REGIONAL SIGNIFICANCE OF PROGLACIAL DELTA-FRONT, REWORKED TUFFS, JAMES ROSS ISLAND AREA

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ABSTRACT. Fine-grained tuffs form a small part of the upper Cenozoic James Ross Island Volcanic Group, exposed on James Ross Island and surrounding islands, northern Antarctic Peninsula. Distinctive tuffs from Hidden Lake, James Ross Island and north-east Tail Island can be subdivided into five lithofacies, which mainly represent rapid deposition out of suspension from sediment-laden currents. Primary sedimentary structures include planar lamination and climbing-ripple lamination. Synsedimentary slumping and the formation of dish and pillar structures represents pore fluid over-pressure, as a result of rapid deposition.

The Tail Island tuffs are composed almost entirely of cuspate glass shards which have subsequently altered to palagonite, with rare crystals of plagioclase and olivine and sparse lithic fragments. The tuffs are envisaged as being derived from a nearby pyroclastic source. The Hidden Lake tuffs are less shardic with an increase in the proportions of non-cuspate, blocky shards, lithic and crystal fragments indicating derivation from a mixed hyaloclastic and pyroclastic source area. Olivine/plagioclase crystal ratios from the two localities studied reflect the variations in the proportions of olivine-phyric and plagioclase-phyric lavas present at the two localities.

Detailed facies analysis suggests deposition within shallow subaqueous delta front environments fed by glacio-fluvial streams. The petrographic variation observed implies localized erosion and deposition within small unconnected intravolcanic basins. Ophiuroids from the Hidden Lake locality imply a marine environment. However, no faunal evidence is available for the Tail Island sequence.

INTRODUCTION

Fine-grained tuffs form a small part of the James Ross Island Volcanic Group (JRIVG) exposed on James Ross Island and surrounding islands, northern Antarctic Peninsula (Fig. 1). The JRIVG is a thick sequence of hyaloclastite breccias and olivine basalt lava flows, with minor pyroclastic tuffs, tuffaceous conglomerates and tillites. Nelson (1975) indicated that the group consisted of a series of hyaloclastite deltas, developed in a submarine environment, with interstratified subaerial lava flows formed after delta progradation. They are late Cenozoic in age, ranging from 7 Ma on James Ross Island to 300000 yrs on Paulet Island (Baker and others, 1977). Their genesis is believed to relate to post-subduction, ensialic extension east of Trinity Peninsula, following virtual cessation of subduction along the South Shetland trench 4 Ma ago and the subsequent opening of Bransfield Strait (Barker, 1976). The JRIVG unconformably overlies a 5000-m thick sequence of mid- to Upper Cretaceous sediments, deposited within a back-arc basin to the east of the present-day Antarctic Peninsula (Farquharson and others, 1984).

Distinctive fine-grained tuffs showing similar lithofacies occur in two localities within the JRIVG, at north-east Tail Island (57° 35′ W, 63° 40′ S) and at Hidden

