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Palaeomagnetic, $^{40}Ar/^{39}Ar$, and stratigraphical correlation of Miocene–Pliocene basalts in the Brandy Bay area, James Ross Island, Antarctica

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Abstract: A revised stratigraphy of Cenozoic volcanic outcrops in the Brandy Bay area on James Ross Island is obtained by combining palaeomagnetic and stratigraphical anlysis with $^{40}Ar/^{39}Ar$ dating. The fieldwork was carried out between January and March 2002. Oriented palaeomagnetic samples were obtained from 17 volcanic units, the majority of samples being from lava-fed deltas. Individually the deltas are a few to several hundred metres thick and were formed during voluminous basaltic eruptions within an ice sheet or in a marine setting. Out of the sampled units, 15 carry a stable primary magnetization; six were of normal polarity and nine were reversely magnetized. Our $^{40}Ar/^{39}Ar$ dating constrains the emplacement of most of the Brandy Bay basalts to the Gilbert chron, with the youngest dated unit having an age of 3.95 Ma and the oldest 6.16 Ma. The mean palaeomagnetic field direction from 14 units has an inclination I = -76° and declination D = 352°, α_{95} = 7°. The results further suggest that the lava caps on some of the deltas have high remanent intensity and should generate recognizable aeromagnetic anomalies. The combination of palaeomagnetic and isotopic analysis with field mapping methods in a single field area is unique in Antarctica so far and demonstrates that the combination can yield rigorous local stratigraphy in a geographically remote volcanic terrain having discontinuous outcrops.

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Introduction

The James Ross Island Volcanic Group (JRIVG) is a large alkali basaltic volcanic province situated near the northern tip of the Antarctic Peninsula (Fig. 1). It contains extensive outcrops of lava and hyaloclastite sequences formed in a marine or englacial setting during the late Cenozoic (Nelson 1975, Skilling 1994, 2002, Smellie 1999 and unpublished). The JRIVG offers excellent exposures of lava-fed deltas and their stratigraphical correlation and dating should provide important insights into palaeoenvironmental conditions, such as extent of glacial cover at the time of their formation. The outcrops are, however, lithologically similar regardless of age, and are discontinuous. Attempts to construct a rigorous stratigraphy have failed so far (cf. Nelson 1975, Smellie 1999).

Reversals of palaeomagnetic polarity have been much used as a stratigraphic tool in volcanic regions for half a century (e.g. Hospers 1954, McElhinny 1973), across distances ranging from 10^{-1} to 10^{4} km. Atypical primary remanence directions in individual extrusive or intrusive units have also been applied occasionally in local correlation. In contrast to many other regions, palaeomagnetic studies of volcanic rocks in Antarctica have been relatively few, particularly for the Antarctic Peninsula, a region with several Cenozoic volcanic fields (Smellie 1990, 1999). In this paper the mapped field relationships, magnetic stratigraphy and $^{40}Ar/^{39}Ar$ chronology of the Brandy Bay area in north-western James Ross Island are presented. Our results provide new insights into the stratigraphy and volcanic activity of the area as well as being the first palaeomagnetic and $^{40}Ar/^{39}Ar$ results published for the JRIVG.

Geological setting

The James Ross Island Volcanic Group dominates the outcrop geology of James Ross Island (JRI), Vega Island and several small islands in Prince Gustav Channel (Fig. 1). It also includes the southern Tabarin Peninsula, islands in Antarctic Sound and southern Dundee Island, nearby to the north-east of JRI (e.g. Smellie 1999). These volcanic rocks unconformably overlie relatively unconsolidated Cretaceous marine sediments (e.g. Bibby 1966, Crame *et al.* 1991). The JRIVG is principally made up of alkaline basalts erupted in a back-arc extensional setting during the slowing stages of subduction of Drake Passage oceanic crust at the

