AGE, DISTRIBUTION AND ERUPTIVE CONDITIONS OF LATE CENOZOIC ALKALINE VOLCANISM IN THE ANTARCTIC PENINSULA AND EASTERN ELLSWORTH LAND: REVIEW

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Abstract. The distribution and principal lithological characteristics of alkaline volcanic rocks in the Antarctic Peninsula region are reviewed. The outcrops show a significant geographical distribution restricted largely to flanking areas, the likely loci of substantial post-subduction normal faulting. Most outcrops contain contrasting magmatic and phreatomagmatic deposits. The latter are the commonest pyroclastic rocks and are further divisible into hyaloclastites and hyalotuffs (*sensu stricto*) based on the morphology and vesicularity of the individual pyroclasts. The alkaline volcanism occurred between 15 Ma and the present, with well-defined peaks of activity at 5–7, 1–2 and < 0.2 Ma. The available age data are insufficient to demonstrate clearly any temporal or spatial variations in the volcanism, but there is no apparent correspondence between the radiometric ages and the five phases of volcanism previously recognised in the James Ross Island Volcanic Group. Although glacial conditions probably existed during much of the eruptive period, unambiguous evidence of a subglacial origin for the outcrops has not been forthcoming, although it seems likely, at least for outcrops in northern Alexander Island and eastern Ellsworth Land.

Introduction

The Antarctic Peninsula has been the locus of major continental magin calc-alkaline magmatism for at least 200 Ma (e.g. Pankhurst, 1982; Saunders and others, 1982; Weaver and others, 1982; Thomson and Pankhurst, 1983). During Tertiary times, this particular magmatism ceased perhaps progressively northwards as off-set sections of the Aluk spreading centre collided with the Antarctic Peninsula trench and were consumed, resulting in a sutured Antarctic–Pacific plate (Herron and Tucholke, [illegible]6; Barker, 1982; Saunders and others, 1982). Following this transformation, two major tectonomagmatic events have occurred:

(i) generation of up to 32 km of semi-oceanic crust in Bransfield Strait, a youthful (< 1.3 Ma) marginal basin (Ashcroft, 1972; Barker, 1976, 1982; Roach *in* Garrett and Storey, 1987);

(ii) eruption of alkaline volcanic rocks from numerous centres scattered widely throughout the Antarctic Peninsula (e.g. Laudon, 1972; Bell, 1973; Nelson, 1975; Saunders, 1982; González-Ferrán, 1983*a*; Smellie and others, 1984; Fig. 1).

The volcanism in Bransfield Strait has been the focus of several recent investigations (e.g. González-Ferrán and Katsui, 1970; Baker and others, 1975; Weaver and others, 1979). By comparison, the alkaline volcanism is poorly known and there is some confusion regarding its outcrop distribution. Although numerous field descriptions have been published, not all the outcrops have been described, and others have been included using criteria of doubtful stratigraphical significance. Because of their importance in the tectonic, magmatic and palaeoenvironmental evolution of the region (e.g. Garrett and Storey, 1987; Smellie, 1987), the young alkaline volcanic rocks are currently being investigated in detail by the British Antarctic Survey and

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University of Nottingham. The geochemistry, petrogenesis and tectonic setting have been reviewed by Smellie (1987). This paper describes the distribution and principal features of the outcrops, evidence for the age of eruption and the eruptive environment.

OUTCROP DISTRIBUTION AND CHARACTERISTICS

A variety of discriminants was used to distinguish the young alkaline volcanic rocks, although for several outcrops the full range of evidence is lacking.

(i) Alkaline geochemistry and presence of ultramafic nodules: these are the only diagnostic criteria. Only one period of alkaline volcanism is known, and ultramafic nodules (mantle-derived) do not occur in the calc-alkaline rocks (cf. Smellie, 1987).

(ii) Miocene–Recent age: Upper Cenozoic calc-alkaline volcanicity is restricted [illegible] the islands west of northern Antarctic Peninsula (cf. Barker, 1982; Smellie and others, 1984), and this is the only area where overlap in age may occur. Farther south, Upper Cenozoic outcrops can be assigned to the alkaline volcanic period with more confidence.

(iii) Presence of palagonitized vitric tuffs and tuff-breccias: so far, all known occurrences of these rocks are restricted to the alkaline outcrops. However, since the physical appearance of pyroclastic rocks is determined by many factors in addition to geochemistry (e.g. magma rheology and volatile content, environment of eruption), the possibility obviously exists that similar-looking rocks with calc-alkaline compositions may be discovered.

(iv) Predominance of fresh 'olivine basalts': use of this term conforms to Macdonald and Katsura's (1964) definition as a basaltic rock containing significant modal olivine. Since olivine basalts, especially those with unaltered olivine, are extremely rare in the calc-alkaline series, this is a good general discriminant. However, a few exceptions are known (e.g. Upper Cretaceous and Upper Cenozoic basalts in the South Shetland Islands: Smellie and others, 1984).

On the basis of these criteria, alkaline rocks of the group may be recognized throughout the Antarctic Peninsula area, from eastern Ellsworth Land in the south to the South Shetland Islands in the north (Fig. 1).

Eastern Ellsworth Land

Small, isolated outcrops occur near Mount Matheson in the Merrick Mountains (Laudon, 1972, 1982; Vennum and Laudon, in press) and at Henry Nunataks (Rowley and others, 1985; Fig. 2). The frost-shattered rubbly outcrop at Mount Matheson is composed of brown, partially palagonitized tuffs and lapillistones, containing numerous black vesicular lava clasts overlain by highly vesicular to scoriaceous black lava, *pahoehoe* in part. The total stratigraphical thickness is only 10–12 m. At Henry Nunataks, however, there is a 200–250 m thick south-easterly dipping sequence of vesicular lavas alternating with rubbly scoriaceous flow rocks (K. S. Kellogg, pers. comm., 1985).

Other outcrops are restricted to several nunataks in the Rydberg Peninsula–Snow Nunataks area (Fig. 2). The small outcrop at Rydberg Peninsula consists of black, highly vesicular lava (Renner and others, 1982), there are good exposures of bedded (?) volcanic rocks on Sims Island and thick exposures (170–570 m) of a variety of volcanic and volcaniclastic rocks occur along the 50-km long chain of peaks forming Snow Nunataks (O'Neill and Thomson, 1985).

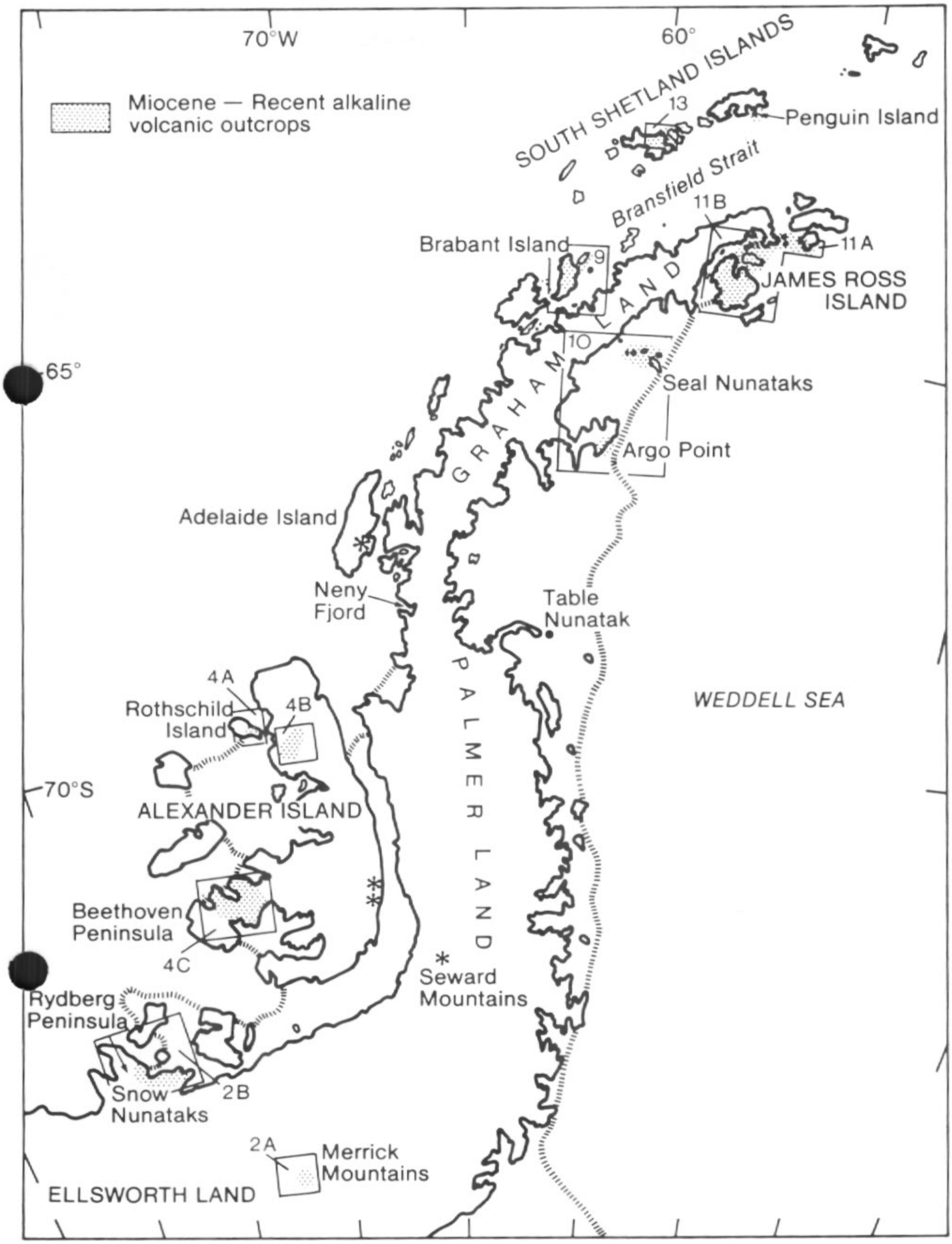

Fig. 1. Map of the Antarctic Peninsula, showing the locations of all known outcrops of Miocene–Recent alkaline volcanic rocks, figured maps (numbered boxes) and localities mentioned in the text. (* = outcrop consisting entirely of dyke(s) or plug(s).)