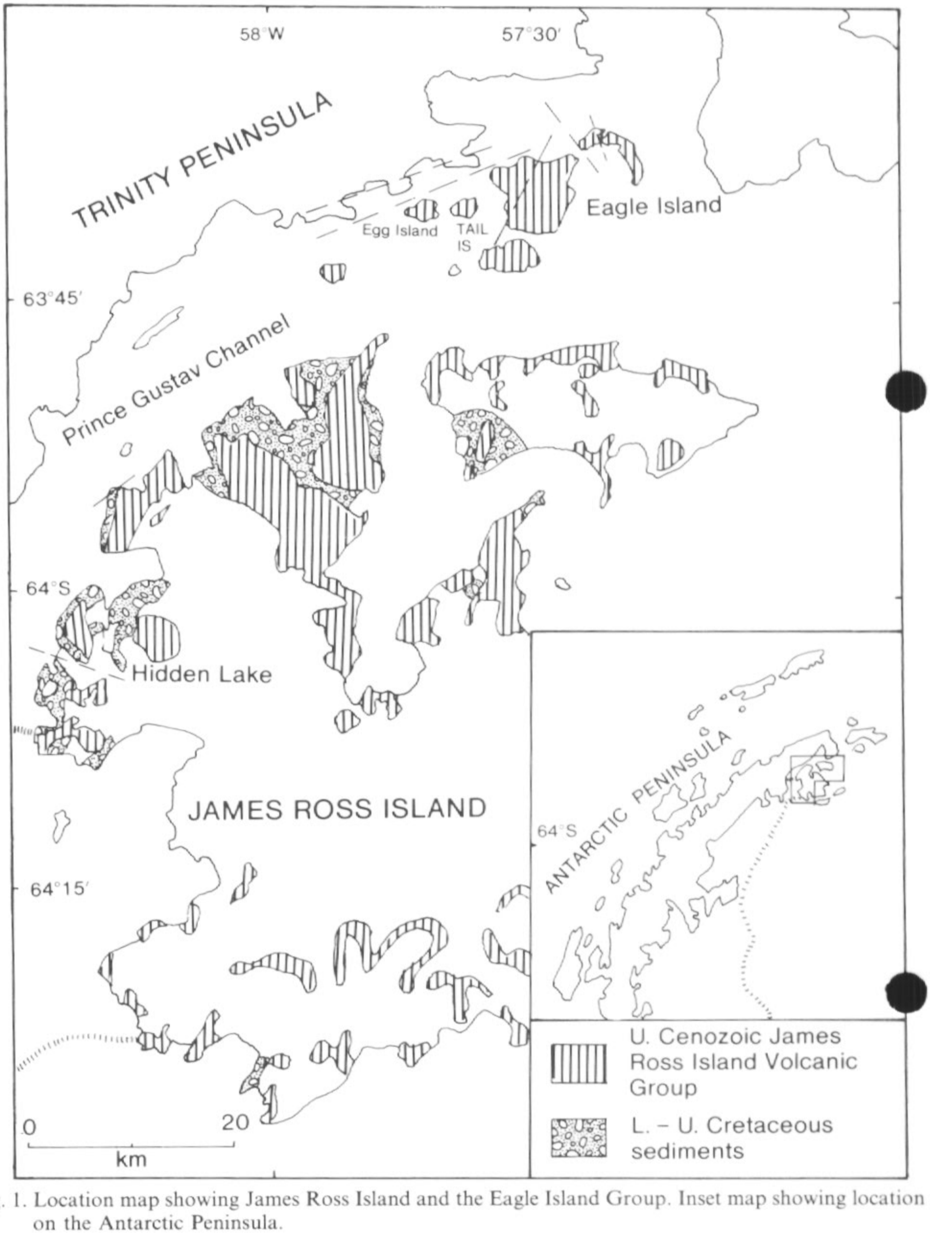

Fig. 1. Location map showing James Ross Island and the Eagle Island Group. Inset map showing location on the Antarctic Peninsula.

Lake, James Ross Island (58° 21′ W, 64° 02′ S) (Fig. 1). Both localities have been visited previously (Bibby, 1966; Nelson, 1975), but more detailed examination during the 1985–86 field season permits re-evaluation of these rocks.

Tail Island

Fine-grained tuffs form a small, prominent yellow–brown cliff, approximately 60 m above sea level on north-east Tail Island. The lower 2 m of the cliff are composed