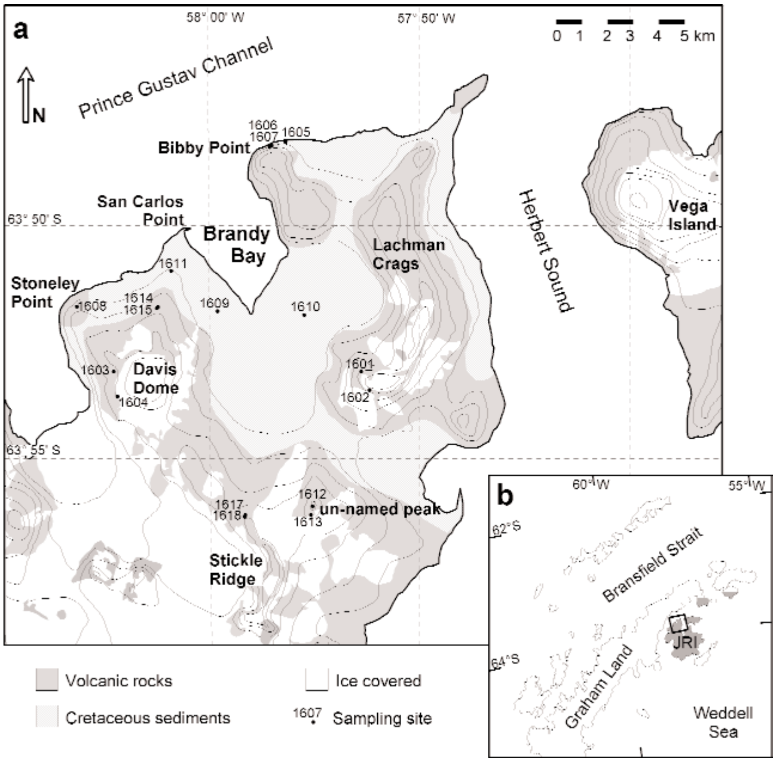

Fig. 1. Maps showing the location of James Ross Island (JRI) and the study area (Brandy Bay, situated at the northern end of the Ulu Peninsula). The palaeomagnetic sampling locations are also indicated.

South Shetland trench (Nelson 1975, Hole *et al.* 1994, Smellie 1999). Subduction continues today but at a very slow rate (Larter 1991). James Ross Island is by far the largest individual outcrop of the group, forming a large polygenetic stratovolcano with a basal diameter of at least 40–60 km (Smellie 1990). Inland exposures are few because of extensive present-day ice cover, but there are several largely snow-free areas around the coast, particularly on the west and north-west sides, which collectively comprise the Ulu Peninsula. The central ice cap rises to more than 1600 m a.s.l. at Mount Haddington, which was probably the source of most of the voluminous basaltic eruptions which constructed the James Ross Island volcano. The Brandy Bay area, at the northern end of Ulu Peninsula, is the largest ice-free part of JRI and forms the subject of this paper.

The exposed geology of JRI is dominated by several lava-fed deltas, individually up to several hundred metres thick. They consist of horizontal subaerial lava flows overlying steeply dipping hyaloclastite breccias (Nelson 1975). Glacial sedimentary outcrops are also widespread, separating the volcanic units and overlying the Cretaceous bedrock (Pirrie *et al*. 1997 and unpublished, Carrizo *et al*. 1998, Jonkers *et al*. 2002, Hambrey & Smellie in press). Other (fewer) outcrops are mainly tuff cones and rare dykes. There is evidence for eruptions in both englacial and lacustrine settings (Nelson 1975, Smellie 1999 and unpublished).

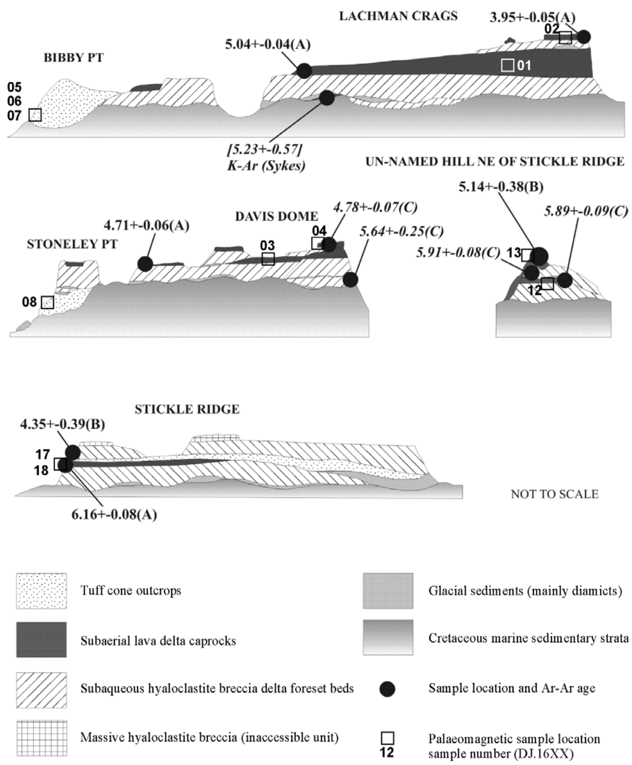

Fig. 2. Schematic vertical sections through the major lava-fed delta outcrops in the Brandy Bay area. Approximate locations of $^{40}Ar/^{39}Ar$ dated samples and palaeomagnetic samples are also shown. Not to scale.

