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The Cape Purvis volcano, Dundee Island (northern Antarctic Peninsula): late Pleistocene age, eruptive processes and implications for a glacial palaeoenvironment

J.L. SMELLIE[1], W.C. MCINTOSH[2], R. ESSER[2] and P. FRETWELL[1]

[1]*British Antarctic Survey, High Cross, Madingley Road, Cambridge CB3 0ET, UK*
[2]*New Mexico Geochronology Research Centre, New Mexico Institute of Mining & Technology, 801 Leroy Place, Socorro, NM 87801-4796, USA*
jlsm@bas.ac.uk

Abstract: Cape Purvis is a conspicuous promontory on southern Dundee Island. It forms a prominent mesa that contrasts with the smooth, shield-like (snow-covered) topography of the remainder of the island. The promontory is composed of fresh alkaline basaltic (hawaiite) volcanic rocks compositionally similar to younger lavas on Paulet Island 5 km to the east. The outcrop is one of the youngest and northernmost satellite centres of the James Ross Island Volcanic Group. $^{40}Ar/^{39}Ar$ isotopic dating indicates that the Cape Purvis volcano is 132 ± 19 ka in age. The examined sequence probably formed as a lava-fed delta during a subglacial eruption late in the glacial period corresponding to Isotope Stage 6, when the ice sheet surface elevation was 300–400 m higher than at present. A remarkable unidirectional age progression is now evident, from volcanic centres in Prince Gustav Channel (*c*. 2.0–1.6 Ma), through Tabarin Peninsula (1.69–*c*. 1 Ma) to Cape Purvis and Paulet islands (132–few ka). The age variations are tentatively ascribed to construction of progressively younger volcanic centres at the leading edge of an easterly-opening deep fault system, although the origins of the postulated fault system are unclear.

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Key words: hawaiite, hyaloclastite, ice sheet, lava-fed delta, Pleistocene, subglacial

Introduction

Dundee Island (63°29'S, 55°58'W) is situated at the northern tip of the Antarctic Peninsula, about 50 km east of Tabarin Peninsula and a few km south of Joinville Island (Fig. 1). Very little rock is exposed and the island rises to *c*. 624 m in a smooth snow and ice shield that dominates the island. The coast is formed of ice cliffs, which are unbroken except for a few small unnamed rocky bluffs and a prominent low-lying triangular promontory (Welchness) at the western extremity. Cape Purvis is the most prominent topographical feature. Situated on the south side of the island, it is a conspicuous mesa, oval in plan view, and largely covered by snow and ice (Figs 2 & 3). Cape Purvis was discovered and roughly charted by Sir James Clark Ross in December 1842. Falklands Islands Dependencies Survey personnel subsequently surveyed it topographically in January 1947 and December 1953.

Very little information exists on the geology of Cape Purvis. An unspecified coastal locality was described as composed of irregularly and unevenly bedded basaltic tuffs, agglomerates and scoria, forming a section at least 100 ft (30 m) thick and exposed in an ice-capped slope at least 175 ft (53 m) high (unpublished field notes of R.J. Adie and W.N. Croft, 24 January 1947). Baker *et al.* (1973) described a broadly similar sequence comprising agglomerates or hyaloclastites with pillows in a sparse yellow matrix. Based on a petrographical comparison, the volcanic rocks were regarded as part of the same volcanic province as the alkaline basaltic James Ross Island Volcanic Group (JRIVG). Baker *et al.* (1973) rejected a model of volcanic delta progradation into the sea (cf. Nelson 1975) and instead suggested a broad sequence of lithofacies whose formation was ascribed to gradually shoaling submarine eruptions.

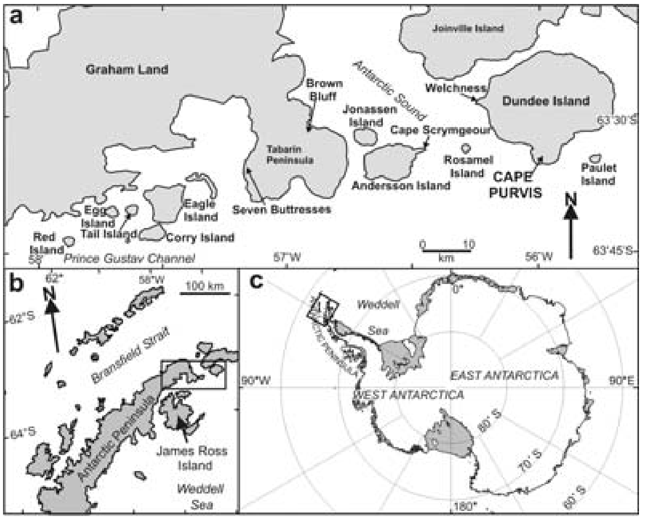

Fig. 1. Location map showing the position of Cape Purvis and other localities mentioned in the text in relation to northern Antarctic Peninsula and Antarctica.

Fig. 2. View of Cape Purvis looking north. Note the distinctive mesa-like morphology and the prominent scarp at 250 m on the right side. The conspicuous tall cliff section just right of centre was examined.

The Cape Purvis lithologies, in particular, were regarded as the deepest-water pyroclastic facies whose outgassing and degree of fragmentation (a supposed empirical measure of explosivity) were controlled by an inferred greater depth of water overlying the eruptive vent(s) compared to other lithologies in the JRIVG. The present elevation of these supposed deep-water facies, up to 300 m above sea level, was attributed to post-eruptive regional tectonic uplift since the late Pliocene together with subordinate eustatic changes, although no evidence was presented to support those suggestions.

During the present investigation of the JRIVG, Cape Purvis was visited on 11 January 2004. The only extensive and readily accessible section is situated at the south-west end of the headland and consists entirely of fresh-looking volcanic rocks. Because of the topography of Cape Purvis, which is largely inaccessible, the section examined is probably the same as was visited by all previous workers. The results and implications of the new study, which should still be regarded as a reconnaissance, are reported here.

