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The stratigraphy and geochronology of Adelaide Island

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Abstract: The Mesozoic-Cenozoic volcanic arc of the Antarctic Peninsula is represented on Adelaide Island by a sedimentary and volcanic succession intruded by plutons. ^{40}Ar–^{39}Ar step-heating age spectra have been obtained from volcanic rocks and hornblende separates from sedimentary clasts of plutonic origin. These spectra show evidence for some argon loss, but, in general, have plateau ages which are consistent with the mapped stratigraphy and with other geochronological controls, suggesting that they approximate to original ages. As a result the following events in the evolution of Adelaide Island can be recognized: 1) mostly marine Mesozoic sedimentation, 2) Early Cretaceous (*c.* 141 Ma) plutonism (recorded in clasts from conglomerates), 3) Cretaceous volcanism, 4) Late Cretaceous (possibly Tertiary) sedimentation, 5) Early Tertiary volcanism, which was acidic in eastern outcrops and intermediate elsewhere, and 6) Eocene intermediate volcanism and deposition of arc-derived conglomerates. Volcanism was possibly coeval with known Palaeocene-Eocene plutonic activity on Adelaide Island (part of the Antarctic Peninsula Batholith) and with volcanism of similar age in northern Alexander Island and the South Shetland Islands. The volcanism on Adelaide Island and the South Shetland Islands, at least, was associated with a westward migration of the Antarctic Peninsula arc.

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Introduction

During most of the Mesozoic and Cenozoic the Antarctic Peninsula was an active volcanic arc, resulting from eastward-dipping subduction of oceanic crust beneath the continental crust of the Antarctic Peninsula (Thomson 1982, Storey & Garrett 1985). The Antarctic Peninsula can be divided into three tectonic regions (Macdonald & Butterworth 1990):

i) an accretionary prism and fore-arc basin on Alexander Island (e.g. Butterworth 1991, Doubleday *et al.* 1993),

ii) a magmatic arc in much of Graham Land and Palmer Land (e.g. Meneilly *et al.* 1987) comprising the Antarctic Peninsula Volcanic Group (APVG; Thomson 1982) and Antarctic Peninsula Batholith (APB; Leat *et al.* 1995), and

iii) a back-arc region represented by the Larsen and Latady basins (e.g. Macdonald *et al.* 1988).

On Adelaide Island, on the western seaboard of the Antarctic Peninsula (Figs 1 & 2) a 2.5 km thick sedimentary and volcanic succession of late Mesozoic to early Cenozoic age is exposed, which belongs to the APVG (Thomson 1982, Smellie *et al.* 1994). Adelaide Island is situated on the western flank of the arc, in a fore-arc or, more likely, an intra-arc position. In the Early Tertiary, westward migration of the arc towards the ocean trench was associated with plutonism on Adelaide Island (Pankhurst 1982, Pankhurst *et al.* 1988) and was part of the APB (Leat *et al.* 1995). Subduction ceased in this vicinity between about 20 and 16 m.y., after ridge crest-trench collision (Larter & Barker 1991).

Dewar (1970) mapped the island geologically and erected a tripartite stratigraphy, comprising two sequences of well-bedded sedimentary and volcaniclastic rocks separated by massive, unbedded and commonly fragmental lavas. These sequences are intruded by plutons (Andean Intrusive Suite) and numerous dykes. Later work, notably by Jefferson (1980) and Hamer (1981), suggested that the stratigraphy was more complex; in particular, Late Cretaceous or Tertiary plant fossils (Jefferson 1980) occur within a sequence which elsewhere includes an Upper Jurassic fauna (Thomson 1972). The locally excellent exposure of thick sedimentary sections, together with the presence of interbedded and cross-cutting, potentially dateable igneous rocks, makes Adelaide Island a prime source of information on relationships between magmatism, sedimentation and tectonic events in this large segment of the Antarctic Peninsula magmatic arc.

The aim of the present work is to use multiple methods of dating (^{40}Ar–^{39}Ar, K–Ar, fission track) in order to constrain the stratigraphy of Adelaide Island, to show how sedimentation and volcanism changed with time and, where possible, to correlate these changes with known large-scale tectonic developments in the Antarctic Peninsula (cf. Barker *et al.* 1991).

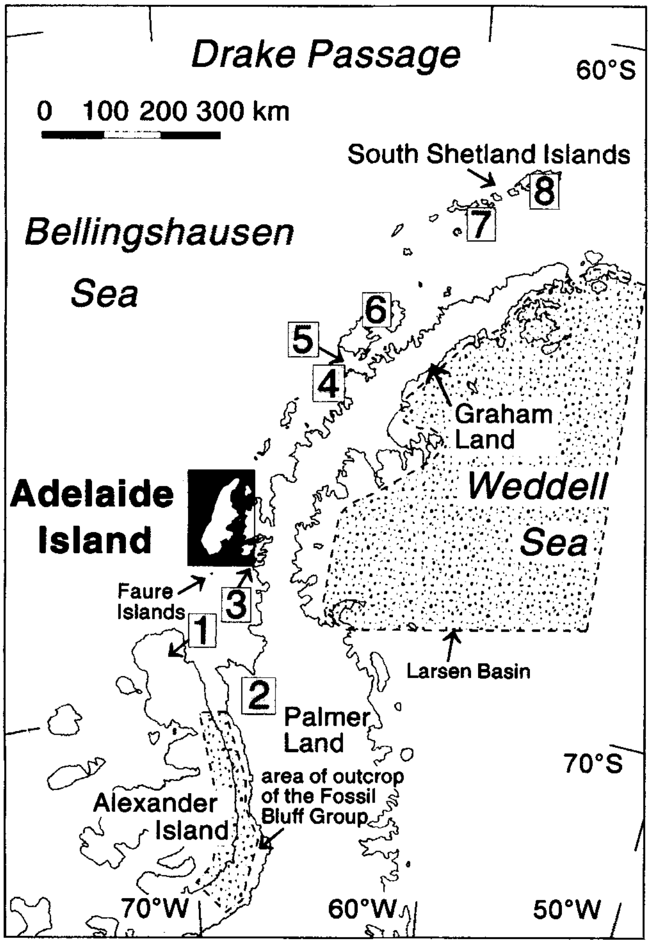

Fig. 1. Map of the Antarctic Peninsula showing the position of Adelaide Island and the limits of the mainly Mesozoic Larsen (back-arc) and Fossil Bluff Group (fore-arc) basins. Numbered boxes refer to areas of Early Tertiary magmatism (from Pankhurst 1982, Smellie *et al.* 1984 and R.J. Pankhurst, unpublished data 1995): 1) northern Alexander Island, 2) north-western Palmer Land (J. Scarrow, personal communication 1995), 3) Horseshoe Island, 4) Argentine Islands, 5) Wauwermans Islands, 6) Anvers Island area, 7) Livingston Island, and 8) King George Island.

Previous geochronological data

A small number of volcanic and plutonic rocks from Adelaide Island (and its vicinity) have been dated by the Rb–Sr method. A rhyolite from Webb Island has a poorly constrained age of 67 ± 17 Ma (Thomson & Pankhurst 1983; error (2 σ) readjusted in Smellie *et al.* 1994). Granodiorite-granite plutons on Wright Peninsula and Anchorage Island have Early Tertiary ages of 60 ± 3 and 62 ± 2 Ma, respectively (Pankhurst 1982). Gabbro and aplite on the Faure Islands (35 km south of Adelaide Island) have an age of 48 ± 4 Ma (Moyes & Pankhurst 1994).

