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Petrography and provenance of the Marambio Group, Vega Island, Antarctica

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Abstract: Late Cretaceous sedimentary rocks assigned to the Santa Marta (Herbert Sound Member) and López de Bertodano (Cape Lamb and Sandwich Bluff members) formations of the Marambio Group, crop out on Cape Lamb, Vega Island. Although previous studies have recognized that these sedimentary rocks were derived from the northern Antarctic Peninsula region, the work presented here allows the provenance and palaeogeographical evolution of the region to be described in detail. On the basis of both sandstone petrography and clay mineralogy, the Herbert Sound and Cape Lamb members reflect sediment input from a low relief source area, with sand grade sediment sourced from low grade metasediments, and clay grade sediment ultimately derived from the weathering of an andesitic source area. In contrast, the Sandwich Bluff Member reflects a switch to a predominantly andesitic volcaniclastic source. However, this sediment was largely derived from older volcanic suites due to renewed source area uplift, with only a minor component from coeval volcanism. Regional uplift of both the arc terrane and the western margin of the James Ross Basin was likely during the Maastrichtian.

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Introduction

The Mesozoic sedimentary basins of the Antarctic Peninsula region provide a valuable record of palaeoenvironmental evolution from the Late Jurassic to the ?Eocene. Recent studies have focussed on providing the stratigraphical framework for these basins (e.g. Crame *et al.* 1991), allowing detailed sedimentological and palaeoenvironmental studies (e.g. Pirrie *et al.* 1991a, see also review by Macdonald & Butterworth 1990). Advances in the understanding of the stratigraphy and sedimentology of these basins now provide the framework for a series of detailed provenance and diagenesis studies. Provenance studies will allow more precise documentation of the palaeogeographical evolution of the Antarctic Peninsula region.

In this paper, a petrographical study has been completed on part of the Cretaceous sequence exposed in the James Ross Island Basin. Strata assigned to the Marambio Group on Cape Lamb, Vega Island (Fig. 1) were selected for study for two reasons:

1) the stratigraphy and sedimentology of this sequence are well documented (Pirrie *et al.* 1991a), and
2) field studies revealed a stratigraphical variation in sediment composition, implying a change in source area geology.

Regional geological setting

The strata exposed on Cape Lamb peninsula, Vega Island represent part of an extensive sedimentary sequence of approximately Barremian-Eocene age, which crops out in the James Ross Island area (see Pirrie *et al.* 1992) (Fig. 1). Deposition was to the rear of an active magmatic arc, related to south-eastward subduction of proto-Pacific oceanic crust (Elliot 1988, Macdonald *et al.* 1988). This magmatic arc is now represented by the Antarctic Peninsula, which can be subdivided into four main tectonic units: 1) basement, 2) accretionary complex, 3) intra-arc sedimentary rocks, and 4) arc volcanic and cogenetic plutonic rocks. Outcrops of the basement are scarce, although the mid-Palaeozoic orthogneiss unit probably underlies much of the northern Antarctic Peninsula region (Milne & Millar 1989). The basement is overlain by a Permian-Triassic accretionary complex, the Trinity Peninsula Group (TPG), which is a low grade metasedimentary unit (Smellie 1987). Small intra-arc non-marine basins (represented by the Botany Bay Group, Farquharson 1984) overlie the TPG and contain sediment derived from the TPG. The basins are in turn overlain, and intruded by a major suite of Mesozoic-Tertiary, calc-alkaline magmatic arc volcanic and cogenetic plutonic rocks, the Antarctic Peninsula Volcanic Group (APVG) (Thomson 1982). To the east of the arc terrane, Cretaceous-Tertiary sedimentary rocks accumulated in the James Ross Basin, a sub-basin of the larger Larsen Basin (Macdonald *et al.* 1988, Del Valle *et al.* 1992). The stratigraphical sequence within the James Ross Basin has been subdivided into three major units; the Gustav, Marambio and Seymour Island groups (see review by Pirrie *et al.* 1992). The Cretaceous strata which crop out on Vega Island are assigned to the Marambio Group. Del Valle *et al.* (1982) assigned the Vega Island sequence to the López de Bertodano Formation and described a 205 m section, interpreted as being mid-Campanian in age, whilst subsequent palynological and macrofossil studies suggested a late Campanian-Maastrichtian age (Askin 1983, Dettmann & Thomson 1987,

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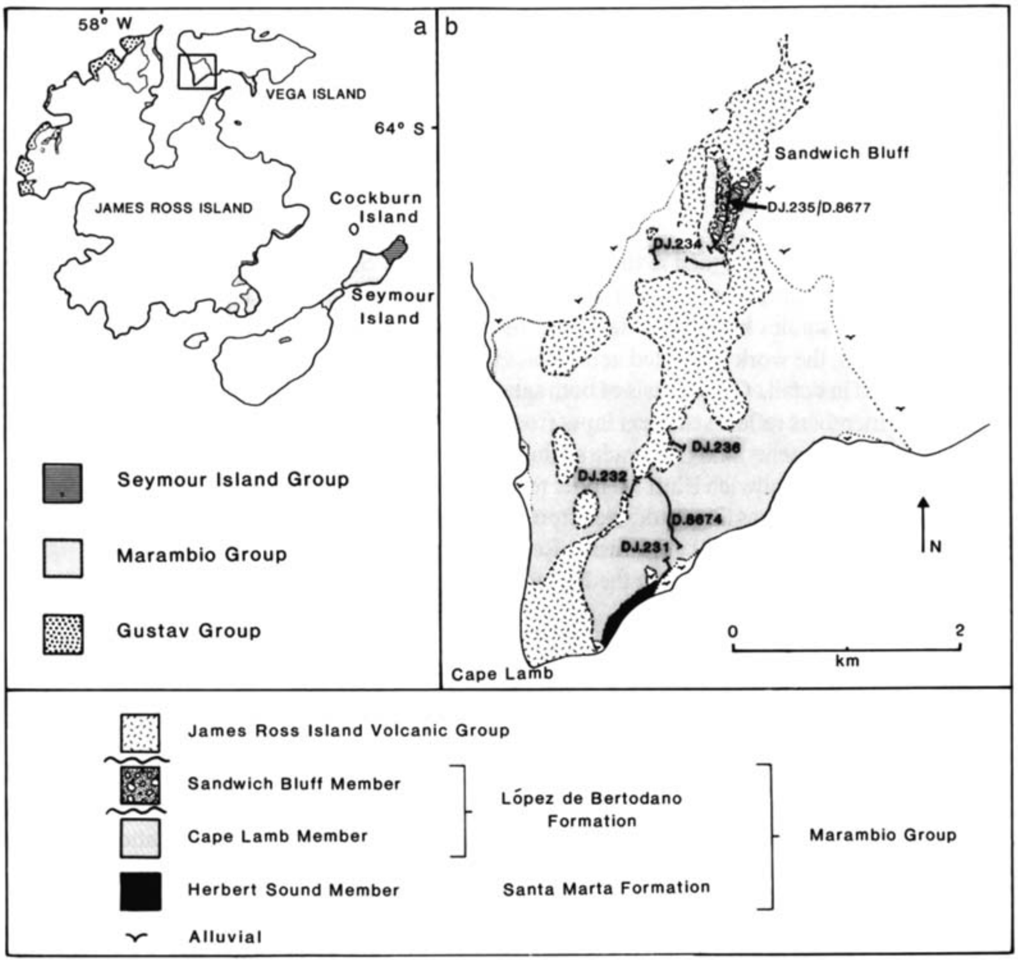