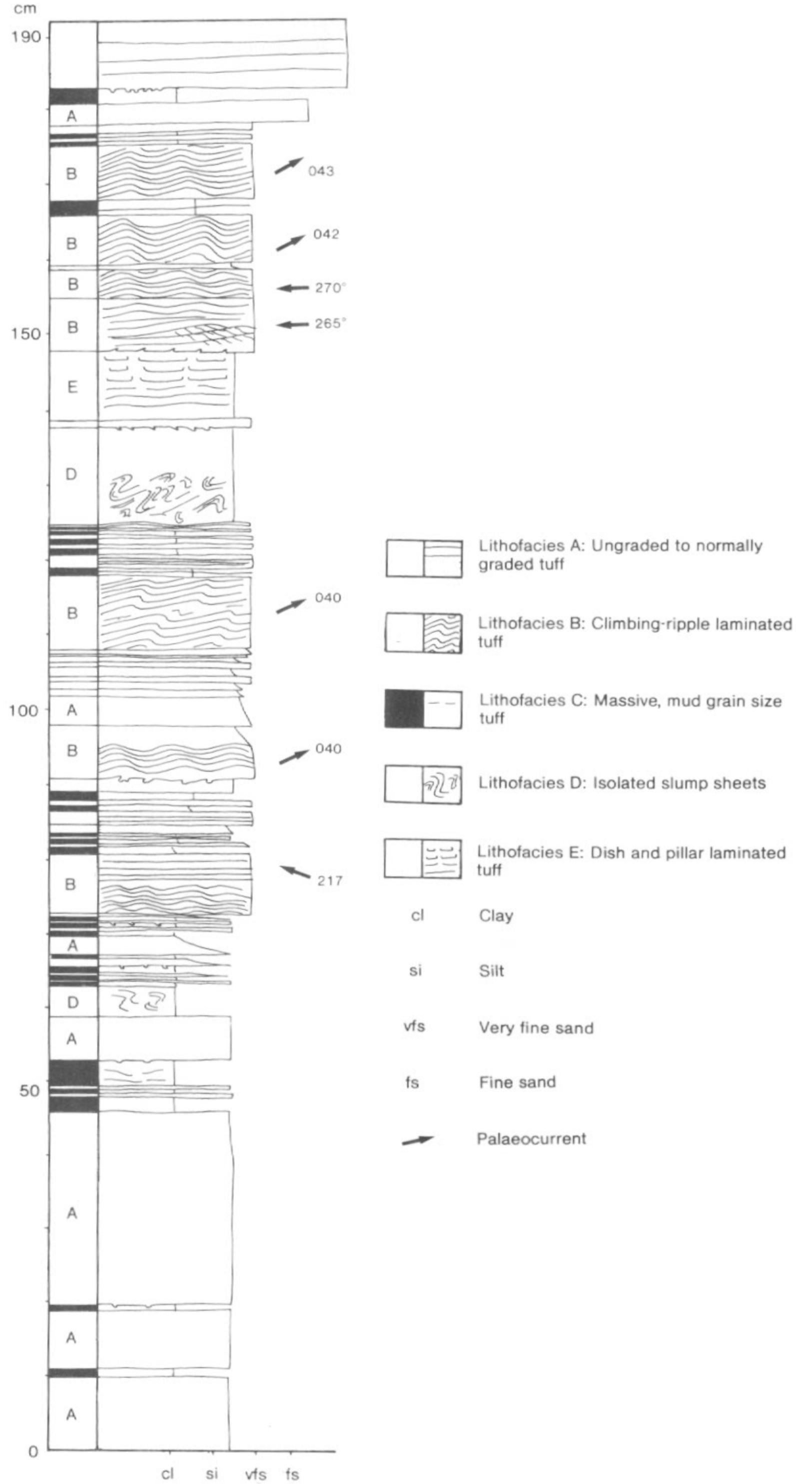

Fig. 2. Detailed section through the fine-grained tuffs, north-east Tail Island.

of thinly bedded, fine-grained tuffs (Fig. 2), the base of which is not exposed. They are sharply overlain by a single cross set, 1 m thick, composed of coarse-grained palagonite tuff, which is, in turn, erosionally overlain by palagonite breccia. Only the thinly bedded tuffs will be described in this paper.

The tuffs can be divided into five lithofacies on the basis of sediment grain size and sedimentary structures (Fig. 2). Grain size is described following the Wentworth scale (Collinson and Thompson, 1982), rather than the twofold subdivision proposed by Fisher and Schmincke (1984).

Lithofacies A: ungraded to normally graded tuffs

Lithofacies A, forming 50 % of the beds, is composed of yellow–brown, silt to very fine sand-grain-size tuffs. Of the beds measured, 68 % are ungraded, whilst 32 % show normal grading. Most beds are massive, rarely showing planar lamination. Lower bed boundaries are sharp, commonly showing loading, whilst upper bed contacts are sharp planar, with bed thickness ranging between 0.5 and 26 cm, with an average of 2 cm.

Lithofacies A represents rapid deposition out of suspension, from high concentration currents. The ungraded beds imply either a constant current velocity and sediment input, or an absence of finer-grained material within the current. The normally graded beds represent deposition from suspension in a decelerating current. The beds may represent the T_a and T_{ab} subdivisions of turbidites, or the deposits of sediment grain flows.

Lithofacies B: climbing-ripple laminated tuffs

Lithofacies B, forming 8 % of the beds measured, is composed of yellow–brown, ungraded to rarely normally graded, very fine sand grade tuffs. All beds show well-developed climbing-ripple lamination (Fig. 3). Individual climbing-ripple sets are