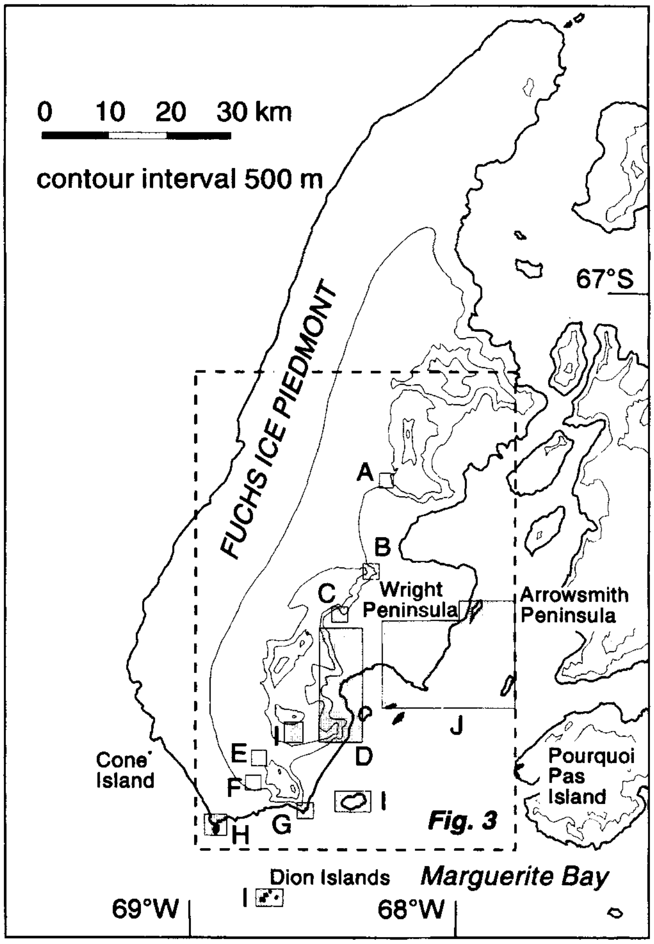

Fig. 2. Map of Adelaide Island showing the area covered by the geological map (Fig. 3) and the location of stratigraphical sections A to J (Fig. 4). Areas I and J correspond to the areas of mainly intermediate and basic volcanic rocks, and mainly acidic volcanic rocks, respectively, shown in Fig. 3.

Sedimentary and volcanic succession

The sedimentary and volcanic succession on Adelaide Island was re-mapped (Fig. 3) during two summers (1990–92). A broad two-fold division was adopted: well-bedded sequences dominated by sedimentary and volcaniclastic lithologies (areas A–H, Fig. 2), and poorly bedded sequences dominated by basaltic to rhyolitic volcanic rocks (areas I and J). The local stratigraphies of areas A to H are summarized in Fig. 4. Correlation between areas is difficult because of discontinuous outcrops and an absence of mappable marker beds, but the following are proposed:

1) The south-western and some of the north-eastern outcrops of Adelaide Island (areas A, E, F, G & H, Fig. 2) consist of heterolithic sedimentary and volcaniclastic sequences dominated by sandstone, interbedded with siltstone, conglomerate, breccia and tuff. Marine fossils occur at several localities (Fig. 4), including Buchia Buttress, southern Mount Bouvier, Milestone Bluff, Window

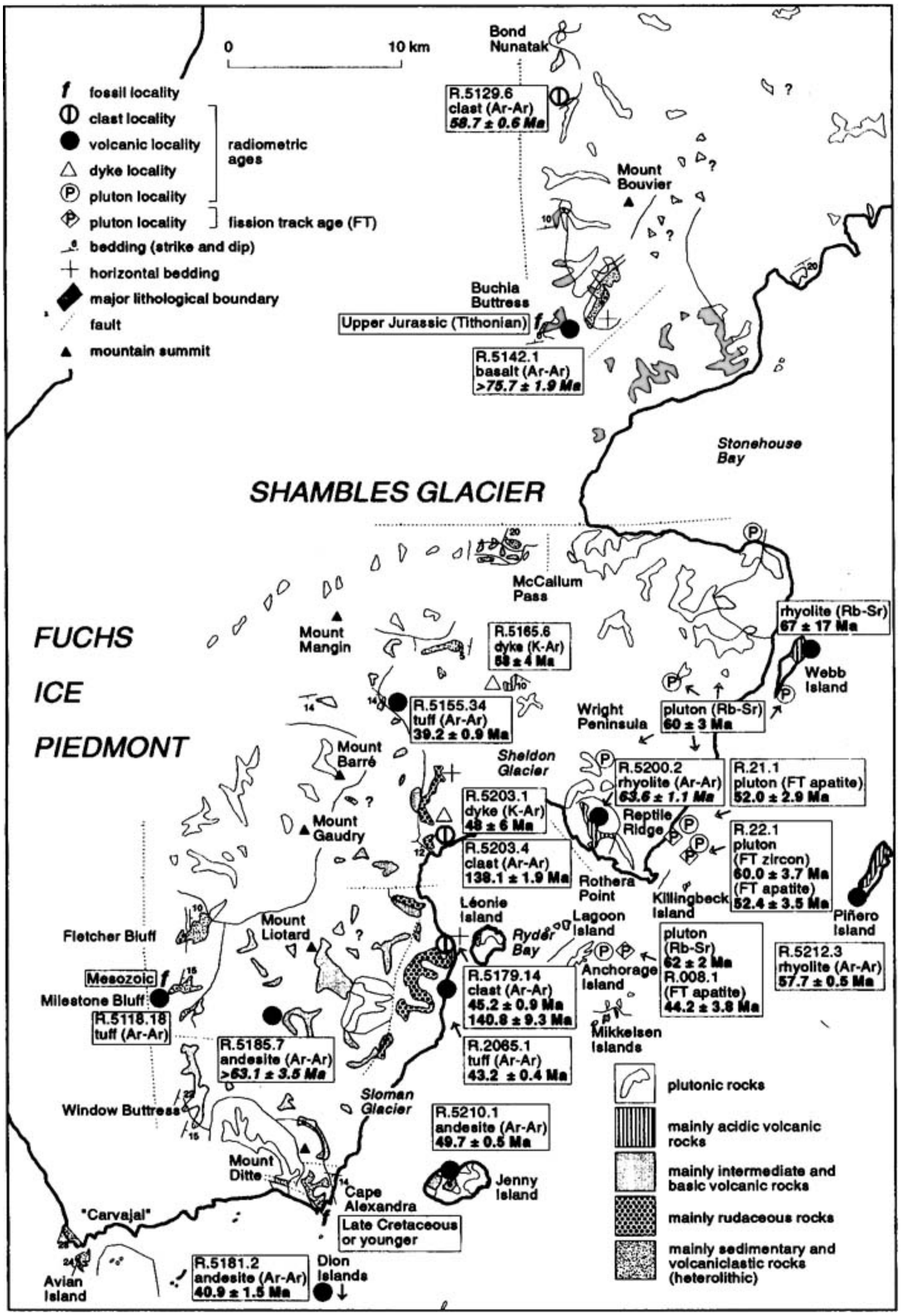

Fig. 3. Geological map of south-eastern and central Adelaide Island also showing the location of samples dated by radiometric and fission track methods. Ages in italics are probable minimum ages taken from the maximum significant argon-argon step age (see Table I). Errors on argon-argon and fission track ages are 1 σ, and on Rb–Sr and K-Ar ages 2 σ. Rb–Sr ages are from Pankhurst (1982) and Thomson & Pankhurst (1983). All the pluton localities on Wright Peninsula plot on the same isochron (R.J. Pankhurst, personal communication 1995).

Buttress and in the area of the Chilean station, "Carvajal" (Thomson 1969, 1972, Thomson & Griffiths 1994). The oldest strata dated are at Buchia Buttress (area A) and contain Late Jurassic (Tithonian) ammonites and bivalves (Thomson 1972). At Milestone Bluff (area E) belemnite fossils indicate a broadly Mesozoic age. The youngest fossiliferous strata are at Cape Alexandra (area G) and contain angiosperm plant material (Jefferson 1980). Although it is possible that the Cape Alexandra succession is as old as Late Albian, the organization of the second-order veins on the angiosperm leaves suggests it is younger (D.J. Cantrill, personal communication 1995).

Existing fossil evidence suggests that most of these sequences are marine and probably Mesozoic, although the Cape Alexandra sequence may extend the age range into the Tertiary.