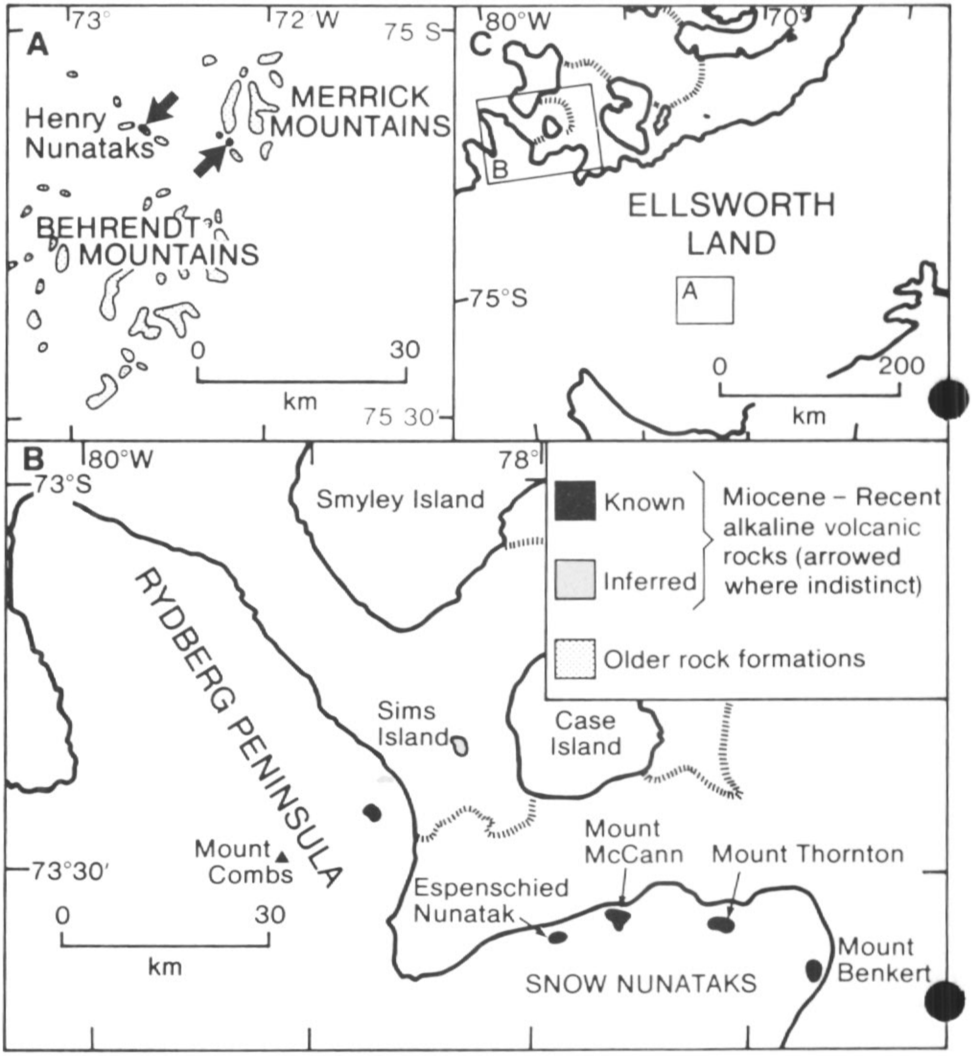

Fig. 2. Sketch maps showing alkaline volcanic outcrops in A, Merrick Mountains (based on Vennum and Laudon, in press) and Henry Nunataks, B, Rydberg Peninsula and Snow Nunataks and C, their location in eastern Ellsworth Land.

Snow Nunataks may represent a number of separate lava- or tuff-cones emplaced along a single, approximately east–west-trending fissure. Although the lithologies are similar throughout the group, the volcanic sequence observed at each nunatak is different. At Espenschied Nunatak there are frost-shattered exposures of rubbly, dark reddish brown and black lapilli-tuffs and tuff-breccias, whereas exposures at Mount McCann, 16 km to the east, represent an almost continuous pile of gently dipping lavas, 250–300 m thick. These are mostly highly vesicular pillow lavas capped by more massive black vesicular flows. Frost-shattered blocky vesicular lavas occur as thin or lenticular flows within the predominantly volcaniclastic sequence at Mount

Fig. 3. 350-m thick multiple channel-fill sequence cutting volcaniclastic beds at western Mount Benkert, Snow Nunataks.

Thornton, and at the eastern end of Mount Benkert thin pillow lavas and pillow-breccias form the basal unit of subhorizontal repetitive lava/tuff-breccia/lapilli-tuff sequences. Brown and tan-coloured palagonitized equivalents of the volcaniclastic rocks at Espenschied Nunatak occur at all the other nunataks, the degree of palagonitization seemingly increasing from west to east along the chain of nunataks. All contain vesicular black pillow and lava clasts and sideromelane shards and they are mostly massive or poorly-graded deposits. However, at Mount Benkert the repetitive lava-tuff sequence apparently grades laterally westwards into bedded volcaniclastic units without lava flows. The bedded units include thinly laminated [illegible]wn tuffs (with small-scale grading) and lenses of coarser basaltic debris interbedded with massive brown and tan-coloured lapilli-tuffs and tuff-breccias. Almost 350 m of largely inaccessible channel-fill deposits cut the bedded units at the western end of Mount Benkert (Fig. 3). These display large-scale washout features, with each unit having a curviplanar base beneath graded and cross-laminated beds. Large pods of (?) lava occur high in the channel-fill deposits, and a network of sinuous mafic dykes cut all lithologies at Mount Benkert and also at Mount Thornton.

Alexander Island

Five altered camptonite dykes with alkaline compositions cut Aptian sedimentary rocks in south-eastern Alexander Island (Horne and Thomson, 1967; Smellie, unpublished geochemical data).

Volcanic rocks form seven nunataks on Beethoven Peninsula, and the morphology of snow-covered Mount Tchaikovsky and Chopin Hill suggests that they too are volcanic in origin (Bell, 1973; Burn and Thomson, 1981; Hole, unpublished

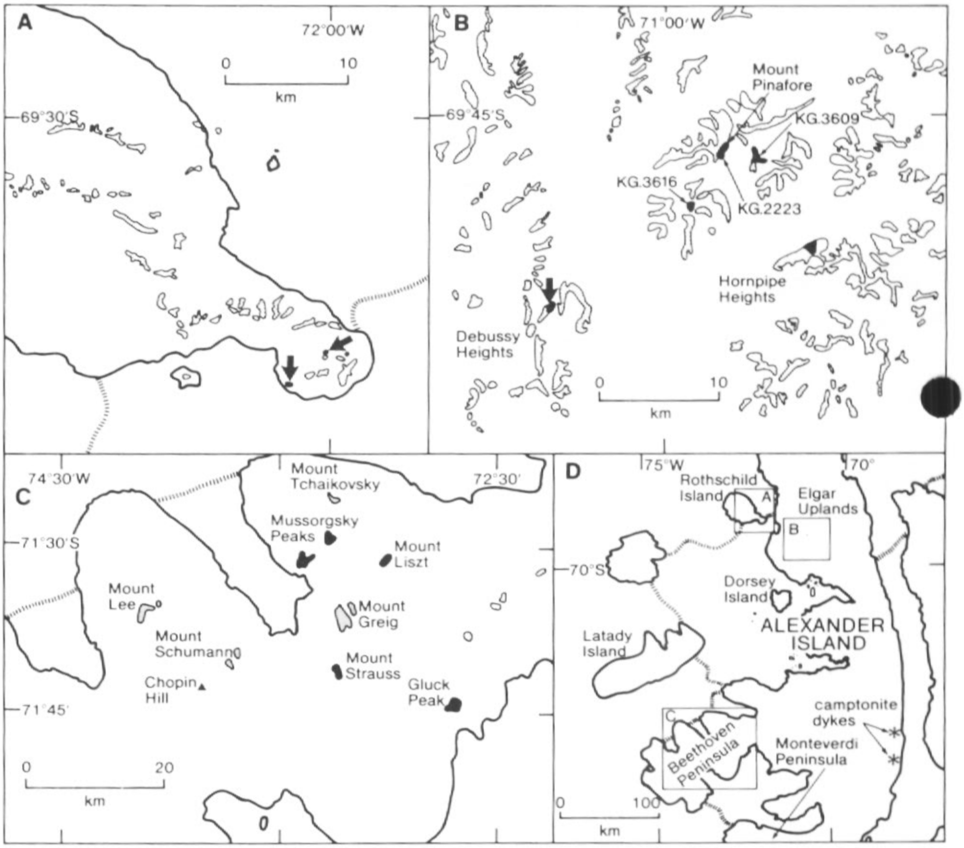

Fig. 4. Sketch maps of A, Rothschild Island, B, Elgar Uplands and C, Beethoven Peninsula, and their relative locations on Alexander Island (D), showing the distribution of alkaline volcanic outcrops. See Fig. 2 for legend; KG. 2223, 3609 and 3616 are geological stations referred to in the text.

information; Fig. 4). Together they form part of a much larger, mostly unexpo[illegible] outcrop identified by a prominent magnetic anomaly extending from Monteverdi Peninsula north–north-west towards Latady Island (Renner and others, 1982). At Mussorgsky Peaks, the lower 180 m is formed of poorly stratified yellow-brown lapillistone, in beds up to 10 m thick containing scattered quartzofeldspathic inclusions, interbedded with thinner (~ 3 m) bed of laminated palagonitized tuff and crystal tuff. Irregular, cross-laminated beds and deep washout channels are common. The rocks pass up, through a 20-m transitional sequence containing interlensed pillow-disintegration breccias, into about 100 m of palagonitized vitric tuff-breccia containing abundant complete and fragmented basaltic pillows. Subvertical dykes, some of which are composite, cut the volcaniclastic sequence at east Mussorgsky Peaks.

