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Lithostratigraphy of Miocene–Recent, alkaline volcanic fields in the Antarctic Peninsula and eastern Ellsworth Land

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Abstract: Miocene–Recent alkaline volcanic rocks form numerous outcrops scattered widely throughout the Antarctic Peninsula and eastern Ellsworth Land. They occur mainly as short-lived (typically 1–2 million years) monogenetic volcanic fields but include a large outcrop area in northern Antarctic Peninsula which includes several substantial polygenetic shield volcanoes that were erupted over a 10 million year period (the James Ross Island Volcanic Group (JRIVG)). As a whole, the outcrops are of considerable importance for our understanding of the kinematic, petrological and palaeoenvironmental evolution of the region during the late Cenozoic. Until now, there has been no formal stratigraphical framework for the volcanism. Knowledge of the polygenetic JRIVG is still relatively poor, whereas a unifying lithostratigraphy is now possible for the monogenetic volcanic fields. For the latter, two new volcanic groups and twelve formations are defined, together with descriptions of the type sections. The volcanic fields (both polygenetic and monogenetic) vary in area from *c.* 1 to 4500 km^2, and aeromagnetic data suggest that one may exceed 7 000 km^2. The rocks are divisible into two contrasting petrological 'series', comprising basanites–phonotephrites and alkali basalts–tholeiites. The JRIVG is dominated by alkali basalts–tholeiites but also contains rare basanites, and phonotephrite–tephriphonolite compositions occur in minor pegmatitic segregations in sills. By contrast, in the monogenetic volcanic fields, basanites–phonotephrites generally form the older outcrops (mainly 15–5.4 Ma) and alkali basalts–tholeiites the younger outcrops (4(?)–<1 Ma). Throughout the region, erupted volumes of alkali basalts–tholeiites were an order of magnitude greater, at least, than those of basanite–phonotephrite compositions. Interpretation of the lithofacies indicates varied Miocene–Recent palaeoenvironments, including eruption and deposition in a marine setting, and beneath Alpine valley glaciers and ice sheets. Former ice sheets several hundred metres thick, and fluctuating ice surface elevations, which were generally higher during the eruptive periods than at present, can also be demonstrated.

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Key words: alkaline volcanism, Antarctic Peninsula, lithostratigraphy, monogenetic, palaeoenvironment, polygenetic, volcanic field

Introduction

The Antarctic Peninsula region has been a major continental consuming plate margin for most of Mesozoic and Cenozoic time, with a complicated history of plate interactions (e.g. Grunow 1993, Storey *et al.* 1996, McCarron & Larter 1998, McCarron & Smellie 1998). Subduction ceased progressively northward during the Cenozoic, as offset sections of a spreading centre collided with the trench (Barker 1982) except at the South Shetland trench, where it continued at a very slow rate (Larter 1991). Each section of downgoing slab is thought to have become detached along the former spreading axis, resulting in the development of "no-slab windows" and the generation of small-volume asthenospheric melts with alkaline compositions (Hole *et al.* 1991a, 1993, 1995, Hole & Saunders 1996). These were erupted throughout the Antarctic Peninsula, forming small, short-lived monogenetic volcanic fields (Fig. 1; Smellie 1987, Smellie *et al.* 1988, Hole 1988, 1990a). Conversely, where subduction continued (as at the South Shetland trench), slab window development did not occur and plume-related alkaline magmas were erupted in the back-arc region, forming large polygenetic shield volcanoes with multiple satellite centres and a prolonged history of eruptions extending over 10 million years (James Ross Island area; Smellie 1987, Sykes 1988a, Hole *et al.* 1995). Rapid access to the surface for the alkaline magmas was facilitated by the presence of block faults (Smellie 1987). Although the faulting is related to regional extension, Hole *et al.* (1995) demonstrated that major extension has probably not occurred. The alkaline volcanism was coincident with glacial conditions in the region and many of the volcanic outcrops in the region show evidence for interaction with glacial meltwater (e.g. Smellie *et al.* 1993, Smellie & Skilling 1994, Smellie & Hole 1997).

This paper summarizes the principal results of recent research into the alkaline volcanic fields in the Antarctic Peninsula and eastern Ellsworth Land and uses the information to erect the first rigorous lithostratigraphy. Outcrops in the South Shetland Islands, included in a previous review of alkaline volcanism in the region (Smellie *et al.* 1988) are excluded here; despite some alkaline characteristics (principally high sodium contents), they are otherwise "normal" calc-alkaline and tholeiitic basalts probably related to slow subduction at the South Shetland trench (unpublished information of the author). With the exception of the James Ross Island Volcanic Group (JRIVG), all of the stratigraphical names used in this paper are new. The outcrops discussed are an important source of information on the kinematic, petrological and palaeoenvironmental evolution of the Antarctic Peninsula region during the late Cenozoic.

Systematic descriptions of the volcanic lithostratigraphy

Classical lithostratigraphical procedures, which are based predominantly on sedimentary formations, can be difficult to apply to volcanic outcrops (e.g. Ricci *et al.* 1993). According to Whittaker *et al.* (1991), defined formations "should have or should once have had physical continuity". Sedimentary formations are also normally limited to a single sedimentary basin and names should not normally be extended to adjacent basins. These conditions are violated by many volcanic fields in which large and small volumes of erupted magma are clustered around multiple discrete volcanic centres, which may or may not overlap laterally. Terrestrial volcanic fields may also form no obvious part of a sedimentary basin. In this paper it is proposed that volcanic fields can be regarded as the volcanic equivalent of sedimentary basins. Thus, the presence of discrete volcanic fields, separated geographically and not overlapping, can be used as a principal criterion for identifying and delimiting volcanic formations. Thereafter, normal rules for distinguishing lithostratigraphical units are applied; for example, presence of bounding unconformities and lithological distinctiveness within each volcanic field (cf. Whittaker *et al.* 1991). Using these criteria, the group status of the volcanic and sedimentary JRIVG is reaffirmed, and two new groups containing twelve new formations are identified. Distinguishing characteristics of the different rock units are summarised in Table I. The division into rock groups broadly follows LeMasurier & Thomson (1990), who divided the Antarctic Peninsula region into volcanic provinces. Outcrops of the two new groups (Seal Nunataks and Bellingshausen Sea groups) are separated geographically by > 500 km and they are situated in the tectonically contrasting fore- and back-arc regions of the former Antarctic Peninsula magmatic arc. The Merrick Mountains outcrops are unusual for the region in being situated within the Mesozoic arc terrain. They were grouped by LeMasurier & Thomson (1990) within the Bellingshausen Sea Volcanic Province and that association is continued here. Compositional names of the lavas are after Le Bas *et al.* (1986).

James Ross Island Volcanic Group

Name and history: Originally called the Ross Island Formation by Andersson (1906), who conducted the earliest studies. The name was changed to James Ross Island Volcanics by Adie (1953) and, finally, James Ross Island Volcanic Group (JRIVG) by Nelson (1975). However, constituent formations were not defined. Reconnaissance studies of parts of the sequence were made by British geologists (Bibby 1966, Baker *et al.* 1977, and unpublished Falklands Islands Dependencies Survey reports by Croft 1947 and Stoneley 1952). The only geographically comprehensive investigation was by Nelson (1975), who also published a geological map of the entire group. The most detailed study, including lithofacies descriptions, isotopic (K–Ar) ages and a large database of chemical analyses, was by Sykes (1988a, 1988b), although that work was confined to outcrops mainly in northern James Ross Island.

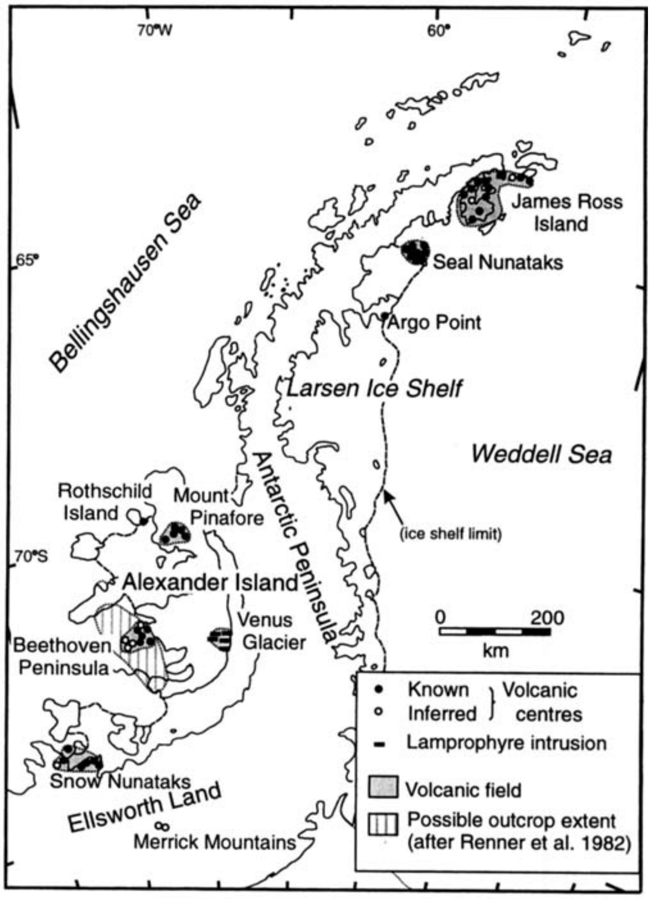

Fig. 1. Sketch map of the Antarctic Peninsula and eastern Ellsworth Land, showing the location and distribution of the alkaline volcanic fields discussed in this paper.