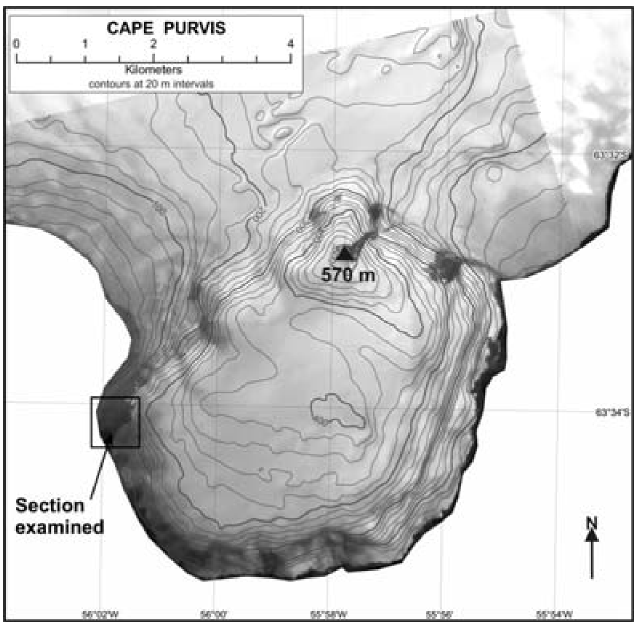

Fig. 3. Shaded-relief topographical map of Cape Purvis, showing the location of the section examined. Rock outcrops are indicated in dark grey.

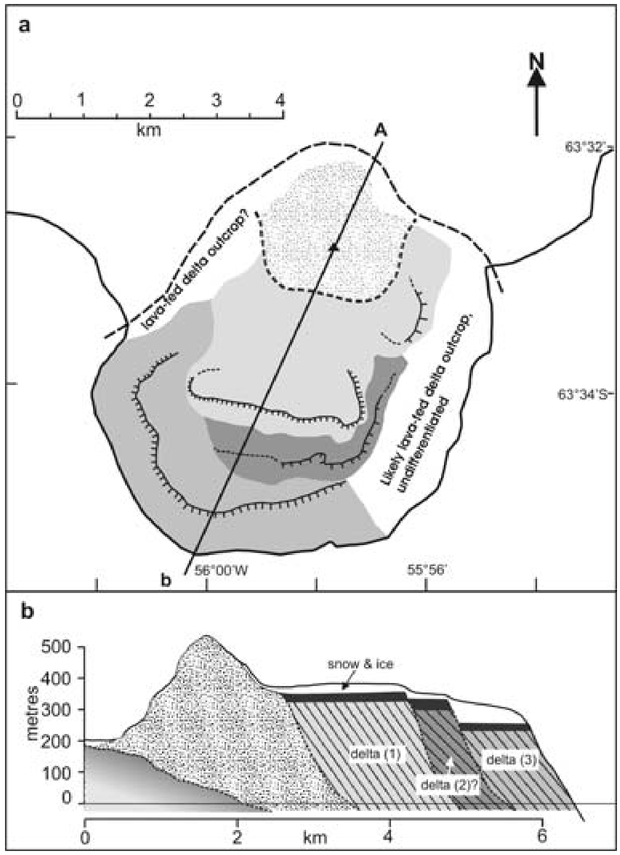

Fig. 4. Schematic geological map of **a.** Cape Purvis and **b.** preferred hypothetical sketch cross-section. The outcrop is interpreted as a monogenetic edifice erupted in a glacial setting, with a single contiguous lava-fed delta inferred to have been emplaced in three stages. The stepped delta morphology is interpreted to reflect a water level affected by a dynamic meltwater hydraulic regime. The steep bedding orientations sketched in the three deltas are schematic only.

Geology of Cape Purvis

Description

Cape Purvis has a prominent mesa-like morphology that measures 5.2 and 6 km in SSW–NNE and WNW–ESE directions, respectively (Figs 2 & 3). It rises to a general elevation of about 300–400 m a.s.l. The landform has steep margins that terminate upward in a conspicuous scarp at about 250 m a.s.l., which is well seen on the south-west, south and south-east sides (Fig. 2). Air photographs suggest that higher subdued scarps are also present, at about 380 m and 340 m, the latter restricted to the south-east side (Fig. 4). The summit area is almost entirely snow and ice covered. It forms a low "dome"-like carapace, and has an un-named hill at its northern edge that has rock exposed and

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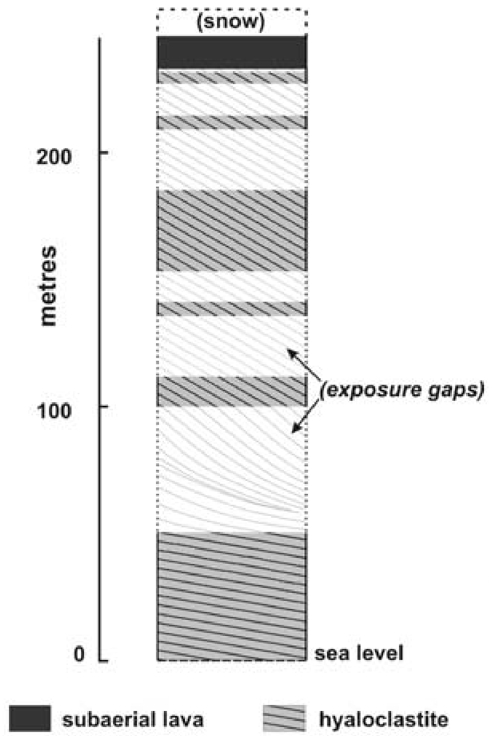

Fig. 5. Schematic vertical profile section illustrating the major lithofacies and bedding characteristics of the section examined at Cape Purvis. The depicted positions if rock exposed in the section are indicative only.