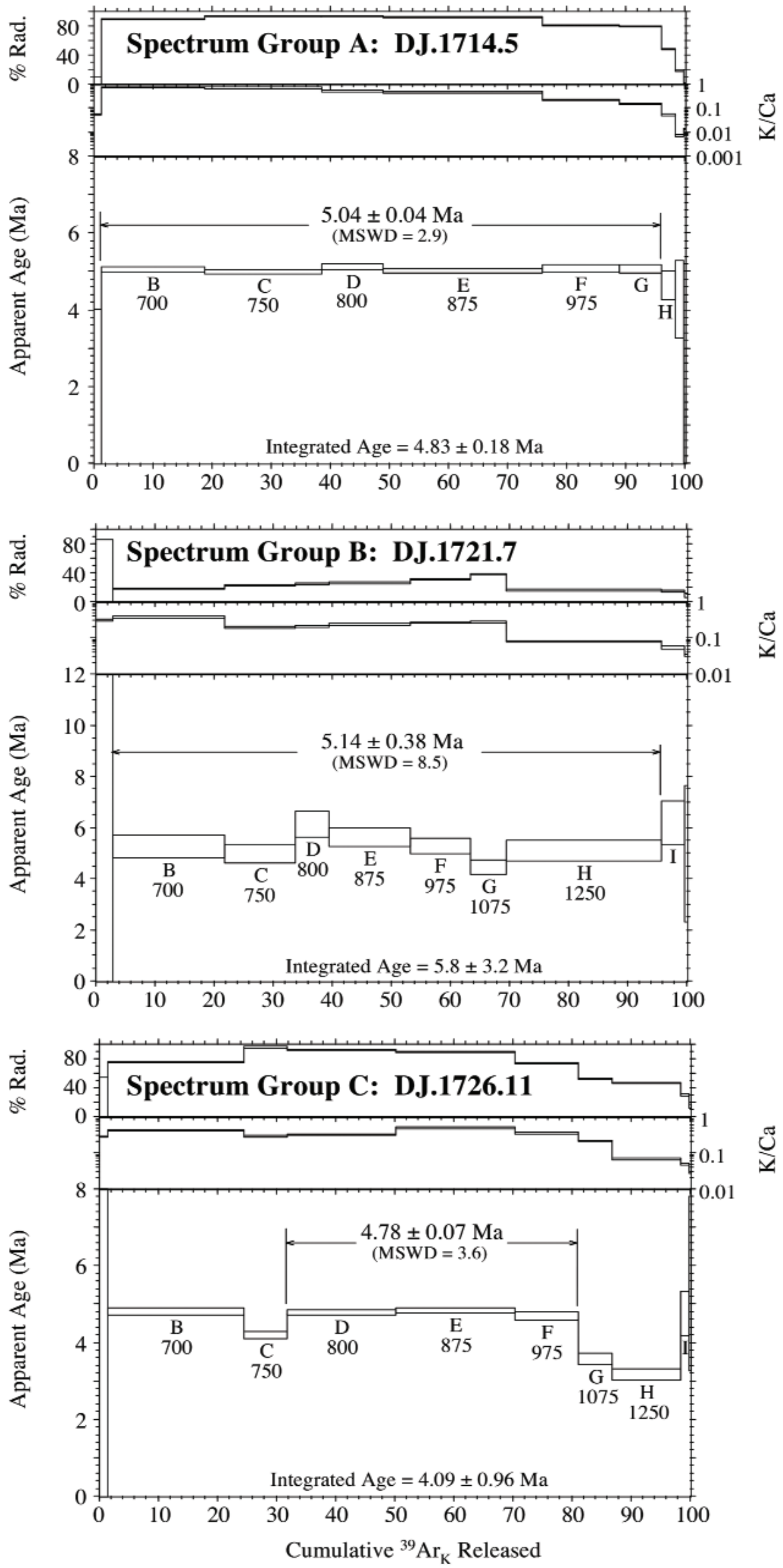

Fig. 3. Representative $^{40}Ar/^{39}Ar$ age spectra for the sample groups, A, B and C, from the Brandy Bay area.

Table I. Results of $^{40}Ar/^{39}Ar$ isotopic dating on basalts from the Brandy Bay area of James Ross Island.

Sample	Volcanic unit	Weight (mg)	*n**	%^{39}Ar	Age** ± 2σ (Ma)	Group***
DJ.1714.5	Lachman Crags main delta	63.6	6	94.8	**5.04 ± 0.04**	**A**
DJ.1718.1	Lachman Crags upper delta	61.0	5	77.1	**3.95 ± 0.05**	**A**
DJ.1721.5	Unnamed hill upper delta	60.1	5	69.3	5.91 ± 0.08	C
DJ.1721.7	Unnamed hill summit intrusion	65.8	7	92.9	**5.14 ± 0.38**	**B**
DJ.1721.11	Unnamed hill lower delta	59.8	3	60.3	5.89 ± 0.09	C
DJ.1722.1	Stickle Ridge lower delta	61.6	7	92.9	**6.16 ± 0.08**	**A**
DJ.1722.6	Stickle Ridge upper delta	60.4	7	91.5	**4.35 ± 0.39**	**B**
DJ.1725.5A	Davis Dome basal delta	61.0	6	81.0	5.64 ± 0.25	C
DJ.1726.11	Davis Dome upper delta	61.9	3	49.3	4.78 ± 0.07	C
DJ.1729.8	Davis Dome main delta	63.2	7	95.0	**4.71 ± 0.06**	**A**

Analytical methods:
Sample preparation and irradiation
Groundmass concentrates were prepared using standard separation techniques (crushing, sieving, frantzing and hand-picking).
Separate was loaded into a machined Al disc and irradiated for 7 hours in the D-3 position, Nuclear Science Center, College Station, Texas.
Neutron flux monitor 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).
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 min.
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 (± 2 σ) 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).
***Results are divided into groups based on age spectra, as detailed in text.