Distribution: James Ross Island, Vega Island and several smaller islands nearby in Prince Gustav Channel and Antarctic Sound (Fig. 2), southern Dundee Island and Paulet Island, Tabarin Peninsula and Cain and Abel nunataks (Graham Land). A related dyke also crops out on Snow Hill Island (Massabie & Morelli 1977, Malagnino 1978).

Subdivision: Nelson (1975) divided the JRIVG into five volcanic phases, each dominated by a lava unit and cogenetic palagonite-altered breccia, and associated sedimentary strata.

Table I. Summary lithostratigraphy, principal characteristics, age and interpretation of Miocene–Recent alkaline volcanic fields in the Antarctic Peninsula and eastern Ellsworth Land.

Volcanic group	Formation	Distinguishing lithological characteristics	Exposed thickness	Age (Ma)	Interpretation
James Ross Island*	Hobbs Glacier**	Matrix-supported conglomerate to pebbly mudstone (diamictite), locally fossiliferous, and laminated tuffaceous sandstone	Mainly < 4 m but possibly up to 25 m	9.9 (one locality)	Glacimarine sedimentation close to ice grounding line (diamictite/conglomerate); periglacial delta-front (sandstones)
	Cockburn Island	Clast-supported conglomerate, pebbly sandstone and medium to coarse sandstone; fossiliferous	> 10 m	3–2.8	Shallow marine (< 100 m); interglacial
	(unnamed volcanic strata)	Multiple superimposed lava-hyaloclastite breccia couplets; rare pillow lava, lapillistone; thick lapilli tuff outcrops	Up to 600 m	<= 10; mainly < 7	Multiple subaerial and subaqueous eruptions; englacial and marine
Seal Nunataks	Bruce Nunatak	Multiple and single large dykes, pillow lava, gravelly sandstone	Up to 200 m	4–< 1	Entirely subaqueous; pillow volcanoes and tuff cones (englacial)
	Christensen Nunatak	Compound lava, lapillistone, lapilli-tuff; minor agglutinate	Up to 100 m	0.7 (one locality)	Mainly cinder cone remnants; subaerial
	Argo Point	Interbedded lava and scoria	175 m	0.8–1.6	Degraded cinder cone; subaerial
Bellingshausen Sea	Mount Pinafore	Interbedded volcanic (lava, hyaloclastite breccia) and volcaniclastic (sandstone, conglomerate) lithofacies.	60–90 m	7.7–5.4	Valley-confined, subglacial ‘outflow facies’
	Hornpipe Heights	Mainly red and black coarse tuff, lapillistone and agglutinate; thin clastogenic lavas	20 m	2.7–2.5	Entirely subaerial; Strombolian
	Overton Peak	Buff gravelly sandstone, minor brown mudstone	100 m	5.4	Subaqueous tuff cones (englacial?)
	Mussorgsky Peaks	Yellowish gravelly sandstone; minor mudstone, pillow breccia, pillow lava; thin dykes	200 m	2.5, 0.68 (two localities)	Subaqueous tuff cones (englacial)
	Mount Grieg	Hyaloclastite breccia, compound lava(?)	100 m	undated	Lava (hyaloclastite-) deltas
	Venus Glacier	Basaltic dykes and sills; all lamprophyres	0.8–2.3 m	15 (one locality)	Minor subvolcanic intrusions
	Mount Benkert	Mainly gravelly sandstone; minor pillow lava, pillow breccia, thin massive lava	350 m	undated	Subaqueous tuff cones (englacial?)
	Mount McCann	Interbedded lava and scoria	60 m	undated	Degraded cinder cones
	Henry Nunataks	Interbedded lavas; minor (?)hyaloclastite breccia	12–100 m	6 (one locality)	Uncertain (too little information)

*only sedimentary formations formally defined in the James Ross Island Volcanic Group; volcanic strata remain to be assigned in a formal stratigraphy
**tentatively includes numerous poorly investigated, undated outcrops mainly in northern James Ross Island

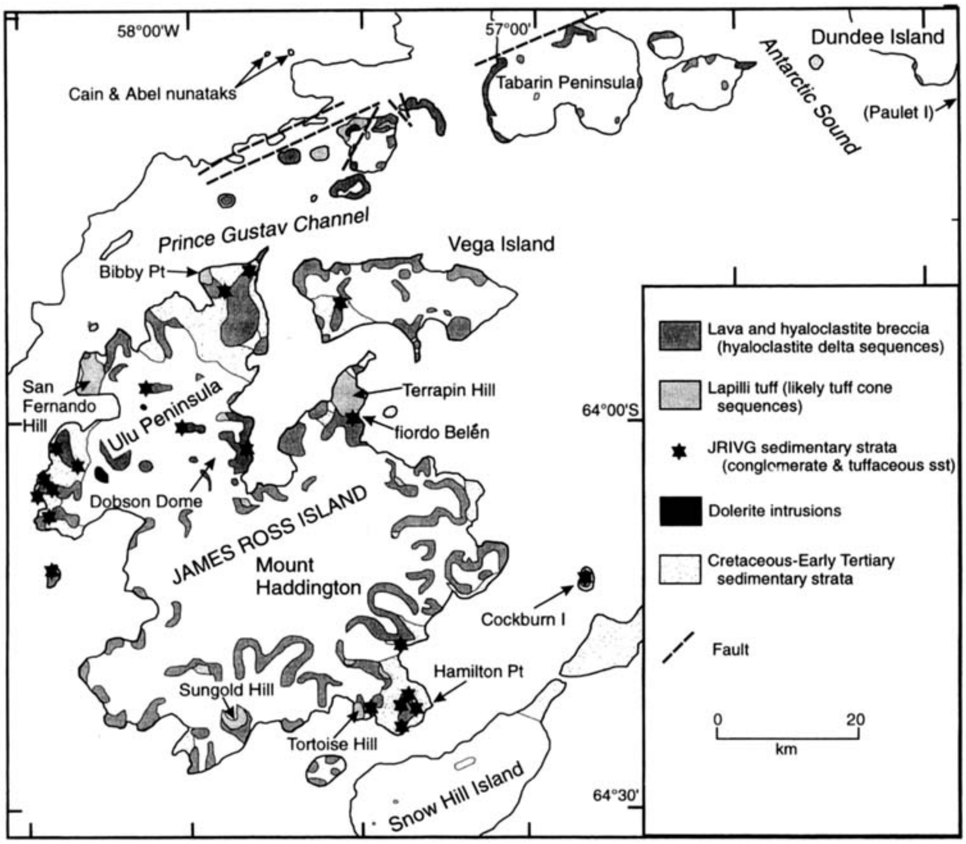

Fig. 2. Sketch map showing the distribution of volcanic outcrops and principal lithofacies in the James Ross Island Volcanic Group, northern Antarctic Peninsula (see Fig. 1 for location).

At least two additional phases, now concealed beneath the ice cap on Mount Haddington, were also postulated based on geomorphological evidence. However, no formations were formally defined. Correlations were based largely on the relative heights above sea level of each lava–breccia couplet, an assumption of no major faulting, the occurrence of distinctive features in some units (e.g. overlap structures,) that are of genetic significance and were assumed to be stratigraphically confined, and using a petrological model of olivine compositions postulated, on minimal evidence, to evolve progressively through the volcanic sequence (from forsteritic compositions in the earliest phases, to more fayalitic compositions in the latest phases). The stratigraphical model was supported by observations particularly on the south-eastern coast of James Ross Island, where up to five volcanic phases are clearly superimposed. However, Nelson (1975) acknowledged the difficulty of correlating over large distances, where exposure is incomplete, because of the close lithological similarities between the individual lava–breccia couplets. Large- and small-scale faults also affect the sequence (Nelson 1975, del Valle & Rinaldi 1992), and there is field evidence that the Mount Haddington volcano has deformed the underlying ductile Cretaceous sedimentary basement and volcanic units in a broad anular outcrop (unpublished information of J.L. Smellie & A.P.M. Vaughan). The deformation style is unclear at present but probably includes faulting, thrusting and local uplift similar to deformation associated with volcanoes that have gravitationally settled into their substrates (cf. Borgia 1994, van Wyk de Vries & Borgia 1996), and possibly block faulting related to regional tectonics (del Valle & Rinaldi 1992). Thus, an absence of stratigraphical complications caused by deformation of parts of the JRIVG cannot be assumed. Sykes (1988a) also demonstrated that olivine compositions throughout the JRIVG do not vary systematically through the sequence and, with the large database of K–Ar isotopic ages now available, it is evident that many of the stratigraphical correlations made by Nelson (1975) are untenable (Fig. 3).

For the sedimentary strata present, two formations have been erected: the Hobbs Glacier Formation (Pirrie *et al.* 1997) and Cockburn Island Formation (formerly the "*Pecten*-conglomerate" of Andersson (1906); Jonkers 1998a, 1998b, Jonkers & Kelley 1998). However, only the sedimentary outcrops at Cockburn Island and south-eastern James Ross Island have been examined in detail. There are numerous additional outcrops known, particularly on Ulu Peninsula, which have only been examinated at a reconnaissance level (Bibby 1966, Sykes 1988a, del Valle *et al.* 1987) and whose field relations, age, correlation and lithological variations of the sedimentary strata are very poorly known.