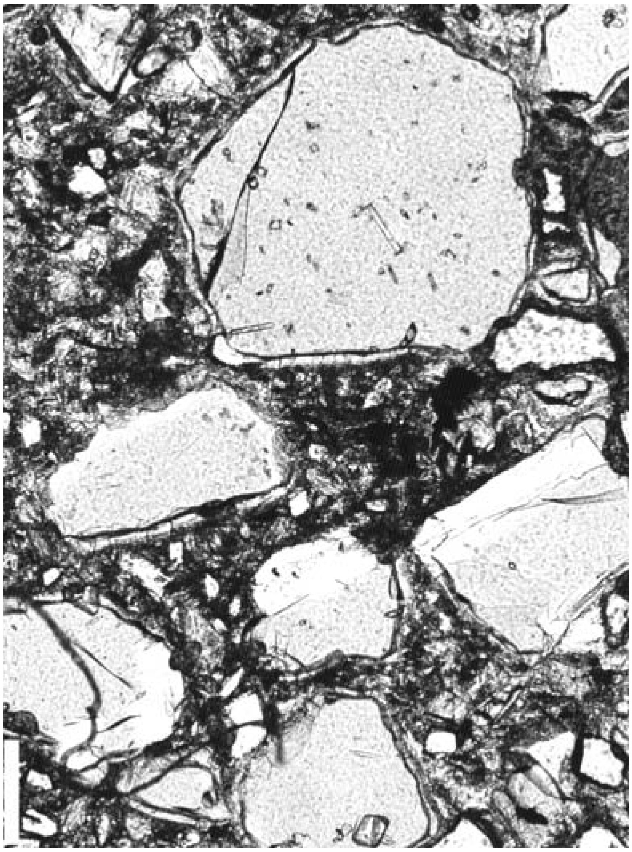

Fig. 6. Photomicrograph of hyaloclastite tuff from Cape Purvis. Note the large non-vesicular glass fragments with blocky shapes, features that are indicative of an origin by non-explosive fragmentation during quenching. The large grains in this sample also show effects of minor abrasion, probably formed during transport in a sediment gravity flow. Sample DJ.2055.2, from 56 m a.s.l. The white vertical scale-bar at the lower left side is 200 um long.

rises to 570 m.

A landing was made by helicopter at just one locality, at the south-western end of Cape Purvis, at 63°34.016'S and 56°01.763'W, where the largest area of snow-free ground is present (Fig. 3). The locality is a tall scree and rock slope capped by a gently dipping snow and ice cover that is continuous with the Cape Purvis ice cap. A schematic vertical profile section is shown in Fig. 5. The crest of the slope examined, at 246 m a.s.l., is composed of near *in situ* blocky rubble derived from coarsely vesicular, crystalline grey–pale grey lava, some with fluidal textures and maroon-coloured oxidation surfaces. Flat-lying compound lava is exposed *in situ* in a 10 m-high crag below the rubble on the seaward side. It consists of flow lobes up to a few metres thick with well-developed brown-coloured pahoehoe surfaces. The exposed base of the lava crag lies at 233 m a.s.l. About 10 m of poorly vesicular finer-grained lava forming steep downslope-dipping pods crops out a few metres below the lava crag. The pods have well-developed glassy surfaces and are locally separated by minor khaki-coloured hyaloclastite breccia. Much of the slope below is covered by scree but there are numerous exposures of coarse hyaloclastite breccia. The breccia is unsorted and massive and has sparse gravel to coarse sand-grade glassy matrix. It is variably rich in lithic blocks and broken lava pillows and contains a few pale khaki-coloured, gravel-grade, hyaloclastite interbeds a few dm thick. Bedding in the breccia is crude and typically 1.5 to 4 m thick. It is steeply-dipping (25–35°?) in the higher exposures, but dips more gently (10°) to the WNW in the better-exposed 50 m-high crags at the foot of the slope. The base of the section is unexposed (below sea level). The total thickness of the observed section, including the lava rubble top, is 246 m.

Petrographically, the summit lavas are holocrystalline, formed by about 30% lathy plagioclase phenocrysts up to 3 mm long that are seriate with the groundmass, less common anhedral clinopyroxene (very pale pink, with narrow darker pink rims) and minor small olivine, in an intergranular groundmass formed of the same minerals together with minor but distinctive rod-shaped opaque oxide. The groundmass clinopyroxene is more strongly pink-coloured than the phenocrysts. The groundmass also contains sparse interstitial patches or domains of finely acicular microlites (probably plagioclase and pyroxene), and two strongly coloured accessory minerals: a pale yellow–intense red-brown pleochroic mineral that may be

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Table I. Geochemical analyses of lavas from Cape Purvis and Paulet Island.

	Cape Purvis (DJ.2055.1)*	Paulet Island (27788)**
SiO_2	47.97	46.41
TiO_2	2.36	2.60
Al_2O_3	16.61	16.33
Fe_2O_3T	11.18	10.88
MnO	0.16	0.16
MgO	6.69	8.11
CaO	9.68	9.60
Na_2O	3.94	4.30
K_2O	1.52	1.34
P_2O_5	0.51	0.83
LOI	-0.3	
H_2O^+		0.09
H_2O^-		0.13
Total	100.32	100.78
Sc	24.14	
Ti	2.34	
V	229.35	
Cr	133.97	
Co	38.66	
Ni	66.55	
Cu	53.35	
Zn	97.54	
Ga	20.62	
Rb	22.31	
Sr	692.99	
Y	27.11	
Zr	200.59	
Nb	39.33	
Cs	0.41	
Ba	239.95	
La	27.77	
Ce	57.19	
Pr	7.39	
Nd	30.77	
Sm	6.46	
Eu	2.12	
Gd	6.41	
Tb	0.95	
Dy	5.21	
Ho	1.02	
Er	2.58	
Tm	0.38	
Yb	2.32	
Lu	0.35	
Hf	4.53	
Ta	2.38	
Pb	3.55	
Th	3.33	
U	1.22	

* major oxides determined by XRF at University of Keele; trace elements determined by ICP-MS at University of Durham.
**data from Baker *et al.* (1977).

aenigmatite, kaersutite or barkevikite; and yellow-brown to bright green likely aegirine-augite.

The matrix in the breccias, and some finer beds lower in the section, consist of vitrophyric medium to coarse sand-grade hyaloclastite dominated by fragments of fresh brown glass. The glass is non-vesicular to poorly vesicular. Planar fracture-bounded blocky clast shapes are characteristic (Fig. 6). The smallest grains are fine sand size (down to *c.* 0.05 mm) and the rocks are poorly sorted. The glass fragments contain up to 30% lathy plagioclase, 5–8% subhedral–anhedral pale greenish to pink clinopyroxene and 2–3% much smaller anhedral olivine. Crystallites and pilotaxitic microlites are present in many glass fragments. Tiny swallow-tail plagioclase quench crystals are also present and acted as nuclei for conspicuous fringes of sub-opaque, densely intergrown acicular pyroxene(?) crystallites. The latter dominate some clasts such that they resemble tachylite.