Geology of the Brandy Bay area

The Brandy Bay area has several lava-fed deltas, abundant mainly thin outcrops of glacial sedimentary rocks, and a few exposed dykes (Figs 1 & 2). In addition, surtseyan cones crop out at Bibby and Stoneley points. Stickle Ridge and an unnamed peak 2.5 km to the north-east are the southernmost units sampled in this study. These are small, isolated erosional remnants of previously more extensive lava deltas. In contrast, Lachman Crags to the east and Davis Dome to the west are less eroded and more extensive remnants of up to three superimposed deltas. Excellent exposures have been carved into these formations by glaciers. Major faults are absent in the volcanic rocks and, thus, tectonic disturbance of the lava deltas is minimal. Only the volcanic outcrops are described here.

Each of the lava-fed deltas contains a prominent and conspicuous planar surface known as a passage zone. Passage zones are formed at the transition between subaqueous and subaerial volcanic rocks (here, horizontal subaerial lavas and steep-dipping subaqueous hyaloclastite breccias) and, as such, they represent a fossil water level (i.e. the elevation of the surface of the palaeo-lake or sea into which the deltas advanced; Jones 1969). Nelson (1975) used the elevation of the passage zones on James Ross Island as a principal means of correlating formations. Underlying Nelson's (1975) study was an assumption that, at formation, the passage zones were horizontal because the deltas were advancing into the sea, and that variable sea levels were recorded by the different elevations of passage zones in the formations. More recent work indicates that the eruptive environment varied between marine and (mainly) glacial, so the restriction to horizontal passage zones may no longer apply (Smellie 1999 and unpublished data). However, coincident passage zone elevations between disparate, otherwise-similar but undated outcrops might still be a useful stratigraphical correlation tool, if used over short distances (< a few km). Conversely, the absence of coincident passage zone elevations cannot be taken as a proof of a lack of correlation, since the two outcrops may be linked by eruption within an ice sheet with a sloping surface. Passage zone elevations on James Ross Island were measured using a hand-held GPS with a built-in altimeter (Garmin, Etrek Summit model) calibrated twice daily to compensate for pressure fluctuations. Accuracy is believed to be generally ± 5–10 m.

Two superimposed deltas are present at Stickle Ridge and the unnamed peak to the north-east (Fig. 2). The outcrops are only 2.5 km apart. Those at Stickle Ridge have passage-zone elevations of 482 m and ≥ *c.* 600 m (the upper delta caprock sequence is eroded). At the unnamed peak, the elevations are 567 m and > *c.* 690 m. The elevations thus provide no clear means of correlation between the two outcrops.

Remains of at least three superimposed lava-fed deltas are found in the imposing areally widespread mesa landforms that comprise Lachman Crags and the northern flank of Davis Dome. The oldest delta at both localities is preserved

Table II. Magnetic properties of basalts from the Brandy Bay area.

Locality	Unit, type	N/n	NRM Am^{-1}	Susc. SIx1000	Mean direction decl.	incl.	k	α_{95} deg.	MDF mT	VGP position lat. N.	long. E.	Pol.
Lachman Crags, main delta	1601 L	4/4	13.0	10	345.1	-73.9	121	8.4	55	+82.0	234.4	N
Lachman Crags, upper delta	1602 L	3/3	23.2	32	154.3	+62.9	527	5.4	24	-65.7	73.3	R
Davis Dome, main delta	1603 L	4/4	1.8	6	307.6	-78.6	254	5.8	34	+68.9	177.5	N
Davis Dome, upper delta	1604 L	4/4	3.7	2	181.7	+86.4	248	5.8	13	-71.1	301.2	R
Bibby Point	1605 P	4/4	11.3	8	2.6	-72.7	329	5.1	14	+84.8	315.7	N
Bibby Point	1606 D	4/4	6.8	12	4.6	-74.9	2392	1.9	8	+87.0	348.5	N
Bibby Point	1607 Ht	4/0	< 0.01	0.3	not possible to measure							
Stoneley Point	1608 D	4/4	5.4	9	16.8	-79.3	819	3.2	11	+81.4	78.6	N
Brandy Bay	1609 D	4/4	5.9	10	11.5	+79.9	23	19.4	20	-44.5	307.4	R
Brandy Bay	1610 D	4/4	0.3	9	168.0	+69.0	1525	2.4	56	-77.0	87.7	R
San Carlos Point	1611 D	4/4	1.9	16	305.3	+82.4	180	6.9	20	-53.3	281.5	R
Unnamed peak, summit	1612 L	4/4	16.2	4	289.5	+85.7	117	9.4	7	-60.0	285.8	R
Unnamed peak, delta	1613 L	4/4	3.0	30	193.7	+71.2	271	5.6	19	-79.3	168.2	R
S. of S.C. Point	1614 H	4/4	1.8	1	289.2	-55.8	83	10.1	41	+40.4	210.2	N
S. of S.C. Point	1615 H	3/0	0.4	0.6	scattered directions			>70				
San Carlos Point	1616 D	Only unorientated hand samples were collected at this site										
Stickle Ridge, lower delta	1617 L	4/4	1.6	10	191.1	+55.1	184	6.8	32	-60.9	140.8	R
Stickle Ridge, lower delta	1618 P	5/4	2.2	1	200.8	+66.0	385	4.7	32	-70.7	167.7	R