Fig. 1.a. Sketch geological map of the James Ross Island area. **b.** Sketch geological map of Cape Lamb, Vega Island showing location of measured sections (after Pirrie *et al.* 1991a). The same section (DJ.235/D.8677) was examined during two field seasons, hence the two location numbers.

Pirrie *et al.* 1991a, Smith 1992).

On the basis of detailed field studies, Pirrie *et al.* (1991a) revised the stratigraphy and sedimentology of the Cape Lamb sequence. A 483 m-thick section was measured, and divided into three stratigraphical units of member status (Figs 1 & 2) which were formally named by Crame *et al.* (1991). The basal unit on Cape Lamb, assigned to the Herbert Sound Member of the Santa Marta Formation by Crame *et al.* (1991), has a maximum observed thickness of 52 m. This late Campanian–early Maastrichtian unit is composed of massive silty mudstones in the lower 30 m, overlain by a 20 m-thick sandstone-dominated packet. An outer shelf depositional setting was tentatively proposed for this unit by Pirrie *et al.* (1991a). The Herbert Sound Member is conformably overlain by the Cape Lamb Member, the basal unit of the López de Bertodano Formation (Crame *et al.* 1991). The Cape Lamb Member has a maximum thickness of 319 m at its type section. It is composed of massive silty sandstones and silty mudstones, with scarce sandstones, mudstones and a single laterally continuous conglomerate bed. Within the member there is a weak coarsening-upward cycle, which is overlain by the thin, laterally-persistent conglomerate bed, in turn overlain by interbedded silty sandstones and sandstones. This sequence was interpreted as representing a regressive-transgressive cycle within a shelf setting, with the thin conglomerate bed representing a transgressive lag conglomerate following regression (Pirrie *et al.* 1991a). Deposition was below storm wave base, with sedimentation in outer shelf and possibly mid to ?inner shelf settings during regression. Pirrie *et al.* (1991a) assigned this member a late Campanian to early and possibly mid Maastrichtian age on the basis of both macrofossils and palynomorphs, although other authors contest this palynological age (see discussion in Pirrie *et al.* 1992). Recent studies by Olivero *et al.* (1992) on the Cape Lamb Member from western Cape Lamb support both the palaeoenvironmental and biostratigraphical interpretations presented here.

The Cape Lamb Member on Vega Island is separated from the overlying late Maastrichtian Sandwich Bluff Member of the López de Bertodano Formation by an angular unconformity (Crame *et al.* 1991). The type section of the Sandwich Bluff Member is 111 m-thick; it is lithologically diverse, being composed of thin conglomerates, pebbly sandstones, sandstones and mudstones. Sedimentological and palynological data, suggest that this member represents a regressive sequence, with a transition through ?mid shelf, lower shoreface and finally marginal marine depositional settings at the top (Pirrie *et al.* 1991a).

The Late Cretaceous sedimentary sequence on Cape Lamb is unconformably overlain by thin glacial diamictites of probable Pliocene age, and an extensive suite of Miocene-Pliocene ensialic alkaline volcanic rocks, the James Ross Island Volcanic Group (Nelson 1975).

Burial history

The burial history of the sequence is reasonably well constrained. During deposition of the Herbert Sound Member and the Cape Lamb Member, basin subsidence approximately equalled sedimentation rate. The unconformity separating the Cape Lamb and Sandwich Bluff members reflects basin uplift during the Maastrichtian. The Sandwich Bluff Member records progressive basin shallowing. Small-scale synsedimentary faulting within this sequence was interpreted by Pirrie *et al.* (1991a) as indicating compression and continued basin inversion during the late Maastrichtian. Palaeocene-Oligocene sedimentation within the basin is, at present, only documented from Seymour and Cockburn islands (see Fig. 1a), implying a basinward shift of the depocentre. Uplift and subaerial exposure of the Cape Lamb area by early Tertiary times is therefore possible. The overlying Miocene-Pliocene James Ross Island Volcanic Group on Cape Lamb was erupted in non-marine conditions (I.P. Skilling personal communication 1990).

Data reported here and in Pirrie *et al.* (1994) support the view that this part of the basin has undergone minimal burial. There is no evidence for the smectite-illite transformation, or the alteration of clinoptilolite-heulandite cements to analcite, suggesting that the sequence has been heated to less than 80°C (cf. Lee & Klein 1986). In addition, apatite fission tracks have not been reset, implying maximum burial temperatures of less than 100°C (Hurford & Carter 1991). Unpublished vitrinite reflectivity results give Ro of 0.36% again compatible with only shallow burial (A.G. Whitham personal communication 1990). Although a general back-arc setting has been suggested for the James Ross Island area (Macdonald *et al.* 1988), there is no evidence for an elevated heat flow. During Marambio Group times it is likely that deposition was on a continental shelf, which acted as a passive extending margin, experiencing an average thermal subsidence profile (Ineson 1989). It is likely that maximum burial depths did not exceed 1 km; actual burial depths may have been significantly less. Hence, although a maximum burial temperature of 80°C can be suggested, the actual burial temperatures were probably much lower.

Samples and methodology

Outcrop samples were collected by the author and co-workers on the 1989 James Ross Island scientific cruise and during the 1985–86 Antarctic field season. Samples were routinely collected from all facies recognized within the Cape Lamb and Sandwich Bluff members; only a single sample was available from the underlying Herbert Sound Member. Sample numbers and stratigraphical location are shown on the composite sedimentary log in Fig. 2. All samples are stored in the geological collections of the British Antarctic Survey, Cambridge.