Because of these problems, it is not yet possible to propose a comprehensive lithostratigraphy for either the volcanic or sedimentary rocks in the JRIVG, nor to describe fully the lithofacies variations within any of the stratigraphical units currently envisaged. For these reasons, no formal description of the constituent units of the JRIVG is attempted here,

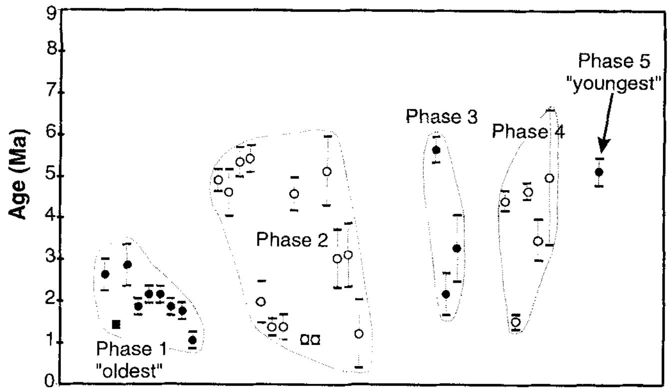

Fig. 3. Summary of isotopic ages for lavas from the James Ross Island Volcanic Group. The data are grouped according to the stratigraphical "volcanic phases" of Nelson (1975). Despite the presence of at least five superimposed volcanic phases (e.g. observed on the flanks of Mount Haddington), there is no obvious support for the published stratigraphy. All ages determined by the K–Ar method. Error bars are 2σ. Includes unpublished isotopic ages of the author.

beyond this summary of the entire group.

Thickness: At least 1470 m, at Mount Haddington.

Lithology, petrology and palaeoenvironment: The JRIVG comprises pillow lava, numerous superimposed lava–palagonitised hyaloclastite breccia couplets, several smaller but geographically widespread outcrops of lapilli tuff, and minor lapillistone (Nelson 1975, Sykes 1988a). Several small pyroclastic cones are present on the south-east side of the island (Strelin & Malagnino 1992). Pillow lava is rare and restricted mainly to Ulu Peninsula, where it is up to 15 m thick and mainly occurs within and at the base of hyaloclastite breccia units. The volumetrically dominant lava–palagonitised hyaloclastite breccia couplets are individually 20–180 m thick. In places, breccia is superimposed on breccia and the intervening lava has been eroded prior to deposition of the younger breccia. The lavas are compound (pahoehoe), forming horizontal sheets formed of up to 30 flow lenses, each lens being 1–5 m thick. Lava lenses are locally interbedded with the topmost few metres of the thick, steep-dipping (25–35°) hyaloclastite breccia beds. The breccias are homoclinally planar stratified, or wavy stratified on a scale of 50–100 m. Beds are massive and 2–5 m thick. They locally contain lenses up to 30 m in length composed of thinly stratified fine lapilli-tuff-grade hyaloclastite. Massive coarse polymict (lithic) breccias up to 20 m thick and extending laterally up to 1 km also occur at the base of some hyaloclastite breccia units. Sequences of lapilli tuff occur at several localities, with large outcrops present at Tortoise, Terrapin, Sungold and San Fernando hills, and Bibby Point (Fig. 2). The deposits exceed 600 m in thickness and comprise thinly and crudely stratified monomict lapilli tuff showing a variety of sedimentary structures, including loading and flame structures, low-angle cross stratification, ripples, scours and deformed (slumped) beds. Monomict lapillistones have a restricted distribution, occurring as thin planar bedded red-coloured units within lava sequences at a few localities.

Sedimentary strata, described as "tuffaceous conglomerates", "marine tuffs" and "diamictites" by Bibby (1966), Nelson (1975) and Sykes (1988a) and tentatively assigned to the Hobbs Glacier Formation by Pirrie *et al.* (1997), have been described at several localities on James Ross Island. The deposits are polymict, with a mixed Antarctic Peninsula and James Ross Island provenance, and comprise poorly sorted matrix-supported conglomerate to pebbly mudstone diamictite with very poorly preserved marine fossils, and laminated volcanic sandstone with only a James Ross Island provenance (described by Pirrie *et al.* (1997) as sand- to silt-grade tuff). The sequences are typically just a few metres thick, possibly ranging up to 25 m in northern James Ross Island. By contrast, the Cockburn Island Formation consists of more than 10 m of bedded medium to coarse sandstone, pebbly sandstone and pebble to boulder conglomerate almost exclusively derived from a JRIVG provenance and containing numerous marine fossils, some reworked probably from Eocene and Cretaceous strata now exposed on Seymour Island to the east (Jonkers 1988a). A sequence composed of polymict conglomerate 3 m in thickness, broadly similar in lithology and structural position to the Cockburn Island Formation but with a mixed Antarctic Peninsula and James Ross Island provenance like the Hobbs Glacier Formation, also crops out at *c.* 60 m above sea level on the north-east coast of James Ross Island (fiordo Belén, del Valle *et al.* 1987). Its stratigraphical affinities are uncertain (Jonkers 1998b).

The cogenetic lava–hyaloclastite breccia couplets (volcanic phases of Nelson 1975) represent multiple superimposed hyaloclastite deltas, formed when subaerial lava(s) entered ponded water, whereas the lapilli tuff outcrops represent tuff cone successions erupted and deposited either subaerially or subaqueously, possibly within the sea or in englacial vaults (cf. Nelson 1975, Pirrie & Sykes 1987, Sykes 1988a, Smellie *et al.* 1988, Skilling 1994, Smellie & Skilling 1994). Some of the structural relationships observed in the volcanic sequences (e.g. various "overlap structures" of Nelson 1975) indicate fluctuating water levels coeval with individual eruptions. They are hard to explain in terms of a marine setting and changes in sea level (cf. Nelson 1975) and are probably diagnostic of englacial eruptions (cf. Smellie in press a, in press b). However, the presence of *in situ* marine fossils in some sedimentary beds and the compositions of authigenic phases in the hyaloclastite breccias (palagonite and phillipsite; unpublished information of British Antarctic Survey) suggest that some parts of the sequence were marine. Diamictite in the Hobbs Glacier Formation was also interpreted as a product of glacimarine sedimentation close to a glacier grounding line (Pirrie *et al.* 1997). Thus, it is likely that the eruptive and depositional environment varied between marine and englacial during the *c.* 10 million year period represented by the JRIVG.

The JRIVG contains the widest compositional range of any alkaline volcanic outcrop in the Antarctic Peninsula region. The lavas are mainly *hy*- and *ne*-normative tholeiites, alkali basalts and hawaiites, together with minor basanite and mugearite (Nelson 1975, Smellie 1987, Sykes 1988a, Hole *et al.* 1995). The most evolved compositions are in pegmatites found in thick sills, which range up to tephriphonolite.

Boundaries: An angular, erosional basal unconformity with Cretaceous sedimentary strata (Campanian–Maastrichtian; Crame *et al.* 1991) is exposed around the margins of James Ross Island, on Vega and Cockburn islands (Bibby 1966, Nelson 1975). The unconformity displays considerable pre-volcanic relief (rising to 213 m in western James Ross Island and up to 330 m on Vega Island, Bibby 1966, Sykes 1988a). In Graham Land, the base of the sequence is unexposed but it is inferred to be an angular unconformity cut in deformed metasedimentary strata of the Permo-Triassic Trinity Peninsula Group (Aitkenhead 1975, Nelson 1975). The upper boundary of the JRIVG is erosional and corresponds to the present-day surface.

Within the JRIVG, the Hobbs Glacier Formation intervenes locally between the basement unconformity and the conformable base of the first overlying volcanic unit of the JRIVG. It is regarded as the oldest lithostratigraphical division of the JRIVG (Pirrie *et al.* 1997). By contrast, the Cockburn Island Formation (confined to Cockburn Island) unconformably overlies JRIVG lava and tuff and its upper surface is eroded (Jonkers 1998a, 1998b, Jonkers & Kelley 1998). The fiordo Belén conglomerates occur within the JRIVG volcanic sequence but the precise stratigraphical context is uncertain (del Valle *et al.* 1987, Jonkers 1998b).

Age: There are numerous isotopic ages for the JRIVG, almost all obtained by the K–Ar method (summarized in Fig. 3, Rex 1976, Massabie & Morelli 1977, Malagnino *et al.* 1978, Smellie *et al.* 1988, Sykes 1988b, Lawver *et al.* 1995). The oldest *in situ* volcanic rocks are hypabyssal intrusions (a plug and a dyke), dated at 6.45 ± 0.60 and 6.8 ± 0.5 Ma, respectively. K–Ar ages obtained on volcanic clasts in associated sedimentary rocks extend the age of volcanism to 7.13 ± 0.49 Ma. The pyroclastic cones on the south-eastern side of the island are largely unmodified by erosion and may be very young (post glacial?, Strelin & Malagnino 1992). By contrast, strontium isotopic ages on shelly material in the Hobbs Glacier Formation suggest that it may range back to 9.9 ± 0.97 Ma (Dingle & Lavelle 1998) and the presence of olivine basalt clasts in the diamictites and interbedded tuffaceous sandstones suggests that the initiation of eruptions in the JRIVG may predate 10 Ma. By contrast, Ar–Ar ages and a fossil pectinid fauna suggest that the Cockburn Island Formation is only 2.8–3 Ma (Jonkers & Kelley 1988). The conglomerate sequence at fiordo Belén has yielded a Sr isotopic age on pectinid fossil material of 6.8 + 1.3/-0.5 Ma (M. Lavelle, in Jonkers 1998b).

Seal Nunataks Volcanic Group

Name and history: This is a new lithostratigraphical unit, named after the principal outcrop area for the volcanic formations. Seal Nunataks were visited first in 1893, when eruptions on two nunataks were recorded, although the account is open to ambiguous interpretation (Smellie 1990a). Published details of the lithofacies and local stratigraphies are sparse.

Distribution: Seal Nunataks; Argo Point, Jason Peninsula (Fig. 4).

Subdivision: The group is divided into the Bruce Nunatak, Christensen Nunatak and Argo Point formations. Their relative ages overlap and they were coeval in part. The ages and field relationships suggest that the Christensen Formation overlies and is generally younger than outcrops of the Bruce Nunatak Formation.