A single lava was analysed. It is a basalt (hawaiite) with relatively low MgO, high TiO_2, CaO, Nb and total alkalis, and moderate LREE-enrichment characteristic of sodic alkaline magmas (Table I). A previously published major oxides analysis of a lava from Paulet Island, 5 km east of Cape Purvis, is also given in Table I for comparison (from Baker *et al.* 1977). It is also a hawaiite and, apart from higher MgO and Na_2O in the Paulet Island sample, the two analyses are remarkably similar.

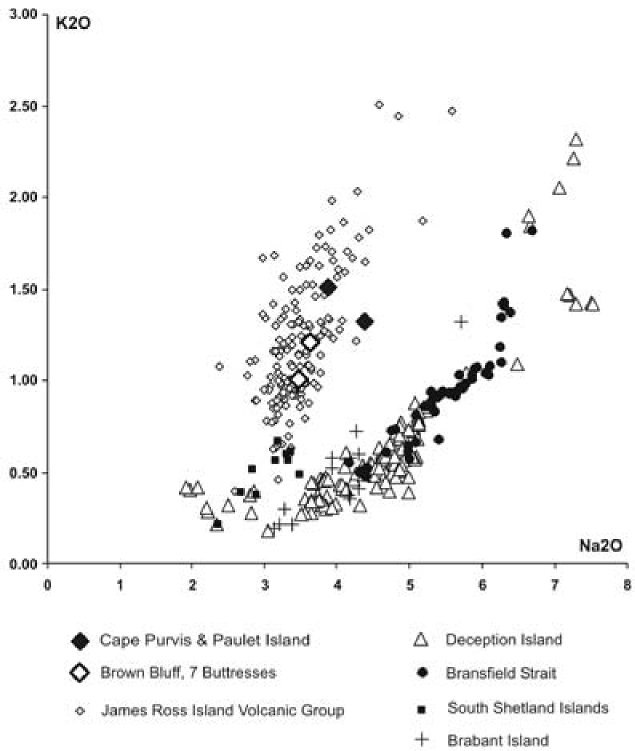

Fig. 7. K_2O vs Na_2O (in Wt.%) for samples of lava from the James Ross Island Volcanic Group and representative lava analyses from other Quaternary volcanic centres in the northern Antarctic Peninsula region. The strong compositional affinity between the Cape Purvis and Paulet Island samples and the James Ross Island Volcanic Group is evident. Data sources: Deception Island (Smellie *et al*. 2002 and unpublished); Bransfield Strait seamounts (Keller *et al*. 2002); alkaline and tholeiitic centres in the South Shetland Islands (Smellie unpublished); and Brabant Island (Smellie *et al*. 2006 and unpublished).

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Interpretation

Although the exposures are discontinuous, the lithologies, field relationships and similar juvenile clast petrography suggest that the entire section is cogenetic. The lithofacies architecture resembles a lava-fed delta similar to the many better-exposed examples seen on James Ross Island and neighbouring islands (Nelson 1975, Skilling 2002, Smellie 2006). The analysed lava is compositionally indistinguishable from those in the JRIVG (Fig. 7), but the presence of clinopyroxene phenocrysts, also noted by Baker *et al.* (1973), is unusual for the JRIVG.

The uppermost, horizontal, compound lava is interpreted as a subaerial caprock analogous to topset beds in a sedimentary delta, with an underlying passage zone at *c.* 230 m a.s.l. A passage zone is an environmental transition preserved as juxtaposed coeval subaerial and subaqueous lithofacies; in other words, a fossil water level (Jones 1969, Skilling 2002, Smellie 2006). The steep-dipping lava lobes underlying the caprock were probably formed where individual subaerial lava lobes penetrated the coeval water surface and travelled short distances down the delta front slope. Their prominent glassy surfaces indicate strong water-chilling, and they also formed pillows and contributed, as pillow-derived fragments, to the associated sparse hyaloclastite matrix. The bulk of the section comprises crude homoclinal beds of fines-poor coarse hyaloclastite breccia, which formed by the quench shattering and mechanical disintegration of (1) lavas similar to those in the overlying caprock, (2) lava lobes in the passage zone and (3) pillows. Much of the fragmentation probably took place at the delta brinkpoint (Skilling 2002). The poor vesicularity in the hyaloclasts is attributed to subaerial degassing of the caprock lavas prior to quench fragmentation, rather than to pressure-related suppression of vesiculation in deep water, as proposed by Baker *et al.* (1973). The somewhat greater vesicularity of the subaerial lavas compared to the hyaloclasts is due to the slow, post-emplacement, conductive cooling and crystallization of the former, leading to late-stage exsolution of any remaining volatiles (cf. LeMasurier 2002). Bedding dips are essentially at the angle of repose for coarse cohesionless sediments and the dips become shallower and tangential toward the base. Together with their massive unsorted appearance, these characteristics suggest that the breccias are delta foreset beds emplaced variably by avalanching of individual clasts and *en masse* from mass flows. There is no evidence in any of the lithologies examined for explosive eruption and generation of pyroclastic material (cf. Baker *et al.* 1973). The presence of lenses of lithic block-rich breccia also suggests that sections of subaerial caprock lavas periodically collapsed and contributed to the delta front (cf. the "rubble breccias" on James Ross Island described by Sykes (1989); see also Skilling (2002)). Such collapses are a common feature in lava-fed deltas forming today in Hawaii (e.g. Hon *et al.* 1993, Mattox & Mangan 1997).

