship within both the Rockefeller and Alexandra mountains is defined by a single regression line (Fig. 6). Since the accepted annealing temperature range for zircon is 240 ± 50°C (Hurford 1986), the data here show that the rocks of Edward VII Peninsula passed through this temperature range between 104 and 83 million years ago, at a rate of *c.* 0.025 mm y^{-1}. Both the K-Ar and zircon fission track ages indicate rapid cooling of the Rockefeller granitoids immediately after emplacement. For the Alexandra mountains there is tentative K-Ar evidence for earlier cooling at *c.* 115 million years after the formation of the migmatite complex but the zircon data suggest that this continued to *c.* 90 Ma.

If both the Rockefeller and Alexandra mountains have a common uplift history in mid–late Cretaceous times, then it follows that substantial differential movement between them must have occurred immediately prior to this, to bring relatively high-grade deep-seated migmatites (Alexandra Mountains) to a similar structural level as the relatively low-grade metasediments and high level granites (Rockefeller Mountains).

The apatite fission-track age profiles for the Rockefeller and the Alexandra mountains are distinctly different, yet the uplift rates are the same as those of the zircons. This implies constant exhumation rates since the initiation of uplift at about 100 Ma, but over different times. Confined mean track lengths (Fig. 6) are of the order of 14 m with a standard deviation of 1.3–1.7 m. Such parameters border between those expected for undisturbed volcanic and basement rocks (Gleadow *et al.* 1986). Similar results have been found in other Antarctic regions (e.g. Fitzgerald & Stump 1991). As the rock units were in the partial annealing zone for a long period of time the negative skewness of some of the distributions supports the notion of slow uplift. All ages

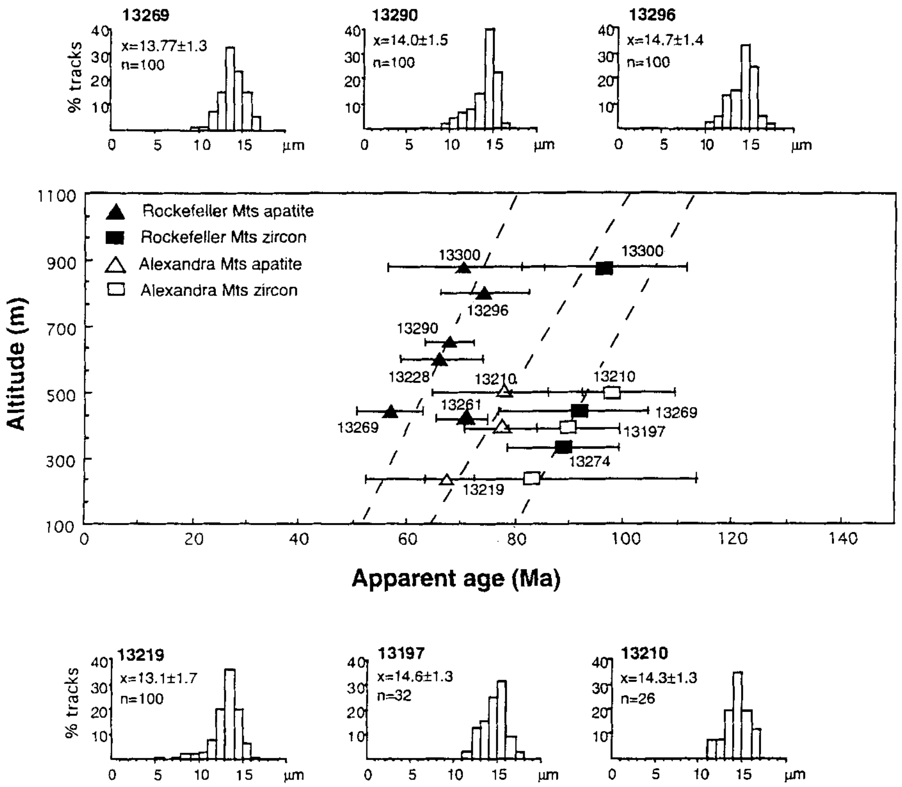

Fig. 6. Sample altitude versus measured age for apatite and zircon fission-track ages from Edward VII Peninsula, Marie Byrd Land. Histograms are of track length distributions for several apatite samples.

record a long history of slow uplift, characteristic of intraplate terranes during rifting, from mid-Cretaceous (*c.* 115 Ma) to early Tertiary (*c.* 50 Ma). The 20 Ma displacement of the apatite age/altitude regression lines suggests that the later stages of late Cretaceous–early Cenozoic uplift involved differential movement between the Alexandra and Rockefeller mountains. The discordance suggests that sustained uplift without a break, at about 0.02 mm y^{-1}, occurred in the Alexandra Mountains until 60 Ma ago, whereas for the Rockefeller Mountains there was a standstill 80–60 Ma ago, before uplift began its final stage at 0.02 mm y^{-1}.