Explanations: L = lava, P = pillows, H = hyaloclastite, Ht = hyalotuff, D = dyke. N is the number of cores collected, n is the number used in obtaining a mean remanence direction. NRM is the mean natural remanence intensity of samples, and susc. is their mean initial susceptibility. k is the precision parameter of the mean direction, and α_{95} is its 95% confidence angle. MDF is the median destructive alternating field, at which half of the NRM has been removed; in those cases where the remanence increases at low demagnetizing fields, the maximum observed intensity was used instead of the NRM in estimating the MDF. Pol = polarity of the palaeo-field.

solely as a thin remnant formed of hyaloclastite breccia; it was not sampled for palaeomagnetic study. By contrast, the two outcrops are dominated by single thick ("main") deltas with passage zone elevations of 349–368 m (Lachman Crags) and 341–354 m (Davis Dome).

The uppermost deltas on Lachman Crags and Davis Dome are much thinner than the main deltas at both outcrops. They have passage zones at *c.* 371–*c.* 470 m (Davis Dome) and 527–579 m (Lachman Crags). They clearly slope to the north at both localities and there is no obvious correlation in elevations between the two outcrops, although there are crude similarities to passage zone elevations in the Stickle Ridge/unnamed peak outcrops to the south.

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

Ten samples were dated using the $^{40}Ar/^{39}Ar$ method (see Fig. 2 for sample locations). Abbreviated analytical methods for the dated samples are given in Table I, and details of the overall operation of the New Mexico Geochronology Research Laboratory are available on request from the laboratory. Table I summarizes the weighted-mean ages. The quality of results from this study varied among the analyses. For discussion, the results are divided into three groups, A–C, on the basis of the shape of the age spectrum and the precision of the weighted-mean age for each step-heating analysis (Fig. 3). Group A ($n = 4$) analyses have flat spectra and weighted-mean age uncertainties < 0.1 Ma. Group B ($n = 2$) analyses also have flat spectra but the weighted-mean ages are somewhat less precise, with uncertainties > 0.1 Ma, possibly because the radiogenic yields and K/Ca ratios tend to be significantly lower relative to Group A analyses. Group C ($n = 4$) analyses have moderately disturbed age spectra, although with relatively precise individual steps. Although the precision of the Group C ages appears to be excellent, the accuracy of their weighted-mean ages should be viewed with some caution.

Palaeomagnetic sampling and experimental methods

In the present survey, the upper and main lava units of the Lachman Crags were sampled, the two upper units of the Davis Dome, the lower unit at Stickle Ridge and the two lava units making up the unnamed peak to its north-east (Figs 1 & 2, Table II). In addition, samples were taken from dykes intruded into hyalotuff at Stoneley Point and Bibby Point, two dykes exposed in the Cretaceous sediments in Brandy Bay and samples from pillows in hyaloclastite deltas were taken at two localities.

Orientated 25 mm diameter core samples were obtained from 17 lava units, mostly four samples per unit distributed laterally over 2–10 m. Azimuth orientations were measured by sighting on the Sun or distant geographic objects with a Brunton compass; estimated errors in azimuth are of the order of 2–3 degrees. In unit DJ.1608 and in five other individual samples there was nothing to sight on, so a value of the magnetic declination estimated from nearby sites or from maps was used. Almost all the samples show no appreciable porosity, and very little chemical weathering (1 mm or less) was seen at their outer surface. Remanence

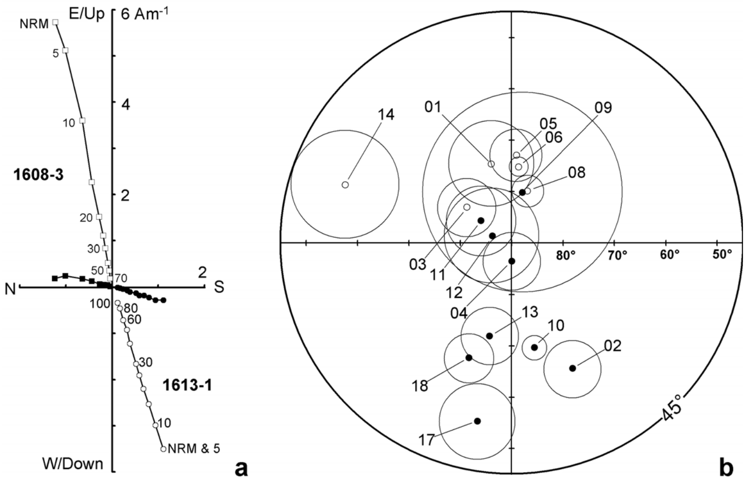

Fig. 4. a. Remanence vectors in two typical samples during AF demagnetization, projected on horizontal and vertical planes (solid and open symbols, respectively). Numbers indicate peak field values in mT. **b.** Average remanence directions from 15 igneous units on James Ross Island, identified with the two last digits of the site numbers of Table II. Open symbols, directions on upper hemisphere (normal polarity); solid symbols, directions on lower hemisphere. 95% confidence circles are indicated. Stereographic projection, 45–90° inclinations.

and low-field susceptibility measurements were made on one specimen of about 22 mm length from each sample. The susceptibility was measured with a Bartington MS-2 meter.