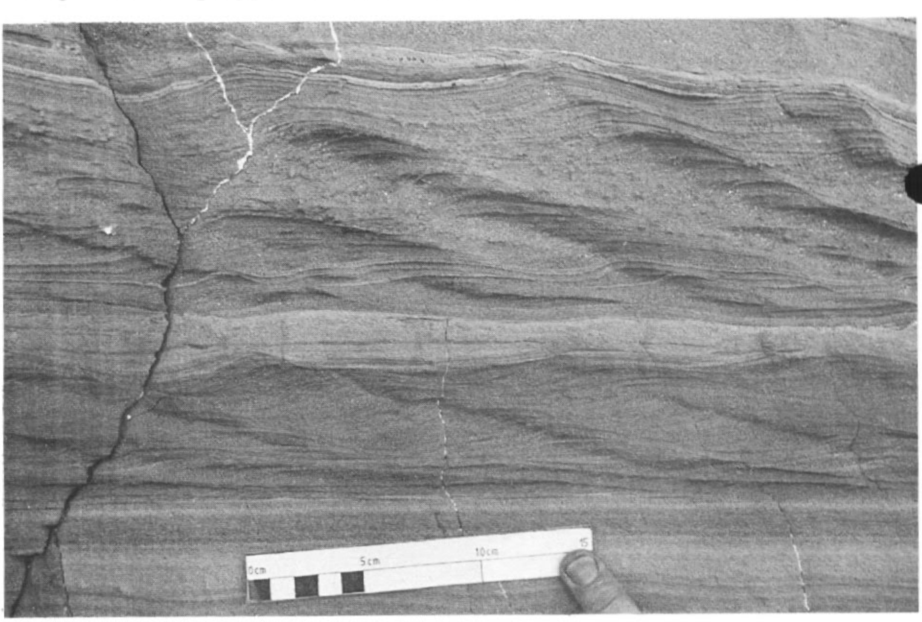

Fig. 3. Lithofacies B, showing type II climbing-ripple lamination (after Allen, 1973). Palaeocurrent from right to left. Scale = 15 cm.

between 3 and 4.5 cm thick, with cosets up to 10 cm thick. Most climbing-ripple sets show stoss-side preservation and a uniform angle of climb between 15° and 23° (type II climbing-ripple lamination of Allen, 1973). Climbing ripples with stoss-side preservation and a decreasing rate of climb, and climbing ripples showing no stoss-side preservation also occur, but are only represented by single beds (type III climbing-ripple lamination of Allen, 1973). A single bed shows a transition from climbing-ripple to planar lamination. Bed thickness varies between 7 and 11 cm, with an average of 9 cm. Lower-bed contacts are sharp planar, with rare loading. Upper-bed contacts are commonly gradational, or are draped by lithofacies C.

Lithofacies B represents rapid deposition under lower flow regime conditions, with sedimentation from suspension with ripples forming by tractional effects at the fluid-sediment boundary (Ashley and others, 1982). The climbing-ripple morphology is controlled by a continuum of processes (Ashley and others, 1982). At low current [illegible]ocities and high net aggradation rates, type II climbing ripples are deposited. With increasing current velocity and a decreasing net aggradation rate, type III climbing ripples are deposited. The transition from climbing-ripple to planar lamination represents low aggradation rates and a high current velocity, with a transfer from lower to upper flow regime conditions.

Lithofacies C: massive to wavy laminated silt–mud tuffs

Lithofacies C, representing 37% of the sequence, is composed of yellow–brown, massive to weakly wavy-laminated, mud to silty-mud grain-size tuffs. Bed thicknesses range between 0.5 and 3.5 cm, and average 1 cm. Most bed contracts are sharp planar. In some instances, lithofacies C drapes climbing-ripple laminated tuffs of lithofacies B, maintaining a constant bed thickness over both ripple crests and troughs.

This lithofacies either represents slow sedimentation from suspension, or the T_e division of turbidity currents.

Lithofacies D: isolated slump sheets

Lithofacies D is represented by two beds, which form 3% of the succession. The beds represent isolated synsedimentary slump sheets, 4 cm and 13 cm thick (Fig. 4). [illegible]d bases are sharp, dominantly planar, whilst upper bed contacts are gradational. The beds are composed of detached folds of lithofacies A, supported within a silty-sand grain-sized tuff matrix (Fig. 5). Fold geometry is highly variable from small, open box folds, approximately 4 cm across, to tight, isoclinally folded, stacked sheets up to 10 cm long (Fig. 5). Fold axes from the isoclinally folded sheets show a weak preferred orientation, north-east–south-west.

Lithofacies D represents redeposited slump sheets. Nelson (1975) suggested that slumping was induced by a volcani-seismic disturbance. Although this may have triggered the slumping, pore fluid overpressure, due to compaction of the rapidly deposited sediments, is likely to have led to sediment instability. This small-scale slumping could therefore easily be triggered by a variety of mechanisms, including slope instability due to the rapid sedimentation rate, rather than a volcani-seismic disturbance.

Lithofacies E: interlaminated very fine sand to mud tuffs

Lithofacies E is represented by only one bed, 9 cm thick, representing 2% of the exposed section. The bed base is sharp planar, with a flame-cast upper bed contact.