Thickness: A maximum thickness of about 650 m is possible assuming continuity of outcrop down to bedrock beneath the Larsen Ice Shelf.

Lithology, petrology and palaeoenvironment: The group is entirely volcanic-derived. It is formed mainly of pillow lavas and dykes together with smaller outcrops of subaqueously-deposited hydrovolcanic tephra, subaerial lavas and Strombolian scoria. The lavas are *Q*-, *hy*- and slightly *ne*-

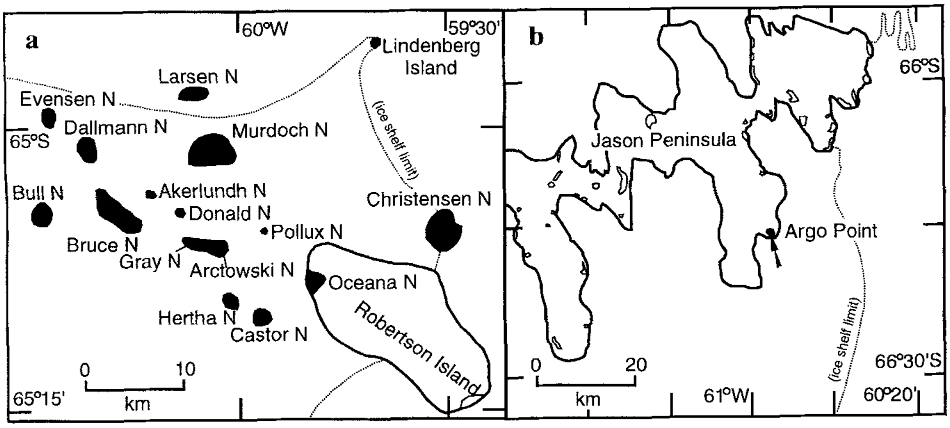

Fig. 4. Sketch maps showing the distribution of volcanic outcrops of the Seal Nunataks Volcanic Group at **a.** Seal Nunataks and **b.** Argo Point. The volcanic outcrops are coloured solid black (also indicated by arrow in b). Exposures of older rock formations are indicated without ornament. See Fig. 1 for the locations of the outcrops in the Antarctic Peninsula.

normative alkali basalts, hawaiites and tholeiites (Saunders 1982, Hole 1990a). The Christensen Nunatak and Argo Point formations are entirely subaerial, whereas the Bruce Nunatak Formation is subaqueous. An englacial palaeoenvironment is likely for the Seal Nunataks outcrops (Smellie & Hole 1997).

Boundaries: The lower boundary is unexposed but an unconformable contact, probably with Jurassic–Cretaceous back-arc basin sedimentary rocks (Seal Nunataks) or Jurassic volcanic rocks (Jason Peninsula), can be inferred from field relationships and the presence of rare metasedimentary xenoliths in the volcanic rocks (Fleet 1968, del Valle *et al.* 1983, 1997, del Valle & Medina 1985, Smellie 1991, Riley *et al.* 1997). The upper boundary is erosional (present-day surface).

Age: 4-<1 Ma (by K–Ar isotopic dating, del Valle *et al.* 1983, Smellie *et al.* 1988). Ages are apparently younger in the more central nunataks and an age progression was inferred by González-Ferrán (1983).

Bruce Nunatak Formation

Name and history: After Bruce Nunatak (65°05'S, 60°14'W), one of the larger nunataks situated on the south-western side of Seal Nunataks.

Distribution: Akerlundh, Arctowski, Bruce, (?)Castor (lower), Evensen, Gray, Larsen, Murdoch, and Oceana nunataks; Lindenberg Island (Fig. 4).

Principal lithological characteristics: Most outcrops consist of multiple or single large dykes (up to 70 m wide) or thick piles of pillow lava lacking interpillow sediment. A few dykes are pillowed and the volcanic succession was probably dyke-fed and erupted from fissures. Some pillow lava outcrops (at Bruce, Gray, Murdoch and Oceana nunataks) are overlain depositionally by buff-coloured gravelly sandstone and sandstone–mudstone strata, which commonly show syn-sedimentary faults and slump structures. Most of the strata correspond to the pillow volcano stage of subglacial and subaqueous volcanoes.

Thickness: About 150 m of rock is exposed in Murdoch Nunatak, but a maximum thickness of about 650 m is possible for the formation as a whole.

Boundaries: The lower boundary is obscured by the Larsen Ice Shelf but the surface is thought to be an unconformity with Upper Cretaceous back-arc basin sedimentary rocks. The upper boundary corresponds to the present-day erosion surface, or is unconformably overlain by subaerial volcanic rocks of the Christensen Nunatak Formation.

Age: 4-<0.2 Ma (K–Ar). The ages cluster mainly around 1.5 Ma and the oldest age (4 ± 1 Ma) may be unreliable. Not all of the outcrops have been dated.

Type section: Bruce Nunatak consists of three ridges formed around multiple dyke zones trending NNE, NE and ESE. Pillow lavas predominate on the flanks and lower slopes of the ridges. The upper parts of the northern ridge consist of yellow-weathering gravelly sandstone with lenses of pillow breccia and rare flattened glassy bombs. The well-developed planar stratification is severely disrupted by syndepositional faulting and major, large-scale, northerly-directed slumping. Bedding involved in the latter shows dips up to 54° and parts of the sequence are partly disaggregated, comprising disorientated more resistant blocks encased in massive sandy matrix.

Key references: Fleet (1968), González-Ferrán (1983), del Valle *et al.* (1983), Smellie *et al.* (1988), Hole (1990a), Smellie (1990a), Smellie & Hole (1997).

Christensen Nunatak Formation

Name: After Christensen Nunatak (65°06'S, 59°31'W), situated at the easternmost limit of Seal Nunataks.

Distribution: Mainly Bull, Castor (upper), Christensen, Dallmann, Donald and Hertha nunataks; also parts of Akerlundh, Arctowski, Evensen, Murdoch and Oceana nunataks and Lindenberg Island (Fig. 4).

Principal lithological characteristics: Mainly subaerially erupted compound lavas and buff or grey lapillistones and lapilli tuffs. The lapilli tuffs are hydrovolcanic deposits. They are >80 m thick at Castor Nunatak and form a crater-like structure with a surface depression 60 m deep and 150 m wide infilled by horizontal lavas. Lapillistones at Donald Nunatak are cinder cone deposits unusually altered to yellow palagonite along subvertical joints. Also present are isolated small outcrops of black weakly welded agglutinate ('spatter'). There is no convincing evidence for the primary landforms, fumaroles and recent eruptions reported. The outcrops are believed to represent the subaerial caps to volcanoes erupted beneath thick ice sheets.

Thickness: The largest outcrop, at Christensen Nunatak, shows about 100 m of exposure but much is obscured by scree. A possible thickness of 200 m of likely compound lavas crops out at Bull Nunatak. The total thickness of the formation is unknown but is probably much less than the Bruce Nunatak Formation.

Boundaries: The lower boundary is obscured by the Larsen Ice Shelf or is an unconformity on the Bruce Nunatak Formation. Isolated outliers of agglutinate and a possible degraded spatter cone rampart overlie the Bruce Nunatak Formation at Murdoch Nunatak. The upper boundary is an erosional surface.

Age: Only dated at Christensen Nunatak (0.7 ± 0.3 Ma by K–Ar).

Type section: Christensen Nunatak, rising to 305 m above sea level, consists of two subhorizontal lava flows interbedded and overlain by yellowish-coloured lapilli tuffs. Evidence for lava–hyaloclastite sequences, similar to those well developed on James Ross Island, has not been confirmed by more recent work. The lower lava at Christensen Nunatak is 20 m thick and columnar jointed, whereas the upper lava is only 3 m thick and massive. Both lavas are highly vesicular and display brick-red, ropy scoriaceous upper surfaces. The interbedded volcaniclastic rocks are mainly subhorizontal, planar-stratified lapilli tuffs of likely hydrovolcanic (tuff cone) type. Bomb sags are developed around some large accessory blocks. The tuffs reach a maximum thickness of about 50 m between the two lavas. There are also minor dykes with no preferred orientation.

Key references: Fleet (1968), González-Ferrán (1983), del Valle *et al.* (1983), Smellie *et al.* (1988), Hole (1990a), Smellie (1990a), Smellie & Hole (1997).

Argo Point Formation

Name: After Argo Point (66°15'S, 60°55'W), a small headland rising *c.* 260 m above the Larsen Ice Shelf, on the south-east side of Jason Peninsula.

Distribution: Argo Point (Fig. 4).

Principal lithological characteristics: Argo Point consists of a degraded cinder cone about 300 m in diameter overlying inaccessible cliffs of interbedded lava and scoria of similar age to the cinder cone.

Thickness: > *c.* 175 m.

Boundaries: The Argo Point Formation is probably unconformable on Jurassic volcanic rocks but the base is obscured by ice. The upper boundary is an erosional surface.

Age: Two basalts from Argo Point yielded K–Ar whole-rock ages of 0.8–1.6 Ma.

Type section: Argo Point.

Key references: Saunders (1982), Smellie *et al.* (1988), Thomson (1990).