One specimen from each unit was stored in a field of 30 µT (0.3 Oe) for a week following measurement of their natural remanence. On remeasurement, no change in the remanence direction was noted in the majority of the specimens; these also had high Königsberger ratios (Q_n = 5–100 in 50 µT field). Small direction changes, presumably due to a viscous remanence component, were seen in those specimens (from units at DJ.1606, 1610, 1611, 1613) that had Q_n in the range 1–4.

Low-field thermomagnetic curves were obtained in air from four lava samples and two dyke samples, using a Bartington MS-2W furnace. All gave different main Curie points (T_c), and they had varying degrees of reversibility. It may be assumed that the dominant carrier of magnetization in these lavas is titanomagnetite, its composition and oxidation state depending on the cooling rate of the lava and other factors. The occurrence of reversible low-T_c curves (100–150°C in the dyke at DJ.1611 and 180°C in the lava at DJ.1602) indicates that the rocks have not suffered any appreciable regional hydrothermal alteration, as according to Ade-Hall *et al.* (1971, fig. 9) *in situ* heating to 150°C will cause such curves to become irreversible with T_c-values increasing towards 400°C. The other T_c-values were about 240°C in the dyke at DJ.1609, and 480°C, 575°C, 600°C in the lavas at DJ.1613,1617 and 1601 respectively. The last result is evidence of a highly oxidized phase, in agreement with the fact that the remanence in that unit has high coercivity.

Remanence measurements were made at the University of Iceland in a four-probe static fluxgate magnetometer manufactured by Institut Dr Förster, Reutlingen, Germany. All specimens were demagnetized at least at 5, 10, 15, 20, 25, 30, 40 and 50 mT peak alternating fields (AF) in a Molspin two-axis tumbler. Minor directional changes commonly occurred at the first one or two steps of the AF treatment due to viscous remanence, and in 12 reversely magnetized specimens a slight increase in intensity was also seen. However, in the 10 to 40 mT interval the directions in all specimens were highly stable, changes between demagnetization steps generally being 1° or less. At 40 mT and beyond, the primary remanence in a part of the specimen collection was becoming weak (0.1 A m^{-1} or less) and small secondary remanence components began to show up in some specimens. These components are probably both anhysteretic and rotational remanences acquired during AF treatment, and viscous remanence picked up in the time (< 1 min) between the AF treatment and measurement. When the presence of secondary components was noted, the demagnetization and measurement procedure was repeated and the results averaged. The majority of the specimens were demagnetized at 60 mT peak fields and further, specimens from 12 units up to 90 or 100 mT. No systematic changes of the remanence directions were seen to take place in any specimen.

The remanence results were processed by a simple form of the principal component analysis as suggested by Kirschvink (1980, section 4.3). After omitting measurements at the lowest and/or highest demagnetizing fields when the presence of secondary components was evident (see above), the principal direction was in all cases computed from measurements after 7 to 10 treatment steps between 5 and 70 mT. Maximum angular deviations from these directions did not exceed 5° in any specimen, and they averaged 2°. See Fig. 4a for the behaviour of two typical specimens.

Palaeomagnetic direction results

Remanence directions from each site were averaged as unit vectors according to standard procedures in palaeomagnetism. The results along with computed virtual geomagnetic pole positions are shown in Table II; no tectonic tilt correction has been applied as the area seems to be undisturbed. Table II also gives natural remanence intensities, susceptibilities and median destructive AF

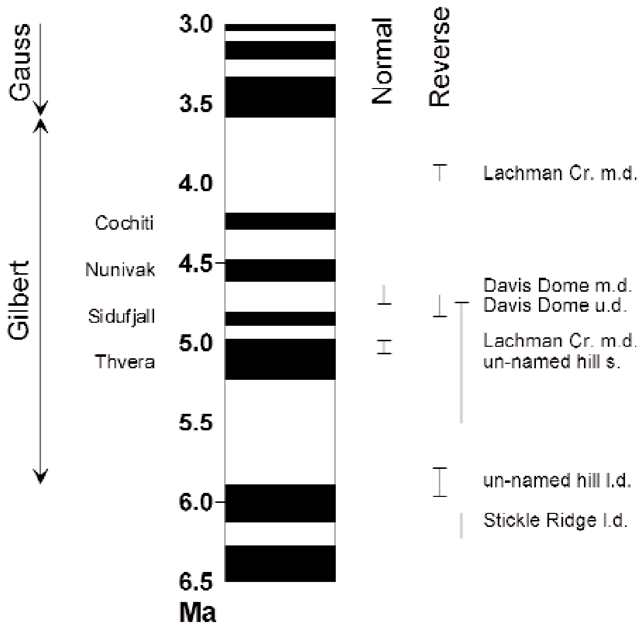

Fig. 5. Positions of the dated units from Brandy Bay within the geomagnetic polarity time scale for the period 3–6.5 Ma BP (from Cande & Kent 1995). All but one of the dated samples are from the Gilbert chron. The older normal polarity unit (main Lachman Crags lava delta) apparently dates from the Thvera subchron. (u.d. = upper delta, m.d. = main delta, l.d. = lower delta, s. = summit intrusion).

values for the sites; all these properties were broadly similar within each site so that only their mean values are given.