The mesa morphology is distinctive and is consistent with its interpretation as a small volcanic centre dominated by lava-fed delta progradation, similar to basaltic Surtseyan and tuya edifices formed in marine and glacial environments, respectively (cf. Smellie in press). The prominent scarp at *c.* 250 m is a slope break formed by the delta front. The additional presence of scarps at 340 and 380 m is also interpreted to indicate the possible presence of two other delta constructs (Fig. 4), although "delta 2" in Fig. 4 is rather weakly defined by the topography. The relationships between the three possible deltas can be interpreted in at least three ways:

1. The edifice is not monogenetic but underwent at least three phases of effusive activity, with construction of three successive lava-fed deltas at different times. Thus each delta would have been associated with a different water level, variably 90–*c.* 130 m higher than the lowest delta (i.e. higher sea levels or thicker ice sheets); or
2. If the edifice was erupted in an ice sheet, the three possible delta segments may be cogenetic and contiguous. In this scenario, the simple unidirectional (southerly) lowering of the three delta tops reflects a meltwater lake that lowered during the eruptive period; each later phase of delta growth reflects a lower meltwater lake surface. Such variations in water levels during subglacial eruptions, especially lake drainage, are now known to be a common and diagnostic feature of subglacially erupted basaltic centres and are widespread in the JRIVG (Smellie 2006).
3. They are a series of topographical steps caused by successive down-slope mass movements. Similar features of hydroclastic deltas, ranging from large-scale sector collapses to smaller-scale edifice settling, have been described in Marie Byrd Land by LeMasurier (2002).

These suggestions are necessarily speculative. Although the existing data are permissive, we currently do not favour an explanation as down-stepped blocks for the following reason: the lower two scarps can apparently be traced wrapping around the east and west flanks of the edifice, which is an unlikely morphological pattern for simple collapse blocks. However, our preferred interpretations, as multiple superimposed deltas or a single delta emplaced during a period of falling meltwater lake elevation, cannot be definitive at this time.

The prominent triangular peak on the north flank, which rises *c.* 150 m above the ice-covered mesa surface, probably represents the locus of the eruptive vent, at least for the final stages of activity of the Cape Purvis volcano. It is interpreted tentatively here as a pyroclastic cone and also

Table II. New $^{40}Ar/^{39}Ar$ isotopic ages on basalts from Cape Purvis, Seven Buttresses and Brown Bluff.

Sample	Locality	*n**	$\%^{39}Ar$	Age (Ma)**	Error 2σ (Ma)
DJ.2055.1b	Cape Purvis	7	97.7	0.132	0.19
DJ.2051.4	Brown Bluff	7	94.0	1.22	0.39
DJ.436.1	Seven Buttresses	3	67.4	1.69	0.03

Analytical methods:

Sample preparation and irradiation

Groundmass concentrates were prepared using standard separation techniques (crushing, sieving, magnetic separation, ultrasonic cleaning and hand-picking). The final grain size for each sample was approximately 60–120 µm. Each separate was loaded into a machined Al disc and irradiated for two seven-hour irradiations in the D-3 position, Nuclear Science Center, College Station, Texas. Neutron flux monitor was Fish Canyon Tuff sanidine (FC-1). Assigned age = 27.84 Ma (Deino & Potts 1990) equivalent to Mmhb-1 at 520.4 Ma (Samson & Alexander 1987). Aliquots of groundmass concentrate were analysed by the furnace incremental-heating age-spectrum method, in most cases using ten heating steps ranging from 650°C to 1700°C.

Instrumentation

Mass Analyzer Products 215-50 mass spectrometer on line with automated all-metal extraction system. Samples step-heated in Mo double-vacuum resistance furnace. Heating duration 9 minutes. Reactive gases removed by reaction with 3 SAES GP-50 getters, 2 operated at ~450°C and 1 at 20°C, together with a W filament operated at ~2000°C.

Notes:

*n = number of steps used in weighted mean age calculations.

** Weighted mean age calculated by weighting each age analysis by the inverse of the variance; Weighted mean errors (± 2σ) calculated using the method of (Taylor 1982), multiplied by square root of MSWD if MSWD > 1; Decay constants and isotopic abundances after Steiger & Jäger (1977).

inferred to have formed from an early stage of the volcano, since subglacially-erupted basaltic edifices with lava-fed deltas (tuyas) are characteristically constructed on an early-formed subaqueous tuff cone composed of explosively generated hyaloclastite tephra (cf. Smellie 2000; Fig. 4b). The volume of the entire volcano is at least 6 km^3, but it may have been much larger originally (see below).

$^{40}Ar/^{39}Ar$ analytical methods and results

A single sample of crystalline grey lava from the subaerial caprock at Cape Purvis was dated using the $^{40}Ar/^{39}Ar$ method. In addition, two other samples from the area were dated: from Brown Bluff and Seven Buttresses on Tabarin Peninsula (Fig. 1). The results and abbreviated analytical methods for the dated samples are presented in Table II and Fig. 8; detailed analytical results and information on the overall operation of the New Mexico Geochronology Research Laboratory are available on request from the laboratory.

The samples yielded $^{40}Ar/^{39}Ar$ ages ranging from 1.69 to 0.132 Ma (early to late Pleistocene). The samples from Cape Purvis (DJ.2055.1b) and Seven Buttresses (DJ.436.1) yielded well-defined age spectra, which provided the most precise, accurate and reliable age determinations in this study. Those ages are 0.132 ± 0.019 and 1.69 ± 0.03 Ma,