2) Easterly outcrops (areas C & D) consist of thick-bedded conglomerates interbedded with minor sandstone and tuff. Similar lithologies also crop out at Fletcher Bluff (area E). The conglomerates are rich in arc-derived plutonic and volcanic clasts up to 1 m in diameter, which were supplied from a source area to the east and deposited from mass flows. In area D, conglomerates are overlain

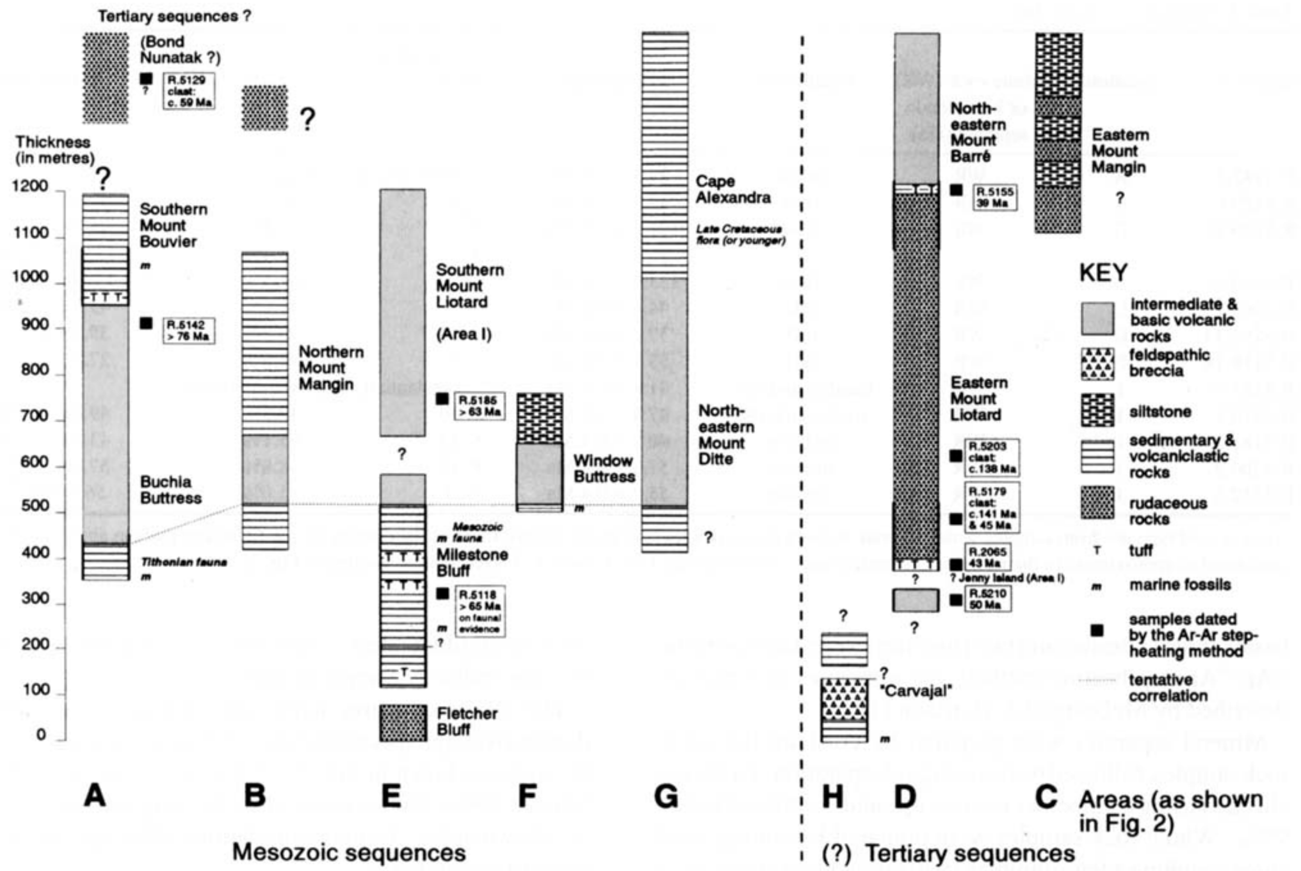

Fig. 4. Stratigraphic sections through the sedimentary and volcanic succession, including approximate original argon ages. The location of areas A to I are given in Fig. 2. Thick-lined boxes represent measured sections. Thin-lined boxes represent estimated thicknesses. For errors on the ages see the text and Table I.

by volcanic rocks, whereas at Fletcher Bluff (area E) conglomerates are overlain by marine sedimentary rocks. Therefore, the strata overlying the conglomerates at Fletcher Bluff and in area D are lithologically different and it is possible that they are also different in age.

3) Intermediate and basic volcanic rocks crop out at many localities on Adelaide Island (Figs 3 & 4) and on Jenny Island, Lagoon Island, Mikkelsen Islands, southern Dion Islands and Cone Island. Massive basalt, basaltic andesite and andesite flows and/or sills are typical, but breccias (including hyaloclastite) are locally common. Volcanic sequences up to 530 m thick have been measured and they are estimated to be 1000 m thick in some inaccessible outcrops. Tuffs and sedimentary deposits are generally minor. The volcanic rocks occur at several stratigraphical levels: within and overlying Mesozoic sedimentary sequences (e.g. areas A & E), and underlying and overlying the conglomeratic succession (area E).

4) Thick sequences of dacitic and rhyolitic volcanic rocks are confined to Wright Peninsula and adjacent islands (Webb, Killingbeck and Piñero islands). They are generally poorly bedded and contain massive, flow-banded and brecciated dacite and rhyolite, tuff and minor tuffaceous sandstone and conglomerate. The relationship of these sequences to other areas is unclear, although clasts, possibly derived from this sequence, occur in conglomerates near the top of the conglomeratic succession on north-eastern Mount Barré (area D).

Palynology

In order to constrain the biostratigraphy further, nineteen siltstone and sandstone samples, obtained from different parts of Adelaide Island, were prepared for palynology. No stratigraphically useful microfossils were found. However, some long-ranging, poorly preserved trilete spores and bisaccate pollen occur in one sample (R.2060.6) from eastern Mount Liotard (A.M. Duane, personal communication 1994). Their presence suggests that deposition occurred in a non-marine environment.

Argon-argon dating

Three hornblende separates (derived from clasts in conglomerates) and nine whole-rock samples (three tuffs, one

Table I. Summary of argon data.

sample no.	location	whole rock (WR) or hornblende separate (Hb)	sample type	total gas age	plateau data steps	%^{39}Ar	plateau age
R.5142.1	A	WR	basalt	39.3 ± 0.8 Ma	substantially reset age spectrum		
R.5129.6	A	Hb	clast	49.0 ± 0.4 Ma	2–9	90.0%	49.5 ± 2.2 Ma
R.5179.14	D	Hb	clast	101.3 ± 0.5 Ma	1–5	34.2%	44.2 ± 1.1 Ma
					9–12	58.4%	133.5 ± 2.4 Ma
R.5203.4	D	Hb	clast	133.9 ± 0.5 Ma	6–10	81.5%	137.0 ± 2.6 Ma
R.2065.1	D	WR	tuff	44.1 ± 0.4 Ma	6–9	41.6%	43.3 ± 0.4 Ma
R.5155.34	D	WR	tuff	37.7 ± 0.5 Ma	7–11	50.3%	39.5 ± 0.7 Ma
R.5118.18	E	WR	tuff	33.1 ± 0.4 Ma	3–6	42.0%	27.8 ± 0.6 Ma
R.5185.7	I	WR	basaltic andesite	41.8 ± 0.8 Ma	substantially reset age spectrum		
R.5210.1	I	WR	trachy-andesite	47.4 ± 0.4 Ma	7–10	42.3%	49.6 ± 0.5 Ma
R.5181.2	I	WR	andesite	40.2 ± 0.4 Ma	8–13	65.1%	43.5 ± 1.0 Ma
R.5200.2	J	WR	rhyolite	51.3 ± 0.4 Ma	8–13	48.8%	57.7 ± 1.1 Ma
R.5212.3	J	WR	rhyolite	55.7 ● 0.4 Ma	4–7	75.0%	56.9 ± 0.6 Ma

Ages in bold type are from samples with moderate to good plateaux ages (satisfying at least three of the criteria for a satisfactory plateau age), which are considered to approximate to their original magmatic ages. All errors are 1 σ. Letters A–J refer to areas located in Fig. 2.

basalt, three andesites and two rhyolites) were dated using the ^{40}Ar–^{39}Ar step-heating method, the principles of which are described by McDougall & Harrison (1988).

Mineral separates were prepared by crushing the whole rock samples, followed by heavy liquid separation. Purity was checked using a binocular microscope and confirmed to be > 99%. Whole rock samples were prepared by cutting small cores weighing a few grammes from the hand specimen, so as to exclude weathering crusts, veins and amygdales.

Samples were irradiated in the Petten Reactor, Holland, with cadmium shielding and rotated 180° about the longitudinal axis of the package at half the irradiation time, to minimize the effect of transverse flux gradients. Six standards were placed at intervals along the irradiation package to allow the irradiation dosage (J-value) at the sample positions to be interpolated to an accuracy of better than ± 1%.

Argon analysis was carried out at the Department of Earth Sciences, University of Liverpool. Irradiated samples were loaded into degassed molybdenum crucibles and then baked overnight in the evacuated extraction line to 200°C. Samples were heated by radio-frequency induction for 30 min at each successive temperature and the temperature was measured with a platinum-rhodium thermocouple. The evolved gas was cleaned up using a liquid nitrogen-cooled trap and titanium getters. The gas composition was analysed using a modified AEI MS10 mass spectrometer with automatic scanning. Discrimination was corrected for by analysing aliquots of purified atmospheric argon at regular intervals. The correction factor for Ca- and K-derived argon isotopes are those used by Mussett (1986).