The tuff sampled at DJ.1607 carries a very weak remanence. At DJ.1614, two pillows were sampled which yielded average directions differing by 14° of arc but their combined direction is used here. In the breccia sampled at DJ.1615, the three samples have widely scattered directions; it may be noted that they had very high coercivity. At DJ.1618, one sample which was cored from a small pillow some distance away from the others, carried a soft and unstable remanence so it has been discarded.

The field directions from the sites are shown in Fig. 4b. Before calculating their mean direction we discard the reversely magnetized unit DJ.1609 which has a 95%-confidence angle α_{95} of 19°; in the remaining 14 units the α_{95}-values are 10° or less. They have (after inversion of eight reversed directions) a mean with declination D = 352.5°, inclination I = -75.9°, precision parameter k = 30, α_{95} = 7.3°, and angular standard deviation = 15°. This mean direction is within 2° of the central axial dipole field at the mean location of the sites (about 63.9°S, 57.95°W) which is D = 0°, I = -76.2°. Our results are very similar to those reported from 39 Late Tertiary igneous units in the McMurdo Volcanic Province at 78°S by Mankinen & Cox (1988). However, the number of units involved in our study is much too small to make comparisons in detail with these and other palaeomagnetic collections from the Antarctic region, or to draw any conclusions about the overall properties of the geomagnetic field (see discussion in Kristjánsson 2002).

Discussion

The $^{40}Ar/^{39}Ar$ ages (Table I, Fig. 2) suggest that the oldest deltas crop out at Stickle Ridge and the unnamed peak nearby (6.16 and 5.89–5.91 Ma, respectively). Although the ages do not overlap and are thus statistically dissimilar, those at the unnamed peak are of poorer quality and a correlation is not wholly precluded using the isotopic evidence. The oldest delta beneath the Davis Dome outcrop is dated at *c.* 5.64 Ma, an age indistinguishable from and supported by an imprecise K–Ar age of 5.23 ± 0.57 Ma published by Sykes (1988) for a "basal sill" (probably a lava delta caprock) below Lachman Crags.

The upper delta at the unnamed peak near Stickle Ridge yielded an imprecise age of 4.35 ± 0.39 Ma. It is of broadly

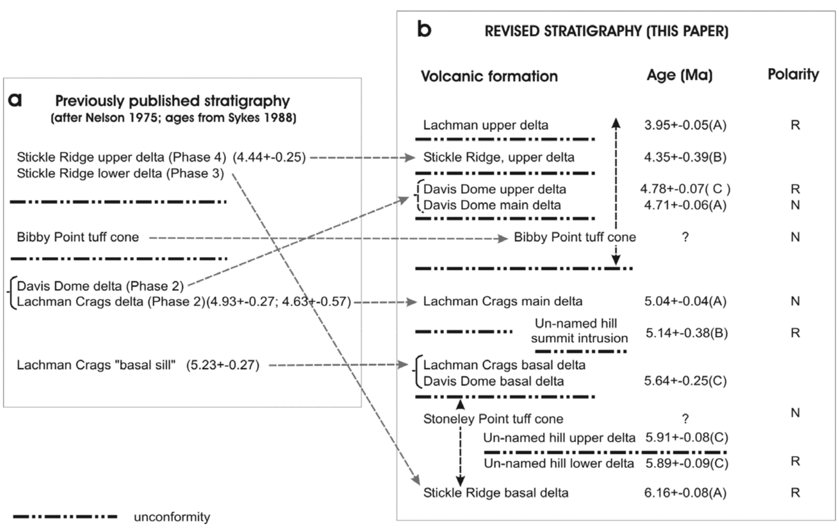

Fig. 6. Stratigraphy of volcanic formations in the Brandy Bay area. **a.** Previously published stratigraphy of Nelson (1975), augmented by K–Ar isotopic ages of Sykes (1988); Nelson used volcanic "phases" rather than formations to denote his stratigraphy. **b.** New stratigraphical scheme based on the present study and using results from field mapping, palaeomagnetic analyses and $^{40}Ar/^{39}Ar$ dating. Letters after $^{40}Ar/^{39}Ar$ ages are a guide to relative reliability of the ages (see text and Fig. 3).

similar age to the main and uppermost deltas at Davis Dome but has a very much higher passage elevation.

Most of the sampled units belong to the Gilbert chron. Out of the 15 palaeomagnetic sampling sites successfully analysed, six yielded normal polarity and nine reversed polarity (Table II). Some directions are clearly quite similar (Fig. 4b), especially those in units at DJ.1605 and DJ.1606 which differ by only just over 2°. We therefore suggest that the pillow lava (DJ.1605) and the dyke (DJ.1606), although 1 km apart, may belong to the same volcanic event (i.e. eruption of the Bibby Point tuff cone, within which outcrop both sampled units occur). Another pair of directions, differing by less than 4°, is seen at DJ.1611 (dyke) and DJ.1612 (lava); however, these localities are separated laterally by about 10 km which makes it unlikely that they represent simultaneous events.