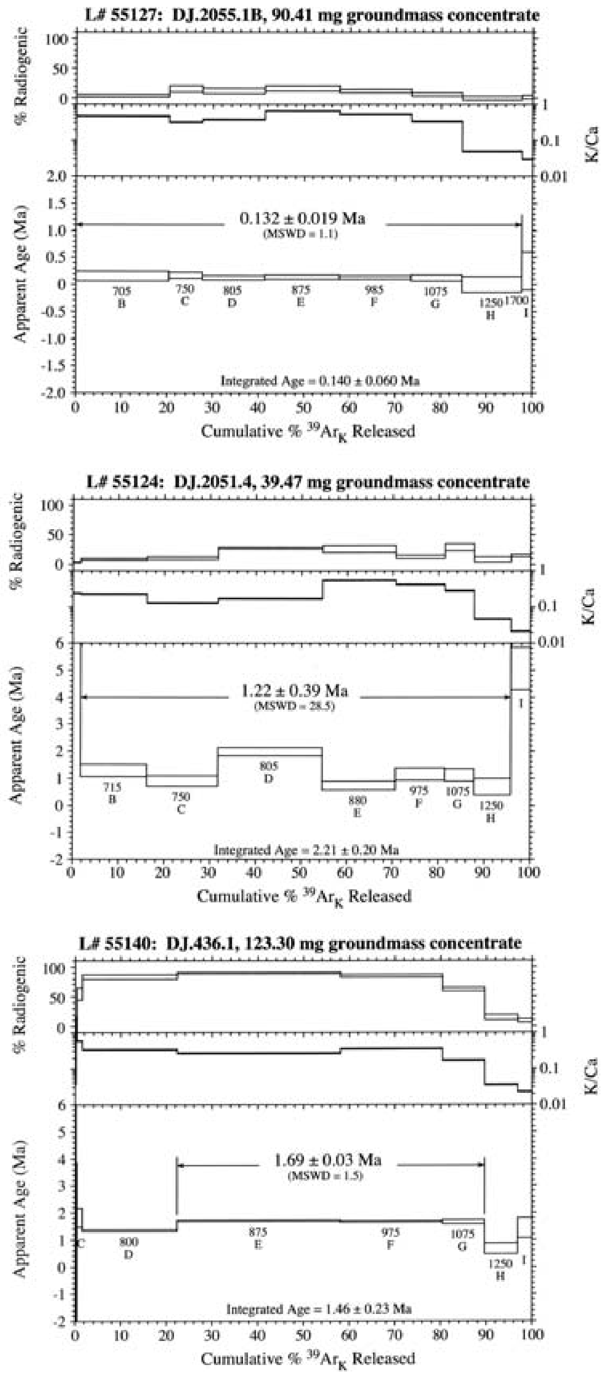

Fig. 8. $^{40}Ar/^{39}Ar$ age spectra for samples from Cape Purvis (DJ.2055.1), Brown Bluff (DJ.2051.4) and Seven Buttresses (DJ.436.1).

respectively. The individual steps from the analyses for both samples are quite precise relative to the range of age spectra yielded by typical basaltic groundmass concentrates, with a narrow range of 2σ uncertainties. Weighted-mean ages were calculated for the broad central portions of both spectra, wherein the ages of individual steps agreed or nearly agreed at the 2σ level. The spectrum for the Cape Purvis sample is

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essentially flat, with the exception of a final low precision, low-radiogenic-yield step. The data for that sample also form a well correlated linear array on an inverse isochron plot, yielding a $^{40}Ar/^{36}Ar$ intercept near the atmospheric ratio (295.5) and an intercept age (0.146 ± 0.032 Ma) that agrees within error with the spectrum weighted-mean age. For the Seven Buttresses sample, the initial and final steps had low precision and low radiogenic yields, but the spectrum has a well-defined flat central section from which a weighted mean age was calculated. The weighted mean age is essentially identical to the intercept age on an inverse isochron plot (1.71 ± 0.04 Ma), but with a less precise $^{40}Ar/^{36}Ar$ intercept (276 ± 31). The new age on the Seven Buttresses sample is a significant improvement on the previously published imprecise K–Ar age from that locality (0.9 ± 0.2 Ma; Rex 1976).

By contrast, the step-heating analyses on the sample from Brown Bluff (DJ.2051.4) yielded a moderately disturbed spectrum with no well-defined age, although with relatively precise individual steps. Moreover, the calculated integrated (total gas) age (2.21 ± 0.20 Ma) is significantly different from the weighted mean age (1.22 ± 0.39 Ma), largely as a result of very high initial and final low-precision steps. The precision of the weighted mean age on the Brown Bluff sample is only moderate and its accuracy should be viewed with some caution. However, it is indistinguishable within error from the published K–Ar age from the same locality (1.1 ± 0.1 Ma; Rex 1976). The reason for the disparity between our integrated total-gas age and the published K–Ar age, which should be broadly similar, is unknown at present.

Discussion

The late Pleistocene Cape Purvis volcanic outcrop is interpreted as one of the youngest and northernmost centres in the JRIVG. It demonstrates that activity in the JRIVG continued to comparatively recent times, and some of that activity was relatively voluminous (i.e. a minimum of 6 km^3 of lava and breccia erupted at Cape Purvis; not recalculated to dense rock equivalent). The closest known outcrops of the JRIVG occur in Antarctic Sound and Prince Gustav Channel (Nelson 1975). Previously published results of K–Ar dating for other JRIVG outcrops between Prince Gustav Channel and Paulet Island are presented in Table III. The Prince Gustav Channel outcrops yielded ages between 2.0 and 1.6 Ma, with pairs of samples obtained at each of two outcrops yielding conflicting ages (2.0 and 1.7 Ma). The localities have not been revisited and this conflict has not been resolved. Using the new $^{40}Ar/^{39}Ar$ data, Seven Buttresses is now better dated as 1.69 ± 0.03 Ma, whereas the age of the Brown Bluff outcrop remains imprecise at about 1 Ma. The youngest of the new ages was obtained on the sample from Cape Purvis, which is precisely dated as 0.132 ± 0.019 Ma. This is the youngest age yet obtained for the JRIVG. It is broadly similar (i.e. both are very young) to the published age for Paulet Island (0.3 ± 0.1 Ma, obtained by the less precise K–Ar method). The location of the Paulet Island sample was simply described as from the north end of the island but it was probably obtained from the basal flat-lying older lava series on the island rather than the overlying pyroclastic cones, in which good $^{40}Ar/^{39}Ar$ dating materials are scarce. Those cones are well preserved and their age is probably very young, conceivably only a few thousand years under present weathering conditions (cone degradation is strongly influenced by climate, particularly rainfall, and degradation can be advanced after just a few years in a wet climate, or negligible even after several thousand years in more arid regions). This suggests that two periods of eruptive activity occurred on Paulet Island.

Nelson (1975) suggested, from the presence of pyroclastic deposits, that a volcanic centre(s) may have existed between Tail and Eagle islands, and he regarded the Seven Buttresses outcrop as part of a larger centre 1.5–6.5 km in radius. From a combination of our own observations in Prince Gustav Channel, and those of Nelson (1975), we interpret most of the islands as the remains of

Table III. Published K–Ar isotopic ages of James Ross Island Volcanic Group outcrops in Prince Gustav Channel, Tabarin Peninsula and Antarctic Sound.