The standard used was Bern Muscovite 4M and the age has been taken as 18.55 ± 0.40 (1 σ) Ma, based on data published by Frisch (1982). This error has been included in the quoted error. The plateau dates and errors have been calculated from a mean of the individual plateau steps weighted by the error on each individual step. The decay constants are those recommended by Steiger & Jäger (1977).

The results of argon dating are summarized in Table I, displayed as age spectra in Figs 5 & 6, and interpreted below, by area (as shown in Fig. 2). All errors given are 1 σ (e.g. Mussett 1986). The localities where the samples were collected are shown in Fig. 3 and interpretations of the age spectra are summarized in Fig. 7.

Although some samples have spectra indicative of argon loss (e.g. R.5142.1, R.5185.7 & R.5118.18; Fig. 5), many of the results satisfy most of the criteria for plateau ages. These criteria (Mussett & Taylor 1994) are:

i) the plateau should consist of a minimum of four consecutive steps with apparent ages within 1 σ error of each other,

ii) the plateau should incorporate over 50% of the released ^{39}Ar,

iii) the selected steps should produce an isochron with a MSWD less than 2.5,

iv) the isochron age should be within the error range of the plateau age, and

v) the initial ratio (^{36}Ar/^{40}Ar) on the isochron should be within error of the atmospheric ratio (295.5).

None of the results in this study fulfill all five criteria, but five samples (R.5129.6, R.5179.14, R.5203.4, R.2065.1, R.5155.34 and R.5210.1) satisfy three or four of the criteria and nearly satisfy the remainder. In addition, sample R.5212.3 has a well-defined plateau and a plateau age within the error range of the isochron age suggesting that the plateau age is probably also reliable. Samples R.5181.2 and R.5200.2 have convex-upward age spectra and more poorly defined, but recognizable, plateaux in the highest temperature steps,

Table I. (cont.) Summary of argon data.

sample no.	location	whole rock (WR) or hornblende separate (Hb)	sample type	isochron data			maximum step age where different from plateau age and ^{39}Ar > 2% (% ^{39}Ar in brackets)
				isochron age	initial ratio	MSWD	
R.5142.1	A	WR	basalt				75.7 ± 1.9 Ma (17%)
R.5129.6	A	Hb	clast	50.3 ± 1.2 Ma	289.7 ± 13.3	59.1	58.7 ± 0.6 Ma (6%)
R.5179.14	D	Hb	clast	45.2 ± 0.9 Ma	293.1 ± 8.3	1.3	
				140.8 ± 9.3 Ma	252.8 ± 72.5	27.5	
R.5203.4	D	Hb	clast	**138.1 ± 1.9** Ma	285.0 ± 15.3	51.1	
R.2065.1	D	WR	tuff	**43.2 ± 0.4** Ma	300.6 ± 5.0	0.4	48.1 ± 0.4 Ma (9%)
R.5155.34	D	WR	tuff	**39.2 ± 0.9** Ma	296.5 ± 10.1	1.7	84.8 ± 2.6 Ma (2%)
R.5118.18	E	WR	tuff	28.0 ± 0.6 Ma	294.5 ± 9.4	4.3	
R.5185.7	I	WR	basaltic andesite				63.1 ± 3.5 Ma (8%)
R.5210.1	I	WR	trachy-andesite	**49.7 ± 0.5** Ma	294.5 ± 5.0	1.2	
R.5181.2	I	WR	andesite	**40.9 ± 1.5** Ma	316.9 ± 25.3	9.8	
R.5200.2	J	WR	rhyolite	56.2 ± 0.5 Ma	304.5 ± 3.2	1.1	63.6 ± 1.1 Ma (5%)
R.5212.3	J	WR	rhyolite	**57.7 ± 0.5** Ma	274.2 ± 7.3	2.6	

Ages in bold type are from samples with moderate to good plateaux ages (satisfying at least three of the criteria for a satisfactory plateau age), which are considered to approximate to their original magmatic ages. All errors are 1 σ. Letters A–J refer to areas located in Fig. 2.

yielding estimates of the minimum ages for these rocks. Age spectra with convex-upward patterns at low temperatures are probably due to alteration products, which were observed in these rocks in thin section. Samples R.5142.1, R.5118.18 and R.5185.7 have substantially reset age spectra where no plateau is preserved. A probable minimum original age can be estimated from the maximum step age, where the step includes a significant proportion (taken as > 2%) of the released ^{39}Ar.

Area A

R.5142.1 is a basalt from near the summit of Buchia Buttress. Its age spectrum shows evidence for argon loss or alteration, but the highest temperature step (probably released from plagioclase), with an age of about 76 Ma, is taken as the minimum age of extrusion.

R.5129.6 is an amphibole mineral separate from a granitoid clast, in a conglomerate 1 km south of Bond Nunatak. It has a poor plateau between 45 and 50 Ma. The increase in step age with temperature for the "plateau" suggests that there may have been significant argon loss, possibly reflecting resetting by the nearby pluton at Mount Bouvier. The highest temperature step with more than 2% ^{39}Ar has an age of 59 Ma and is probably a minimum original (plutonic) age, prior to erosion and incorporation as a clast in the conglomerate.

Area D

R.5179.14 is a hornblende mineral separate from a gabbroic clast in a conglomerate from eastern Mount Liotard. It has an age spectrum with a distinctive double plateau (Fig. 6). The lower plateau is at 45.2 ± 0.9 Ma, the upper one is at 140.8 ± 9.3 Ma, and there is a concomitant steep increase in the Ca/K ratio of the degassing phase (derived from the ^{37}Ar/^{39}Ar ratio). The hornblende has a high Ca/K ratio and high blocking temperature (Harrison 1981), and probably contributed to the older, higher temperature plateau interpreted here as a likely original magmatic age (Early Cretaceous) for the pluton from which the clast was derived. Relatively rare areas of alteration are also present (observed using a Scanning Electron Microscope with Energy Dispersive X-ray microanalyser). These areas include fine-grained alkali feldspar and muscovite, which are K-rich, have low Ca/K ratios and relatively low blocking temperatures (McDougall & Harrison 1988). The alkali feldspar and muscovite were probably the main contributors to the younger, lower temperature plateau, which thus records a partial resetting event. Other samples collected nearby, (R.2065.1 and R.5203.4) lack evidence of this resetting event, suggesting that it occurred prior to clast formation.

R.5203.4 is an amphibole mineral separate from a banded meta-igneous clast of intermediate composition, in a conglomerate bed on south-eastern Mount Barré. It has a poor plateau age of 138.1 ± 1.9 Ma, which is similar to the upper plateau age of R.5179.14 and is interpreted as a minimum original (magmatic or regional metamorphic) age.

R.2065.1 is a rhyolitic tuff from eastern Mount Liotard. It has a broad U-shaped spectrum which indicates the presence of excess argon, possibly derived from underlying older rocks. However, the U shape is not very pronounced and the plateau at 43.2 ± 0.4 Ma is probably close to the original age of extrusion.

R.5155.34 is a dacitic tuff from north-eastern Mount Barré. It has a reasonably well-defined plateau at 39.2 ± 0.9 Ma, with apparent ages increasing in the high temperature steps to a maximum of about 85 Ma. The maximum step age represents only a small proportion of the total ^{39}Ar (2.3%), but the four highest temperature steps (comprising 10% of the total ^{39}Ar) give ages > 40 Ma. The plateau age represents either a reset age or, more likely, the original age of the tuff. The higher

