Antarctic Science 6 (3): 365–374 (1994)

Central volcanoes as sources for the Antarctic Peninsula Volcanic Group

PHILIP T. LEAT and JANE H. SCARROW

British Antarctic Survey, Natural Environment Research Council, High Cross, Madingley Road, Cambridge CB3 0ET, UK

Abstract: From at least the Early Jurassic to the Miocene, eastward subduction of oceanic crust took place beneath the Antarctic Peninsula. Magmatism associated with the subduction generated a N-S linear belt of volcanic rocks known as the Antarctic Peninsula Volcanic Group (APVG), and which erosion has now exposed at about the plutonic/volcanic interface. Large central volcanoes from the APVG are described here for the first time. The structures are situated in north-west Palmer Land within the main Mesozoic magmatic arc. One centre, Zonda Towers, is recognized by the presence of a 160 m thick silicic ignimbrite, containing accidental lava blocks up to 25 m in diameter. This megabreccia is interpreted as a caldera-fill deposit which formed by land sliding of steep caldera walls during ignimbrite eruption and deposition. A larger centre, Mount Edgell-Wright Spires, is dominated by coarse-grained debris flow deposits and silicic ignimbrites which, with minor lavas and fine-grained tuffs, form a volcanic succession some 1.5 km thick. Basic intermediate and silicic sills *c.* 50 m thick intrude the succession. A central gabbro-granite intrusion is interpreted to be a high-level magma chamber of the Mount Edgell volcano.

Received 4 January 1994, accepted 16 February 1994

Key words: Antarctic Peninsula, volcano, caldera, ignimbrite, breccia, lava

Introduction

The Antarctic Peninsula is a magmatic arc which is an extension of the Andean orogenic belt and related to eastward subduction of oceanic lithosphere (Suárez 1976, Saunders & Tarney 1982, Pankhurst 1982, 1990). The exposed expression of this arc is partly plutonic, partly volcanic. The plutons, forming the so-called 'Andean intrusive suite' (Adie 1955), range in age from Late Triassic to Tertiary (Rex 1976, Pankhurst 1982). They comprise a mafic-felsic, calc-alkaline association dominated by dioritic to granodioritic and granitic compositions. The volcanic rocks, which comprise the Antarctic Peninsula Volcanic Group (APVG, Thomson 1982), range in age from Early Jurassic to Early Tertiary (Rex 1976, Thomson & Pankhurst 1983). The APVG is also predominantly calc-alkaline, consisting of basalts, basaltic andesites, abundant andesites and dacites, and rhyolites (West 1974, Weaver *et al.* 1982, Davies 1984, Smellie 1991). It is quite separate from a suite of Late Tertiary alkali basalt centres (Smellie *et al.* 1993 and references therein) which post-date cessation of subduction. These age constraints imply that the APVG and the 'Andean intrusive suite' are approximately contemporaneous and regionally related.

The APVG comprises sub-aerial lavas and volcaniclastic deposits which include numerous ignimbrites. It forms successions up to 3 km thick (Dewar 1970). No successful attempts have been made to document facies variations in the volcanic rocks of the Antarctic Peninsula, or to determine the relationship of the volcanic rocks to possible source areas, although Smellie *et al.* (1984) attempted this in the South Shetland Islands. The presence of locally developed agglomerates (Fleet 1968, Matthews 1983a, 1983b, Moyes & Hamer 1984, Smellie *et al.* 1984, Smith 1987), and tuffaceous hypabyssal intrusions (West 1974) within the APVG implies the presence of volcanic vents, but no central volcanoes have yet been unambiguously identified. The purpose of this paper is to describe field relationships that suggest the presence of major volcanic centres within the APVG in northern Palmer Land (Fig. 1). The criteria we use to identify the central volcanoes derive from application of integrated models of large central systems (e.g. Lipman 1984). Shallow erosion levels of central volcanoes may be recognized by thick intra-caldera ignimbrite accumulations, whereas deeper levels have central plutonic complexes which represent high-level magma chambers. Bacon *et al.* (1990) used such criteria to identify Cretaceous calderas in a magmatic arc in Alaska. Furthermore, models which relate changes in volcanic lithofacies to depositional environments in active volcanoes (Hackett & Houghton 1989) can be applied to ancient deposits, such as the APVG. In the APVG one potential centre, Zonda Towers, is interpreted as a caldera with a thick, silicic, intra-caldera ignimbrite. Another potential centre, Mount Edgell, is dominated by coarse-grained, pyroclastic volcanic rocks and adjacent gabbroic material. It is interpreted as a stratovolcano with a central gabbro intrusion. The deposits and intrusions crop out in north-west Palmer Land, where the volcanic part of the Mesozoic arc is particularly well exposed (Fig.1). The region lies above a 100 km wide magnetic anomaly, the Pacific Margin Anomaly, which is thought to represent a main batholith intruded during the development of the Mesozoic–Tertiary magmatic arc (Garrett 1990,