In order to elucidate the petrography and provenance of the Cape Lamb sequence, 50 samples were examined. Twenty representative sandstones were selected for point counting; 1000 points were counted per thin section, with a point count interval of 0.1 mm and a track spacing of 0.5 mm. The sandstones were point-counted for all grains, using the 'QFL' method (Dickinson 1970). Using this technique, all sand-sized monominerallic fragments within a section are counted as single grains, even if they occur within polyminerallic lithic grains. Sandstones point-counted were routinely stained for plagioclase and K-feldspar using the method of Houghton (1980). The clay mineralogy of 14 samples was examined by XRD analysis of the <2μm fraction. Ten of these samples were analysed at the University of Manchester on a Philips PW2253/20 diffractometer operating at 20 Kv and 20 μA using CuKα radiation. Air-dried, untreated oriented mounts were analysed between 2 and 30°2θ and were subsequently glycolated and heat treated (to both 400°C and 550°C) to aid clay mineral identification. Four samples were analysed on a Philips PW1730 diffractometer, housed in the Department of Earth Sciences, University of Cambridge, using CuKα radiation. Samples were prepared as smear slides, and were analysed between 2 and 36°2θ for untreated, glycolated and heated (to both 400°C and 550°C) samples. Sample preparation for clay mineralogy followed the method of Jeans (1978). Zircon and apatite fission track dating was carried out on three sandstone samples by Dr A. Carter at the University of London.

Sandstone petrography

Previous work on the sandstone petrography and clay mineralogy of the Cape Lamb sequence is very limited. Del Valle *et al.* (1982) stated that the composition of the sandstones and conglomerates indicated that the sediments were derived from the Trinity Peninsula Group, the Antarctic Peninsula Volcanic Group, possibly Mesozoic sedimentary rocks, and a plutonic source other than the Antarctic Peninsula Volcanic Group. However, no data were presented. Olivero *et al.* (1992) provided a brief petrographical description of samples from the Cape Lamb Member, but no point count data were presented. In a general petrographical study of the James Ross Basin fill Pirrie (1991) included three sandstone point count analyses and four clay mineral XRD analyses from Cape Lamb; these data are incorporated here.

The sandstones studied range from arkosic arenites to sub-arkoses to sub-lith-arenites and lithic arenites (*sensu* Pettijohn *et al.* 1972, Fig. 3). The framework grains and major accessory minerals are described briefly below.

Quartz. Both monocrystalline (Qm) and polycrystalline quartz (Qp) occur throughout, although Qp grains are only a minor component (range 0–4.6%, mean 2.3%) (Fig. 4a). Qm grains predominantly show undulose (>5°) extinction, although grains with straight extinction are also present. Qp grains usually comprise >3 subcrystals, although *grains with 23*

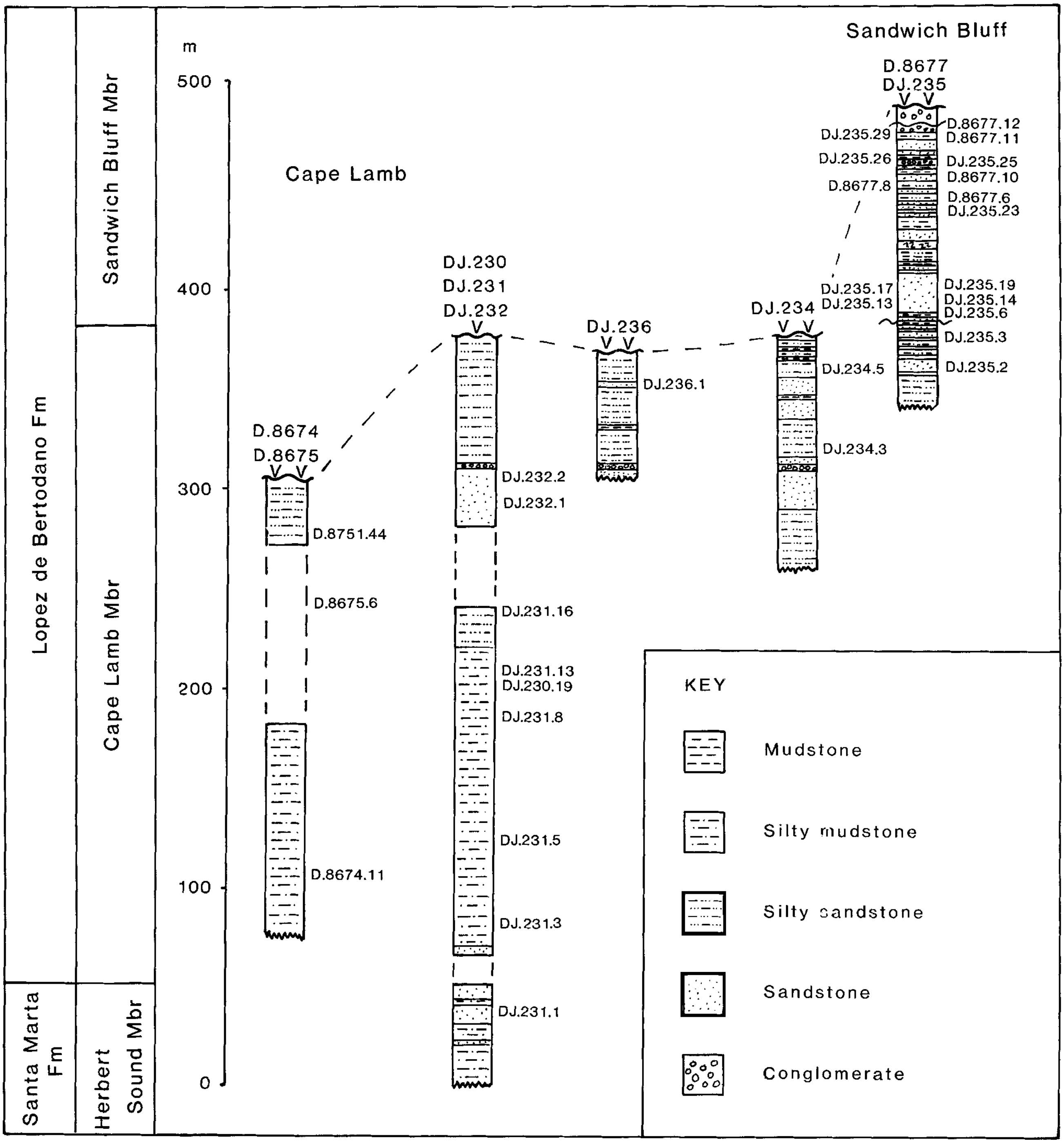

Fig. 2 Composite sedimentary log for Cape Lamb showing the stratigraphical positions of samples either point-counted or analysed by XRD in this study.

subcrystals also occur. The Qp grains typically show undulose (>5°) extinction and have sutured crystal boundaries.