Two contrasting modes of occurrence have been identified in the volcanic outcrops in Elgar Uplands, northern Alexander Island (Fig. 4). Subhorizontally bedded sequences, characterized by thick (up to 60 m) olivine basalt flows (some displaying superb colonnade and entablature jointing: Fig. 5) interbedded with relatively thin (up to 25 m) units of palagonitized breccia, lapillistone and tuff (cf. Burn and

Fig. 5. Basalt lava near Mount Pinafore, Elgar Uplands (KG. 3609; Fig. 4B), showing well-developed colonnade and entablature columnar jointing. The flow is approximately 60 m thick.

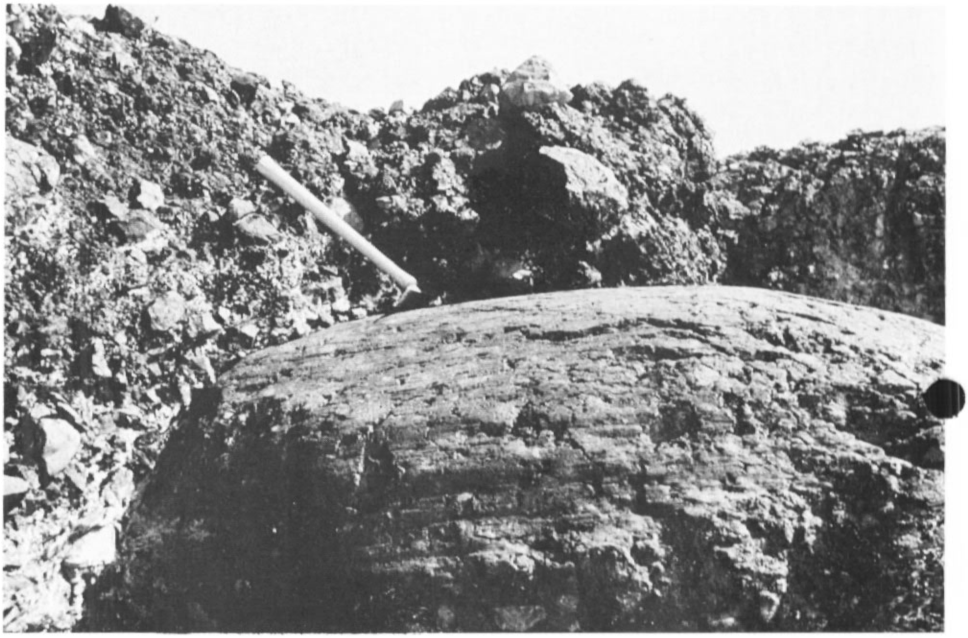

Fig. 6. Basaltic *aa* lava unconformably overlying a surface of glacially striated Lower Tertiary volcanic rocks at Mount Pinafore (KG. 2223; Fig. 4B). The hammer shaft is 34 cm long. Photograph by R. W. Burn.

Fig. 7. Aerodynamically moulded basaltic bombs in agglutinate at Hornpipe Heights, Elgar Uplands. The hammer head is 17 cm long.

Fig. 8. Agglutinate sequence at Hornpipe Heights, Elgar Uplands, steeply banked against paler-coloured, deformed Mesozoic metasedimentary rocks. The buttress of dark-coloured agglutinate in the foreground is about 15 m high.

Thomson, 1981), crop out around Mount Pinafore. Diamictite is present at the base of the volcanic sequences at two localities (KG. 3609, 3616), and a basaltic *aa* lava unconformably overlies a glacially striated pavement at a third locality (KG. 2223; Fig. 6). Olivine-rich peridotite nodules are extremely common at all localities in the Elgar Uplands. Much thinner (< 2 m) olivine- and olivine-plagioclase-phyric lavas are interbedded with thick (up to 20 m) agglutinate deposits at Hornpipe Heights (Fig. 4). The agglutinates overlie a black lapillistone of variable thickness and are [illegible]king rocks, predominantly formed of aerodynamically moulded vesicular bombs up to 30 cm long (Fig. 7). A variable *ortho-* to *para*-conglomeratic breccia occurs locally at the base of the section. The entire sequence is unconformably draped on a steeply inclined (40°) surface cut in Mesozoic metasediments (Fig. 8).

On Rothschild Island (Fig. 4), three small outcrops contain irregularly bedded, pale yellow and brown, coarse and fine palagonite tuffs and lapillistones displaying cross-laminations, channels and microfaults (Care, 1980). They are best exposed in a 100-m high cliff, which is crudely columnar-jointed throughout and is intruded by a few dykes containing sparse ultramafic nodules. Ultramafic nodules also occur in lava clasts in some beds, and there are a few grey, stratified normally graded lapilli-tuffs. Two of the outcrops may have been capped originally by massive or brecciated lava, now present as piles of black scoriaceous scree.

The tiny outcrop of volcanic rock on a small island 20 km north-west of Dorsey Island (Fig. 4), previously assigned a (?)Pliocene–Recent age (British Antarctic Survey, 1981), is an andesite with numerous phenocrysts of hornblende, augite, hypersthene, opaque oxide and apatite, which probably formed during the Late Cretaceous–Early Tertiary period of calc-alkaline volcanism (cf. Burn, 1981).

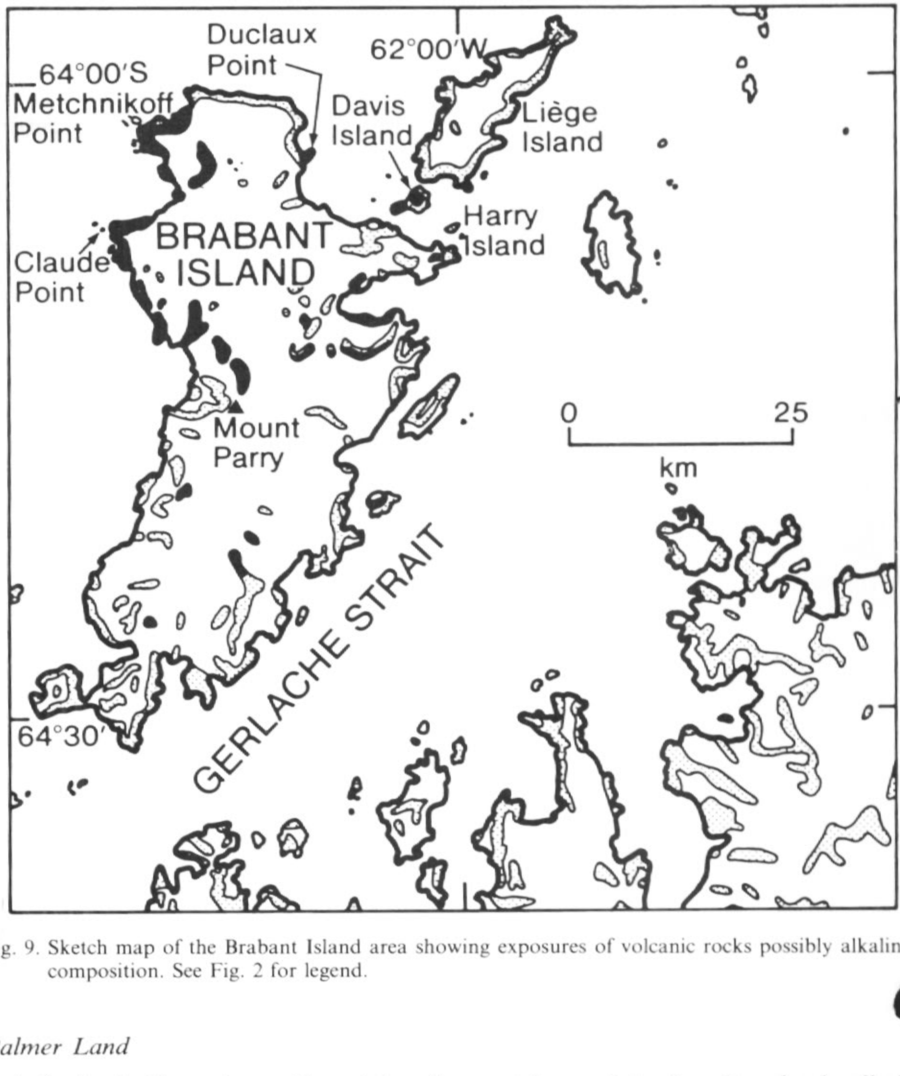

Fig. 9. Sketch map of the Brabant Island area showing exposures of volcanic rocks possibly alkaline in composition. See Fig. 2 for legend.

Palmer Land

A fresh alkaline microgabbro dyke of uncertain age intrudes altered calc-alkaline volcanic rocks in the Seward Mountains (Singleton, 1979; Smellie, 1987; Fig. 1). With the possible exception of Table Nunatak, a flat-topped snow-free feature with gently but persistently steaming meltpools which may be due to high heat flow related to former volcanism (D. I. M. Macdonald, pers comm., 1985), the Seward Mountains dyke is the only known expression of alkaline volcanism in Palmer Land. The reported 'palagonite tuff' from north-western Palmer Land (Rowe, 1973, p. 60) can be discounted: the specimen is a reddish coloured spherulitic rock which closely resembles a devitrified calc-alkaline rhyolite.

Western Graham Land

Dewar (1970, p. 54) described an unusual hypabyssal complex cutting leucogranodiorite in central Square Peninsula, Adelaide Island (Fig. 1). It consists of an altered basalt pipe 5 m in diameter from which two basalt dykes emanate. A third dyke, containing abundant ultramafic enclaves, abuts the plug at its western margin. This dyke has striking plumose titanaugite in harrisitic layers, probably developed by chilling of the dyke against the plug, although Dewar (1970, p. 64) considered the plug to be the younger intrusion. Nichols (1955) described lamprophyre dykes cutting granite in Neny Fjord, but the occurrence has yet to be confirmed and the dyke compositions are unknown.