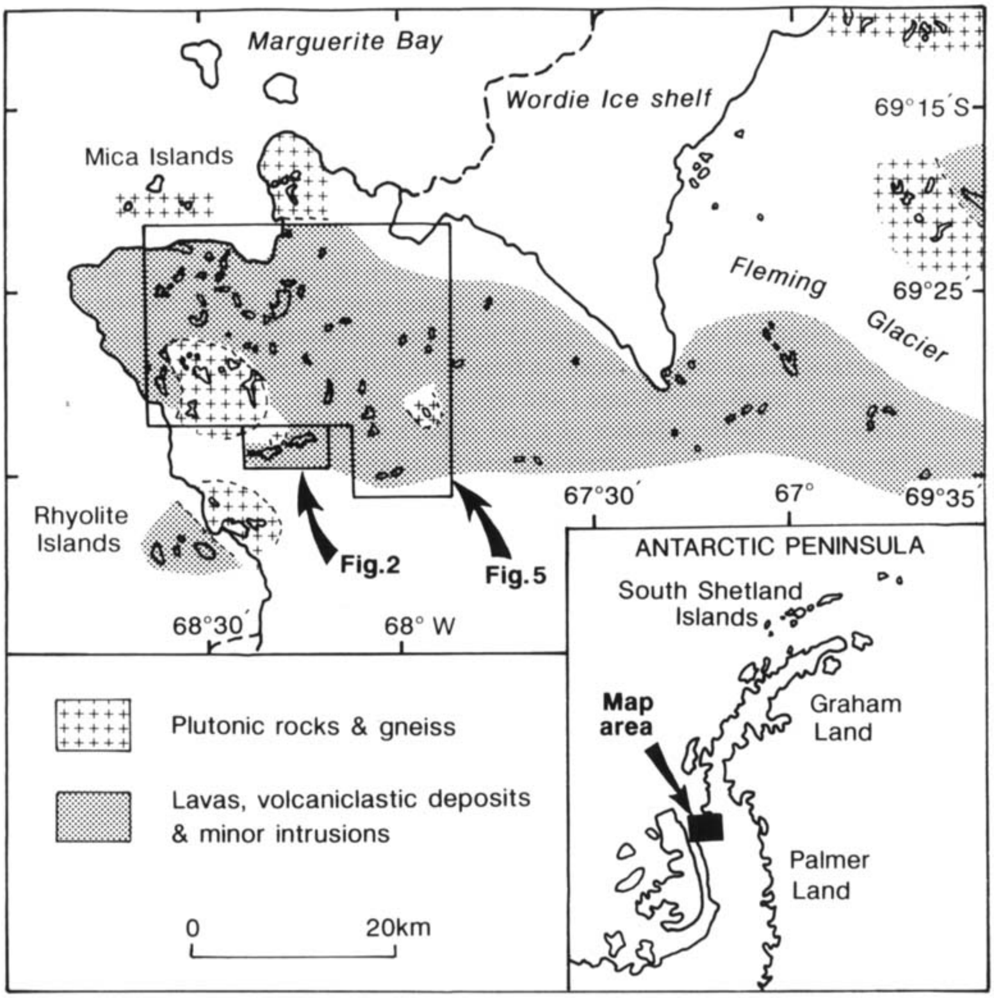

Fig. 1. Sketch geological map of north-west Palmer Land. Boxes indicate areas shown in more detail in Figs 2 & 5.

Maslanyj *et al.* 1991).

Procter (1959) and Davies (1971, 1984) carried out the only previous geological fieldwork in this area. Thomson & Pankhurst (1983) presented Rb-Sr isotopic data for volcanic rocks from northern Palmer Land. These yielded no convincing isochrons, although they form a linear array with an approximate 175 Ma slope. More recent Rb-Sr data for volcanic rocks from a single nunatak near Mount Edgell suggest an age of 153 ± 2 Ma (R.J. Pankhurst personal communication, 1993). These data suggest a Middle–Late Jurassic age for the volcanic rocks described in this paper. No published geochronological data exist for intrusive rocks of north-west Palmer Land.

Field relationships

Zonda Towers

Zonda Towers is a 7 km long by 1 km wide ENE–WSW trending ridge (centred on 69°32'S, 68°19'W) which has some 500 m of relief above glacier level. It exposes various volcanic and intrusive rocks (Fig. 2). The east-facing buttress of Zonda Towers exposes a compositionally diverse volcanic sequence in which coarse-grained ignimbrite dominates (Fig. 3).

Unit B, the basal volcaniclastic deposit, is a clast-supported breccia containing compositionally varied, up to 1 m diameter, clasts of volcanic rocks. The matrix is a crystal-rich tuff which contains no recognizable fiamme.

Unit C is a crystal-rich, rhyolitic ignimbrite containing a compositional range of clasts, which are dominantly basic to intermediate lava fragments. Angular lithic clasts up to 2 cm are common, although some larger clasts are up to 1 m diameter. The unit is matrix-supported and strongly lithified. Welding is suggested by fiamme with maximum/minimum length ratios of *c.* 3.