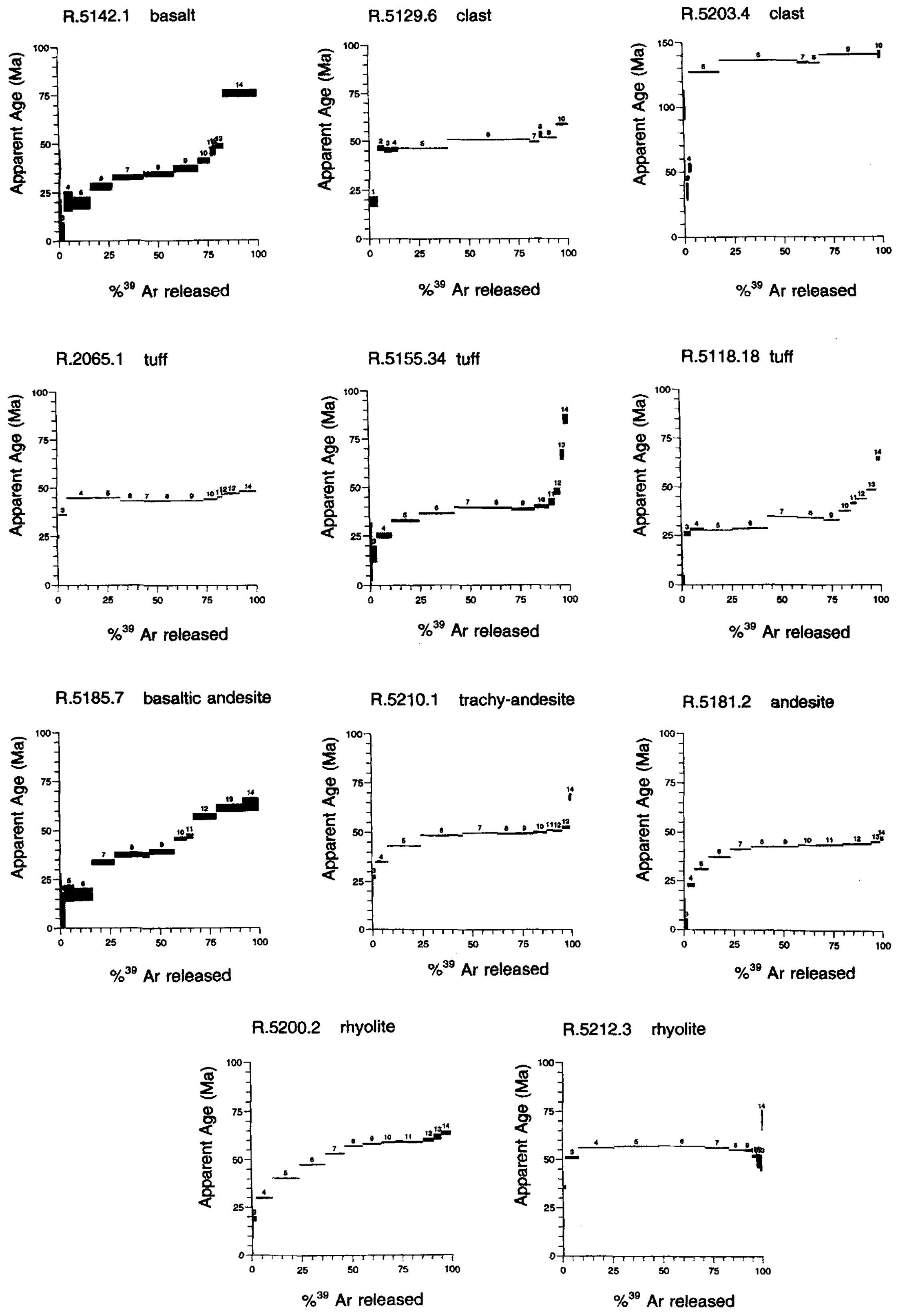

Fig. 5. Argon age spectra. The length of the box for each step is the percentage of the total sample ^{39}Ar released in the step and the height, the apparent age of the step ± 1 σ error. More complete data are given in Table I. (The age spectrum for sample R.5179.14 is shown in Fig. 6).

temperature steps may be the result of contamination from older lithic fragments, which are also present in the hand specimen.

Area E

R.5118.18 is a dacitic tuff from Milestone Bluff. It has a disturbed age spectrum with a poor plateau at steps 3 to 6, age 28.0 ± 0.6 Ma, and with apparent ages generally increasing in the higher temperature steps (indicating considerable argon loss). This tuff is interbedded with strata containing Mesozoic fossils (belemnites), suggesting that the age spectrum (including the plateau) has been substantially reset.

Area I

R.5185.7 is a basaltic andesite from southern Mount Liotard. The argon spectrum steps up gradually to a maximum of about 63 Ma, which is a minimum estimate of the age of extrusion. The general pattern of the age spectrum is broadly similar to sample R.5142.1 in area A.

R.5210.1 and R.5181.2 are andesites from Jenny Island and southern Dion Islands, respectively. They both have similar-looking spectra and reasonable plateau ages of 49.7 ± 0.5 and 40.9 ± 1.5 Ma, respectively.

Area J

R.5200.2 is a rhyolite from Reptile Ridge. It has a very poor plateau age of 56.2 ± 0.5 Ma and a spectrum indicative of significant argon loss. The three highest temperature steps (representing 14% of the released ^{39}Ar) give ages greater than 60 Ma, up to a maximum of about 64 Ma. Since this rhyolite is intruded by a pluton giving a Rb–Sr age of 60 ± 3 Ma (Pankhurst 1982; error 2 σ) it is likely that this sample's original age is $\geq$ 60 Ma.

R.5212.3 is a rhyolite from Piñero Island. It gives an age of 57.7 ± 0.5 Ma from a well-defined plateau, suggesting that there has been no significant argon loss.

Plutons

Plutonic rocks belonging to the Andean Intrusive Suite are widespread on Adelaide Island and range in composition from gabbro (norite) to monzogranite, although most are quartz dioritic and granodioritic (Moyes 1985). In some places plutons clearly intrude parts of the sedimentary and volcanic succession and it has previously been assumed that the Andean Intrusive Suite is younger than the whole of the succession (Dewar 1970).

Fission track dating

Fission track analysis was carried out on three granodiorite samples (from Wright Peninsula, an islet to the east of Wright Peninsula, and from Anchorage Island) by the London Fission Track Research Group, University College, London (Table II). All errors given are 1 σ. The apatite data are broadly comparable and record a similar cooling history. The zircon date of 60.0 ± 3.7 Ma on one sample is significantly older and records either the age of intrusion or a total resetting event, but it is not possible to tell which using fission track data alone. The date confirms the Rb–Sr age of 60 ± 3 Ma (error 2 σ; Pankhurst 1982), derived from several plutonic outcrops on Wright Peninsula (including locality R.22) and Webb Island (R.J. Pankhurst, personal communication 1995). In the absence of evidence for resetting, the apatite and zircon ages can each be assumed to be magmatic. Sample R.22.1 was modelled (using the apatite and zircon data) in order to determine the cooling history of the pluton (A. Carter, personal communication 1994). After about 60 Ma, when the

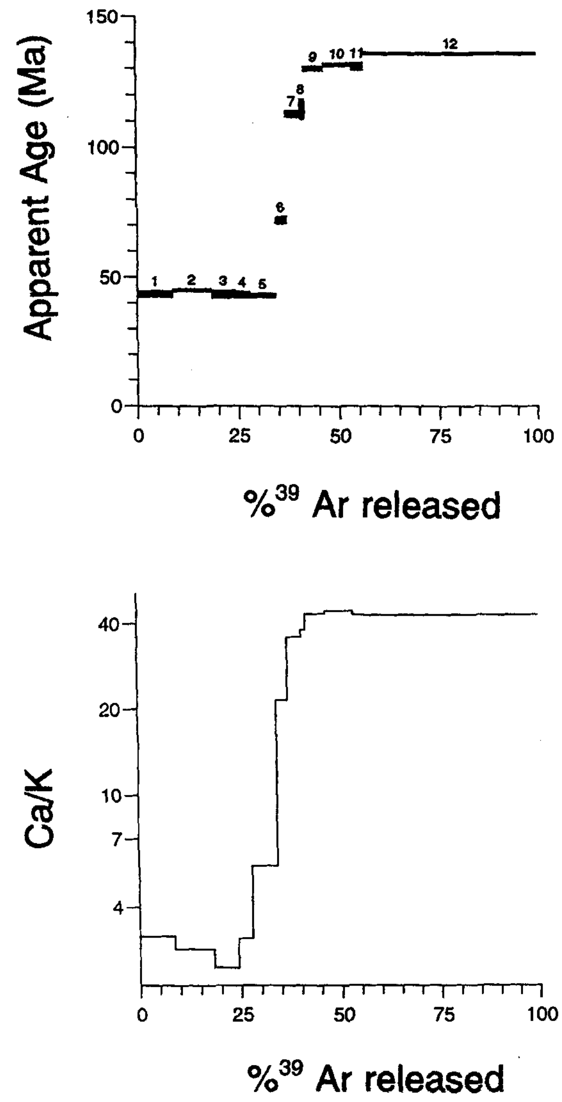

Fig. 6. Argon age spectrum for sample R.5179.14 showing its "double plateau" and the concomitant Ca/K ratio spectrum of the gas-releasing phase (derived from the ^{37}Ar/^{39}Ar ratio).