Volcanic rocks of likely late Tertiary or Pleistocene age have been recorded on Anvers, Brabant and Liège islands, and several islands in Bransfield Strait (Hooper, 1962; González-Ferrán and Katsui, 1970; Alarcón and others, 1976; Gledhill and others, 1982; Bell, 1984), although information on all occurrences is sparse and not all of the localities have been visited. Only a few can be considered as alkaline outcrops using the criteria outlined earlier (Fig. 9). Petrographical examination of specimens from other supposed upper Cenozoic outcrops (cf. Hooper, 1962; Bell, 1984) indicates calc-alkaline affinities for these rocks, some of which have yielded Paleocene–Oligocene ages (Rex, 1972).

On Brabant Island up to 300 m of subhorizontal, columnar-jointed basic–intermediate lavas of the Bahía Bouquet Formation (?Pleistocene: Alarcón and others, 1976; Fig. 9) unconformably overlie (?) Tertiary terrestrial sedimentary rocks, and were probably erupted from several centres: volcanic necks have been postulated at Duclaux Point, Mount Parry, an unnamed peak *c.* 10 km south–south-east of Mount Parry, and Davis Island (González-Ferrán and Katsui, 1970; Alarcón and others, 1976). Horizontally bedded vesicular basaltic lava flows of Pleistocene age cap thick agglomerates at the north end of the island, particularly at Metchnikoff Point (Ringe, 1985), and a 100–200 m thick sequence of thin vesicular lava flows, followed by yellow hydroclastic tuffs is capped by a black glassy flow at Claude Point (British Antarctic Survey, 1986). Gently dipping, palagonite tuffs and fresh basalt lavas, that possibly correlate with the Bahía Bouquet Formation, crop out on Liège and Davis islands, and a small islet close to Harry Island (Bell, 1984). Because of the complicated tectonic setting of these rocks, which were probably formed in a tensional environment following ridge crest–trench collision (cf. Smellie, 1987), it is unlikely that all are of alkaline compositions.

Eastern Graham Land

A degraded scoria cone about 300 m across crops out at Argo Point, eastern Jason Peninsula (Saunders, 1982; Fig. 10). The cone is breached on its northern side and its flanks are dotted with numerous blocks and bombs. Cliff exposures below the cone consist of interbedded lava and scoria. Ropy flow textures are common and some lavas contain sparse felsic enclaves.

Seal Nunataks contain at least 16 small volcanic outcrops, several of which may be well-formed volcanic cones (Lindenberg Island, Dallman, Donald, Bruce and Bull nunataks, and a tiny parasitic crater on Murdoch Nunatak: González-Ferrán, 1983*a*; Fig. 10). The outcrops consist of subhorizontally bedded, yellow-brown and reddish, very friable palagonite tuffs, lapillistones and agglomerates, which locally contain abundant ultramafic nodules (Fleet, 1968; González-Ferrán, 1983*a*; del Valle and others, 1983). Lavas are uncommon, mostly occurring as loose piles of *aa*, but a massive *pahoehoe* lava occurs at Christensen Nunatak (Fleet, 1968). Highly vesicular basalt dykes are prominent in most nunataks. Fumarolic activity is said to be widespread (González-Ferrán, 1983*a*) and may account for the 'volcanic eruption' reported in 1893 (Larsen, 1894).

Outcrops in north-eastern Graham Land centre on James Ross Island, extending

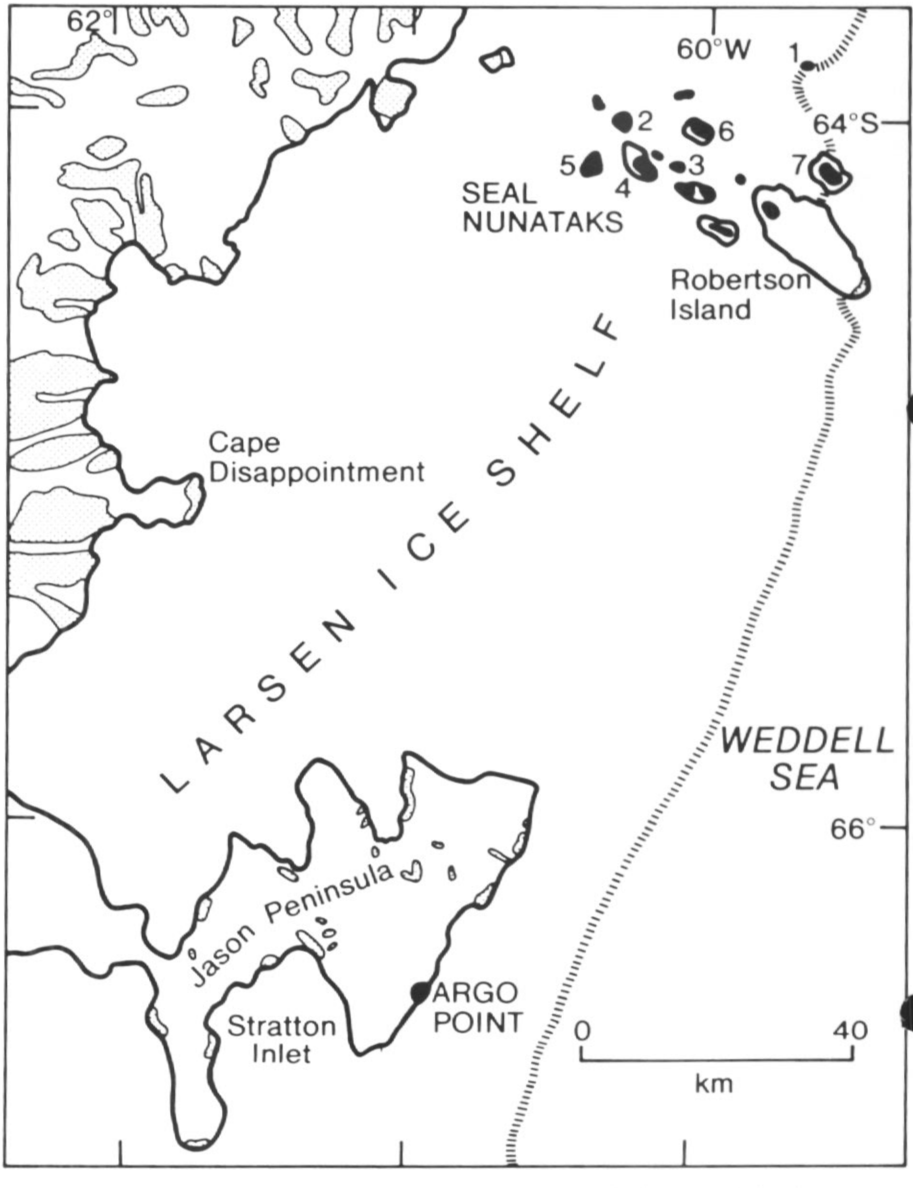

Fig. 10. Sketch map of Seal Nunataks and Jason Peninsula, eastern Graham Land, showing outcrops of alkaline volcanic rocks. See Fig. 2 for legend. (1, Lindenberg Island; 2, Dallman Nunatak, 3, Donald Nunatak; 4, Bruce Nunatak; 5, Bull Nunatak; 6, Murdoch Nunatak; 7, Christensen Nunatak.)

across Prince Gustav Channel to Trinity and Tabarin peninsulas, islands in Antarctic Sound and Dundee and Paulet islands (collectively called the James Ross Island Volcanic Group (JRIVG): Baker and others, 1973; Aitkenhead, 1975; Nelson, 1975; Fig. 11). James Ross Island is a composite shield volcano which may have provided a nucleus around which lavas and palagonite breccias were deposited. A second, smaller shield volcano was probably centred on Tabarin Peninsula and included

Fig. 11. Sketch map showing outcrops of the James Ross Island Volcanic Group in A, the Antarctic Sound area and B, James Ross Island. Two small outcrops of JRIVG on nearby Trinity Peninsula are beyond the limits of the map. See Fig. 2 for legend.

outcrops in Antarctic Sound. At least five, possibly seven, volcanic phases were recognized by Nelson (1975), although his stratigraphy has not been confirmed by radiometric dating (see below). Each volcanic phase is represented by a lithologically tripartite congeneric unit, comprising basal structureless, highly vesiculated, subaqueous tuffs overlain by up to 152 m of coarse palagonite breccias disposed in

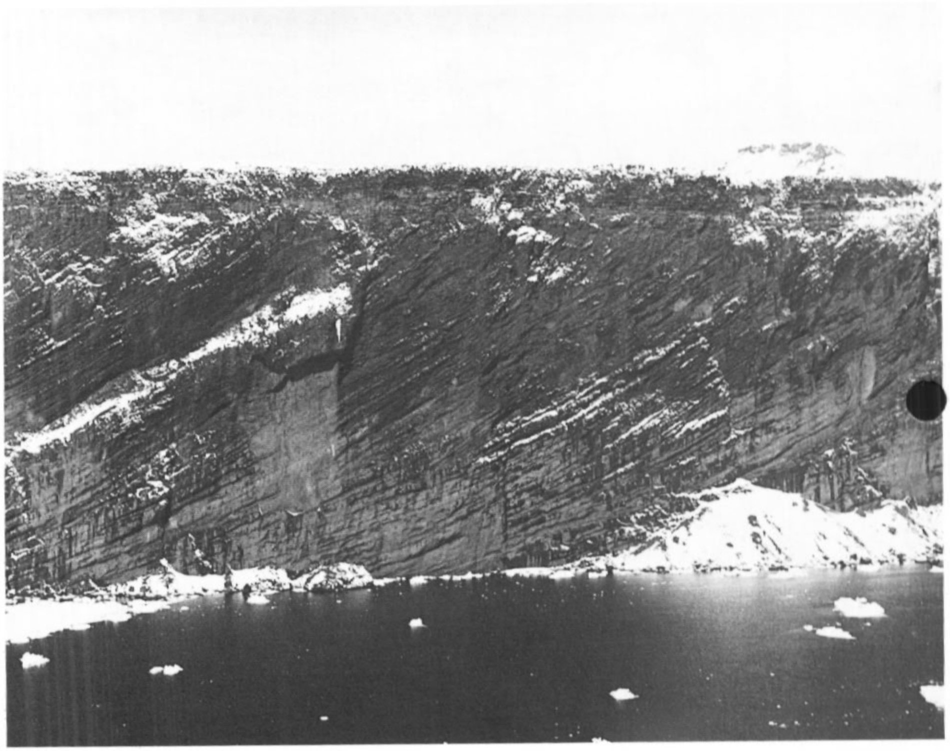

Fig. 12. Steep-dipping hyaloclastite flow-foot breccias overlain by flat-lying *pahoehoe* lavas on Vega Island, near James Ross Island. The cliff section is about 200 m high. Photograph by HMS *Endurance*, 1986.