Unit D is an ignimbritic megabreccia (Fig. 4a). A light brown-grey, rhyolitic ignimbrite, similar to unit C, contains angular accidental blocks up to 25 m in diameter. Sheets of ignimbrite separating the blocks are commonly 0.5–1 m thick, although some larger pockets of ignimbrite are present. Fiamme contained within blocks have maximum/minimum length ratios of *c.* 10 and define a foliation that parallels the margins of the blocks. Since this cannot be a compaction effect, we suggest that the ignimbrite shows, at least incipient, welding. The blocks are mostly red-weathered, porphyritic

https://doi.org/10.1017/S0954102094000568 Published online by Cambridge University Press

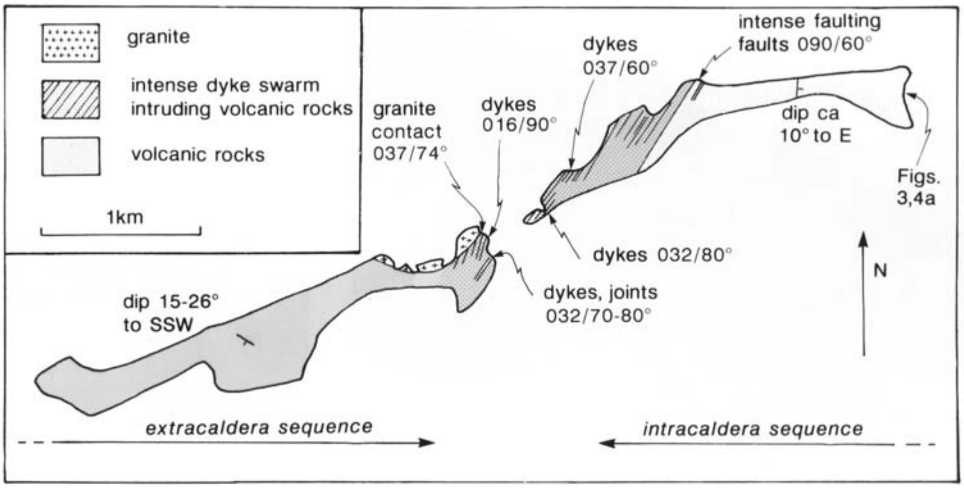

Fig. 2. Sketch geological map of Zonda Towers.

to aphyric, basic to intermediate lavas. Some blocks up to 12 m in diameter are coherent clasts, others are partly brecciated, contain patches and veins of the ignimbrite, and pass into pods of lava clasts in an ignimbrite matrix. The blocks increase in abundance from the base of unit D, forming *c.* 90% of the deposit above 30–40 m from its base.

Unit E is a *c.* 50 m thick, matrix-supported, silicic ignimbrite. It contains abundant lithic clasts of a polymict lava population dominated by porphyritic andesite. Blocks over 0.3 m diameter were only observed in the uppermost 5 m of the deposit, where up to 1.2 m diameter blocks occur. The matrix of the deposit is grey and feldspar phenocryst-rich. No sharp contact separating units D and E was observed. For this reason they are interpreted as belonging to the same eruptive unit.

Unit F is a 4 m thick breccia deposit. It consists of red-weathered lava clasts <1 m in diameter in a red, fine-grained, shale-like matrix. Large lithic clasts are angular whereas small clasts are rounded.

Unit G is a densely welded silicic tuff > 20 m thick. It contains a polymict population of accidental, angular lava blocks up to 0.3 m diameter. The dark grey tuff contains subspherical to strongly flattened black fiamme up to 2 cm diameter. We interpret this as an ignimbrite.

Dykes dominate the central area of Zonda Towers (about 1 km NE and SW of the central col) (Fig. 2), and are individually 1–50 m thick. Dyke trends are consistently NNE–SSW (strike 16–37° W of north), and are near-vertical or steeply E-dipping. Grain sizes in the dykes range from fine to coarse, and compositions vary from intermediate to silicic. Many dykes intrude earlier dykes of the swarm (Fig 4b). Locally, however, slivers of fractured and altered volcanic rocks up to 50 m wide are preserved between dykes. The dykes are locally strongly iron-stained and contain disseminated pyrite. A granite, containing abundant dioritic enclaves, and locally layered on a dm scale intrudes the dykes west of the central col. The intrusive contact is concordant with the dyke trend at the col, but becomes strongly cross-cutting to the east.