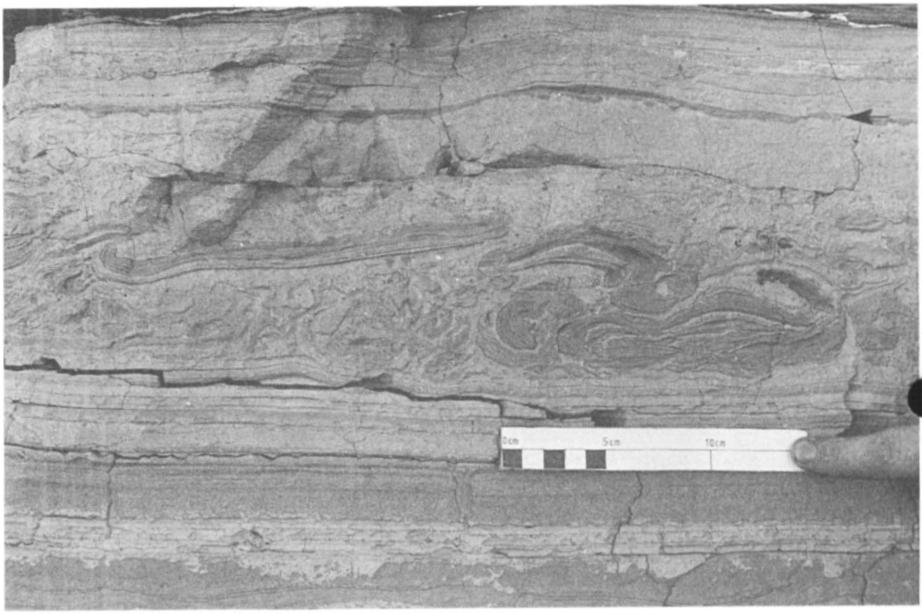

Fig. 4. Slump sheet (lithofacies D) showing isolated slump folds within a silty-sand grain-size tuff matrix. Note the thin bed of lithofacies A (arrowed), showing well-developed loading. Scale = 15 cm.

Individual flame structures are small, up to 5 mm high. The lower 6 cm of the bed is composed of massive, yellow–brown silty–very fine sand-grade tuff. This grades up into 3 cm of interlaminated yellow–brown silty–very fine sand-grain size tuff and weakly wavy laminated darker brown mud-grain size laminae, 1–2 mm thick. Within the lower part of this unit the thin mud-grade tuff laminae are laterally continuous, whilst those forming the upper part of the bed pass laterally into dish and pillar structures (Fig. 5). Individual dish structures are between 0.5 and 2 cm wide, weakly concave, with sharply upturned margins forming the pillars, up to 0.5 cm long.

The silt to very fine sand-grade laminae within this lithofacies are interpreted as having been deposited rapidly out of suspension from sediment-laden currents. T[illegible] thin interbedded mud tuff laminae represent lower current-energy deposition from suspension. Following deposition, compaction and dewatering led to the lateral migration of pore fluid to points where continued vertical fluid escape was possible, as envisaged by Lowe and Lopiccolo (1974). Vertical fluid movement continued until deposition of the overlying bed. The presence of dish and pillar structures implies rapid discontinuous deposition.

HIDDEN LAKE, JAMES ROSS ISLAND

A similar sequence of fine-grained tuffs is exposed 0.5 km west of Hidden Lake, on James Ross Island (Fig. 1). The tuffs occur at the base of the JRIVG and unconformably overlie Upper Cretaceous sediments of the Marambio Group (Ineson and others, 1986). The tuffs are 5 m thick, and are sharply overlain by a thick sequence of palagonite breccias. Although the sequence is less well exposed than that at Tail Island, the same lithofacies are present. Lithofacies A, B and C commonly occur, with rare weakly slumped horizons. Climbing-ripple laminated tuffs (lithofacies

Fig. 5. Synsedimentary slump sheet (lithofacies D) showing stacked isoclinal sheets (Area 1). Lithofacies E showing well-developed dish and pillar structures (Area 2). Lithofacies B, climbing ripple lamination (Area 3). Note reversal of palaeocurrents (arrowed).

B) dominate the succession. Bibby (1966) collected some 30 ophiuroid impressions from this locality, and further specimens were collected during the 1985–86 field season. In addition a single echinoid was collected by J. R. Ineson during the 1982–83 field season (J. R. Ineson, pers. comm., 1986). Although limited, this fauna implies a marine environment of deposition for the Hidden Lake tuffs. No faunal evidence is available from the Tail Island locality.

PALAEOCURRENTS

Limited palaeocurrent data, obtained from climbing-ripple lamination (lithofacies B), at the Tail Island locality suggests a palaeocurrent towards the south-west (Fig. 5). However, the palaeocurrent data are variable, with two beds giving a palaeocurrent towards the north-east. Nelson (1975) stated that the palaeocurrent data from this locality indicated deposition within a basin centred between the Egg Island and Ea[illegible] Island volcanic centres. The palaeocurrent data suggest that transportation was dominantly towards the south-west, in the direction of the Egg Island volcanic centre. No palaeocurrent data were obtained from the Hidden Lake locality.

Palaeoslope data obtained from the slump sheets (lithofacies D) are ambiguous. Nelson (1975) described an increase in the degree of disturbance of the slump sheets towards the south-west, implying derivation from the north-east. No detailed measurements of fold axes, or fold orientation, have been obtained although the available data suggest derivation from the south-west.