steep-dipping foreset beds then subhorizontal highly vesicular *pahoehoe* lava (Fig. 12). The breccias are hyaloclastites formed of poorly vesicular blocky glass shards and juvenile lava fragments together with numerous complete and fragmented pillows. The proportion of pillows ranges from 20 to 90%. Sandstones with stratigraphic[illegible] undiagnostic ophiuroids form the basal beds of the JRVIG succession at one locality (Bibby, 1966, p. 26) and there are thin-bedded subaqueous tuffs showing a variety of structures indicative of deposition from traction and turbidity currents (Pirrie and Sykes, 1987). Pyroclastic tuffs are rarely present, and pockets of marine tillite with *Chlamys anderssoni* locally separate the JRIVG from underlying Upper Cretaceous rocks (British Antarctic Survey, 1983). There are at least four volcanic plugs on James Ross Island, a few vesicular dykes and a small laccolith (Palisade Nunatak). Small well-preserved craters occur on Paulet Island and the plateau edge north-east of Mount Haddington (Fig. 11), and probably represent the most recent manifestations of volcanic activity in the area (Baker and others, 1973; British Antarctic Survey, 1982).

Numerous olivine basalt and microgabbro dykes in eastern Graham Land have been correlated lithologically with the JRIVG (Elliot, 1966; Fleet, 1968; Marsh, 1968; Stubbs, 1968; Aitkenhead, 1975; Medina and Ramos, 1983). However, there is minimal evidence for the age and chemical affinities of the dykes and they are omitted from Fig. 1.

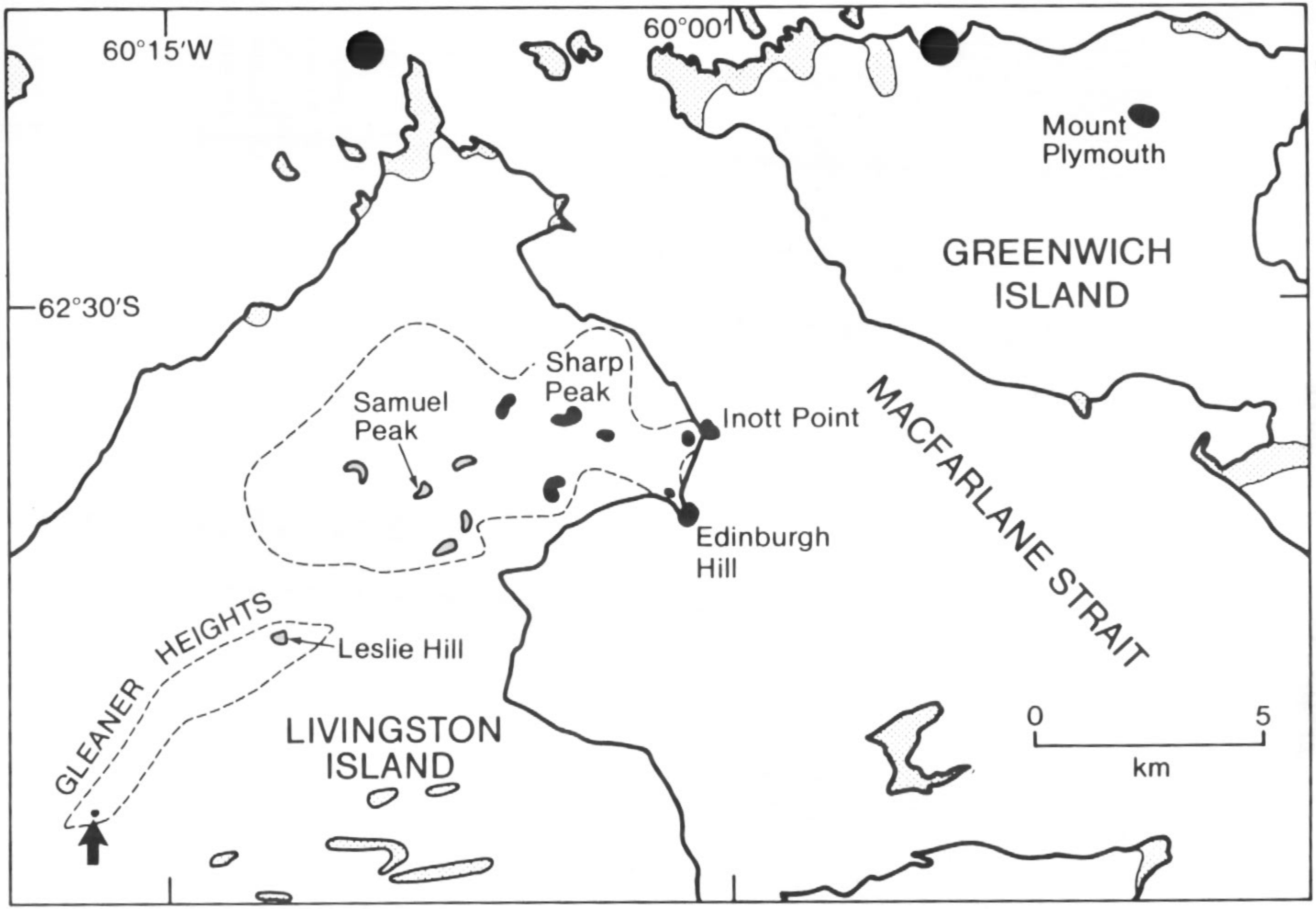

Fig. 13. Sketch map of parts of Livingston and Greenwich islands, South Shetland Islands, showing exposures of alkaline volcanic rocks. The inferred sub-ice extent of the Livingston Island outcrops is indicated by dashed lines. See Fig. 2 for legend.

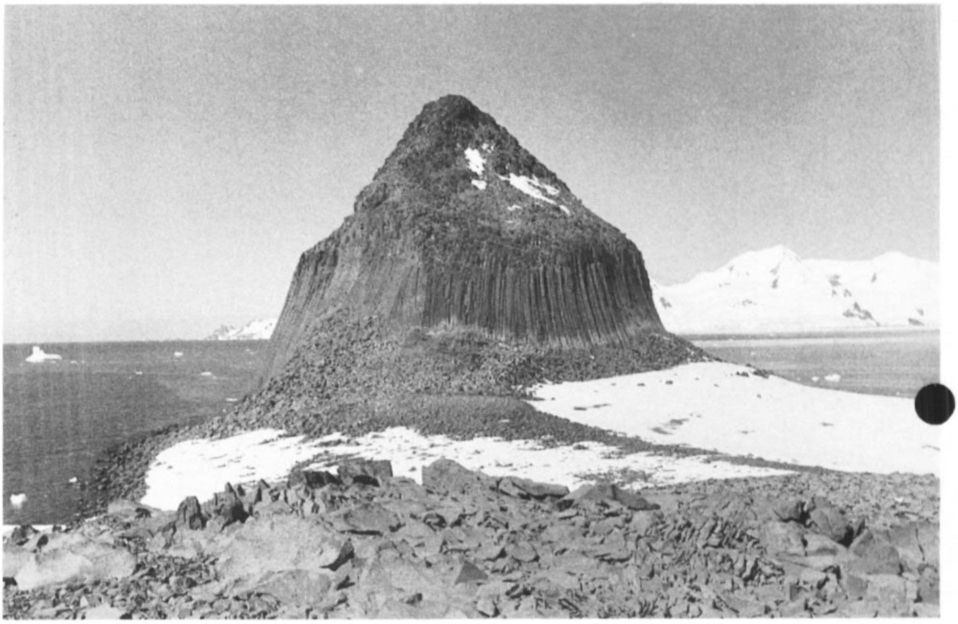

Fig. 14. Columnar-jointed dolerite plug at Edinburgh Hill Livingston Island, looking south-east. The plug is about 110 m high.

South Shetland Islands

Penguin Island (Fig. 1) consists of a largely uneroded stratocone with a prominent crater (Deacon Peak) within which is located a tiny scoria cone (Marr *in* Tyrrell, 1945; González-Ferrán and Katsui, 1970; Weaver and others, 1979; Birkenmajer, 1982*b*). A partly flooded, nearly circular explosion crater occurs on the east side of the island (Petrel Crater); it may be of similar age to the remains of a larger explosion crater west of Deacon Peak, although the latter may simply be a scar left after sector collapse of the Deacon Peak stratocone. The lowest exposed unit (Marr Point Formation: Birkenmajer, 1982*b*) comprises about 50 m of gently dipping plateau lavas of blocky *aa* type interbedded with tephra and beach sand. The lavas thic[illegible] towards the north-east, possibly indicating derivation from a vent in that direction. The Marr Point Formation is overlain unconformably by steep-dipping quaquaversal beds of the principal cone (Deacon Peak Formation), consisting of alternating poorly consolidated reddish tuffs, lapillistones and rare agglomerates; thin black scoriaceous lavas occur in the basal sections. A plug encased in baked tephra blocks the main vent and is exposed in an isolated stack on one side of the main crater. The small central cone within the main crater is built of red-brown and black clinkery rubble and is breached by lava on its east side. Petrel Crater is a maar with associated thin deposits (2–5 m) of loose ejectamenta.