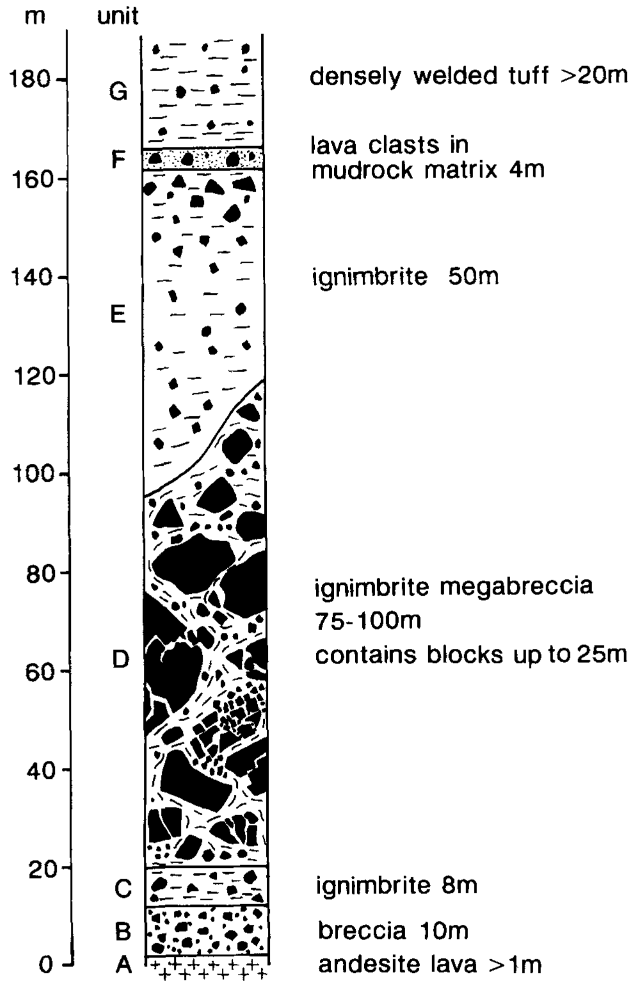

Fig. 3. Geological log of the intracaldera ignimbrite succession exposed in the east buttress of Zonda Towers.

https://doi.org/10.1017/S0954102094000568 Published online by Cambridge University Press

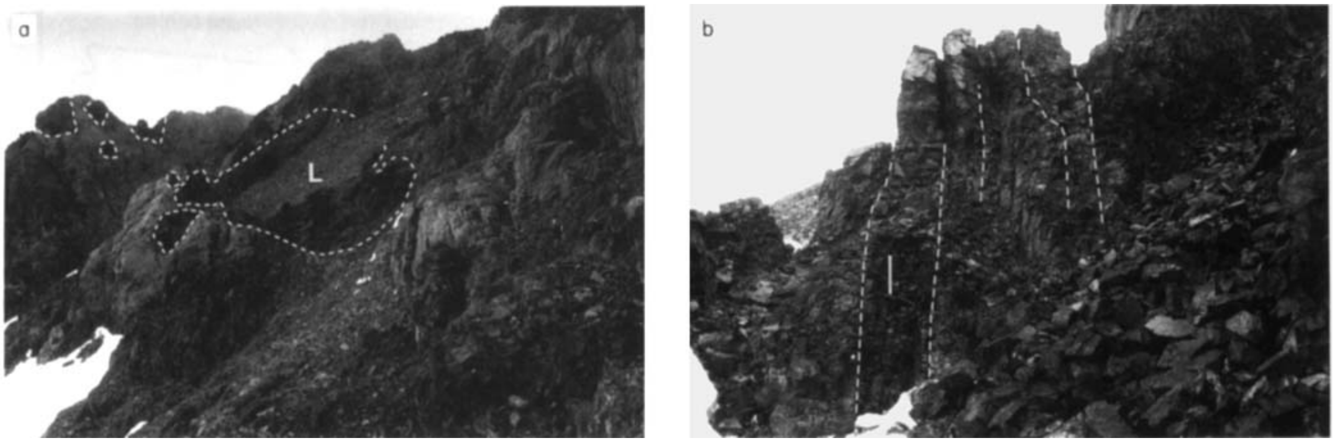

Fig. 4. Field photographs of Zonda Towers caldera-related rocks: **a.** East buttress megabreccia, with lava blocks (highlighted) in ignimbrite matrix, the lava block in the foreground (L) is 25 m across, **b.** Dyke swarm, west of central col, the hammer is 70 cm long. The margins of four dykes in the centre of the photograph are highlighted.

The western area of Zonda Towers consists of relatively thinly bedded volcanic rocks which dip shallowly westward. The accessible succession contains inter-bedded mafic lavas (*c.* 3 m thick), ignimbrites (*c.* 6 m thick), and massive volcanic breccias. The breccias consist of clast-supported deposits 3–30 m thick, which vary in grain size from fine-grained, to conglomeratic with plutonic inclusions. Abundant basaltic material in scree at the base of the cliffs suggests that basaltic lava is an important component throughout the inaccessible upper part of the succession. Some of the volcanic flow tops, particularly towards the top of the pile, show evidence of iron oxidation, indicating sub-aerial extrusion. The whole volcanic succession is cut by faults and mafic dykes both of which become more abundant eastward. The proportion of brecciated material in the accessible part of the succession becomes more abundant eastward where it contains coarser and more diverse clasts. Adjacent to the central granitic col the volcanic pile is cut by granitic sills up to 1 m thick which we interpret as offshoots from the granite pluton at the col. These observations, and the 15–26° dip of the volcanic rocks towards 190–290° (NNE–SSW), suggest that the volcanic rocks formed a flank of a volcanic edifice centred around eastern Zonda Towers.

Mount Edgell

Mount Edgell and surrounding nunataks (Fig. 5) cover an area of *c.* 350 km^2. The summit of Mount Edgell (69°20'S, 69°40'W) is the highest point in north-west Palmer Land (1676 m). Mount Edgell is composed predominantly of volcanic rocks with abundant coarse pyroclastic and volcaniclastic deposits. Basalt to rhyolite lavas form a minor proportion of the exposed volcanic rocks; other rocks are plutonic and hypabyssal. The volcanic deposits dip at 10–45°, generally toward the SE or SW. Some of these dips are probably a result of post-deposition tilting, and so cannot be used uncritically to infer palaeotopography.