Bellingshausen Sea Volcanic Group

Name and history: Outcrops included in this group are scattered widely across Alexander Island and also occur at Snow Nunataks, Sims Island, Rydberg Peninsula and Merrick Mountains (Figs 5 & 6). All were included in the "Bellingshausen Sea Volcanic Province" by LeMasurier & Thomson (1990) and the name is retained here, modified to conform with lithostratigraphical nomenclature. The outcrops are of recent discovery and were described by Horne & Thomson (1967), Bell (1973), Care (1980), Burn & Thomson (1981), O'Neill & Thomson (1985), Thomson & Kellogg (1990) and Rowley *et al.* (1990). Detailed studies of the geochemistry and physical volcanology of the Alexander Island outcrops were published by Hole (1988, 1990b), Smellie *et al.* (1993), Smellie & Skilling (1994) and Smellie & Hole (1997). The Mount Pinafore Formation outcrops have been proposed as sequence holotypes for products of subglacial

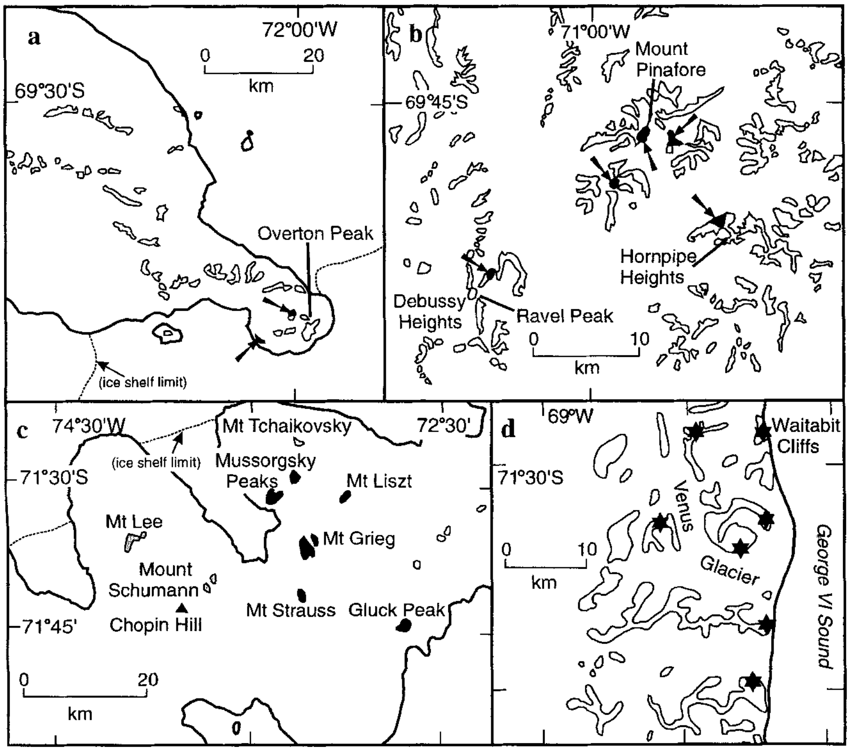

Fig. 5. Sketch maps showing the distribution of known (solid black) and inferred (grey) volcanic outcrops of the Bellingshausen Sea Volcanic Group in Alexander Island. **a.** Rothschild Island, **b.** Mount Pinafore, Debussy Heights and Hornpipe Heights, **c.** Beethoven Peninsula, **d.** South-eastern Alexander Island (star symbols indicate dyke and/or sill localities). Small outcrops in a and b are also indicated by arrows. Exposures of older rock formations are indicated without ornament. See Fig. 1 for the locations of the outcrops within Alexander Island.

eruptions of 'sheetflow type', erupted beneath valley glaciers (Smellie *et al.* 1993).

Distribution: North, south-west and south-east Alexander Island; south-east Rothschild Island; Beethoven Peninsula; south-east Alexander Island; Snow Nunataks, probably Sims Island and Rydberg Peninsula; Merrick Mountains.

Subdivision: Nine formations are defined: Mount Pinafore, Hornpipe Heights, Overton Peak, Mussorgsky Peaks, Mount Grieg, Venus Glacier lamprophyres, Mount Benkert, Mount McCann and Henry Nunataks formations. The Venus Glacier lamprophyres consist entirely of dykes and sills.

Thickness: The thinnest sequence occurs on the Merrick Mountains (<12 m) and the thickest at Beethoven Peninsula and Snow Nunataks (at least 300–400 m, possibly much greater than 400 m assuming continuity of outcrop down to pre-volcanic bedrock; Smellie *et al.* 1988, 1993, Smellie & Hole 1997). Intrusions of the Venus Glacier Formation are generally <1.0 m in thickness (Horne & Thomson 1967 and unpublished field notes of P.A. Doubleday, British Antarctic Survey).

Lithology, petrology and palaeoenvironment: The group is entirely volcanic, formed of dykes/sills, basaltic lavas and a variety of subaerial and subaqueous volcaniclastic lithofacies. Eruptive palaeoenvironments ranged from subglacial (beneath thin valley glaciers at Mount Pinafore/Debussy Heights; beneath a thick ice sheet at Beethoven Peninsula and probably Overton Peak (Rothschild Island) and Snow Nunataks) to entirely subaerial (Hornpipe Heights, Hole 1990c, Smellie *et al.* 1993, Smellie & Hole 1997). The volcanic outcrops form two contrasting compositional groups: *hy*- and slightly *ne*-normative alkali basalts, hawaiites and tholeiites (Beethoven Peninsula; Snow Nunataks/Rydberg Peninsula) and strongly undersaturated *ne*-normative basanites and phonotephrites (all other localities, Smellie 1987, Hole 1988, 1990b, 1990c, Hole & Thomson 1990, Rowley & Thomson 1990, Thomson & O'Neill 1990, Hole *et al.* 1991b). The Venus Glacier lamprophyres comprise compositionally distinctive alkali basalts, potassic trachybasalts and phonotephrites (Rowley & Smellie 1990 and unpublished data of the author), and they are also petrographically different from other Cenozoic alkaline rocks in the Antarctic Peninsula (lamprophyres, Horne & Thomson 1967).

Boundaries: Most of the volcanic outcrops on Alexander Island unconformably overlie deformed metasedimentary rocks of the LeMay Group (Jurassic–Cretaceous, Holdsworth & Nell 1992), although contacts at Beethoven Peninsula and Rothschild Island are obscured by ice. An outcrop at the summit of Mount Pinafore unconformably overlies calc-alkaline arc volcanic sequences of the subduction-related Alexander Island Volcanic Group (Elgar Formation, early–middle Eocene, McCarron & Millar 1997). Dykes in the Venus Glacier area intrude middle Cretaceous formations of the Fossil Bluff Group (Horne & Thomson 1967, Moncrieff & Kelly 1993). In each outcrop area, the alkaline volcanic and dyke formations are the youngest rocks present and their upper boundary corresponds to the present erosion surface.

Age: Three groups of ages (K–Ar) are evident, corresponding to 15 Ma (Venus Glacier), 7.7–5.4 Ma (Mount Pinafore/Debussy Heights, Rothschild Island, Merrick Mountains) and 2.7–<1 Ma (Beethoven Peninsula, Hornpipe Heights, Smellie *et al.* 1988). Not all of the outcrops have been dated.

Mount Pinafore Formation

Name: After Mount Pinafore (69°46'S, 70°58'W), a prominent mountain massif rising to *c.* 1100 m in northern Alexander Island.

Distribution: Ravel Peak (Debussy Heights) and three localities on Mount Pinafore (Fig. 5).

Principal lithological characteristics: Multiple sequences mainly composed of two principal lithofacies associations, a basal association of volcaniclastic lithofacies (sandstone, conglomerate) and an upper association of volcanic lithofacies (lava, hyaloclastite breccia). The two associations form cogenetic "couplets" that are superimposed up to four times locally (e.g. Debussy Heights). The volcaniclastic sections comprise beds of hydroclastic tephra deposited predominantly from traction currents and as mass flows. The reworking was coeval with eruptions. Many beds also contain a variety of clasts derived from the underlying pre-volcanic bedrock and associated diamictites were possibly derived from coeval glaciers. The lava–hyaloclastite breccia lithofacies represent basalt effusion and generation of breccia by chilling (thermal shock), granulation and spallation during quenching by contact with glacier ice and meltwater, probably in valley-confined

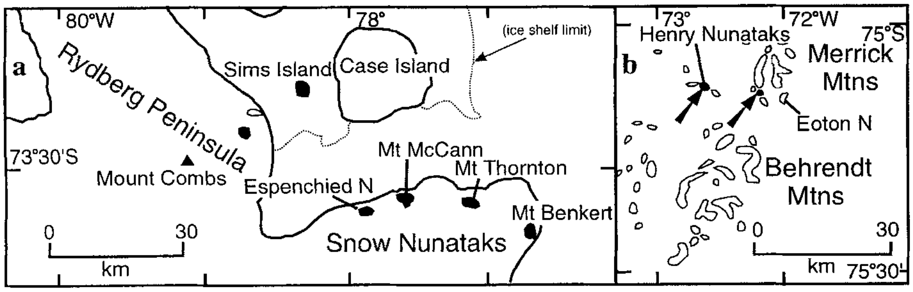

Fig. 6. Sketch maps showing the distribution of volcanic outcrops of the Bellingshausen Sea Volcanic Group in eastern Ellsworth Land. **a.** Snow Nunataks, Rydberg Peninsula and Sims Island, **b.** Merrick Mountains. Symbols and ornaments as in Fig. 3. See Fig. 1 for locations of the outcrops.

subglacial tunnels. The deposits are crudely comparable to eskers.

Thickness: All the sequences are relatively thin, typically just a few tens of metres, ranging locally to *c.* 70 m.

Boundaries: Basal contacts are usually well exposed. The underlying pre-volcanic surfaces are typically steep-dipping and show polishing, striations and molding owing to erosion by Miocene valley glaciers coeval with the alkaline volcanism. The upper surface is erosional.

Age: K–Ar whole-rock isotopic dating of the three sequences at Mount Pinafore and that at Ravel Peak indicate eruptions in latest Miocene times (7.7–5.4 Ma). A significantly younger age of 3.9 Ma obtained from one of the Mount Pinafore outcrops is likely to be unreliable (reset).