Most of the outcrops on Livingston and Greenwich islands (Fig. 13) consist of a sub-central, fresh dolerite plug encased in stratified lapilli-tuffs (Ferguson, 1921; Díaz and Teruggi, 1956; Hobbs, 1968; Smellie and others, 1984; Smellie, unpublished information). Lavas are extremely rare and the deposits were probably erupted from numerous small, overlapping volcanic centres. Well-developed columnar jointing is a feature of all the plugs (Fig. 14). Compositionally, the plug at Edinburgh Hill may be tholeiitic (Dupre, 1982), and it is uncertain how the outcrop relates to the alkaline

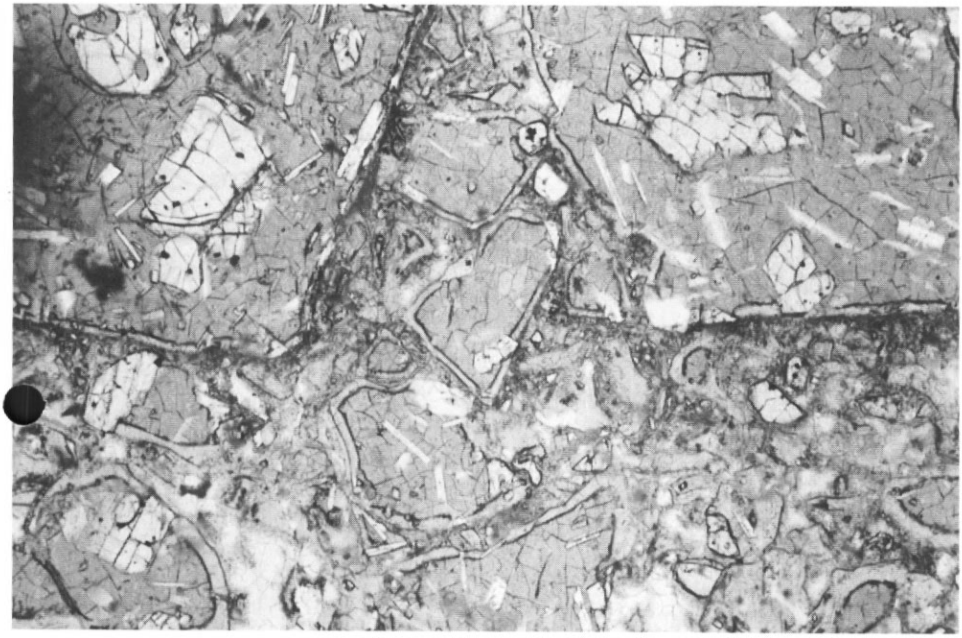

Fig. 15. Photomicrograph of a typical hyaloclastite from James Ross Island, showing characteristic non-vesicular, blocky sideromelane clasts and sparse matrix.

province. The lapilli-tuffs are yellow-brown, monomict, pervasively palagonitized rocks; accidental clasts (granitoids and deuterically altered volcanic rocks) occur in only one vent (Inott Point). Gently inclined or flat-lying stratification is present at all localities, ranging from 1 to 40 cm in thickness. The coarser, thicker, lapilli-rich beds are either massive or reverse- to normal-graded, whereas the thinner tuff-rich beds typically contain well-developed parallel lamination. Very low-angle cross-stratification is rarely present. Air photograph interpretation suggests that the eastern outcrop on Livingston Island bestrides a gently east-sloping, subdued topographical surface cut in older (Cretaceous?) volcanic rocks.

PYROCLASTIC DEPOSITS

Since this review is based principally on a literature survey, it is neither possible nor is it the intention to provide a quantitative volcanological treatment of the individual alkaline outcrops. However, even a qualitative appraisal of the available information permits at least three broad groups of pyroclastic deposits to be recognized.

Magmatic deposits

Small, well-formed, steep-sided cones composed predominantly of red and black cindery lava rubble, in places interbedded with *pahoehoe* and *aa* lava flows, are typical airfall products of strombolian volcanic activity. The best examples occur at Penguin Island (Deacon Peak and the small cinder cone within the summit crater), Argo Point, Seal Nunataks and Paulet Island (summit cone). Eroded strombolian deposits are also common and include the spectacular agglutinate sequence at Hornpipe Heights in northern Alexander Island (Figs 4, 7), with its abundance of reddened, aero-

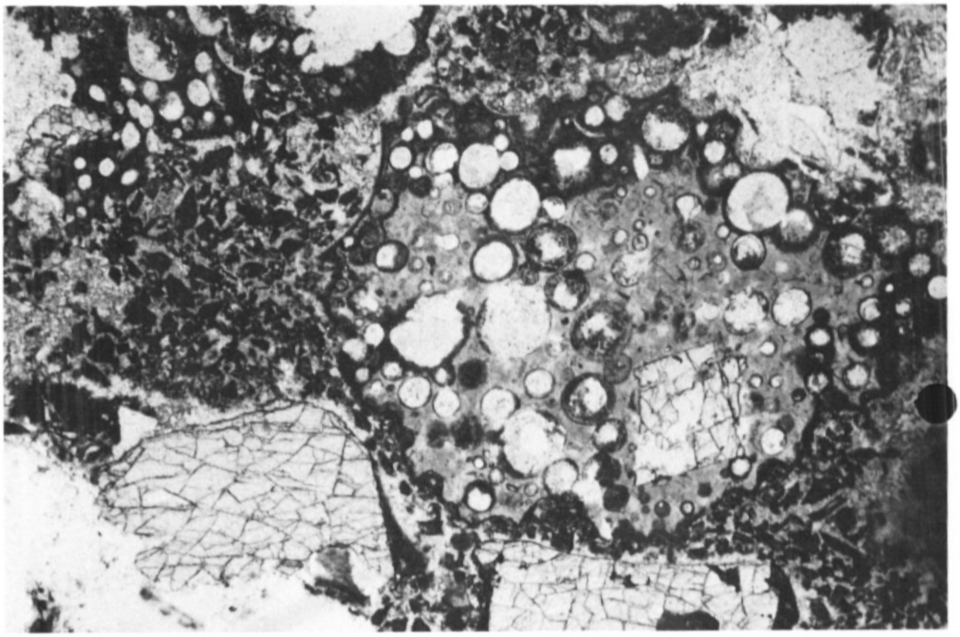

Fig. 16. Photomicrograph of a typical hyalotuff from Beethoven Peninsula, Alexander Island, showing highly vesiculated clasts with cuspidate margins and abundant matrix formed of shards.

dynamically moulded vesicular bombs, and stretched and twisted ribbons produced by pulling apart of magma during magma fountaining. The weakly welded agglutinate is plastered on a steep valley slope at an angle greater than the stable angle of repose for cohesionless sediments (Fig. 8). The significance of the pyroclastic rocks of strombolian type is that they represent unambiguous subaerial magmatic effusivity. Within any sequence, they tend to form the latest erupted units.

Phreatomagmatic deposits

Hydroclastic deposits formed by phreatomagmatic eruptions form most of the rocks exposed in many outcrops. They are particularly characteristic of the lower units in any sequence and are much more diverse lithologically than the strombolian airfall deposits. As a group, they are distinguished by a striking pale yellow-brown colour due to pervasive palagonitization of the abundant vitric clasts. The deposits are predominantly vitric tuff-breccias which have been collectively called hyaloclastites by many other workers. However, the term has been misused, and the published information and preliminary petrographical study indicate that at least two broad genetic groups can be distinguished based on lithological criteria described by Honnorez and Kirst (1975).

(i) *Hyaloclastites* are the predominant pyroclastic facies in the JRIVG (the palagonite breccias described by Nelson (1975)) and parts of the Beethoven Peninsula sequence of Alexander Island. The deposits are composed of dense, blocky sideromelane fragments and shards of low vesicularity and negligible fine-grained matrix, that probably formed mainly by mechanical granulation and spalling of glassy lava crusts (Fig. 15). In the JRIVG, the hyaloclastites are disposed in large-

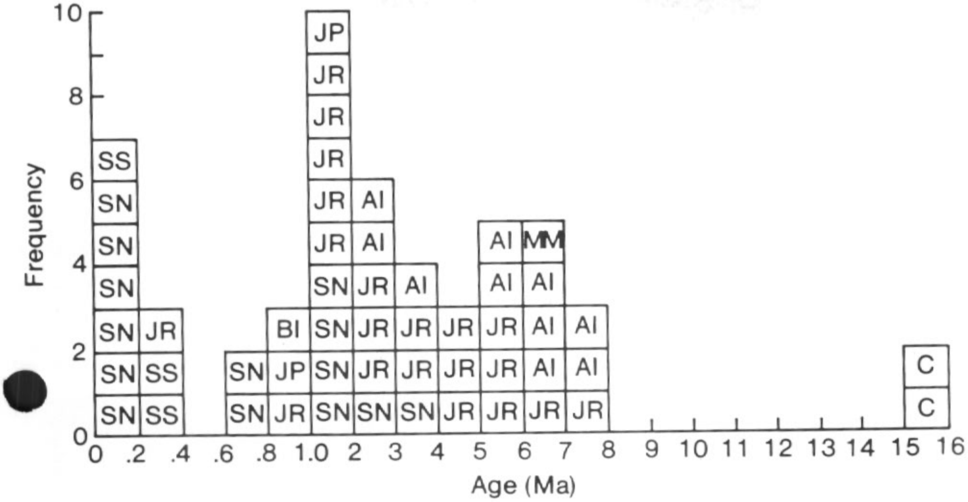

Fig. 17. Frequency histogram showing all published and new K–Ar whole-rock ages for Antarctic Peninsula area alkaline volcanic rocks. AI, Alexander Island; BI, Brabant Island; C, camptonite dykes; JP, Jason Peninsula; JR, James Ross Island area; MM, Merrick Mountains; SN, Seal Nunataks; SS, South Shetland Islands.

scale (~ 150 m thick) cross-bedded units which pass up into subaerial lavas. Nelson (1975) envisaged an origin as hyaloclastite deltas formed where largely degassed lava streams entered seawater. Nelson (1975) also described other subaqueous tuffs with rounded clasts, fine stratification, cross-laminations, slumping and washout structures, which may represent more distal (?)pro-deltaic sediments reworked and redeposited by (?)turbidity and traction currents (cf. Pirrie and Sykes, 1987).