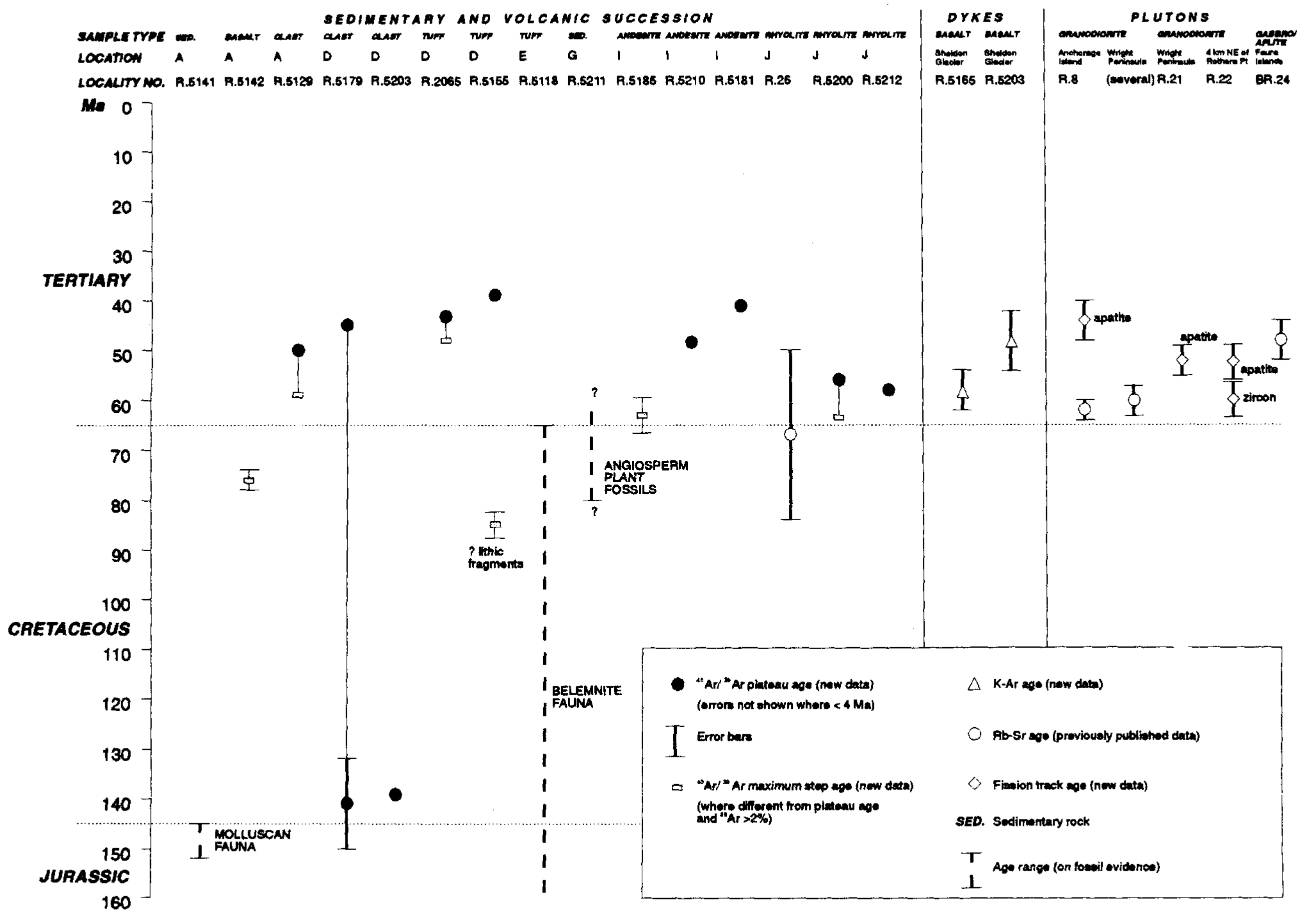

Fig. 7. Geochronology of Adelaide Island, including Ar–Ar, K–Ar, Rb–Sr and fission track dating and fossil ages. Location letters (A to J) correspond to areas shown in Fig. 2. Errors are 1 σ for argon-argon and fission track ages and 2 σ for K-Ar and Rb-Sr ages. Previously published Rb–Sr data are taken from Pankhurst (1982) and Thomson & Pankhurst (1983). Fossil evidence is included from Thomson (1972), Jefferson (1980) and Thomson & Griffiths (1994).

temperature was about 220°C (the approximate closure temperature for zircon), cooling was relatively slow and fairly continuous, falling below 60°C (the temperature below which tracks in apatite are considered stable) at about 40 Ma.

Dykes

Dykes are common in some parts of Adelaide Island, and are of basic and intermediate composition. At least two phases of dyke intrusion are present. Dykes intrude both the sedimentary and volcanic succession and the Andean Intrusive Suite, but appear to be generally more common in the former. The ages of the dykes are poorly constrained, although geochemical similarities with the plutons and complex cross-cutting relationships between dykes and plutons tentatively suggest that some dykes were penecontemporaneous with plutonism. Locally, peperitic breccias contain dacitic clasts which indicate that some intrusions were broadly contemporaneous with the sedimentary and volcanic succession. Two dykes (on northern Wright Peninsula and Webb Island) have alkaline compositions and are distinct from the other (calc-alkaline) intrusions. One of the alkaline dykes (containing ultramafic enclaves) intruded

Table II. Summary of fission track data. All errors are 1 σ.

sample no.	Location	Mineral	Lithology	Fission-track age No. of grains	Age
R.8.1	Anchorage Island	apatite	granodiorite pluton	8	44.2 ± 3.8 Ma
R.21.1	Wright Peninsula (5 km N of Rothera Point)	apatite	granodiorite pluton	11	52.0 ± 2.9 Ma
R.22.1	Islet 4 km NE of Rothera Point	apatite	granodiorite pluton	20	52.4 ± 3.5 Ma
		zircon			60.0 ± 3.7 Ma

Table III. Summary of K–Ar data. All errors on ages are 2 σ.

Sample no.	Location	Sample type	Lithology	% K[1]	Atmospheric ^{40}Ar (nl)	(%)	Radiogenic ^{40}Ar (volume nl/g)	K-Ar age[2]	Average age[2]
R.5165.6	E Sheldon Glacier	hornblende	basaltic dyke	0.174	0.46	73.52	0.3976	57.8 ± 3.7 Ma	58 ± 4 Ma
				0.174	0.88	73.17	0.3963	57.7 ± 3.5 Ma	
R.5203.1	SW Sheldon Glacier	hornblende	basaltic dyke	0.177	2.12	90.98	0.3370	48.3 ± 10.0 Ma	48 ± 6 Ma
				0.177	1.39	86.40	0.3375	48.4 ± 6.4 Ma	

[1]error on K is less than 1%, [2]error on ages is 2 σ

a pluton (Dewar 1970, Smellie 1987, Smellie *et al.* 1988) indicating that these alkaline dykes represent a younger (post-pluton) phase of dyke emplacement.

Potassium-argon dating

Two new K-Ar ages were obtained from hornblende phenocrysts in calc-alkaline dykes on Adelaide Island (Table III). Errors on ages are 2 σ.

Hornblende mineral separates were prepared by crushing the whole rock samples followed by heavy liquid separation. The laboratory work was carried out at the Natural Environment Research Council Isotope Geosciences Laboratory in Keyworth. Potassium concentrations were determined on duplicate sample dissolutions, using a Laboratory Equipment IL543 flame photometer with an internal lithium buffer. The precision of potassium analyses is estimated at ± 1%. Argon measurements were carried out on a VG Micromass 1200 mass spectrometer using a ^{38}Ar-enriched tracer. The ages were calculated using the decay constants of Steiger & Jäger (1977).