Type section: The outcrop on the south-western spur of Mount Pinafore is the type section for this formation. It is described in detail by Smellie & Skilling (1994).

Key references: Burn & Thomson (1981), Hole (1988), Smellie *et al.* (1988, 1993), Hole & Thomson (1990), Hole *et al.* (1991b), Smellie & Skilling (1994).

Hornpipe Heights Formation

Name: After Hornpipe Heights (69°52'S, 70°35'W), an irregular ridged massif rising to c. 1200 m south of Mount Pinafore, northern Alexander Island.

Distribution: Only a single outcrop is included in this formation. It is present on the north-western side of Hornpipe Heights overlooking Sullivan Glacier (Fig. 5).

Principal lithological characteristics: There is little published information on the sequence at Hornpipe Heights and the opportunity is taken here to provide a more detailed description (based on unpublished field notes of M.J. Hole, British Antarctic Survey). The sequence has a general dip of *c.* 40°N (range typically 35–45°) except locally where it drapes upstanding knolls in the underlying bedrock. The (?)lowest bed (upper contact erosional) is a polymict orthobreccia composed of abundant angular blocks of LeMay Group sandstone and basalt, vesicular lapilli and a sandy matrix. It has a crude statification that becomes better-defined upwards by concentrations of coarser and finer clasts. The next bed up-sequence is a widespread black lapillistone, which is up to 3 m thick in hollows but thins up-dip and over basement highs to <0.5 m. It is overlain by a varied sequence about 7 m thick composed of alternating yellowish, buff- and red-coloured coarse tuffs and lapillistones, the latter with dispersed bombs commonly showing flattening parallel to bedding, crude planar stratification and reverse grading. Normal grading is also rarely present and many beds are truncated by minor unconformities. Some finer beds also show delayed reverse grading confined to the top parts of beds and rare finer tuffs show ripple-like small-scale folds that verge up-dip. Steep faults are common and they may be draped by lapillistone beds. Higher parts of the sequence, up to *c.* 20 m thick, comprise thick beds of striking red agglomerate (agglutinate) mainly formed of large ovoid ropy-textured bombs with fluidal aerodynamically molded surfaces and minor coarse lapilli. The beds commonly coarsen and thicken upwards and they are weakly welded. The agglutinate sequence is overlain along uneven channel-like surfaces up to 50 m wide and 10 m deep by multiple thin (generally 1–2 m thick) lavas, many of which alternate with thin (0.3–0.5 m) agglutinates. The lavas thin up-slope. They rarely show poor columnar jointing but platy bed-parallel jointing is ubiquitous. A yellow discoloration is evident in the topmost few dm of lapillistones underlying some lavas.

The scarcity of fine tuff, either as beds or matrix, and the abundance of red or black highly vesicular ash and lapilli (many with fluidal "droplet" surfaces) and bombs are characteristics of fall tephra, the products of "dry" eruptions of low energy Strombolian type. The basal polymict orthobreccia, with its abundant LeMay Group clasts, may represent a product of initial vent-clearing eruptions; the proportion of basement-derived accidental clasts diminishes rapidly above the basal bed but such clasts are seldom completely absent. The common reverse grading, thinning over basement highs and multiple shallow unconformities were probably caused by local remobilization (as grain flows) of unstable beds of cohesionless sand- and gravel-grade pyroclasts shortly after deposition on the very steep substrate (the angle of dip exceeds the stable angle of repose for cohesionless sediments). Other evidence for contemporaneous slope instabilty consists of syndepositional faulting, minor slumping (ripple-like folds?) and channelized surfaces. The lavas are probably clastogenic flows whose ubiquitous platy appearance is probably caused by shearing during laminar flow of a viscous liquid. The yellow discoloration of some beds is caused by marginal palagonitization of sideromelane and tachylite. Such alteration is most commonly found in hydrovolcanic and subaqueous tephra, but there is no evidence for hydrovolcanism or subaqueous deposition. The alteration is marginal to clasts and may be due to surface weathering in a moist environment. However, the conspicuous restriction of some alteration to the upper parts of beds overlain by lavas also suggests the possibility of a local snow cover melted by the lavas, the small quantities of meltwater released then causing the alteration. The location of the vent responsible is unknown but the overall coarseness of the sequence, abundant large bombs and clastogenic lavas suggest that it was within a few hundred metres. Although the presence of lavas on the topographically higher parts of the outcrop could suggest a vent close to the ridge crest, a vent locus beneath Sullivan Glacier seems more likely.

Thickness: Up to 20 m of the formation is preserved.

Boundaries: The lower boundary is a highly uneven, steeply dipping (*c.* 45°) erosional surface formed in deformed metasedimentary rocks of the LeMay Group; several upstanding rocky knolls of LeMay Group are preserved and are draped by the Hornpipe Heights Formation. The surface shows no signs of pre-volcanic glacial erosion. The upper boundary conforms to the present day erosion surface. The outcrop is obscured down-dip by Sullivan Glacier.

Age: Two basanite lavas have yielded K–Ar isotopic whole-rock ages of 2.5 ± 0.8 and 2.7 ± 0.2 Ma.

Type section: Outcrop at Hornpipe Heights, described above.

Key References: Smellie *et al.* (1988), Hole (1990c).

Overton Peak Formation

Name: After Overton Peak (69°41'S, 71°58'W), one of the Desko Mountains rising to *c.* 550 m on south-eastern Rothschild Island.

Distribution: Two rounded, predominantly scree-covered hills and a 100 m-high cliff situated north-west and west of Overton Peak, respectively (Fig. 5).

Principal lithological characteristics: Mainly crudely bedded and normal-graded yellowish gravelly sandstones and minor brown mudstones showing faint planar stratification and cross lamination, respectively, in beds 0.2–1 m thick. Large- and small-scale faults are conspicuous and wash-out channels are locally common. Bedding dips generally at 18–25° but orientations are very variable suggestive of post-depositional slumping. Three basalt dykes are also present, one of which is *c.* 50 m wide. Although studied only at reconnaissance level, the Overton Peak Formation appears to closely resemble the better-described Mussorgsky Peaks Formation (below) and a similar origin (eruptions beneath a thick ice sheet) is inferred.

Thickness: >100 m.

Boundaries: No contacts with other rock formations are exposed but the lower boundary is presumed to be unconformable on the LeMay Group and the upper boundary is the present-day erosion surface.

Age: One of the largely scree-covered hill outcrops has yielded an age of 5.4 ± 0.7 Ma (K–Ar).

Type section: The cliff exposure 5 km west of Overton Peak is selected as the type section for this formation and is described and illustrated by Care (1980).

Key References: Care (1980), Smellie *et al.* (1988).

Mussorgsky Peaks Formation

Name: After Mussorgsky Peaks (71°44'S, 73°41'W), two prominent nunataks near the head of Brahms Inlet, Beethoven Peninsula, south-western Alexander Island.

Distribution: Mussorgsky Peaks, Mount Liszt, Mount Grieg, Mount Strauss and Gluck Peak. Four additional outcrops, at Mount Tchaikovsky, Mount Lee, Mount Schumann and Chopin Hill, have not been visited but may also be formed of volcanic rocks of this formation (Fig. 5).

Principal lithological characteristics: Outcrops are dominated by crudely bedded yellowish gravelly sandstones. Other lithofacies include thin-bedded sandstone–mudstone, sandy pillow-fragment breccia and minor pillow lava; several outcrops also contain thin basalt dykes. Large- and small-scale syn-sedimentary faulting and slumping are common and conspicuous. The volcaniclastic lithofacies are sedimented hydroclastic tephra, representing a variety of mass flows deposited mainly from proximal high- and low-density turbidity currents and debris flows. The different styles of sedimentation present have been related to a model of variable eruption dynamics during subaqueous (englacial) tuff cone construction in a subglacial setting.

Thickness: 200 m of section is exposed on the western of the two nunataks at Mussorgsky Peaks but total thicknesses >500 m are possible for the Beethoven Peninsula outcrops, assuming continuity of outcrop down to sub-ice pre-volcanic bedrock.

Boundaries: The lower boundary is unexposed (obscured by ice) but the formation is presumed to be unconformable on LeMay Group. The upper boundary generally conforms to the present day erosion surface but, at Mussorgsky Peaks and Mount Grieg, the formation is overlain by the Mount Grieg Formation across an uneven undulating gently dipping surface. The upper surface may be a syn-depositional compound unconformity (slump scar) formed by multiple large-scale sector collapses of the volcanic edifices.

Age: A sample from Mussorgsky Peaks was dated as 2.5 Ma, and another at Gluck Peak as 0.68 ± 0.97 Ma (by K–Ar; the latter unpublished data of M.J. Hole). Other outcrops on Beethoven Peninsula are undated.

Type section: The western (larger) of the two nunataks at Mussorgsky Peaks. The section is up to 200 m high and 3 km long and is described in detail by Smellie & Hole (1997).

Key references: Bell (1973), Hole (1990b), Smellie & Hole (1997).

Mount Grieg Formation

Name: After Mount Grieg (71°36'S, 73°11'W), a prominent nunatak rising to *c.* 600 m at the head of Brahms Inlet. Although the entire sequence is inaccessible, it is very well exposed on its north-western face where a section 300–400 m high is easily observed by binoculars; only the upper 100–150 m corresponds to the Mount Grieg Formation.

Distribution: Western nunatak of Mussorgsky Peaks; Mount

Grieg (Fig. 5).