The reverse polarity at DJ.1602 (Lachman Crags upper delta) is in agreement with its isotopic age of 3.95 ± 0.04 Ma (Table I), which indicates that the delta was emplaced in the latest part of the Gilbert chron (Fig. 5). Conversely, the main delta at Lachman crags has normal polarity and its age (5.04 ± 0.04 Ma) is consistent with the Thvera subchron. Our palaeomagnetic results for the main and upper deltas at Davis Dome apparently show that those two deltas have opposite polarities. An erosional surface separates the two, and if confirmed, the change in polarity suggests a hiatus between the formation of the deltas. This, however, conflicts with their apparently identical $^{40}Ar/^{39}Ar$ ages. The isotopic dating places the main Davis Dome delta in a period of reversed polarity. Its age (4.71 ± 0.06 Ma) is believed to be amongst the most reliable that we obtained (Table I). The age of the upper delta (4.78 ± 0.07 Ma) is less reliable, but it is consistent with its reverse polarity, placing it in between the Nunivak and Sidufjall subchrons. A normal polarity for the main Davis Dome delta would suggest that it may belong to either the Sidufjall or Thvera subchrons (Fig. 5). However, it must be kept in mind that this geomagnetic polarity scale is not likely to be exact as regards the ages of chron boundaries or even the number of reversals actually occurring.

The main deltas of the Lachman Crags and the Davis Dome were considered to be formed in a single eruption by Nelson (1975). The outcrops are only 9 km apart and the passage zone elevation differences (5–20 m) are not large considering the distances over which they were obtained (the Lachman Crags delta outcrop is 9 km long), and the variations are probably within error of the GPS-altimeter measurements. Thus, the results suggest that the passage zones for these deltas are essentially co-planar horizontal surfaces. Whether these two deltas derive from the same eruption can now be tested with the isotopic and palaeomagnetic data. Although the error margins do not overlap (i.e. they are statistically distinct), the Ar/Ar ages of the two units are sufficiently similar not to exclude a common origin. Both the main deltas have normal polarity, and the mean remanence directions at our sites in them (1601 and 1603 in Table II) differ by 10°. As the 95% confidence radii of these means are about 8° and 5° respectively and there may e.g. have been some local magnetic anomalies affecting the ambient geomagnetic field directions during emplacement, it is not possible to state with any certainty whether our observations represent the same direction or two significantly different ones. We therefore cannot exclude the possibility of these two deltas being one formation, but neither the isotopic ages nor the palaeomagnetic data provide convincing support for a common origin.

No material suitable for dating was found in the tuff cone outcrops at Stoneley and Bibby points, but constraints can be obtained from the field relationships. The age of the Bibby Point surtseyan cone is uncertain but it must be < 5.04 Ma. It lies unconformably on the lower Lachman Crags delta but has the same polarity. It may therefore belong to any of the events of the Gilbert chron or even the Gauss chron. The lowermost delta at Davis Dome overlies the Stonely Point tuff cone and it must therefore be > 5.64 Ma.

The dykes found in the Cretaceous sediments in Brandy Bay (DJ.1609, DJ.1610 and DJ.1611) have not been dated and they cannot be linked stratigraphically to any of the deltas. All are reversely magnetized. Considering that all of the dated units belong to the Gilbert chron it seems reasonable to assign these dykes to the same period.

A summary of the volcanic stratigraphy of the Brandy Bay area, based on the combined results of our palaeomagnetic analysis, stratigraphical mapping and isotopic dating, is presented in Fig. 6 and is compared with the previously published stratigraphy. The most notable features of the revised stratigraphy are:

1. The inclusion of considerably more volcanic formations than previously. The number of formations, excluding dykes, increases from 6 to 13.
2. The combined application of the three independent methods has increased confidence in identification of volcanic units.
3. The ages of the dated units are more precise, with smaller errors. It is now established that volcanism in the Brandy Bay area extended over more than a 2 Ma, with units dating from the period 6.16–3.95 Ma.

The remanence intensity of the JRI volcanic units reaches to over 20 A m^{-1}. In this respect they are comparable to ocean-ridge basalts, and it may be expected that bodies of these rocks having a single polarity will generate recognizable aeromagnetic anomalies. However, such model computations and comparisons with observations are beyond the scope of the present paper.

Conclusions

We have reported the results of a combined palaeomagnetic, field mapping and isotopic dating study of volcanic strata on part of James Ross Island. The lack of tectonic disturbance of the volcanic sequences and the low alteration state enable good quality results (in terms of palaeopole location and isotopic dating) to be obtained. As a result of our study, the stratigraphy of the James Ross Island Volcanic Group in the Brandy Bay area is much better known and contains more volcanic units than were previously recognised. Since some of these units are formed within a glacier and others in a marine setting (Smellie 1999 and unpublished data), the revision will be important in deciphering the palaeoenvironmental history of the northern Antarctic Peninsula region. A combined study such as this one, when applied to Cenozoic volcanic rocks of the Antarctic Peninsula and elsewhere is therefore a very valuable tool not only for improving regional stratigraphical mapping generally, but also for more globally far-reaching studies of past climate change and the behaviour of the Earth's magnetic field in the southern hemisphere.

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