Feldspar. Plagioclase (P) and K-feldspar (K) occur in varying proportions throughout the sequence studied, although the ratio of total feldspar (F=P+K) to total quartz (Qt=Qm+Qp) is on average 2.5. Plagioclase is usually more abundant than K-feldspar, and appears less diagenetically altered (Fig. 4b). Plagioclase feldspars range from small sub-rounded grains to sub-angular, fractured, fresh euhedral crystals showing compositional zoning.

Lithic fragments. Lithic volcanic (Lv) and low grade lithic meta-sediment (Lsm) grains are recognized. Lv grains predominate and include glass shards, pumice and andesitic fragments. Andesitic grains, composed of plagioclase phenocrysts within a fine grained or aphanitic groundmass, are the main Lv grain type present (Fig. 4c). The Lv grains show variable

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degrees of alteration. Lsm grains are a less abundant framework component, and are dominantly composed of an aggregate of quartz and mica. These grains typically have sutured crystal boundaries and show marked undulose extinction.

Accessory minerals. The dominant accessory minerals are biotite, hornblende, glauconite, muscovite, pyrite, pyroxene, zircon, sphene and apatite. Biotite and hornblende are the two most abundant accessory minerals. Glauconite and pyrite are also common although an authigenic origin is likely for these grains. Some samples, particularly in the Sandwich Bluff Member, are rich in heavy minerals, with up to 13% modal content. Wood fragments, calcareous and agglutinated foraminifera and calcispheres commonly occur.

Sandstone modal data

In most provenance studies, medium grained sandstones are preferentially selected for point-counting, because of the recognized grain size control on sediment composition (Ingersoll *et al.* 1984). However, medium-grained sandstones are scarce within the Cape Lamb sequence and samples ranging from poorly sorted, silty, very fine sandstones to very coarse sandstones were included in this study. Within the upper part of the sequence, there is an apparent grain-size control on sandstone composition, with larger grains being volcaniclastic, whereas finer-grain sizes are more quartz-rich. However, the Gazzi-Dickinson point-counting technique was used to minimize the influence of grain size on petrographical data (Ingersoll *et al.* 1984).

Diagenetic alteration may also modify significantly the original framework composition of volcaniclastic sediments. A number of diagenetic processes have modified the original framework compositions observed in this study. Both Qm and feldspar grains show considerable evidence for silicate dissolution and calcite replacement, although the remnant detrital grains can be identified. Lv grains show extensive alteration, with the replacement of the fine-grained groundmass by clay minerals, calcite and rarely zeolites. Some Lv grains have undergone ductile deformation with the formation of pseudo-matrix. Although grain boundaries are indistinct, the original grain can usually be identified. Some authigenic glauconite or glauconite-chlorite grains reveal relict igneous textures (cf. Jeans *et al.* 1982) implying the diagenetic alteration of a Lv precursor grain. Biotite grains are commonly splayed, with the development of carbonate and pyrite cements along the cleavage planes. Some pyroxene grains show preferential dissolution and partial replacement by carbonate cements. This diagenetic alteration may have caused minor modification of the sandstone modal composition, although in all of the thin sections studied, unidentified grains never exceeded 1% modal content. Several sections studied contained abundant, apparently displacive, carbonate cement; this has modified the sediment texture without affecting the sediment modal composition. The diagenesis of the sequence studied is discussed in detail by Pirrie *et al.* (1994).

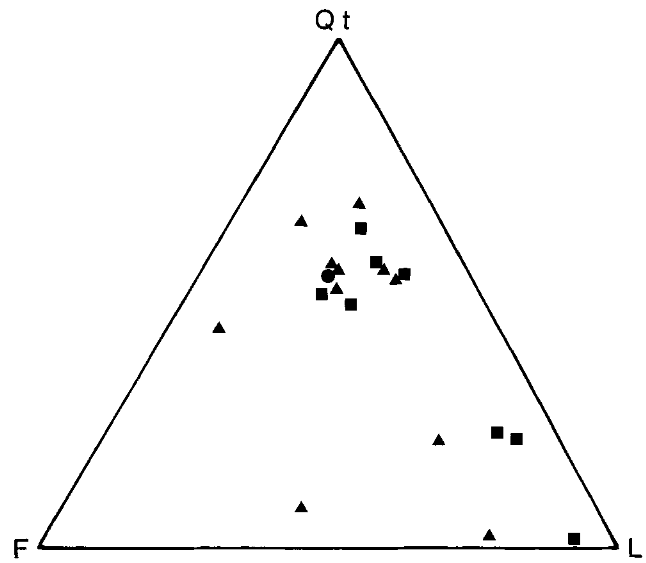
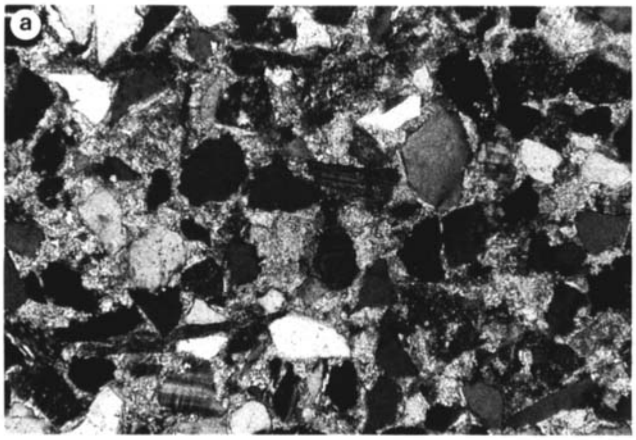


Fig. 3 Ternary diagram showing quartz total (Qt = Qm + Qp), feldspar (plagioclase + alkali feldspar) and lithics (Lv + Lsm). Circle = Herbert Sound Member, triangle = Cape Lamb Member and square = Sandwich Bluff Member.