PETROGRAPHY

The grains forming the tuffs are composed of three types, glass shards, crystals (olivine and plagioclase) and lithic fragments, and are set in a fine-grained matrix.

Glass shards

On Tail Island the tuff fragments are composed of 93% glass shards, 2% lithics and 5% crystal fragments. The shards are cuspate, with relict vesicle walls forming their margins, often showing alteration to palagonite. These shards are pyroclastic in origin, formed by the explosive disruption of a vesiculating lava. Despite alterati[illegible] to palagonite, they retain pristine outline, indicating little secondary transportati[illegible] with deposition in a proximal site. The shards range in size from 0.25 to 2.0 mm, whilst crystal and lithic fragments are larger, being up to 6 mm across. The abundance of pyroclastic shards suggests the occurrence of periodic pyroclastic eruptions within the area.

In contrast, the tuffs at Hidden Lake have a rather different composition, despite their sedimentological similarity to the Tail Island deposits. These tuffs contain only 72% vitric fragments and an increase in the crystal fraction. Hyaloclastic shards lacking the cuspate and vesicular walls occur admixed with pyroclastic shards. The hyaloclastic shards resulted from more passive granulation of hot lava in water, leaving a blocky appearance with straight edges and a more regular shape. Within the deposit individual laminae are defined by variations in the proportion of hyaloclastic to pyroclastic shards, with a maximum of 30% hyaloclastic shards. The maximum grain size of the Hidden Lake tuffs is larger than that at Tail Island, with shards up to 4 mm across and a concomitant increase in the size of crystal and lithic fragments.

The Hidden Lake tuffs were derived from a mixed-source area of both pyroclastic and hyaloclastic deposits. The pristine shard outlines again suggest negligible transport. The shards show little alteration, being preserved as clear, pale yellow sideromelane.

It is unclear petrographically whether the palagonitization of the shards occurred immediately after eruption, or during redeposition in a subaqueous environment. It has been shown that palagonitization of basaltic glass occurs mostly at ambient temperatures during weathering and diagenesis (Fisher and Schmincke, 1984). Alteration of the Tail Island shards probably occurred during reworking and deposition. Incipient alteration may have started on eruption due to magmatic or ground water. However, the total absence of shard palagonitization at Hidden Lake suggests that this is unlikely.

[illegible]ystal fragments

Crystal fragments of olivine and plagioclase represent the phenocryst phases present in the ascending magmas of the JRIVG. Their presence in all types of JRIVG rocks, including the flow lavas and palagonite breccias, suggests that all magmas were olivine-phyric, and sometimes plagioclase-phyric. The two minerals occur in roughly equal fractions in the Tail Island tuffs, with 2% olivine and 3% plagioclase. This is consistent with lava samples from the Tail Island area, which contain more plagioclase phenocrysts than lavas on James Ross Island. In comparison with Tail Island, the Hidden Lake tuffs show a greater proportion of crystals, with the crystal fraction being dominated by olivine. This reflects the greater amount of olivine-only phyric lavas on James Ross Island.

Crystals are commonly encased in a rim of glass, suggesting that adhesion between the lava and the surface of the phenocrysts was sufficient to resist the disruptive force of vesiculation and shard production. This has been documented in other pyroclastic rocks (e.g. Fisher and Schmincke, 1984).

Olivine compositions from the larger grains are forsteritic with estimated 2 Vs: 85–90° ($Fo_{(85-96)}$). This is consistent with olivine phenocryst compositions in the lavas and other members of the JRIVG.

Lithic fragments

Lithic fragments constitute small proportions of the tuffs at both localities and they are consistently co-magmatic with the shards at both localities. The lithic fragments are composed of apparently identical sideromelane glass as the shards, and contain crystals of the same composition as the solitary crystals. They are frequently vesicular and at Hidden Lake they show compaction textures in the form of faint colour banding and streaked or elongated vesicles. They are classified as lapilli, some showing complete palagonitization, especially on Tail Island. Rare fiamme up to 4 mm long occur in the Hidden Lake tuffs. In addition, these deposits contain a few fragments of dark brown, tachylitic glass which may be associated with the vesiculating margins of pillows.

Matrix

The nature and proportion of matrix is variable between individual laminae. These vary between those showing open pore spaces to those in which original pore space is totally filled with varying proportions of clay, zeolite and carbonate.

The shards in the Tail Island tuffs are altered to orange–brown palagonite. They show concentric zoning and some have a turbid or opaque interior. The colour of the shards is related to the degree of alteration, ranging from the pale yellow of pristine sideromelane to dark golden brown with increased alteration. Although the Hidden Lake tuffs are not palagonitized, some shards in them show surficial alteration. The presence of abundant pristine shards at both localities suggests that the interstitial clay is allogenic.