Locality	Age (Ma)	2σ error (Ma)	Reference
Paulet Island	0.3	0.1	Baker *et al.* 1977
Brown Bluff	1.1; 1.1	0.1; 0.1	Rex 1976
Seven Buttresses	0.9	0.2	Rex 1976
Beak Island	2.0; 1.7	0.2; 0.2	Rex 1976
Eagle Island	2.0; 1.7	0.2; 0.2	Rex 1976
Tail Island	2.7	0.5	Rex 1976
Red Island	1.6	0.2	Baker *et al.* 1977

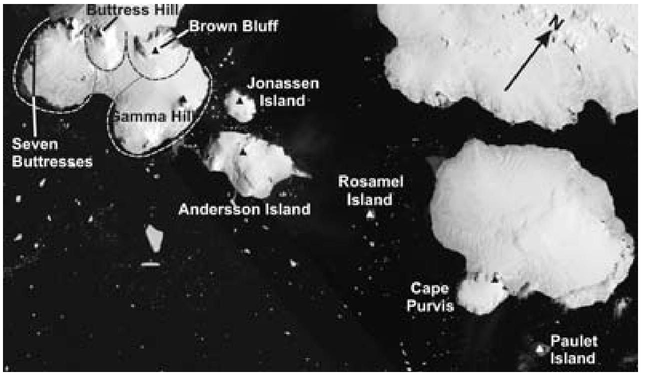

Fig. 9. Mosaic of two Landsat images (NASA/USGS LANDSAT ETM+ path 215 row 104, 29/01/2000, and NASA/USGS LANDSAT ETM+ path 215 row 105, 21/02/2000) showing the morphology and linear distribution of volcanic centres in the James Ross Island Volcanic Group between Tabarin Peninsula and Paulet Island. The outlines of inferred and known centres on Tabarin Peninsula are shown by dashed lines. Possible positions of main eruptive vents shown by solid triangles.

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Fig. 10. Photograph of Jonassen Island (left) and Brown Bluff (right), looking west. The mound-like morphology and stratigraphy of both features are consistent with an origin as monogenetic, subglacially erupted, volcanic centres. Views of the geological sequences exposed at both of these centres, presented by Skilling (1994) and Smellie (2006), can be compared with our interpreted section of the Cape Purvis volcano (Fig. 4 and see text).

several small monogenetic volcanic centres. On the basis of the topography, the outcrops on Tabarin Peninsula can also be divided into four centres, at least, each about 5–10 km in diameter (Fig. 9). Jonassen, Andersson and Rosamel islands are also volcanic centres (Fig. 10), and lavas on Paulet Island are the subaerial lava caprock of another, on which two overlapping pyroclastic cones were constructed (cf. Baker *et al.* 1973). Notwithstanding uncertainties in the isotopic ages, and their derivation by different dating methods, there is a remarkably consistent unidirectional age progression from Prince Gustav Channel (oldest centres), through Tabarin Peninsula (centres with intermediate ages) to Dundee and Paulet islands (youngest centres). The centres are also aligned conspicuously along either a single curved trend or two linear trends: 070N between Red Island and Jonassen Island; 090N between Andersson Island and Paulet Island.

The simplest explanation for the age and alignments is that the centres were erupted along faults, which may have opened up at younger times in northeast and east directions. A similar fault control on age and position was suggested for alkaline volcanoes in Marie Byrd Land, which young away from a presumed mantle plume-related, raised central area (LeMasurier & Rex 1989). They related the age variations between the different volcanic centres to fractures opening up at younger times at progressively more distal locations during domal uplift. The James Ross Island volcanism may also be related broadly to a thermal anomaly, i.e. to decompression melting of upwelling asthenospheric mantle in a pre-existing lithospheric "thinspot" at the eastern rear of the Antarctic Peninsula (Hole *et al.* 1995). Unlike Marie Byrd Land, however, the candidate fault system is *tangential* rather than radial to the presumed centre. The origin(s) of the postulated fault system are therefore unclear. They may be (1) reactivated, inherited (i.e. pre-JRIVG), regional-scale faults created during undetermined past plate tectonic movements, (2) caused by doming and extension related to local "plume-head" tectonics and thus coeval with the JRIVG, or (3) they may be a consequence of extensional stresses transmitted into the far back-arc region during marginal basin opening in Bransfield Strait, which took place during the past 4 m.y. (e.g. Barker & Austin 1998, Lawver *et al.* 1995). However, irrespective of their origin, any deep faults present are likely to have been exploited by the alkaline JRIVG magmas during their emplacement.

From the outcrop characteristics alone, it is unclear whether the Cape Purvis volcano was erupted in a marine or glacial setting. However, for lava-fed deltas to form, ponded water must be present during effusion. A non-glacial lacustrine setting is unlikely in view of the very young age of the centre and absence of any suitable topography that might have confined water. For a marine origin, nearly 400 m of post-eruption uplift would be required to explain the present-day elevation of the deltas. Although Baker *et al.* (1973) suggested that uplift may have occurred, they showed no evidence beyond inferring a possible association with faulting. Although a relationship with faulting is also suggested by us on the basis of the well-defined age progression and alignment of volcanic centres, we know of no field evidence that demonstrates differential uplift anywhere in the JRIVG, and the vertical component (if any) of inferred structures in Prince Gustav Channel and Antarctic Sound is unknown.

An origin by subglacial eruption is also possible for the Cape Purvis volcano, and we favour this possibility. In subglacially erupted basalt volcanoes (tuyas), passage zone elevations are usually taken as an indication of the elevation of the associated ice sheet surface, but it is also known that passage zone elevations may be several tens of metres lower than the surrounding ice sheet (Smellie in press). Thus, the elevation of the delta surface, which in glacially-emplaced lava-fed deltas is typically 50–100 m higher than the passage zone, is probably a closer general approximation to the elevation of the enclosing ice sheet. If the Cape Purvis volcano erupted through an ice sheet, the elevation of the surface of that former ice sheet may have been at least 350 m above present sea level at that locality (i.e. approximate surface elevation of "delta 1"; Fig. 4). This is substantially thicker than the ice sheet present today and implies that the volcano was constructed during a glacial period. The oval shape of the outcrop can also be interpreted as additional support for a thicker former ice sheet. The mesa is asymmetrical and has a "V"-shaped northern termination composed of 100–300 m high, steep, NW- and NE-facing slopes (Fig. 3). The geology is also asymmetrical, with likely tuff cone deposits at the north and lava-fed delta(s) to the south (Fig. 4). We suggest that the volcano may originally have been much larger, with a more symmetrical shape caused by encircling lava-fed deltas.