Sandstone modal data are shown on a QtFL ternary diagram (Fig. 3) and in Table I. As can be seen, there is a wide scatter of points, with no immediately apparent stratigraphical trends between the three members. The data are replotted in Fig. 5. The plots showing the ratios of plagioclase to total feldspar, and of Lv to total lithic grains show a very marked covariance. There is also a general trend throughout the section to higher proportions of plagioclase to total feldspar and Lv to total lithic grains in samples from the Sandwich Bluff Member than the Herbert Sound or Cape Lamb members. Fig. 5 also shows that the samples point counted fall into two separate groups: a dominant composition of $Q_{50-60}F_{20-25}L_{20-25}$ (e.g. sample DJ.231.16), with a series of pulses of more feldspathic and lithic sandstones throughout the section studied (e.g. sample DJ.234.3).

Clay mineralogy

The mineralogical composition of the <2 μm fraction of 14 samples, was analysed by XRD. The clay mineralogy of all of the samples examined is dominated by a smectitic clay mineral. There is an apparent change stratigraphically in the mineralogy of the fine grained fraction. Samples from the Herbert Sound Member and the base of the Cape Lamb Member contain mica, chlorite/kaolinite, quartz and calcite in addition to smectite. In contrast, the Sandwich Bluff Member samples typically lack mica, quartz, calcite and chlorite/kaolinite, and are composed of smectite and a zeolite mineral of the heulandite-clinoptilolite group.



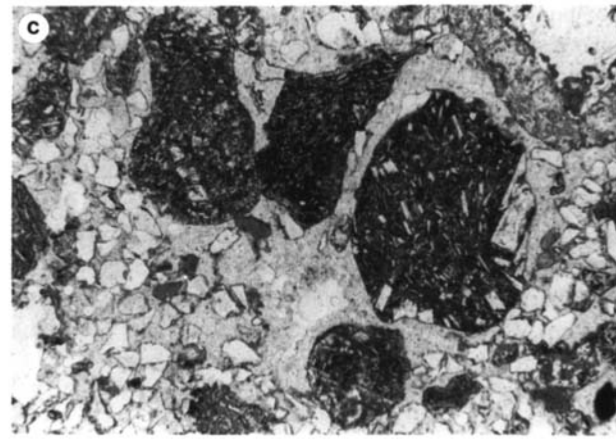


Fig. 4a. Photomicrograph of quartz-rich sandstone under crossed polars with minor plagioclase and microcline feldspar. Note compaction of biotite mica and calcite cement. Sample number DJ.231.1, Cape Lamb Member, Maximum field of view = 2 mm. **b.** Photomicrograph of plagioclase feldspar-rich sandstone under crossed polars. Sample number DJ.234.3, Cape Lamb Member. Maximum field of view = 5 mm. **c.** Photomicrograph taken under plane polarized light, of large andesitic lithic-volcanic grains with fine grained sediment composed of quartz. Sample number D.8677.12, Sandwich Bluff Member. Maximum field of view = 5 mm.

Table I. Summary table of sandstone point count data.

Sample	Grain size	Qm	Qp	Qt	P	K	Ft	Lv	Lsm	Lt	Mu	Bi	Opq	Hbl
DJ.231.1	vf-f	47.4	2.7	54.1	19.1	3.1	23.9	10.4	10	22	0.2	1.9	1.9	1
DJ.231.3	s-vf	40.7	2.8	63.8	16.4	-	24	5.6	2.8	12.4	0.6	9	16.4	1.1
DJ.231.5	f-vf	2.4	0.4	3	20.1	-	21	58.2	-	76	-	0.4	4	0.4
DJ.230.19	s-vf	57.4	4.6	68.5	6.9	3.7	11.8	10.2	7.6	19.7	0.2	2.1	2.1	2.1
DJ.231.13	s-vf	42.7	3.4	52.5	4.7	6.5	12.7	19.8	10.8	34.8	-	4.7	3.9	0.4
DJ.231.16	s-vf	43.5	2.7	55.6	10.6	8.2	22.5	9.1	9.1	21.9	0.9	1.5	8.5	2.7
D.8751.44	vf-f	35.1	4.2	43.5	31.3	11.8	47.7	5.3	2.7	8.8	0.4	0.8	1.5	3.8
DJ.232.1	vf-f	44.5	2.4	50.5	15.4	7.3	24.4	8.3	15	25.1	0.6	1.2	1.2	1.6
DJ.232.2	vf-f	49.2	1.9	55.3	6.6	13.7	22	4.7	16.3	22.7	0.6	2.6	1.1	0.6
DJ.234.3	m	7.7	-	8	48.5	-	50.6	37.5	2.2	41.4	-	0.7	2.2	1.1
DJ.235.2	s-vf	16.7	0.8	20.5	18	-	21.1	47.5	2.2	58.4	0.3	2.2	7.9	2.5
DJ.235.3	vf-f	41.7	3.1	54.5	9.8	2	14.4	12.6	13	31.7	-	3.9	3.9	5.5
DJ.235.13	vf	48.2	2.4	56	7.6	5	13.9	10.2	17.1	30.1	0.2	1.3	1.7	3.7
DJ.235.17	vf-f	50.5	3.7	63	9.7	2.1	14	5.8	14.2	23	0.2	2.1	0.9	5.6
DJ.235.19	vc	19.3	0.9	22	5.8	0.4	6.8	64.6	0.9	71.2	-	0.9	1.3	1.8
D.8677.6	vf-f	44.3	1.1	48	14	7.9	23.2	12.1	15.1	28.8	0.4	2.3	1.5	-
D.8677.10	vf-f	40.7	3.6	50.4	21.6	2	27	14.4	5.4	22.6	0.8	1	0.8	4.9
DJ.235.26	f-m	42.1	3	54.1	8.2	0.7	10.7	18.3	11	35.2	-	3	3	4.3
D.8677.12	vc	22	0.8	53.3	8.5	0.8	9.5	65.3	0.8	67.2	-	-	-	0.8
DJ.235.29	c-vc	1.4	0.7	2.2	6.5	-	6.7	87.7	1.4	91.1	-	-	-	-

Qm - monocrystalline quartz, Qp - polycrystalline quartz, Qt- quartz total, P - plagioclase, K - alkali feldspar, Ft - total feldspar, Lv - lithic volcanics, Lsm - lithic meta-sediments, Lt - total lithics, Mu - muscovite, Bi - Biotite, Opq - opaques, Hbl - hornblende, Sph - sphene, Gla - glauconite, Px - pyroxene, Zr - zircon.