Sample R.5165.6, from a basaltic hypabyssal intrusion on the east side of Sheldon Glacier, gave an age of 58 ± 4 Ma. Sample R.5203.1, from a basic dyke which intruded conglomerates in area D on the west side of lower Sheldon Glacier, gave an age of 48 ± 6 Ma. The first age is similar to

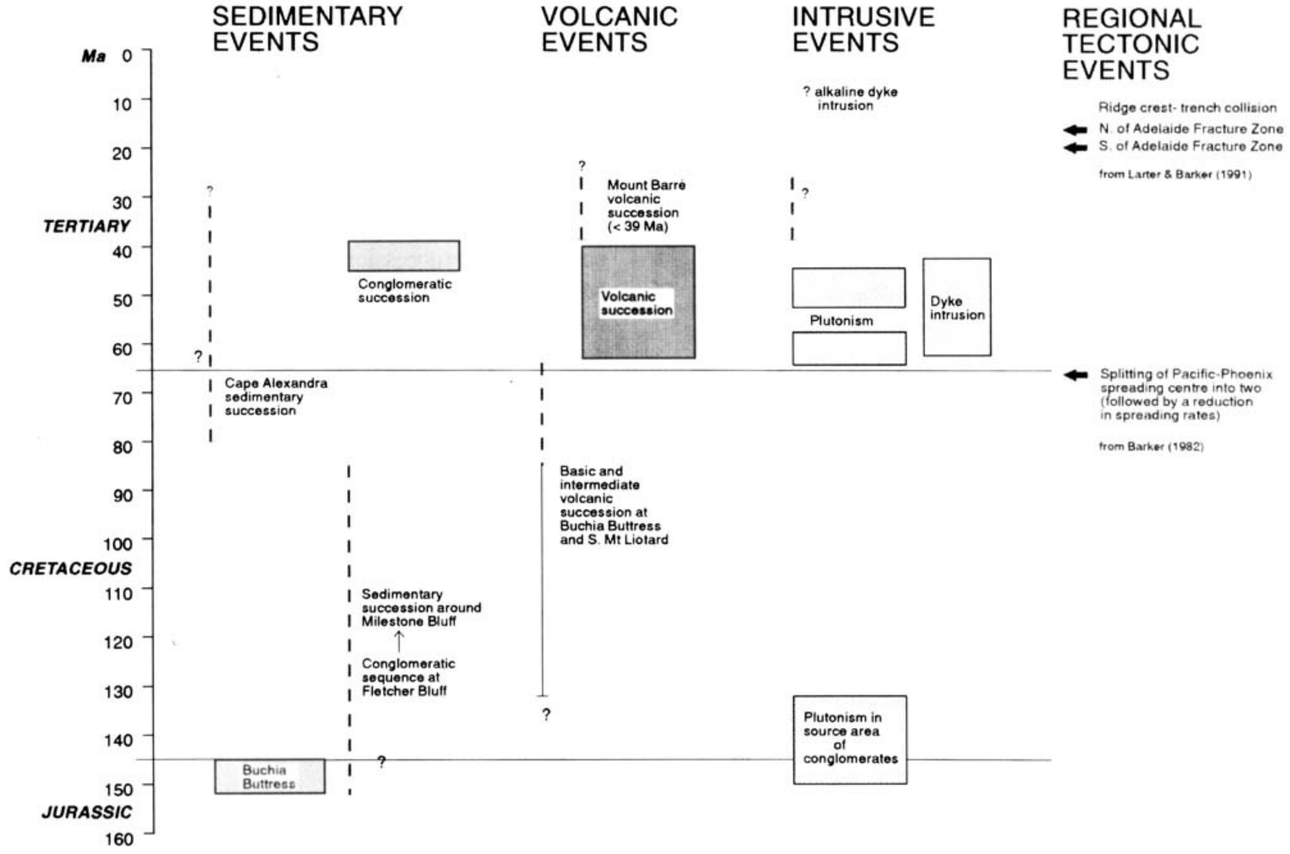

Fig. 8. Summary of sedimentary, volcanic and intrusive events on Adelaide Island and their relationship to regional tectonic events.

Rb–Sr ages (*c.* 60–62 Ma) from the more acidic plutons on Anchorage Island and Wright Peninsula (Pankhurst 1982), suggesting that the dyke was intruded penecontemporaneously with some of the plutons. The second age is similar to the Rb–Sr age of 48 ± 4 Ma for a pluton on the Faure Islands (Moyes & Pankhurst 1994).

Discussion

Most samples give reasonable argon ages, which are consistent with the local stratigraphy derived by mapping (Fig. 4). For instance, in western Ryder Bay (Fig. 2 areas D & I) the following ages were obtained (in ascending stratigraphical order): andesite on Jenny Island (49.7 ± 0.5 Ma), tuff (43.2 ± 0.4 Ma), conglomerate (containing two clasts giving ages of 140.8 ± 9.3 Ma (partially reset to 45.2 ± 0.9 Ma) and 138.1 ± 1.9 Ma), and tuff (39.2 ± 0.9 Ma).

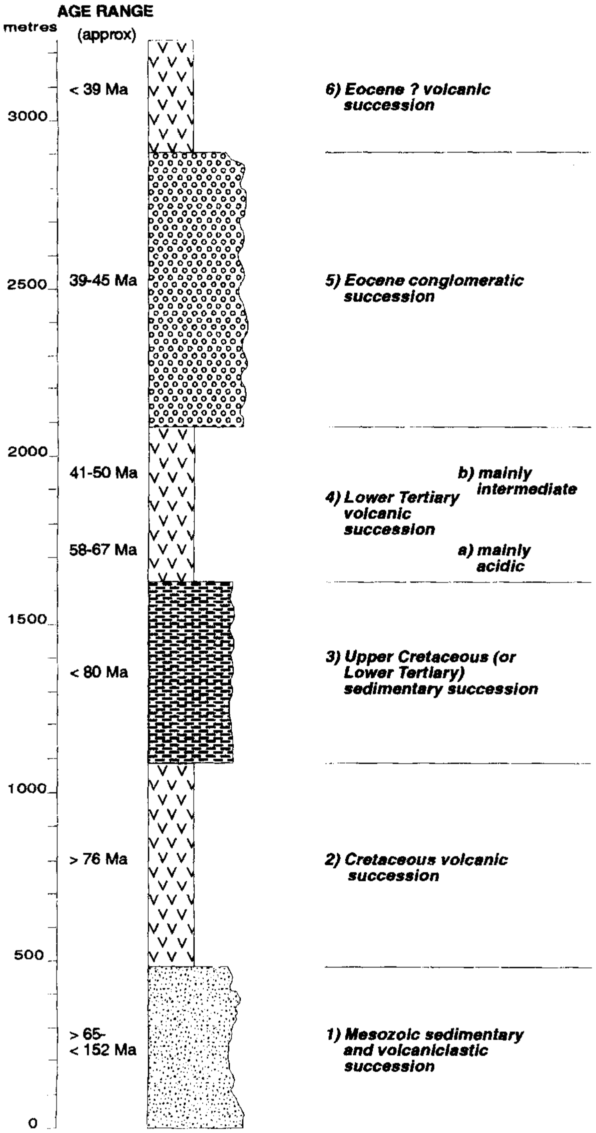

Fig. 9. Stratigraphy, thickness and age of the sedimentary and volcanic succession on Adelaide Island. Note: thicknesses of successions may change substantially due to lateral variation in thickness.

We believe that most of the argon spectra show statistically and geologically acceptable plateaux and they provide good estimates for the original age of the volcanism. This interpretation has significant implications for the stratigraphy and evolution of Adelaide Island (summarized in Fig. 8). The sedimentary and volcanic succession on the island can be divided into several chronological units, each with statistically separable age ranges (Fig. 9), thus allowing comparisons with sequences of similar age in other parts of the Antarctic Peninsula (Fig. 10). Mainly as a result of our study, the following magmatic and sedimentary episodes are now recognised on Adelaide Island:

Mesozoic volcaniclastic sedimentation

Late Jurassic marine volcaniclastic sedimentation on Adelaide Island correlates in age with marine sedimentary rocks in the South Shetland Islands (Thomson 1982, Crame *et al.* 1993), Alexander Island (Butterworth *et al.* 1988), western Palmer Land (Thomson 1975) and the Larsen Basin (Farquharson 1983). In contrast to Adelaide Island, fine-grained sedimentary rocks predominate in each of these other areas. Thus, across the region the Upper Jurassic was a period of marine sedimentation, corresponding on Alexander Island to a change from trench-slope fill to a fore-arc basin (Doubleday *et al.* 1993).

Early Cretaceous plutonism

The evidence for Early Cretaceous plutonism comes from the conglomeratic succession of eastern Mount Liotard and eastern Mount Barré (area D; Fig. 2). These conglomerates contain mainly volcanic and plutonic clasts, and their clast composition, coarse grain size and angular matrix suggest derivation from a proximal, uplifted and dissected arc source, probably situated to the east of the present outcrop area. The conglomerates contain clasts of plutonic origin (with different compositions and textures) from which hornblende separates from two clasts give concordant plateau ages of about 140 Ma. These ages are similar to those of plutonism and crustal extension in north-west Palmer Land (Vaughan & Millar 1996) and they probably indicate an Early Cretaceous period of plutonism/metamorphism in the source area of the Adelaide Island conglomerates.

Cretaceous volcanism

Volcanic rocks of intermediate and basic composition overlie the Mesozoic sedimentary and volcanic succession. Undiagnostic age spectra from basalt R.5142.1 and andesite R.5185.7 only suggest eruptions occurring before 75 and

63 Ma, respectively. It is probably significant that the age spectra of these two samples are more disturbed than those of lavas with younger ages, probably as a result of reheating by later plutons. It is possible that the Cretaceous volcanic succession on Adelaide Island broadly correlates in age with widespread terrestrial intra-arc Cretaceous volcanic rocks in the South Shetland Islands (Smellie *et al.* 1980, 1984, Crame *et al.* 1993) and relatively coarse-grained volcaniclastic strata on the western margin of the Larsen Basin (Farquharson 1982).