The accessible occurrences of *lavas and volcaniclastic deposits* in the Mount Edgell area are listed in Table I. Of a total of *c.* 640 m of section inspected, 33% is lava, 22% is ignimbrite, and 45% volcaniclastic. Lavas comprise thick, locally autobrecciated flow-banded rhyolites, and basalt flows. Silicic, welded and non-welded, ignimbrites dominate the volcaniclastic deposits. The thicknesses of the ignimbrites (individually up to 100 m) and local relatively coarse grain size (Fig. 6a) indicate relatively large-volume, eruptions of rhyolite tephra, locally ponding in topographic depressions. These eruptions might have been related to caldera-forming events, although no caldera structure has been identified on Mount Edgell. Epiclastic deposits form a major component of the volcaniclastic rocks, and are divided in this paper according to the nomenclature of Smith (1986) into, (i) bedded, clast-supported *normal stream flow deposits*, (ii) massive to crudely bedded, largely clast-supported, poorly sorted *hyperconcentrated flood flow deposits*, and (iii) massive, matrix-supported, poorly sorted *debris flow deposits*. The proportions of these lithofacies have implications for the interpretation of depositional environment. In detail, debris flow deposits, including lahar deposits, dominate epiclastic deposits proximal to volcanic sources, whereas normal stream and hyperconcentrated flood flow deposits dominate distal epiclastic deposits (cf. Hackett & Houghton 1989, Waresback & Turbeville 1990). Most of the epiclastic deposits observed in the Mount Edgell area (Table I) are massive, matrix-supported, and poorly sorted (Fig. 6b), and are interpreted as debris flow deposits; relatively few are clast-supported (Fig. 6c) and interpreted as stream or flood deposits. The dominance of debris flow deposits implies that the epiclastic deposits represent a proximal facies of the source volcano.

Thick (>50 m) *sills* were observed at four localities in the

https://doi.org/10.1017/S0954102094000568 Published online by Cambridge University Press

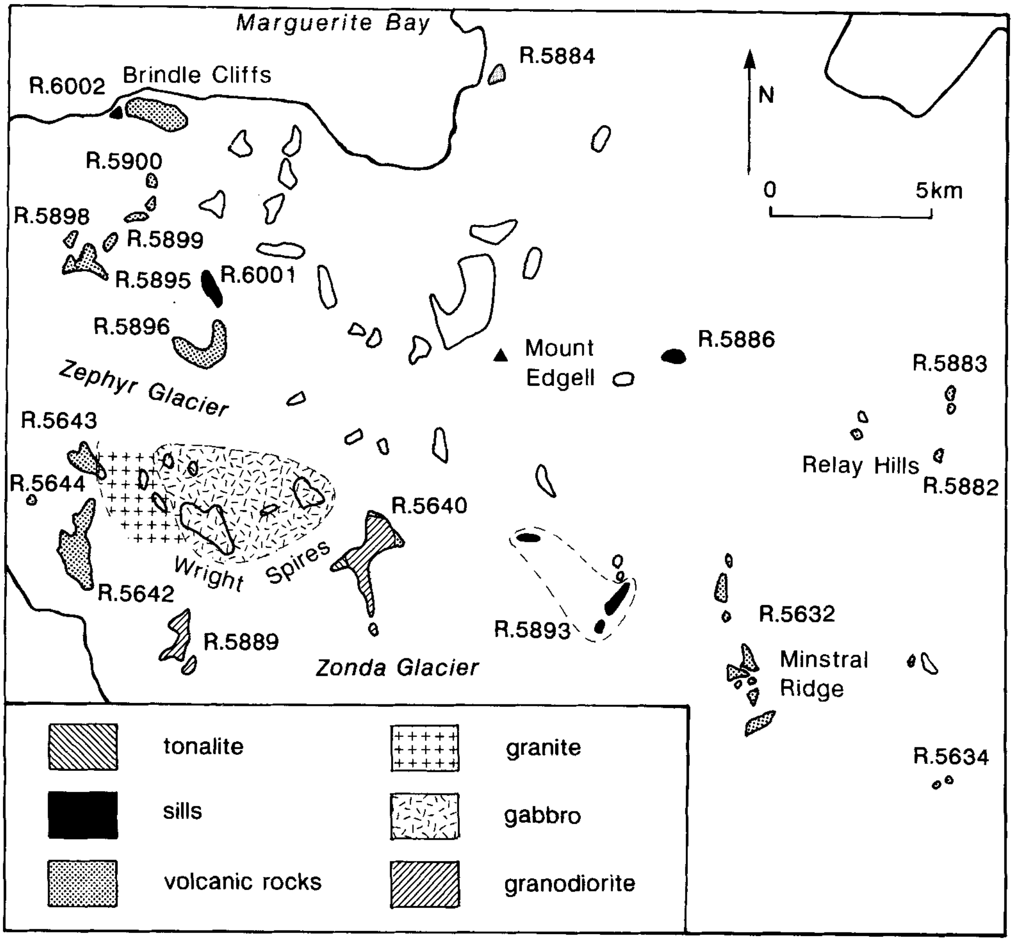

Fig. 5. Sketch geological map of the Mount Edgell area; blank outcrops are inaccessible.