Provenance discussion

In provenance studies on sequences partially derived from volcaniclastic sequences, one of the principal objectives is to distinguish between clasts from coeval volcanism and from the reworking of older volcanic suites (Zuffa 1985). The Vega Island sequence is interpreted as having been derived from two major units, which occur within the northern Antarctic Peninsula region. The plagioclase and Lv framework grains were probably derived from the calc-alkaline andesitic rocks of the Antarctic Peninsula Volcanic Group (APVG); the accessory minerals pyroxene and hornblende also probably came from this source. The dominant smectite clay is detrital in origin, but probably formed as a weathering product of the APVG (see discussion below). The majority of the quartz and the Lsm grains, however, were probably derived from the Trinity Peninsula Group (TPG). On northern Antarctic Peninsula, this unit comprises low-grade metasedimentary rocks (Smellie 1987). The predominance of undulose extinction within the Qm grains supports derivation from a low rank metamorphic terrane (cf. Basu *et al.* 1975), as does the predominance of Qp grains with >3 subcrystals. However, a minor contribution of quartz from either volcanic or plutonic rocks associated with the APVG cannot be discounted. The K-feldspar may have been derived from either a plutonic or volcanic source associated with the APVG, or from the TPG, although Smellie (1987) recognized considerable alteration of K-feldspar within the TPG which is not observed in the studied samples.

The relative sediment contribution from the APVG and the TPG fluctuated with time; there is no evidence for a temporal unroofing trend of the arc terrane (cf. Pirrie 1991). In the Herbert Sound and the Cape Lamb members the dominant sandstone composition is relatively quartzose (50–60%) with subequal feldspar and lithic framework grains. K-feldspar is relatively common compared with the Sandwich Bluff Member. The lithic framework grains include both Lv and Lsm grains. The fine grained sediment fraction is dominated by smectite, with minor chlorite/kaolinite, mica, quartz and calcite.

On the basis of these data, the sand fraction in the Herbert Sound and Cape Lamb members is interpreted as having been derived predominantly from the TPG (see Fig. 6). Enrichment of quartz relative to labile framework grains due to depositional processes in high energy shallow marine environments has been noted by previous authors (Mack 1978). This may have led to minor quartz enrichment relative to feldspar and lithic grains in the Herbert Sound Member and in the coarsening-upward regressive cycle within the Cape Lamb Member. The sandstones which occur within these intervals are typically moderately to well sorted, implying either hydrodynamic sorting or a source area limitation on grain size. Although the framework composition of these sandstones implies provenance from the TPG, a minor component from the APVG is recognized. Whether or not the original detrital ratio between the supply of TPG and APVG detritus has been modified by the depositional environment or process cannot be determined.

As shown in Fig. 5, two discrete and petrographically distinct intervals of predominantly volcaniclastic detritus are recognized in the Cape Lamb Member. The stratigraphically lower volcaniclastic unit (sample DJ.231.5) is a thin normally graded sandstone, predominantly composed of andesitic Lv grains, along with abundant pumice and cuspate glass shards. Individual grains within this unit show similar degrees of diagenetic

Table I. continued. Summary table of sandstone point count data.

Sample	Sph	Gla	Px	Zr	Other	Qp>3	Qp2-3	Qp/Q	Q/F	P/K	P/F	Lv/L
DJ.231.1	-	1.2	-	0.8	0.3	36	64	0.05	2.26	6.18	0.36	0.51
DJ.231.3	-	1.7	-	-	2.8	80	20	0.06	2.65	-	1	0.66
DJ.231.5	-	-	-	-	-	100	-	0.14	0.14	-	1	1
DJ.230.19	0.2	0.7	1.6	0.2	0.2	84	16	0.07	5.8	1.87	0.65	0.57
DJ.231.13	-	3	-	-	-	100	-	0.07	4.1	0.7	0.4	0.64
DJ.231.16	-	3	-	-	0.3	63	37	0.06	2.39	1.29	0.56	0.5
D.8751.44	-	2.7	0.4	-	-	64	36	0.11	0.91	2.64	0.73	0.67
DJ.232.1	0.3	1.7	-	0.5	-	50	50	0.05	2.06	2.11	0.68	0.36
DJ.232.2	-	2.1	0.2	0.2	-	78	22	0.03	2.51	0.48	0.33	0.22
DJ.234.3	-	-	-	-	-	-	-	-	0.16	-	1	0.94
DJ.235.2	-	1.1	-	0.5	0.3	33	67	0.05	0.96	-	1	0.96
DJ235.3	-	4.3	-	-	-	57	43	0.07	3.8	5	0.8	0.49
DJ.235.13	0.2	1.3	1.3	-	-	73	27	0.05	4.03	1.52	0.6	0.37
DJ.235.17	-	2.8	0.6	1.5	0.2	70	30	0.07	4.58	4.5	0.8	0.29
DJ.235.19	-	2.7	1.3	-	-	100	-	0.04	3.21	13	0.93	0.99
D.8677.6	-	1.1	-	-	-	100	-	0.02	2.07	1.76	0.64	0.44
D.8677.10	-	2.8	1.8	-	-	77	23	0.08	1.87	10.5	0.91	0.73
DJ.235.26	0.7	3.2	1.8	0.2	0.2	85	15	0.07	5.05	12	0.92	0.63
D.8677.12	-	0.8	-	-	-	100	-	0.04	2.45	10	0.91	0.99
DJ.235.29	-	-	2.2	-	-	-	100	0.33	0.33	-	1	0.98

Qm - monocrystalline quartz, Qp - polycrystalline quartz, Qt- quartz total, P - plagioclase, K - alkali feldspar, Ft - total feldspar, Lv - lithic volcanics, Lsm - lithic meta-sediments, Lt - total lithics, Mu - muscovite, Bi - Biotite, Opq - opaques, Hbl - hornblende, Sph - sphene, Gla - glauconite, Px - pyroxene, Zr - zircon.