(ii) *Hyalotuffs* are more widely distributed than hyaloclastites and are the commonest pyroclastic rocks in most outcrops away from the JRIVG. They consist of vitric tuffs and poorly sorted, tuff-rich lapillistones largely composed of angular, moderate to highly vesicular sideromelane and tachylite tephra (Fig. 16). Within any deposit, juvenile clast morphology varies from highly cuspidate (due to high vesicle density) to blocky, probably indicating synchronous pyroclastic disruption (volatile disintegration) and quenching by ice, water or water vapour, although the processes involved are particularly complex (e.g. Kokelaar, 1986). Some sequences contain prominent channel-like features and are parallel- and cross-laminated, features invariably interpreted as evidence for a possible subaqueous origin (cf. Bell, 1973; Care, 1980). However, except for large-scale features (e.g. the channel at Mount Benkert, Snow Nunataks), similar structures also characterize indurated tuff-rings formed by pyroclastic surges during phreatomagmatic eruptions (Fisher and Schminke, 1984; Wilson and Smith, 1985). One such sequence on Alexander Island is crudely columnar-jointed throughout (Care, 1980) and is interpreted here as possible evidence for heat retention in a hydroclastic deposit. However, it is unlikely that the origin of all the laminated, channelled sequences can be explained so simply, due to the ease with which unconsolidated tephra are redistributed by epiclastic processes.

AGE OF THE VOLCANISM

Stratigraphical evidence for the age of eruption of the alkaline volcanic rocks is imprecise. The suite as a whole is clearly post-Cretaceous, and on Adelaide Island an alkaline dyke cuts Lower Tertiary intrusive rocks. On Cockburn Island, in the James Ross Island area, the basalts are overlain by the well-known '*Pecten* conglomerate', the age of which is itself uncertain, although it is probably no older than 6 Ma (Zinsmeister and Webb, 1982). However, fresh appearance, un-eroded volcanic landforms and evidence of glacial interaction are all general signs of a very young age, emphasized at Seal Nunataks by present-day fumarolic activity. Further analysis of the time-span and evolution of the volcanism is entirely dependent on radiometric age determination.

Forty-five K–Ar whole-rock ages have been published for these rocks, mostly from the northern end of the Antarctic Peninsula (Table I). New determinations made at the British Geological Survey laboratories using conventional K–Ar techniques a[illegible] presented here (Table II). They include two samples from the JRIVG; the remainder are from east-central Graham Land and extensive outcrops on Alexander Island.

It should be emphasized that K–Ar dating of such young material is often imprecise, due mostly to the large correction for atmospheric Ar content (see Table II). Other factors, such as system blanks, sample heterogeneity and incomplete fusion of large samples, can easily result in slightly discrepant ages. For example, samples from Seal Nunataks analysed by Rex (1972, 1976) contain radiogenic Ar at levels below the limits of detection, resulting in ages of less than 0.2 Ma, whereas ages from the same area determined by del Valle and others (1983) range from 0.7 ± 0.3 Ma to 2.8 ± 0.5 Ma. Inter-laboratory comparisons are very uncertain in this age range, and detailed interpretation of the data must be made with caution.

Within the limits set by these qualifications, we can probably draw some overall conclusions from the complete set of data, which is shown in the form of a histogram in Fig. 17.

(i) The oldest results are two dates of 15 Ma for camptonite dykes in eastern Alexander Island. Their relationship to the other alkaline volcanic rocks is unknown, and should perhaps be regarded with suspicion in view of the apparent 7 Ma hiatus before the next oldest age for rocks of this group. Alkali basalts in the Jones Mountains about 800 km farther west–south-west have given discordant K–Ar ages, but with a concentration in the 7–10 Ma interval, which is taken as the most likely time of eruption (Rutford and others, 1972). Apart from the camptonite dykes, the[illegible] would represent the earliest known rocks of this type in the study area.

(ii) Other ages span the period from about 8 Ma ago down to the present (i.e. from late Miocene times). This is consistent with the geological relationships (see above). There are apparently three periods of more intense volcanism, at 5–7 Ma, 1–2 Ma and < 0.2 Ma, although the peaks in the histogram could be partly a result of concentrated sampling in a few areas.

(iii) There are *apparent* changes in the geographical location of volcanism with time. Except for the camptonite dykes, the Alexander Island volcanism spans the range 2–8 Ma and is responsible for the oldest peak in the histogram. Activity in the James Ross Island area spans the range 1–7 Ma but is apparently concentrated at the younger limit together with the new ages from Jason Peninsula, and with one still younger age of 0.3 Ma from Paulet Island. Finally the activity at Seal Nunataks may be bimodal, with one group of ages in the 1–2 Ma acme and another at < 0.2 Ma. As noted above, this bimodality may be a result of inter-laboratory bias. The younger group is also consistent with ages close to the limit of radiogenic Ar detection for

Table I. Radiometric ages of Cenozoic alkaline volcanic rocks from the Antarctic Peninsula*

Locality	*Rock type*	*Age (Ma)*	*Reference*
South Shetland Islands			
Mount Plymouth,	Basaltic plug	0.2±0.3	1,2
Greenwich I.	Basaltic plug	0.2±0.4	1,2
Gleaner Heights, Livingston I.	Basaltic lava	0.1±0.4	1,2
James Ross Island Volcanic Group			
South Tail I.	Lava, Phase I	2.7±0.5	3
James Ross I.	Lava, Phase II	2.0±0.5; 1.4±0.2; 1.4±0.3	3,4†
	Lava, Phase II	4.6±0.4	3,4
	Lava, Phase III	2.2±0.5; 3.3±0.8	3,4
	Lava, Phase IV	3.5±0.5	3,4
	Dolerite sill	5.4±0.3; 6.5±0.3	4
	Lava	4.6±0.4	4
	Clast in tuff	2.1±1.0	3,4
	Clasts in breccia	5±1; 7±1	5
Seymour I.	Dyke	6.8±0.5	6
Beak I.	Lava	1.7±0.2; 2.0±0.2	4
Eagle I.	Lava	2.0±0.2; 1.7±0.2	4
Red I.	Lava	1.6±0.2	7
Paulet I.	Lava	0.3±0.1	7
Tabarin Peninsula	Lava	1.1±0.1; 1.1±0.1	4
Tabarin Peninsula	Lava	0.9±0.2	7
Seal Nunataks			
Åkerlundh	Lava	< 0.1	3,4
Åkerlundh	'Volcanic'	0.7±0.3	8
Larsen	Lava	< 0.1	3,4
Larsen	'Volcanic'	1.5±0.5	8
Unspecified	Lava	< 0.1; < 0.1	3,4
Gray	'Volcanic'	< 0.2	8
Arctowski	'Volcanic'	1.4±0.3	8
Christensen	'Volcanic'	0.7±0.3	8
Bruce	'Volcanic'	1.5±0.3	8
Donald	'Volcanic'	< 0.2	8
Evensen	'Volcanic'	1.4±0.3	8
Oceana	'Volcanic'	2.8±0.5	8
Oceana	Lava	3.0±0.5	3,4†
Elephant Island	'Volcanic'	< 1	9
Alexander Island			
Waitbit Cliffs	Camptonite dyke	15±1; 15±1	10
Eastern Ellsworth Land			
Merrick Mountains	Basalt	6	11

* The data in this table were published with a variety of isotopic constants, but none is sensitive to correction to current conventional values.

† Localities incorrectly identified by Rex (1972, 1976), correctly positioned here.

References: 1, Pankhurst and Smellie, 1983; 2, Smellie and others, 1984; 3, Rex, 1972; 4, Rex, 1976; 5, Malagnino and others, 1978; 6, Massabie and Morelli, 1977; 7, Baker and others, 1977; 8, Del Valle and others, 1983; 9, Ringe, 1985; 10, Rex, 1970; 11, Halpern, 1971.

isolated basaltic plugs and lavas of mildly alkaline character which occur in the South Shetland Islands. These may be associated in some way with the opening of Bransfield Strait as a Recent marginal basin.

(iv) It should be noted that the Alexander Island samples reveal a relatively extended period of volcanism there, comparable to that of the JRIVG. Thus the data

Table II. New K–Ar ages for alkaline volcanic rocks from the Antarctic Peninsula

Locality and sample no.	*K_2O(%)*	*^{40}Ar (rad nl/g)*	*% Ar (atmos.)*	*Age (Ma)*
		James Ross Island Group		
Persson Island (dolerite sills)				
D. 8408 . 56a	1.568	0.2727	90.1	4.5 ± 0.5
D. 8408 . 58b	1.272	0.2650	91.6	5.4 ± 0.7
		Jason Peninsula		
Argo Point (olivine basalt)				
R. 217.7 (lava)	0.668	0.0265	96.2	1.0 ± 0.3
		0.0211	88.4	0.8 ± 0.1
R. 218.3 (intrusion)	0.493	0.0313	96.8	1.6 ± 0.5
		0.0254	96.0	1.3 ± 0.3
		Alexander Island		
Elgar Uplands area (tephrite lavas)				
KG.2217.16	1.869	0.2829	89.4	3.9 ± 0.4
KG.2217.14	1.342	0.2811	80.4	5.4 ± 0.3
KG.2217.13	1.151	0.2694	62.2	6.0 ± 0.2
		0.2791	79.2	6.2 ± 0.3
KG.2223.4	2.027	0.5429	69.2	6.9 ± 0.2
KG.2223.3	1.564	0.4344	81.0	7.1 ± 0.4
KG.2230.1	1.311	0.3947	88.4	7.7 ± 0.6
		0.3859	85.6	7.6 ± 0.6
		0.3732	84.6	7.3 ± 0.4
KG.2431.5	2.353	0.5522	52.0	6.0 ± 0.2
		0.57911	71.0	6.3 ± 0.2
Rothschild Island (basanite lava)				
KG.3619.4	2.167	0.3812	86.0	5.4 ± 0.7
Hornpipe Heights (basanite lava)				
KG.3612.5	2.357	0.1891	91.1	2.5 ± 0.8
KG.3608.9	2.115	0.1845	75.4	2.7 ± 0.2

K_2O values are means of duplicate or triplicate determinations $\pm 1.0\%$. Decay constants: Steiger and Jäger, 1977.

cannot at present be used to argue for a simple unidirectional shift of activity with time, either northwards (Baker and others, 1977) or westwards.