Zeolite, possibly phillipsite (Nelson, 1975), commonly occurs within the matrix. Rarely, large crystals of zeolite occur recrystallized within pore spaces. Carbonate is also present in large pore spaces and as secondary veins within both the Hidden Lake and Tail Island tuffs, being more abundant in the former. It is commonly found infilling vesicles within lithic fragments and preferentially crystallizing around olivines. In this setting it is associated with chlorite (Nelson, 1975).

REGIONAL SIGNIFICANCE

Although the fine-grained tuffs described here form a small part of the JRIVG, they have an important bearing on any palaeogeographical interpretation. Nelson (1975) suggested that the JRIVG was formed as a series of subaqueous hyaloclastite deltas, and subaerial lava flows formed following delta progradation. Thus formation was envisaged within both subaqueous and subaerial environments, although a subglacial setting was also considered possible. The discovery of tillites separating the JRIVG from the Upper Cretaceous sediments at some localities (British Antarctic Survey, 1983, p. 28), along with the presence of JRIVG material within the tillites, indicates the presence of significant glaciation within the James Ross Island area prior to, and contemporaneous with the formation of the JRIVG (Nelson, 1975; Sykes, 1986). A subglacial setting for part of the JRIVG does, therefore, seem likely and much of the marginal sedimentation may be proglacial in character. A similar subglacial setting has been suggested for many of the Cenozoic alkali-basalt volcanics from the Antarctic Peninsula (Burn and Thomson, 1981; M. J. Hole, pers. comm., 1987).

Detailed facies analysis of these fine-grained tuffs suggests that deposition was dominantly from suspension. Rapid depositional rates are shown by the presence of climbing-ripple lamination and common load-casts. Both lithofacies D and E are a result of rapid deposition, with small-scale slump sheets (lithofacies D), triggered by over-pressure during de-watering and small-scale dish and pillar structures (lithofacies E), formed by lateral and vertical fluid migration during de-watering.

Similar sequences of lithofacies have been described from a variety of glacio-fluvial and glacio-lacustrine environments (Jopling and Walker, 1968; Banerjee and McDonald, 1975; Gustavson and others, 1975; Drewry, 1986). Sequences of climbing-ripple laminated and planar laminated fine-grained sediments, along with turbidites and slumps, have been described from delta-front environments, where a supra- or subglacial stream has entered a standing body of water (Banerjee and McDonald, 1975; Rust and Romanelli, 1975). Jopling and Walker (1968) envisaged climbing-ripple laminated sandstones being deposited out of suspension from density underflows of sediment-laden water entering a glacial lake. Similar sequences of lithofacies can be deposited within glacial meltwater channels, but are less likely to be preserved (Drewry, 1986).

At Hidden Lake the presence of both ophiuroids and echinoids supports a marine environment of deposition, with a deltaic body building out into a shallow marine setting. The absence of faunal evidence from the Tail Island locality may suggest that deposition was within either a non-marine environment or a marine proglacial delta-front environment, in which only a limited fauna with a low preservation potential would be expected.

The two areas are petrographically distinct. The Tail Island sequence is dominantly composed of cuspate pyroclastic glass shards, along with rare plagioclase, olivine and lithic fragments. These are envisaged as being derived from a proximal source area. The tuffs at Hidden Lake show an admixture of both cuspate pyroclastic glass shards and more blocky hyaloclastic shards, along with olivine, rare plagioclase and lithic fragments. These tuffs are thought to have been derived from a mixed hyaloclastic/pyroclastic source area. However, both pyroclastic and hyaloclastic shards may be produced, along with pillows, within a single volcanic sequence, as seen on James Ross Island and on Beethoven Peninsula, Alexander Island (M. J. Hole, pers. comm., 1987). A more reliable indicator of provenance may be the ratios of olivine to plagioclase crystals within the tuffs. At Tail Island the olivine:plagioclase ratio is 0.7, whereas at Hidden Lake it is 5.5. This reflects the near-equal proportions of plagioclase-phyric and olivine-phyric lavas within the Tail Island area, whereas on James Ross Island the volcanics are dominantly olivine-only phyric. The variation in the phenocryst phases, along with the unmodified shard outlines and variations in type and abundance of shards, suggests localized reworking and deposition within unconnected basins, without intermixing between the two localities.

Deposition of the fine-grained tuffs is therefore envisaged within small, unconnected basins, in delta front environments, fed by glacio-fluvial systems. Unconsolidated contemporaneous pyroclastic deposits were reworked and deposited rapidly, dominantly from suspension. Deposition was within a marine environment at Hidden Lake. The complex interaction of volcanic, glacial and marine processes has led to the formation of the fine-grained tuffs, and it seems likely that similar interactions account for much of the formation of the JRIVG.