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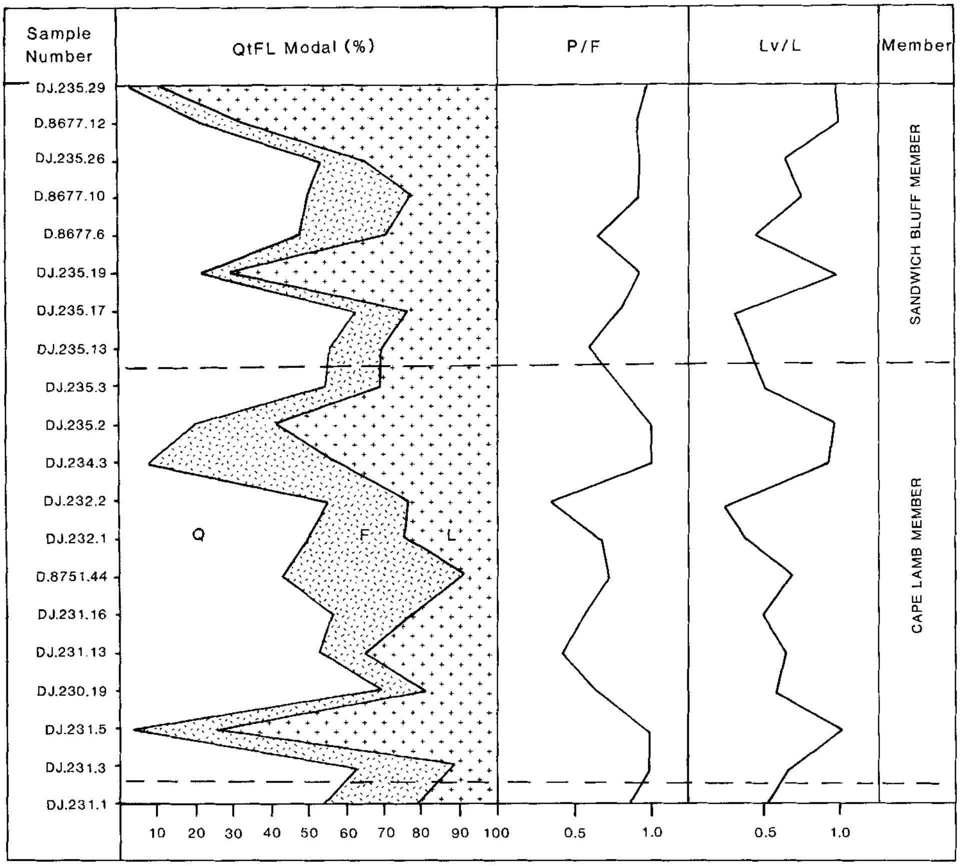

Fig. 5 Schematic diagram showing percentages of quartz, feldspar and lithics versus stratigraphical height, together with ratios of plagioclase to total feldspar (P/F) and lithic volcanic to total lithic grains (Lv/L).

alteration implying post-depositional alteration, rather than sediment alteration prior to deposition. In contrast, the younger volcaniclastic pulse (sample DJ.234.3) is predominantly composed of coarse-grained, subhedral plagioclase feldspars (some of which show compositional zoning), along with andesitic Lv grains, with plagioclase phenocrysts in a fine-grained aphanitic groundmass.

Pirrie *et al.* (1991a) interpreted these normally graded but otherwise structureless beds as representing either deposition from passive settling of airfall detritus, or deposition from a waning low-density turbidity current, with sediment supply related to coeval arc volcanism. The presence of scarce non-volcaniclastic grains within these units implies that deposition from turbidity currents was more likely. The sediment composition indicates coeval arc volcanism. However, the limited effect of this volcanism on the general petrographical signature from Cape Lamb implies that the volcanism was either, distal from the depositional basin, or temporally restricted.

The <2 μm fraction of the Cape Lamb Member is dominated by smectite. Although smectite-dominated clay mineral assemblages can be derived from the weathering of a wide range of lithologies (Weaver 1989), it is likely that in this example they were derived from the APVG. The smectite is interpreted as being predominantly detrital in origin, derived originally from the weathering of the APVG calc-alkaline volcanic rocks. Similar smectite-rich clay mineral assemblages have been described by Jeans *et al.* (1982) from the UK. Rare massive olive-green coloured mudstone beds occur within the upper levels of the Cape Lamb Member. One bed was analysed by XRD (sample DJ.234.5) and is composed solely of smectite. This distinct mudstone facies in the Cape Lamb Member was interpreted by Pirrie *et al.* (1991a) as being due to rapid deposition of fine grained volcaniclastic detritus, following arc volcanism. The absence of any other mineral components suggests that in this sample, the smectite may be at least partially authigenic in origin.

The predominantly fine-grained sediments of the Herbert Sound and Cape Lamb members imply restricted source area relief and limited coarse-grained sediment input to the basin. If coarse-grained sediment was available in the source area, it either bypassed the shelf depositional setting, or was restricted to the basin margin. Previous studies (Elliot 1988, Pirrie *et al.* 1991b) have suggested that, during the deposition of the Marambio Group, a broad stable shelf developed. Correlated sequences in relatively nearshore (Vega Island) and offshore (Seymour Island) depositional sites are both dominated by fine grained sedimentation, there is at present, no evidence that coarse sediment bypassed the shelf. Synsedimentary tectonics were important in controlling sedimentation patterns during the deposition of the Gustav Group in the early stages of basin development (Ineson 1989, Pirrie *et al.* 1991b), but the latter stages during the Late Cretaceous were less affected by basin margin tectonics. This is supported by the relatively minor levels of reworking of older Cretaceous palynomorph taxa

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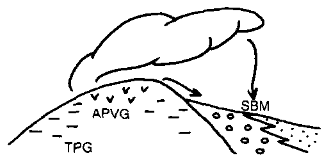
SOURCE	PETROGRAPHY	CONTROLS
Sandwich Bluff Mbr  Sandstone derived from andesitic volcanics of variable age (APVG) with minor metasedimentary source (TPG)	Sandstone Andesitic Lv and P dominated Fine grained sediment Qt/K rich Mudstone Mudstone smectite dominated	Regional source area uplift Increased intensity or proximity of arc volcanism Heavy mineral enrichment in nearshore environments
Herbert Sound Mbr Cape Lamb Mbr  Sandstone derived from metasediments (TPG) and minor volcanic/plutonic source (APVG) Smectite clays sourced from chemical weathering of volcanics (APVG)	Sandstone Qm/Qp rich plus P and K Minor Lv grains Mudstone Mudstones smectite, micas and chlorite/kaolinite	Low relief source area Intense chemical weathering of andesitic source rocks Minor or distal coeval arc volcanism Depositional environment/ process linked enrichment in Qt

Fig. 6 Schematic summary diagram showing the petrography, likely source rocks and controls on provenance for the Vega Island section. Coeval arc volcanism was a minor sediment source throughout deposition.

within the Cape Lamb strata (Dettmann & Thomson 1987, Smith 1992). Therefore it is unlikely that significant volumes of coarser sediment bypassed the wide shelf. Basin margin facies are not preserved, hence it is unknown whether coarse sediment accumulated at the basin margin.