Principal lithological characteristics: At Mussorgsky Peaks, the sequence forms the summit of a mesa. It is composed of dark grey glassy breccia (hyaloclastite) with abundant intact and fragmented basalt pillows. It has a wedge-shaped geometry and crude large-scale, homoclinal, steep-dipping planar stratification interpreted as foreset bedding in a hyaloclastite (or lava) delta which prograded into an englacial lake. The expected overlying subaerial lavas have been eroded away at that locality but they are still preserved as an inaccessible subhorizontally bedded sequence of compound(?) lavas 50–100 m thick above breccias at the summit of Mount Grieg. The contact between the lavas and hyaloclastite breccia at Mount Grieg is hard to distinguish, but there is a prominent contact between the dark grey Mount Grieg Formation lithofacies and bright yellow deposits of the underlying Beethoven Peninsula Formation, which extends down to the level of the surrounding ice sheet (a vertical interval of about 200–300 m).

Thickness: At least 100 m thick at Mussorgsky Peaks. There is an uncertain but probably comparable thickness on Mount Grieg.

Boundaries: At both localities, the basal surface is uneven, undulating and gently dipping on the Beethoven Peninsula Formation (see description above). The upper boundary is the present-day erosion surface.

Age: No parts of the Mount Grieg Formation have been dated directly but, as it is coeval with the Beethoven Peninsula Formation at Mussorgsky Peaks (dated by K–Ar as 2.5 Ma), a similar age is likely at that locality, at least.

Type section: Mount Grieg (see description above).

Key references: Hole (1990b), Smellie & Hole (1997).

Venus Glacier Lamprophyres

Name: After Venus Glacier (71°36'S, 68°27'W) in south-eastern Alexander Island. Dykes/sills are very uncommon in eastern Alexander Island. Most occur in the vicinity of Venus Glacier and only those are distinguished here as the Venus Glacier Lamprophyres.

Distribution: In addition to outcrops described from Waitabit Cliffs, Cannonball Cliffs and Triton Point, alkaline dykes and a sill are now also known to crop out at the Quadrangle, upper reaches of Venus Glacier and Horrocks Block (unpublished field notes of P.A. Doubleday, British Antarctic Survey; Fig. 5).

Principal lithological characteristics: Entirely formed of basaltic dykes and sills, although they may have been feeders for volcanic centres that have been completely removed by erosion. They are petrographically and compositionally distinctive lamprophyres (camptonites) with alkali basalt/basanite–phonotephrite compositions, formed of euhedral phenocrysts of titanaugite, hornblende, altered olivine and minor plagioclase in a coarse groundmass of titanaugite, hornblende, opaque oxide, olivine and pervasive chlorite, zeolite (analcite?) and carbonate (including unpublished information of the author). Phenocrysts of biotite and kaersutite are also present and are much larger than the other phenocrysts. The dykes trend mainly north-eastwards (040–078°N), with a subsidiary trend towards 104°N. An intrusion exposed in the upper Venus Glacier area shows both sill and dyke relationships (unpublished field notes of P.A. Doubleday, British Antarctic Survey).

Thickness: The intrusions are mainly ≤ 0.8 m thick but range up to 2.3 m; the 7.0 m thickness reported by Horne & Thomson (1967) for one dyke was a printing error and it should be 0.7 m (M.R.A. Thomson, personal communication).

Boundaries: The dykes/sills intrude sedimentary rocks of the Pluto Glacier and Neptune Glacier formations (middle Cretaceous) of the Fossil Bluff Group. Although they typically follow faults and fractures in the Fossil Bluff Group, at least one dyke (at Waitabit Cliffs) is cut by a brittle shear zone.

Age: A dyke at Waitabit Cliffs yielded a K–Ar whole-rock age of 15 ± 1 Ma.

Type section: All the intrusions show similar features but the southern dyke at Waitabit Cliffs is probably one of the best exposed, forming a preferentially exhumed, conspicuous wall-like outcrop, and it is selected as the type example for these intrusions.

Key references: Horne & Thomson (1967), Rex (1970), Rowley & Smellie (1990).

Mount Benkert Formation

Name: After Mount Benkert (73°38'S, 76°40'W), Snow Nunataks, which rises to *c.* 700 m and is situated south-east of Carroll Inlet, English Coast (Fig. 6).

Distribution: Snow Nunataks (Mount Benkert, Mount Thornton, basal sequence at Mount McCann). The geographical proximity (only 25 km distant) and apparent lithological similarities (judged from photographs and aerial observations by M.J. Hole, British Antarctic Survey) of Sims Island suggest that it may be related to the Snow Nunataks volcanic field and the Mount Benkert Formation.

Principal lithological characteristics: The sequence exposed at Mount McCann consists of 200 m of pillow basalt capped by 1–5 m of massive to well-bedded orange-brown volcaniclastic rocks described as "hyaloclastite" (probably comparable to the gravelly sandstones described for outcrops on Beethoven Peninsula, Rothschild Island and Seal Nunataks). By contrast, about 350 m of vertical rock face at Mount Benkert is formed entirely of crudely bedded "hyaloclastite", minor pillow lava and pillow breccia and thin massive lavas.

Smaller channels and cross-bedded layers are also recorded and the outcrop is notable for the presence of spectacular, multiple large-scale channel-like unconformities up to 50 m deep. The sequence at Mount Thornton also resembles that at Mount Benkert and is principally formed of massive and thin-bedded volcaniclastic rocks, which overlie poorly exposed pillowed and blocky lava; evidence for slope instability (convolute layering, folding) is common. Basalt dykes, sills and irregular small plugs are present at all three localities. There is a very strong resemblance in lithofacies and lithofacies relationships to the Mussorgsky Peaks and Bruce Nunatak formations, although the Mount Benkert Formation has been studied at reconnaissance level only. The outcrops are tentatively interpreted as representing the pillow volcano and subaqueous tuff cone stages of several small subglacial volcanoes, erupted beneath relatively thick ice sheet(s).

Thickness: More than 350 m are exposed at Mount Benkert and Sims Island.

Boundaries: Contact relationships with other rock formations are unclear and the pre-volcanic basement is unexposed. The formation is overlain at Mount McCann by subaerial lithofacies of the Mount McCann Formation, but the nature of the contact is undescribed. Elsewhere, the upper boundary corresponds to the present-day erosion surface

Age: Unknown, but alkaline composition, lithofacies similarities and freshness suggest that it is part of the Miocene to Recent volcanism of the Antarctic Peninsula region.

Type section: Mount Benkert.

Key references: O'Neill & Thomson (1985), Thomson & O'Neill (1990).

Mount McCann Formation

Name: After Mount McCann (73°34'S, 77°37'W), one of the Snow Nunataks, rising to *c.* 700 m and situated south of Carroll Inlet, English Coast.

Distribution: Snow Nunataks (Espenchied Nunatak; upper sequence at Mount McCann) and Rydberg Peninsula (isolated lava outcrop and possibly Mount Combs; Fig. 6).

Principal lithological characteristics: Scoriaceous and cindery basaltic rubble and massive highly vesicular lavas (Mount McCann); crudely stratified, black and reddish-brown lapilli tuff and tuff breccia intruded by thin (1–3 cm) basaltic dykes (Espenchied Nunatak). The tiny outcrop on Rydberg Peninsula is formed of black highly vesicular lava. Mount Combs was described as a small cone that rises several hundred metres above the surrounding ice surface. Although it is likely to be volcanic, it is entirely snow and ice covered. All the outcrops of the Mount McCann Formation are dominated by subaerial lavas and possible Strombolian tephra. Those at Snow Nunataks possibly represent the subaerial caps to subglacially erupted volcanoes (cf. Mount Grieg and Christensen Nunatak formations).

Thickness: More than 60 m at Mount McCann.

Boundaries: No contacts with other rock formations are exposed. The formation overlies subaqueous lithofacies of the Mount Benkert Formation at Mount McCann, but the contact is unexposed. Elsewhere, the upper surface is the present-day erosion surface.

Age: Unknown, but alkaline composition, lithofacies similarities and freshness suggest that it is part of the Miocene to Recent volcanism of the Antarctic Peninsula region.

Type section: Upper sequence at Mount Thornton (described above).

Key references: O'Neill & Thomson (1985), Smellie *et al.* (1988), Rowley & Thomson (1990), Thomson & O'Neill (1990).

Henry Nunataks Formation

Name: After Henry Nunataks (75°08'S, 72°36'W), on the western side of the Merrick Mountains, eastern Ellsworth Land.

Distribution: Merrick Mountains only. Central nunatak and possibly western end of the easternmost nunatak in the Henry Nunataks; also an unnamed isolated nunatak 5 km west of Eaton Nunatak (Fig. 6).

Principal lithological characteristics: Examined only at reconnaissance level. The Henry Nunataks outcrop consists of a sequence of fine-grained, grey, vesicular basaltic lavas with rubbly surfaces cut by a basalt dyke. At the small nunatak west of Eaton Nunatak is a frost-shattered basanite lava breccia with a palagonite-altered glassy matrix (interpreted as hyaloclastite breccia) overlain by thinner vesicular to scoriaceous lavas.

Thickness: About 100 m at Henry Nunataks; <12 m at the small nunatak west of Eaton Nunatak.

Boundaries: The Henry Nunataks sequence unconformably overlies Mesozoic volcanic rocks (mostly porphyritic dacitic lavas). The base of the other outcrop west of Eaton Nunatak is obscured by ice but it is probably unconformable on Jurassic sedimentary rocks widely exposed in the surrounding area. The upper surface is the present-day erosion surface.

Age: A K–Ar age of 6 Ma was attributed to the outcrop near Eaton Nunatak, but neither analytical details nor the errors for the age were published.

Type section: Central nunatak at Henry Nunataks.

Key References: Halpern (1971), Smellie *et al.* (1988), Thomson & Kellogg (1990), Rowley *et al.* (1990).