Mount Edgell area (Fig. 5). Contacts with country rock are rarely exposed. However, the sills lack features typically found in nearby lava flows, such as autobrecciation, vesicular fabric, and compound structure. They are rather monotonous and structureless, although the body at station R.6001 contains pegmatoid pockets. For these reasons they are interpreted as intrusions rather than lavas. They possess local flow alignment of phenocrysts. In one case, station R.5893, the sill occurs as a main leaf, locally >20 m thick, with at least five parallel minor leaves 1–6 m thick in the underlying 64 m succession of volcanic rocks. This sill crops out on several nunataks, suggesting that it underlies an area of >4 km^2. The remaining three sills have single outcrops and exposures of <1 km^2. Compositions of the sills are varied: the sill at R.5893 consists of dacite with inclusions of andesite forming up to 50% of the rock and having liquid/liquid contacts with the host, that at station R.6001 is basaltic, that at R.5886 is andesitic, and the sill at Brindle Cliffs, station R.6002, is silicic.

Plutonic intrusions form much of the central part of the Mount Edgell area (Fig. 5), and range from norite through tonolite to granodiorite and granite (Davies 1984). The Wright Spires intrusion forms steep, mostly inaccessible cliffs with *c.* 500 m of relief above glacier level. The intrusion consists of biotite clinopyroxene norite which is layered on a scale of 2–4 cm, layers being alternately rich and poor in plagioclase relative to mafic minerals (Fig. 6d). The diameter of the pluton is probably 5–6 km (Fig. 5). A contact with the country rock is observed on the western side where it is separated from volcanic rocks by a marginal granite. The volcanic rocks at this contact are silicic and strongly altered. Brecciation adjacent to the sharp contact with the granite is interpreted to have occurred as a result of the granite intrusion, rather than being an original depositional feature. The granite forms a near vertical sliver between the gabbro and the volcanic rocks. It is heterogeneous and contains abundant mafic synplutonic dykes *c.* 0.5 m wide, and mafic inclusions up to 1 m diameter, many of which have liquid-liquid contacts with the silicic host (Fig. 6e). The position of the granite at the margin of the mafic intrusion, and the liquid-liquid mixing of the silicic and mafic magmas suggests that the granite was generated by melting of country rock (volcanic rocks?) at the margin of the intrusion. There are many known examples of such marginal granites formed by melting of country rock by heat from gabbroic intrusions (e.g. Dickin & Exley, 1981). Another intrusive contact between the plutonic and volcanic material was observed at station R.5640 (Fig. 5)

https://doi.org/10.1017/S0954102094000568 Published online by Cambridge University Press

Table I. Volcanic deposits of the Mount Edgell area.

Station	Description
R.5900	Three *c.* 10 m thick rhyolite lavas separated by 13 m of bedded, poorly sorted, matrix-supported probable debris flow deposits containing angular to semi-rounded rhyolite clasts, inter-bedded with 5–10 cm thick clast-supported deposits and a mafic welded scoria deposit.
R.5898	Silicic welded ignimbrite >40 m thick containing flattened pumice clasts up to 38 cm diameter and angular rhyolite lithic clasts up to 20 cm diameter.
R.5899	Non-welded, matrix-supported, massive, 20 m thick rhyolitic pyroclastic deposit containing rhyolite lithic clasts, overlain by 19 m volcanic breccias (inaccessible) and pyroclastic deposits, overlain by >50 m thick rhyolite lava.
R.5895	Polymict, massive, matrix-supported volcanic breccia deposits >22 m thick containing abundant, angular, mafic, intermediate and silicic lithic clasts up to 40 cm diameter. Debris flow (lahar) origin likely.
R.5896	Massive, poorly sorted, matrix-supported silicic pyroclastic deposit, probably an ignimbrite, containing abundant angular to rounded mafic to silicic lithic clasts, locally up to 1.5 m diameter. Ragged pumice clasts up to 10 cm diameter were locally chilled against the matrix. Deposit >20 m thick, and probably forms the entire *c.* 100 m high cliff.
R.5643	Polymict, massive pyroclastic deposit, clast size, *c.* 1 cm. Very altered by adjacent granite/gabbro intrusion.
R.5644	Basaltic lavas *c.* 50 m thick.
R.5642	Massive, matrix- and clast-supported breccias *c.* 100 m thick containing volcanic and rare plutonic clasts up to 10 cm diameter, within a mafic matrix.
R.5640	Altered volcanic breccias intruded by granodiorite.
R.5884	Well-bedded epiclastic deposits 6 m thick consisting of well-sorted 30 cm thick beds containing clasts about 2 cm diameter. The deposits are overlain by two massive, poorly sorted, matrix-supported deposits totalling 30 m thick, containing andesite-dacite lava clasts up to 20 cm diameter. These two flows, interpreted as lahars, are separated by a 20 cm thick fine-grained vitric layer. The flows are overlain by an 8 m thick red-weathered, homogenous, mafic deposit, of possible air-fall origin.
R.5632	Mafic lavas *c.* 50 m thick.
R.5634	Volcaniclastic deposits *c.* 15 m thick.
R.5882	Autobrecciated andesite lava >20 m thick.
R.5883	Poorly sorted, matrix-supported polymict debris flow deposit >30 m thick containing volcanic clasts 0.5–20 cm across overlain by reworked, stratified deposits, overlain by a monomict andesite breccia >20 m thick, perhaps a block and ash flow.

where a sliver of iron-stained, brecciated volcanic material a few metres wide borders the northern edge of a 2.5 km^2 outcrop of granodiorite and tonalite. The tonalite is foliated and cut by abundant, irregular syn-magmatic granite veins, whereas the granodiorite is non-foliated and contains rare magmatic mafic inclusions. The contact between the tonalite and granodiorite is occupied by a dacite dyke.