During the deposition of the Herbert Sound and Cape Lamb members, the source area probably had a low relief (Fig. 6). Palaeoclimatic studies based on fossil wood indicate a temperate climate, possibly with high rainfall (Francis 1986). The likely sedimentation rate was relatively rapid for a low relief source area. This implies that a major river or rivers supplied the sediment to the basin in the James Ross Island area, as previously envisaged by Macellari (1988), although a deeper marine depositional setting is more likely than the estuarine conditions proposed by Macellari (1988) (see discussion in Pirrie *et al.* 1991a).

Although there is a considerable spread in the available data, there is an upward increase in the abundance of volcaniclastic detritus in the Sandwich Bluff Member (Fig. 5). Associated with this petrographical change is an increase in the lithic volcanic and plagioclase grains, a change in the ratio of P/F, and increased abundance of accessory minerals derived from volcanic sources (hornblende and pyroxene). Sandstones from this member are often poorly sorted; some have a bimodal grain-size distribution with coarser grains composed of well rounded Lv fragments and the finer-grained sediment predominantly composed of quartz and feldspar. Lv grains are commonly highly altered in the Sandwich Bluff Member, although there is variation within some individual samples. Large fractured, euhedral to subhedral plagioclase feldspar grains, some of which show compositional zoning, increase in abundance up section. Many samples within this member are rich in heavy minerals, probably due to the nearshore, high energy depositional setting (Pirrie *et al.* 1991a). To try and determine the heavy mineral provenance ages, fission track age dating was carried out by Dr A. Carter at the University of London, on three samples (DJ.235.17, DJ.235.24, DJ.235.30). Apatite and zircon grains from these three samples show different provenance ages; apatite fission tracks have not been reset, implying that burial temperatures did not exceed 100°C (Hurford & Carter 1991). The apatite fission track ages reflect provenance from three different age units; a dominant 90 Ma source rock, and minor sources of 150 and 320 Ma. The zircon fission track data give different mean ages for the three samples analysed of 110±9, 82±9 and 122±12 Ma.

The petrography of the Sandwich Bluff Member records a transition to sediment provenance from the APVG (Fig.6). Pirrie *et al.* (1991a, b) suggested that this petrographical shift reflected a pulse in coeval calc-alkaline volcanism. Although some units within this member do appear to be derived from coeval volcanism, apatite and zircon fission track data suggest that sediment was also derived from older volcanic sequences. Apatite and zircon grains have been reported from the TPG (Aitkenhead 1975, Smellie 1987) and from the APVG (Elliot 1965). Available data suggest a Permian-Triassic age for the TPG, implying a likely pre-Triassic age (245 Ma) for the detrital apatite and zircon grains within this unit. Plutonism associated with the APVG commenced in the late Triassic, although the

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most important periods of plutonism were Early Jurassic (180–160 Ma), Cretaceous (130–80 Ma) and early Tertiary (60–50 Ma), with an early to mid-Cretaceous age likely for much of the volcanic succession in the northern Antarctic Peninsula region (Pankhurst 1982). Igneous activity was apparently diachronous across the arc, with major arc activity ceasing at 80 Ma in the east but continuing well into Tertiary times in the west (Pankhurst 1982).

On the basis of the fission track data and the likely ages of the source rocks, it is probable that the zircon grains were derived from a number of discrete volcanic/plutonic units within the APVG. The zircon grain mean ages compare well with the dominant Early Cretaceous plutonic/volcanic pulse documented by Pankhurst (1982). In contrast, the dominant apatite fission track age of 90 Ma implies derivation from a younger APVG plutonic/volcanic source, whilst the 150 Ma age implies derivation from an older APVG source. The apatite modal age of 320 Ma is older than the likely depositional age of the TPG, suggesting a poly-cyclic history for the apatite grains. Using the U-Pb method, Miller *et al.* (1987) dated detrital zircon grains from the TPG, which yielded a lower intercept age of 322+7/-8 Ma. This age was interpreted as reflecting intrusion of granitic plutons and an associated metamorphic event (Miller *et al.* 1987, Milne & Millar 1989). The coincidence in the ages of the metamorphic event and the detrital apatite may imply that the apatite fission track age was reset by the metamorphic event. Thus, within the Sandwich Bluff Member, the heavy mineral suite was predominantly derived from a series of older volcanic/plutonic rocks of the APVG, and a minor component from the TPG. Individual zircon crystal ages imply limited derivation from coeval volcanism. These fission track results support the petrographical observation that Lv grains appear to show a range of degrees of alteration within individual samples, and imply different source ages for the lithic framework grains.

The petrography of the Sandwich Bluff Member reflects source-area uplift, minor coeval volcanism and a transition to predominant sediment supply from the APVG and associated plutons. Regional uplift in the Maastrichtian is implied by both the unconformity at the base of the Sandwich Bluff Member and by the change in provenance. Pirrie *et al.* (1991a) described small-scale synsedimentary faulting within this unit, which they interpreted as reflecting compression and continued basin inversion during the late Maastrichtian. Evidence for basin uplift in the Vega Island area, which represents a relatively proximal location within the basin, is important in the understanding of the regional palaeogeography. Previous work has suggested that the sequence on Vega Island correlates with the considerably thicker sequence on Seymour Island (Crame *et al.* 1991, Pirrie *et al.* 1991a, Olivero *et al.* 1992). This lateral thickness variation may be linked to repeated tectonic uplift of the basin margin throughout the Maastrichtian.

Conclusions

Detailed petrographical studies allow the provenance and regional palaeogeography of both the northern Antarctic Peninsula and James Ross Basin area to be interpreted. The Herbert Sound and Cape Lamb members reflect sediment input from a low-relief source area, with sand-grade sediment sourced from the TPG and clay-grade sediment, ultimately derived from the APVG through the weathering cycle. In contrast, the Sandwich Bluff Member reflects source-area rejuvenation, and predominantly volcaniclastic sediment supply with the erosion of coeval and older volcanic rocks. This volcaniclastic sediment is largely sourced from older volcanic/plutonic units; sediment supply from minor coeval volcanism is recognized in the Cape Lamb Member and possibly with increased intensity in the Sandwich Bluff Member. Regional uplift of the basin margin occurred during the Maastrichtian.

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