Late Cretaceous (or Early Tertiary) sedimentation

On plant fossil evidence (Jefferson 1980), mainly fine-grained sedimentary rocks exposed at Cape Alexandra and its vicinity are of Late Cretaceous or Early Tertiary age.

Early Tertiary magmatism

Most isotopically dated andesitic to rhyolitic volcanic rocks in the area have ages ranging between about 41 and 67 Ma. Volcanism on Jenny Island and the Dion Islands occurred between about 41–50 Ma, whereas that on Wright Peninsula and Piñero Island (and, more tentatively, a rhyolite on Webb Island) occurred at about 58–64 Ma. The volcanic rocks are older than the conglomeratic sequences on eastern Adelaide Island. The suite of Tertiary volcanic rocks on Adelaide Island is of similar age to calc-alkaline volcanic sequences on Alexander Island (Burn 1981, McCarron & Millar 1997), and King George Island, in the South Shetland Islands (Smellie *et al.* 1984). Together, these sequences indicate the existence of a major phase of volcanism on the western side of the Antarctic Peninsula during the Early Tertiary.

New zircon fission track ages from plutons and K–Ar ages from hypabyssal intrusions confirm evidence from previously published Rb–Sr ages that plutonism also occurred on Adelaide Island around 60 Ma. It is possible that there was also plutonism of similar age to the gabbro and aplite of the Faure Islands (*c.* 48 Ma). Since some undated plutons and dykes on Adelaide Island intrude Lower Tertiary volcanic sequences and conglomerates, these plutons must be younger than those on Wright Peninsula and Anchorage Island (i.e. <*c.* 40–50 Ma). The age of some of the volcanism overlaps with the overall age range of the plutons and suggests that they are possibly coeval, e.g. the acidic volcanic sequences (area J) and plutons on Wright Peninsula. This period of plutonism on Adelaide Island coincides with widespread magmatism on the western side of the Antarctic Peninsula (Pankhurst 1982) and reflects a major magmatic pulse of the Antarctic Peninsula Batholith (Leat *et al.* 1995). It is possible that this magmatism was related to the splitting of the Pacific-Phoenix spreading centre and reduction in seafloor spreading rates at about this time (Barker 1982).

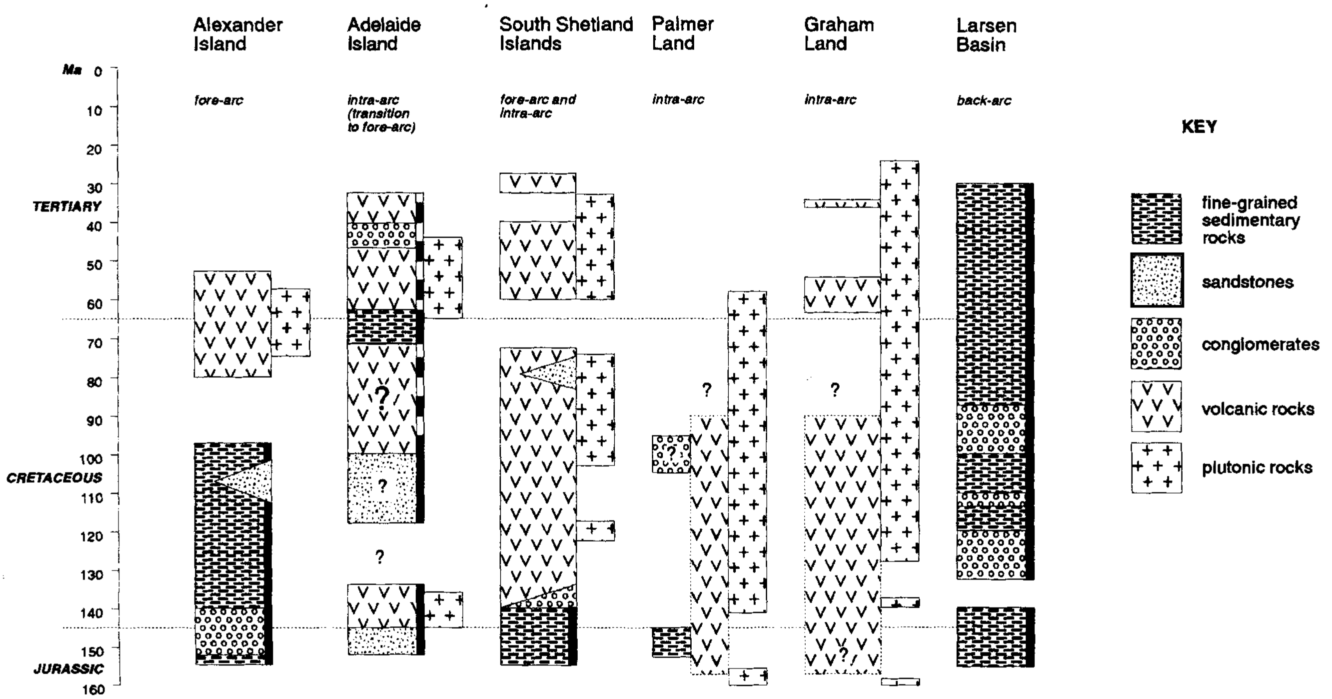

Fig. 10. Summary chart of late Jurassic to Tertiary sedimentation and magmatism in the Antarctic Peninsula. Marine sedimentation/ subaqueous volcanism is indicated by a thick black line on the right-hand side of the column, mixed subaqueous–subaerial sedimentation/ volcanism by a thick broken line. Boxes with thin dotted margins indicate rocks of uncertain age. For locations see Fig. 1. Includes data from this study and Macdonald & Butterworth (1990).

Eocene sedimentation and volcanism

Sedimentation in the Eocene produced sequences composed predominantly of conglomerate in area D (Fig. 2). Argon ages from tuffs above and below the conglomerates (Fig. 4) probably represent original extrusive ages and constrain the depositional age of the conglomerates to mid-Eocene times (39–43 Ma). One of the dated tuff beds (R.5155.34), at the top of the Eocene conglomeratic succession, yielded an argon age of approximately 39 Ma. This bed is overlain by a thick sequence of intermediate volcanic rocks (Fig. 4, area D) indicating an important phase of volcanism of likely Eocene age, similar in age to Tertiary volcanic rocks in the South Shetland Islands. Some dykes which intrude the Eocene conglomeratic succession are probably amongst the youngest rocks present.

Conclusions

The results of several dating methods reported in this paper have added new and important constraints on the stratigraphy of the sedimentary and volcanic succession on Adelaide Island. Although all the samples have suffered variable argon loss or contamination, several samples yielded geologically acceptable plateaux which are consistent with the mapped local stratigraphies and they are interpreted as closely approximating the original magmatic ages. The volcanic rock samples give ages which are similar to, or younger than, geographically associated plutons, and they are likely coeval. Other samples lacking plateaux, also have scattered correlation plots and tend to give ages greater than about 63 Ma (from their maximum step ages). These ages were probably re-set by the younger plutons.

The following geological events are recognized on Adelaide Island (Fig. 8):

1) Mesozoic sedimentation, including marine Tithonian (*c.* 145–152 Ma) deposits at Buchia Buttress.

2) Early Cretaceous (*c.* 140 Ma) plutonism in the source region of the conglomerates (nearby and probably to the east of Adelaide Island).

3) Cretaceous (> 63 and probably > 76 Ma) intermediate to basic volcanism, as seen in the upper part of Buchia Buttress and southern Mount Liotard.

4) Sedimentation of the plant-bearing sequence at Cape Alexandra, which is younger than Late Albian (< 80 Ma).

5) Early Tertiary (< 40–*c.* 62 Ma) plutonism and dyke intrusion, as seen on Wright Peninsula, as well as mainly Early Tertiary (*c.* 41–67 Ma) intermediate to acidic volcanism. Acidic volcanism in the vicinity of Wright Peninsula is older (*c.* 58–67 Ma) than the intermediate volcanism on Jenny Island and Dion Islands (*c.* 41–50 Ma). Therefore, volcanism was pene-contemporaneous, and probably coeval, with plutonism.

6) Eocene (*c.* 39–43 Ma) sedimentation of conglomerates, now exposed on eastern Mount Liotard and Mount Barré, Eocene (< 39 Ma) intermediate volcanism in the area of eastern Mount Barré (overlying the conglomeratic sequence) and intrusion of some dykes.

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