However, it was significantly modified by a southerly-moving ice cover flowing off Dundee Island that must have been thicker than today to create the enhanced northern erosion and "teardrop" profile. The southern part of the outcrop, being on the protected lee side relative to the postulated ice flow direction, remained largely unmodified except for recent marine erosion.

We also note that the age of the volcano (132 ka) coincides with the end of the glacial period represented by Isotope Stage 6 (IS6; Petit *et al.* 1999). During IS6, ice sheets in the region would have been thicker and more extensive. Thus, for the first time, our interpretation of the Cape Purvis volcano might be providing minimum thickness information for the Antarctic Peninsula Ice Sheet in IS6 time.

Two interpretations of the delta segments at Cape Purvis are possible. We suggest that it is less likely that they represent three superimposed deltas in a polygenetic volcanic edifice, since the implied thickness of each of the two upper deltas would have been only *c.* 90 m (delta 2) and 40 m (delta 3). At these thicknesses, and in an ice sheet with a gentle surface gradient under a former polar-continental thermal regime (likely during a recent glacial), the associated glacial cover probably would have been formed mainly of firn and snow. Firn and snow are permeable and unlikely to impede any glacial meltwater, thus preventing the formation of a lake (Smellie 2000, 2001, 2006). Such thin deltas are therefore unlikely to occur unless the glacial regime was similar to, or warmer than, today, when permeable firn and snow thicknesses would have been much thinner and any glacial cover would have contained a correspondingly greater relative thickness of impermeable ice. However, this seems unlikely if eruption took place in a glacial period, presumably colder than today. Rather, we suggest that Cape Purvis may be a monogenetic subglacially-erupted volcano that gave rise to a single contiguous lava-fed delta. Thus, the step-like profile would be due to relatively sudden fluctuations in the meltwater lake surface elevation occurring during the eruptive episode and associated with variable meltwater discharge, as has occurred repeatedly in the JRIVG (cf. Smellie 2006). However, distinguishing unambiguously between these two hypotheses is not yet possible with our present knowledge.

Evidence also exists for subglacial eruption of other centres nearby. It has been convincingly demonstrated for the Brown Bluff centre (Skilling 1994, Smellie & Skilling 1994) and new observations of our investigation are also consistent with subglacial eruptions forming centres in Antarctic Sound:

1. The lava-fed delta that dominates Jonassen Island has a subaerial lava caprock surface at about 200 m a.s.l., but those lavas drop to sea level at the south-west corner of the island (Nelson 1975), signifying a lowering of the water level contemporaneous with the eruption; and
2. Lava-fed deltas form the eastern promontory on Andersson Island (Cape Scrymgeour). The uppermost delta contains two passage zones and it resembles a delta erupted in association with a water level that rose through *c.* 50–80 m during the eruptive period (cf. Smellie 2006). Furthermore, the subaerial lava caprocks directly overlie hyaloclastite tuffs of a subaqueous tuff cone at sea level in the south-west part of the island (Nelson 1975), implying suddenly lowered water levels during eruption, similar to Jonassen Island.

To explain the water level variations preserved in the deltas on Jonassen and Andersson islands, we need to appeal to either unproven and probably unlikely tectonic effects occurring *during* the eruptions, or to eustatically controlled sea level changes, which are also unlikely to change on the short timescale of an effusive eruption (months to years). Moreover, the contacts between subaerial lava and (a) hyaloclastite breccia and (b) subaquous tuffs are two different surfaces in the architecture of the volcano reflecting different elevations in the original pile, not a single originally continuous surface. Unlike the poor exposures at Cape Purvis, the deltas at Cape Scrymgeour are clearly superimposed stratigraphically. On neither island, therefore, can the relationships be explained as a result of down-slope mass movements. By contrast, the water level in a vault during a subglacial eruption is a dynamic feature controlled by the hydraulics of the glacial system. It can vary significantly over a relatively short time (hours to weeks; Björnsson 1988, Skilling 1994, Smellie 2006). Multiple passage zones like those at Cape Scrymgeour are also commonly exposed elsewhere in the JRIVG and only likely to form in a glacial setting (Smellie 2006). Thus, our interpretation of the Jonassen and Andersson islands sequences is that, like Cape Purvis, they are probably small volcanic centres that were erupted subglacially. The highest passage zone occurs at Brown Bluff (*c.* 350 m), whilst those on Jonassen and Andersson islands are significantly lower (*c.* 200 m and < 150 m, respectively), suggesting that the ice sheet either fluctuated significantly in thickness over time or else it had a variable surface topography, e.g. ice flowing off the higher topography of Tabarin Peninsula (and Dundee Island) to feed a low-lying ice stream in Antarctic Sound. Distinguishing between these possibilities cannot be tested until the age of volcanism on Jonassen and Andersson islands is determined.

Conclusions

Cape Purvis is a small volcanic centre formed in late Pleistocene time (132 ± 19 ka). It is compositionally very similar to lavas on Paulet Island and is similarly interpreted as one of the youngest and northernmost outcrops of the JRIVG. There is a remarkable unidirectional, probably

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fault-related migration of JRIVG satellite centres, from Prince Gustav Channel (at *c.* 2.0–1.6 Ma) to Tabarin Peninsula (1.69–*c.* 1 Ma) and across Antarctic Sound to Cape Purvis and Paulet Island (132 ka and younger). The Cape Purvis volcano probably erupted at the end of the glacial period corresponding to Isotope Stage 6 and the outcrop characteristics suggest that the ice sheet at that time had a minimum surface elevation 300–400 m higher than at present.

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