Discussion

Characteristics of the volcanic fields

The volcanic fields vary in size from about 1 to 4500 km^2 (Table II) and have a range of ages from early Miocene (15 Ma) to Recent. The James Ross Island Volcanic Group is probably the largest area of late Miocene–Recent volcanic rocks preserved in the Antarctic Peninsula region, cropping out over *c.* 4500 km^2. It comprises a large polygenetic shield volcano on James Ross Island (Mount Haddington), which is 35–60 km in basal diameter. It was largely effusive, constructed from multiple superimposed hyaloclastite deltas, but includes the products of several tuff cone centres (the largest, at Terrapin Hill, may be 8 km in diameter). Other mainly effusive shield volcanoes in the JRIVG are known or postulated on Ulu Peninsula (major centre at Dobson Dome?), Tabarin Peninsula (20–40 km in basal diameter), Vega Island and islands in Antarctic Sound (Sykes 1988b, Smellie 1990a). The elongate morphology of the Vega Island outcrops suggest that the volcanic sequences there were erupted from a fissure or series of fissures, unusual in the JRIVG. Most of the islands in Prince Gustav Channel are small monogenetic centres constructed of a large proportion of pyroclastic (hydrovolcanic) rocks. The JRIVG volcanism was longer-lived than for any other volcanic outcrop in the region, and may exceed 10 million years. The distribution of ages suggests that there may be a simple age progression in the JRIVG, with younger centres (< 2 Ma) situated mainly to the north and north-east of the older Mount Haddington centre (Baker *et al.* 1977, Sykes 1988b).

By contrast, other Miocene–Recent volcanic fields in the Antarctic Peninsula are monogenetic and available data indicate three principal eruptive periods (*c.* 15, 7.7–5.4 and 2.7–<0.2 Ma). The lifetime of each monogenetic field was typically <1–2 million years and some formations are single short-lived volcanic centres (e.g. Argo Point and Hornpipe Heights). The Hornpipe Heights Formation appears to represent a resumption of volcanic activity in the Mount Pinafore volcanic field, after a break of 3–3.5 million years. With the possible exception of Seal Nunataks, there appear to be no spatial or temporal controls on the distribution of the centres within any monogenetic field, but available information is sparse. The isotopic ages also suggest that monogenetic fields formed by lavas with basanite–phonotephrite compositions are generally older than those with alkali basalt–tholeiite lavas (Table II).

There is a large disparity in the volume of erupted products

Table II. Summary statistics for alkaline volcanic fields in the Antarctic Peninsula and eastern Ellsworth Land, grouped according to petrological "series".

Volcanic field	Approx. area (km^2)	Estimated preserved thickness of deposits (m)	Age (Ma)	Formations	Comments	Reference
Alkali Basalt–Tholeiite "Series"						
JIRVG	4500	up to 1470 m; individual outcrops usually few hundred metres	<10	Hobbs Glacier, Cockburn Island; no volcanic formations defined yet	includes several large shield volcanoes	Nelson 1975, this paper
Seal Nunataks	1400	*c.* 300–650*	(?4)–<1	Bruce Nunatak, Christensen Nunatak	multiple overlapping centres	Smellie & Hole 1997
Argo Point	[1]	>175	0.8–1.6	Argo Point	single volcanic centre	Saunders 1982
Beethoven Peninsula	>2000 (>7000?**)	600–800*	2.5, 0.68	Mussorgsky Peaks, Mount Grieg	multiple overlapping centres	Smellie & Hole 1997
Snow Nunataks	2800	500–600* (likely >> 600 m at Sims Island)	undated	Mount Benkert, Mount McCann	several scattered centres	this paper
Basanite–Phonotephrite "Series"						
Mount Pinafore	250	20–90	7.7–6.0; 2.7–2.5	Mount Pinafore, Hornpipe Heights	few widely separated centres	Smellie *et al.* 1993
Rothschild Island	[5]	100	5.4	Overton Peak	two small very degraded outcrops	Care 1980
Merrick Mountains	[15]	12–100	6 (1 locality)	Henry Nunataks	two small very degraded outcrops	this paper
Venus Glacier***	500	0.1–2.3	15 (1 dyke)	Venus Glacier	dykes and sills only	this paper

* assumes continuity of outcrop to sub-ice bedrock

** note: the distribution of magnetic anomalies suggests that the Beethoven Peninsula volcanic field may be significantly larger than the distribution of surface exposures suggests, possibly extending between Monteverdi Peninsula and Latady Island (Renner *et al.* 1982)

*** compositionally heterogeneous; affinities uncertain

[ ] tentative estimates referring to small volcanic fields consisting of 1–2 centres only

across the region, which varies with the compositions of the erupted magmas. Two broad petrogenetic "series" were recognised by Smellie (1987) and form essentially mutually exclusive outcrops. Basanite–phonotephrite outcrops contain thin sequences (<100 m thick) erupted from small widely separated centres scattered across comparatively small volcanic fields (<300 km^2, Table II). By contrast, eruptions of alkali basalts–tholeiites were much more voluminous and occur within much larger volcanic fields (>1500 km^2). There is no chronological progression between alkali and tholeiite basalts in any field, consistent with petrogenetic interpretations. Fractional crystallization was generally minor and the broad range of basalt types present is believed to be due to partial melting variations (Hole 1988, 1990, Sykes 1988a). Relative degrees of partial melting probably decreased from the tholeiites to alkali basalts. Eruptions were variously from large shield volcanoes (JRIVG) or from multiple, closely spaced and probably overlapping much smaller centres. The largest alkali basalt–tholeiite volcanic field may be the JRIVG (*c.* 4500 km^2), but the monogenetic field at Snow Nunataks is about 2800 km^2 and that in south-western Alexander Island possibly extends over >7000 km^2 based on aeromagnetic surveys (Renner *et al.* 1982). Because all of the outcrops are highly degraded, it is impossible to estimate accurately the volumes of magma erupted. However, from a consideration of the relative thicknesses of preserved deposits and the areal extent of the volcanic fields, erupted volumes of alkali basalt–tholeiite were an order of magnitude greater, at least, than those of basanite–phonotephrite. This is true even if data for the JRIVG polygenetic volcanic field are excluded.

Eruptive palaeoenvironments

Eruptive/depositional environments varied between marine and englacial in the JRIVG (Nelson 1975, Skilling 1994). During the glacial periods, features preserved in the volcanic sequences suggest that coeval glaciers were at least 200 m thick (cf. Smellie in press a, in press b). Conversely, most of the volcanism in the monogenetic volcanic fields was englacial. Eruptions were beneath valley-confined Alpine glaciers in northern Alexander Island (Mount Pinafore Formation). Interpretation of the lithofacies in the Mount Pinafore Formation suggests that glaciers were mainly mainly composed of snow and firn; glacier thicknesses were probably comparable at each outcrop and a few tens of metres thick. The Mount Pinafore Formation outcrops represent "outflow facies" of subglacial eruptions of "sheetflow type" beneath valley-confined glaciers (Smellie *et al.* 1993). The variable elevations of the basal pre-volcanic basement at each locality (1100 m to *c.* 400 m) suggest a significant bedrock palaeotopography and sloping glacier surfaces. The present-day occurrence of most of the outcrops capping ridges indicates that topographic inversion has occurred following substantial post-Miocene erosion. By contrast, products of eruptions beneath much thicker glaciers (corresponding to ice sheets several hundred metres thick) are represented by outcrops at Beethoven Peninsula, Seal Nunataks (Smellie & Hole 1997) and probably also the Overton Peak, Mount Benkert and Mount McCann formations.

Eruptions in the Mount Pinafore and Rothschild Island volcanic fields overlapped in time and occurred in geographically adjacent areas (Fig. 3). The sequences also display features consistent with contrasting ice conditions during the coincident eruptive period. Alpine (valley) glaciers affected vents at higher elevations (Mount Pinafore Formation; Smellie *et al.* 1993) whereas an ice sheet was present farther west, at a lower elevation (affecting the Overton Peak Formation). These conditions are not unlike those prevailing at present but with generally higher ice surfaces in the Miocene. It seems likely that the Miocene glacial topography was broadly similar to that of today and reflected differing bedrock elevations between Rothschild Island and Mount Pinafore. Solely subaerial ("ice-free") volcanism is recorded by the nearby Hornpipe Heights Formation, yet the outcrop of the latter is at a similar topographical elevation to lower parts of the (englacial) Mount Pinafore Formation, indicating that between latest Miocene (*c.* 5.4 Ma) and Pliocene times (2.5 Ma), the general elevation of glacier surfaces in northern Alexander Island diminished. As the base of the Hornpipe Heights Formation is now covered by Sullivan Glacier, local glacier elevations may also have increased slightly since Pliocene times, although it is not possible to estimate the magnitudes of those fluctuations.

A record of surface elevations of former ice sheets is also contained in the extensive JRIVG, Beethoven Peninsula and Seal Nunataks outcrops, and probably also at Snow Nunataks which currently lack diagnostic information. Although the JRIVG outcrop contains the most comprehensive record of temporally fluctuating ice surfaces, the distinction between eruptive units formed under marine and englacial environments is unclear at present and limits its usefulness for understanding the palaeoenvironmental history of the Antarctic Peninsula. Conversely, for the monogenetic volcanic fields at Beethoven Peninsula and Seal Nunataks (and probably Snow Nunataks), the Pliocene–Recent ice sheets were substantially thicker and had surface elevations typically a few hundred metres higher than at present (Smellie & Hole 1997). These outcrops are now extensively glacially degraded and several show evidence for overtopping by former ice. The evidence thus clearly indicates that ice sheet elevations on the low-lying flanks of the Antarctic Peninsula have fluctuated substantially (within a few hundred metres, at least) over the past 2.5 million years, before diminishing to those of the present-day.

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