At station R.5889 (Fig. 5) granodiorite intrudes an older granodiorite with brittle contacts. The younger granodiorite is intruded by many syn-magmatic mafic dykes which range from planar or highly irregular to discontinuous and consisting of enclave swarms. Some enclaves have chilled margins against the host. Where contacts are planar, there is local evidence for mobilization of granite fractions from the partially crystallized granodiorite (Fig. 6f). Examples of such liquid-liquid and brittle magma mixing relationships are common in high-level plutonic intrusions including those below central volcanoes (Blake *et al.* 1965).

Interpretation

Zonda Towers

Eastern area units C, D and E, and probably also B, form a single cooling unit in the terminology of Smith (1960). That is, they were deposited as products of a single eruption, and cooled as a single body. The intimate association of breccia and ignimbrite in unit D strongly suggests that deposition of the blocks occurred at the same time as the ignimbrite, and this unit is a form of co-ignimbrite breccia. However, the large size of the blocks in unit D clearly distinguishes it from extra-caldera breccias deposited from associated pyroclastic flows, that contain blocks no larger than a few metres diameter (cf. Druitt & Sparks 1982, Walker 1985, Druitt &

https://doi.org/10.1017/S0954102094000568 Published online by Cambridge University Press

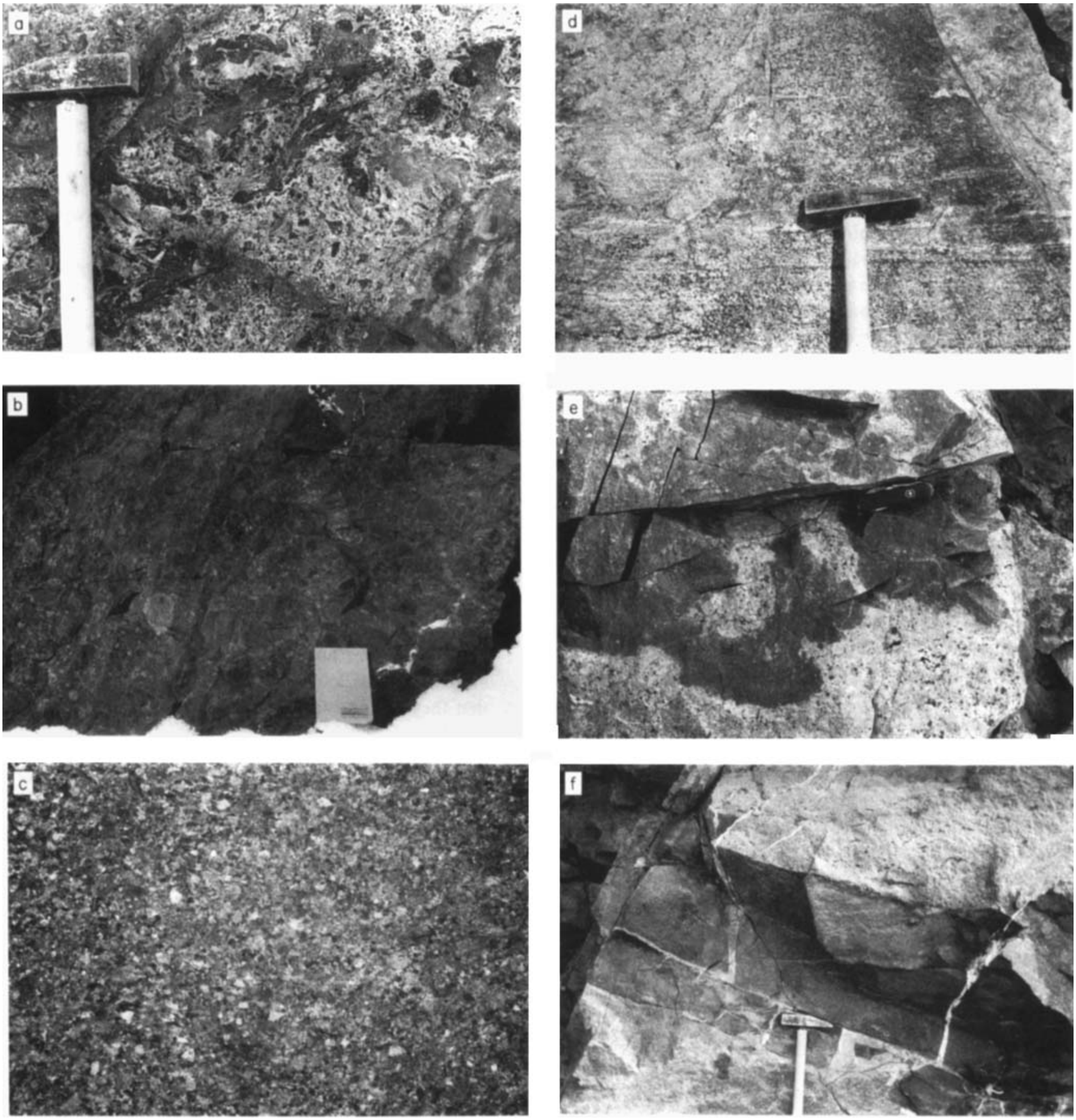

Fig. 6. Field photographs of volcaniclastic and plutonic rocks of the Mount Edgell area: **a.** Fiamme-rich ignimbrite, station R.5898, hammer head is 20 cm long, **b.** Coarse-grained, matrix-supported debris flow deposit, station R.5883, book is 16 cm high, **c.** Clast-supported breccia, station R.5642, the area of rock in the photograph is 20 cm high, **d.** Igneous layering in the Wright Spires norite, **e.** silicic-mafic liquid-liquid mixing in the marginal granite to the Wright Spires norite, station R.5897, **f.** Mafic dyke intruded into granodiorite by brittle deformation, but heat from the dyke has mobilized a granitic fraction from the pluton, which has intruded into the dyke, station R.5889.

Bacon 1986). Transportation of the large blocks in unit D could not have occurred in a pyroclastic flow, so it is suggested that a landslide deposited them. Lipman (1976, 1984) described breccias from the western United States containing blocks of all sizes up to 1 km diameter and having ignimbritic matrixes. The megabreccia deposits occupy obvious intra-caldera settings and were thought by Lipman to have formed by land slip of steep caldera walls during caldera

https://doi.org/10.1017/S0954102094000568 Published online by Cambridge University Press