(v) Even in the JRIVG, where there is a reasonable amount of radiometric da[illegible] we cannot yet use this in a systematic interpretation of the volcanic evolution. Ages from James Ross Island itself, where stratigraphical control is most complete, are mostly older than 2 Ma, but there is no apparent correspondence between ages and the five phases of activity recognized by Nelson (1975) from field observations (see Table I). Moreover, the lavas from islets in Prince Gustav Channel and on Tabarin Peninsula mostly give ages < 2 Ma, and stratigraphical correlation with the flows on James Ross Island should not be attempted.

(vi) Age relationships in the Seal Nunataks area are even more difficult to assess, particularly because of the discrepancies noted above. Although the Recent alkaline volcanic activity extending from Prince Gustav Channel through Seal Nunataks may be taken as generally indicative of a north-east–south-west line of extensional rifting, we are sceptical of the suggestion by González-Ferrán (1983b) that there is a symmetrical increase in ages away from this line through the centre of Seal Nunataks.

Thus the existing age data for the alkaline volcanic rocks of the Antarctic Peninsula area should only be regarded as of reconnaissance value. We suggest that more data will be necessary to evaluate the overall evolution of the province, as well as to test specific hypotheses of geographical shifts in the volcanic loci. Current British Antarctic Survey programmes are designed to approach this in two ways: a detailed geochronological and geochemical study of the sequence on James Ross Island, and a regionally more extensive study, to include all other outcrops.

EVIDENCE FOR A GLACIAL CLIMATE

Despite continuing controversy concerning the maximum age, extent and instability of the West Antarctic ice sheet (e.g. Hughes, 1973; Mercer, 1983), by mid-late Miocene times (10–15 Ma) East Antarctica is believed to have developed a substantial ice sheet (Drewry, 1975; Kenneth, 1977). A significant enlargement is thought to have occurred around Late Miocene–Early Pliocene times (Drewry, 1976), although an [illegible]mnipresent ice sheet (*s.s.*) may not have existed in West Antarctica until the Early Pliocene (Drewry, 1978). This contrasts with evidence from the South Shetland Islands, where an ice sheet may have been present during the Oligocene (⩾ 24 Ma: Birkenmajer and Gázdzicki, 1986) and possibly during two subsequent periods in the Neogene, separated by 'intraglacials' (Birkenmajer, 1985; Birkenmajer and others, 1985; Birkenmajer and Łuczowska, 1987). Moreover, the presence of glacigenic sediments (including lodgement till: Birkenmajer, 1982*a*) containing faceted and striated erratics with a likely East Antarctic provenance, suggests that the Oligocene South Shetland Islands ice cover may have been continuous with a pan-Antarctic ice sheet (Birkenmajer, 1985; Birkenmajer and Wieser, 1985).

Evidence that ice thicknesses in southern Antarctic Peninsula have decreased by at least 500 m locally has led to suggestions that collapse of the ice sheet has occurred within the last 1 Ma (Carrara, 1979; Burn and Thomson, 1981; Clapperton and Sugden, 1982; Waitt, 1983). However, development of an ice sheet of continental proportions is not critical for the formation of the alkaline volcanic rocks by subglacial eruption since eruption(s) beneath local ice caps, valley glaciers or even firn would be sufficient to produce the relatively small thicknesses observed in most Antarctic Peninsula outcrops (cf. Walker and Blake, 1966; LeMasurier, 1972). Indeed, for explosive eruptions to occur in basalt magmas extruded beneath ice, ice thicknesses formerly overlying the sites of alkaline volcanism may not have exceeded a few hundred metres (⩽ 500 m?). This is due, in particular, to the suppressing effect [illegible] the load pressure exerted by the ice, although other factors such as the volume of magma and its rate of eruption may be important (Allen, 1980).

The evidence for the contemporaneity of glaciation and volcanism is strong. The outcrops are visibly glaciated today, and wherever the substratum is exposed it can also be seen to have been glaciated. Moreover diamictites, some containing striated clasts, are associated with several outcrops and are generally interpreted as tillites. A glacial climate can therefore be assumed to have existed during the period in which most or possibly all of the alkaline volcanic rocks were erupted. Evidence occurring in the outcrops themselves is discussed below.

ERUPTIVE ENVIRONMENT

Although a consensus exists that flat-bedded to steeply dipping lavas (some with ropy and/or reddened (oxidized) surfaces) and interbedded strombolian air-fall deposits were all generated by subaerial extrusion, a more diverse origin is envisaged for the hydroclastic deposits, because these may have formed in either subaqueous or subglacial environments.

The occurrence of lava pillows, together with fossil ophiuroids and bivalves in tuffs and tillite on James Ross Island (Bibby, 1966; Nelson, 1975; British Antarctic Survey, 1983) points unambiguously to a subaqueous, glacio-marine environment for at least part of the JRIVG succession, although snow-free (?) inter-glacial conditions may have prevailed at times (Zinsmeister and Webb, 1982). For the islands in the Antarctic Sound area, Baker and others (1973) reconciled the lithologically tripartite sequence formed by each eruptive phase of the JRIVG within a tindar-like model of subaqueous extrusion at different water depths, with subsequent shoaling and transition to subaerial activity as each volcanic pile built up; the pillow-bearing breccias were considered to represent the deepest-water conditions. While this sequence of events may apply locally, Nelson (1975) has also presented a convincing case for a multiple tuya model in James Ross Island, involving widespread hyaloclastite deltas created by subaerial lava streams flowing into the sea and disaggregating to form steeply dipping flow-foot breccias. Isolated pods a[illegible] lenticular masses of pillow lava are not uncommon in this setting (Jones and Nelson, 1970; Furnes and Fridleifsson, 1974; Furnes and Sturt, 1976) and have been observed forming as attached and detached lava buds associated with steep-dipping submarine lava tongues (Moore and others, 1973). Nelson (1975) also ascribed the structureless, highly vesicular tuffs (hyalotuffs), found at the centres of some cone structures, to explosive disintegration during violent early phases of submarine eruptions. Alternatively, some of these structures may represent small littoral cones or simple tuff cones.

Excepting the likely occurrence of minor reworked epiclastic deposits, convincing evidence for either a subaqueous or subglacial origin is absent in the other Antarctic Peninsula and eastern Ellsworth Land outcrops. A glacial climate and subglacial eruption have usually been assumed (Bell, 1973; Care, 1980; Burn and Thomson, 1981; González-Ferrán, 1983*a*; Smellie and others, 1984; O'Neill and Thomson, 1985; Vennum and Laudon, in press) by comparison with better-known superficially similar outcrops in Marie Byrd Land (cf. LeMasurier, 1972). Although many of the outcrops resemble deposits formed in tindars and during subglacial sheet-flow eruptions (e.g. Walker and Blake, 1966; Jones, 1969; Bergh, 1985), the distinction between subaqueous (i.e. marine) and subglacial volcanism remains a major unsolved problem.

Features which may be cited in support of a subglacial origin for Antarctic Peninsula outcrops (excluding the JRIVG) include the following.

(i) Absence of marine terraces, interbedded Cenozoic marine sediments and hyaloclastites containing marine fossils (all outcrops).

(ii) Occurrence of the outcrops at altitudes presumed to be too high (> 1000 m) to be easily explained by uplift of a submarine outcrop by neotectonic processes (northern Alexander Island, Merrick Mountains, Henry Nunataks; but note that the latter outcrop consists only of lavas, with no lithological evidence of interaction with ice).

(iii) Presence of tillite as an integral part of the volcanic sequence (northern Alexander Island).

(iv) Volcanic sequence resting on a glacially striated pavement (northern Alexander Island).

In summary, although a subglacial origin has been cited for many of the outcrops in the Antarctic Peninsula area, our present state of knowledge is such that subglacial eruption is suspected but unproven except possibly for outcrops in northern Alexander Island and Merrick Mountains.

CONCLUSIONS

(1) As a result of this review, it can be shown that there is a significant association of the alkaline volcanic outcrops with areas flanking the Antarctic Peninsula. These positions are the likely loci of major, possibly rejuvenated, normal faults associated with regional post-subduction isostatic recovery following the establishment of a within-plate extensional tectonic setting (Smellie, 1987).

(2) The principal lithological and structural characteristics of the pyroclastic rocks indicate formation during contrasting magmatic and phreatomagmatic eruptions. Hydroclastic deposits associated with the latter are further divisible into hyaloclastites (*s.s.*), which are largely restricted to the JRIVG, and hyalotuffs (*s.s.*).

(3) A review of all published and new K–Ar radiometric ages demonstrates that alkaline volcanism may extend back to 15 Ma (Alexander Island camptonite dykes). There is evidence for at last three periods of more intense volcanic activity, at 5–7, 1–2 and < 0.2 Ma, although these may simply reflect a sampling bias.

(4) There is no clear change in geographical location of the volcanism with time, and there is no apparent correspondence between the radiometric ages and five phases of activity recognized by field observations in the JRIVG.

(5) A glacial climate, possibly punctuated by ill-defined intraglacials, existed during the entire period of eruption of the alkaline volcanic rocks but, despite its widespread inference by other workers, a subglacial origin is unproven except possibly for outcrops in northern Alexander Island and eastern Ellsworth Land.

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