Uplift history during Gondwana break-up

Magnetic anomalies in the south-west Pacific indicate that ocean-floor spreading began at about 84 Ma (Mayes *et al.* 1990), whereas associated rifting and earliest development of sedimentary basins, on the Campbell Plateau for example, occurred *c.* 25 m.y. earlier. In this context, the Marie Byrd Land Cretaceous granitoids are seen as products of anorogenic plutonism associated with rifting and the mineral age (biotite/zircon/apatite) patterns reflect the rift-margin, fault block development and subsequent rapid onset of regional uplift and cooling. Erosion of these blocks would be the source for synchronous Cretaceous–Cenozoic basins. Although none are known from the Pacific coast of Marie Byrd Land (indeed, the continental margin is unusually narrow at this point), the Great South Basin and Campbell Basin of the Campbell Plateau (GSB, CB, Fig. 7) contain a record of continued subsidence, up to 6 km, particularly in the late Cretaceous–early Tertiary. It is possible that analogues of these basins lie to the south of Edward VII Peninsula and the Ford Ranges, in the Byrd Basin (BB, Fig. 7).

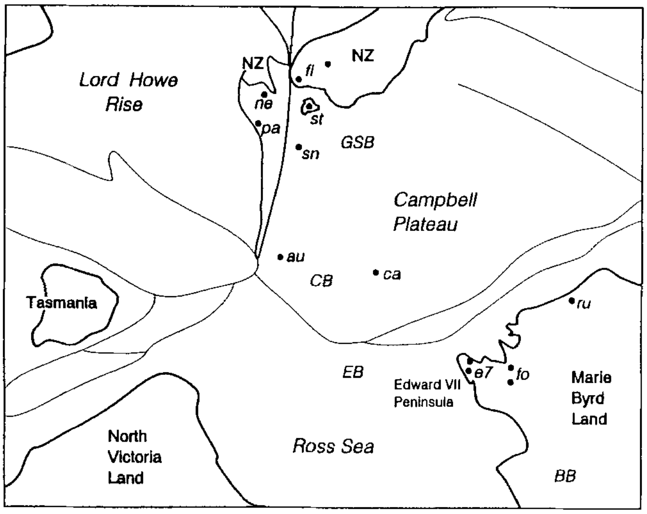

Fig. 7. Reconstruction of the Pacific sector of Gondwana (after Grindley & Davey 1982), showing the location of Cretaceous granitoids: au = Auckland Islands; e7 = Edward VII Peninsula; fi = Fiordland; fo = Ford Ranges; ne = NW Nelson; pa = Paparoa; ru = Ruppert Coast; sn = Snares Islands; st = Stewart Island. Other locations mentioned in text: BB = Byrd Basin; ca = Campbell Island; CB = Campbell Basin; EB = east Ross Sea Basin; GSB = Great South Basin. Solid lines present coastline; dotted lines, 2000 m isobath. New Zealand is reconstructed along the Alpine Fault.

Conclusions

Rb-Sr whole-rock isochron ages of Swanson Formation metasedimentary rocks on Edward VII Peninsula indicate a late Ordovician, *c.* 430 Ma, low-grade (occasionally medium-grade) regional metamorphism, closely comparable with that of the Ford Ranges, Marie Byrd Land, 250 km to the east. However, K-Ar mineral ages of the Swanson Formation range from *c.* 114–440 Ma and reflect the variable but pervasive thermal overprint associated with Cretaceous (Byrd Coast Granite) granitoids throughout the peninsula.

Rb-Sr whole-rock isochron ages of five monzo- and syenogranite plutons in both Rockefeller and Alexandra mountains are 95–105 Ma (mid-Cretaceous), and are correlated with the late phase of Byrd Coast Granite in the Ford Ranges and probable correlatives in southern New Zealand (Fiordland and Stewart Island) and the Campbell Plateau (Snares and Auckland islands). However, their initial $^{87}Sr/^{86}Sr$ ratios, 0.710–0.715, are significantly higher than these correlatives (<0.706).

K-Ar biotite and fission-track zircon/apatite ages indicate commencement of regional uplift 95–100 million years ago, associated with the initial rift of New Zealand/Campbell Plateau from Marie Byrd Land. Fission-track zircon and apatite ages indicate that this uplift continued to at least *c.* 53 Ma ago at a long-term averaged uplift/exhumation rate of 0.025 mm yr^{-1}. Between 100 and 85 Ma the region was uplifted as a single block, but substantial differential movement must have uplifted high-grade migmatites of the Alexandra Metamorphic Complex prior to this phase. Later differential movement, after 85 Ma, continued to uplift/exhume the Rockefeller granitoids alone.

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