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REFERENCES

ALLEN, J. R. L. 1973. A classification of climbing ripple cross lamination. *Journal of the Geological Society of London*, **129**, 537–41.

ASHLEY, G. M., SOUTHARD, J. B. *and* BOOTHROYD, J. C. 1982. Deposition of climbing ripple beds: a flume simulation. *Sedimentology*, **29**, 67–79.

BAKER, P. E., BUCKLEY, F. *and* REX, D. C. 1977. Cenozoic volcanism in the Antarctic. *Philosophical Transactions of the Royal Society of London*, Series B, **279**, 131–42.

BANERJEE, I. *and* MCDONALD, B. C. 1975. Nature of Esker sedimentation. (*In* JOPLING, A. V. *and* MCDONALD, B. C., *eds. Glaciofluvial and glaciolacustrine deltas.* Society of Economic Palaeontologists and Mineralogists, Special Publication No. 23, 132–54.)

BARKER, P. F. 1976. The tectonic framework of Cenozoic volcanism in the Scotia Sea region, a review. (*In* GONZALEZ-FERRÁN, O. *ed. Proceedings of the Symposium on Andean and Antarctic volcanology problems.* Santiago, Chile, IAVCEI, 330–46.)

BIBBY, J. S. 1966. The stratigraphy of part of north-east Graham Land and the James Ross Island Group. *British Antarctic Survey Scientific Reports*, No. 53, 37 pp.

BRITISH ANTARCTIC SURVEY. 1983. *British Antarctic Survey Annual Report 1982–83*. Cambridge, British Antarctic Survey, 63 pp.

BURN, R. W. *and* THOMSON, M. R. A. 1981. Late Cenozoic tillites associated with intraglacial volcanic rocks, Lesser Antarctica. (*In* HAMBREY, M. J. *and* HARLAND, W. B. *eds. Pre-Pleistocene tillites: a record of earth's glacial history*. Project 38 of the International Geological Correlation Programme. Cambridge, Cambridge University Press, 199–203.)

COLLINSON, J. D. *and* THOMSON, D. B. 1982. *Sedimentary structures*. London, George Allen and Unwin Ltd, 194 pp.

DREWRY, D. 1986. *Glacial geologic processes*. London, Edward Arnold Ltd, 276 pp.

FARQUHARSON, G. W., HAMER, R. D. *and* INESON, J. R. 1984. Proximal volcaniclastic sedimentation in a Cretaceous back-arc basin, northern Antarctic Peninsula. (*In* KOKELAAR, B. P. *and* HOWELLS, M. F. *eds. Marginal basin geology*. Geological Society of London, Special Publication No. 16, 216–29.)

FISHER, R. V. *and* SCHMINCKE, H. U. 1984. *Pyroclastic rocks*. Berlin, Springer-Verlag, 472 pp.

GUSTAVSON, T. C., ASHLEY, G. M. *and* BOOTHROYD, J. C. 1975. Depositional sequences in glaciolacustri[illegible] deltas. (*In* JOPLING, A. V. *and* MCDONALD, B. C. *eds. Glaciofluvial and glaciolacustrine deltas*. Society of Economic Palaeontologists and Mineralogists, Special Publication No. 23, 264–80.)

INESON, J. R., CRAME, J. A. *and* THOMSON M. R. A. 1986. Lithostratigraphy of the Cretaceous strata of west James Ross Island, Antarctica. *Cretaceous Research*, **7**, 141–59.

JOPLING, A. V. *and* WALKER, R. G. 1968. Morphology and origin of ripple-drift cross-lamination, with examples from the Pleistocene of Massachusetts. *Journal of Sedimentary Petrology*, **38**, 971–84.

LOWE, D. R. *and* LOPICCOLO, R. D. 1974. The characteristics and origins of dish and pillar structures. *Journal of Sedimentary Petrology*, **44**, 484–501.

NELSON, P. H. H. 1975. The James Ross Island Volcanic Group of north-east Graham Land. *British Antarctic Survey Scientific Reports*, No. 54, 62 pp.

RUST, B. R. *and* ROMANELLI, R. 1975. Late Quaternary subaqueous outwash deposits near Ottawa, Canada. (*In* JOPLING, A. V. *and* MCDONALD, B. C. *eds. Glaciofluvial and glaciolacustrine deltas*. Society of Economic Palaeontologists and Mineralogists, Special Publication No. 23, 177–92.)

SYKES, M. A. 1986. Volcanic studies on James Ross Island, 1985–86. *British Antarctic Survey Reports*, R/1985–86/G5. [Unpublished.]