formation and contemporaneous ignimbrite eruption. Furthermore, Lipman (1976, p.1397) suggested that the presence of such deposits (megabreccias) may be useful guides to identification of the roots of caldera structures in deeply eroded, highly altered, or structurally complex volcanic terranes. We suggest that unit D is an intra-caldera megabreccia deposit. The great thickness (*c*. 160 m) of the whole cooling unit supports this interpretation because it implies that the deposit ponded in a depression such as a caldera. This model implies that Unit C is a ignimbrite deposited during the caldera-forming eruption, but before the onset of caldera subsidence and that Unit E is the continuation of ignimbrite eruption and ponded deposition within the now-formed caldera. The sequence of deposits within the Zonda Towers ignimbrite cooling unit is typical of many caldera-related deposits (Druitt 1985, Walker 1985, Druitt & Bacon 1986) in comprising: 1) a lowermost, relatively fine-grained ignimbrite deposit formed during the initial phase of the eruption before caldera collapse, 2) a middle, coarse deposit related to caldera collapse, and 3) an uppermost, relatively fine-grained deposit representing the waning stages of the eruption.

We interpret the western end of Zonda Towers to be an extra-caldera sequence of lavas and pyroclastic deposits. Caldera-related deposits have not been identified within the western sequence, although they might be present in inaccessible parts of the exposed succession.

The dyke swarm of the central part of Zonda Towers is an intrusive complex at approximately the site of the caldera ring fault. A *c*. 1 km diameter granitic stock intrudes this zone. Steeply dipping 'ring-dykes' are a feature of many deeply eroded calderas (although they are not ubiquitous), where they commonly separate the central foundered block from country rock (e.g. Emeleus 1982, Lipman 1984). The narrow, multi-intrusion character of the Zonda Towers dykes indicates that they are likely to represent a series of post-caldera intrusive events, that might have fed surface lavas.

Because only one side of the caldera has been recognized, it is only possible to suggest a minimum diameter of 2.5 km.

Mount Edgell

Our interpretation of the Mount Edgell area, based on the following, is that it represents a large, composite, central volcano.

a) All lavas and volcaniclastic deposits appear to be sub-aerial.

b) The large volume of debris flow deposits implies the existence of a large topographic edifice as a source area. Moreover, the dominance of matrix-supported debris flow deposits over clast-supported deposits from more dilute flows implies proximity to source.

c) The Mount Edgell area is dominated by a lithofacies association comprising rhyolitic lavas, silicic ignimbrites, and debris flow deposits. This association is comparable to the 'proximal cone-building' lithofacies association forming much of the andesitic composite Ruapehu volcano, New Zealand (Hackett & Houghton 1989). The Mount Edgell volcano, however, clearly erupted more rhyolitic material, notably in the form of ignimbrite, than Ruapehu.

d) The presence of the sills supports the likelihood of local eruption of the volcanic rocks of Mount Edgell, with some magma being intruded rather than erupted. Eroded, large, central volcanoes commonly expose large volumes of compositionally-diverse minor intrusions: examples include the Snowdon Volcanic Centre, North Wales (Howells *et al.* 1991) and Cenozoic volcanoes in Colorado (Lipman *et al.* 1969).

e) The layered norite intrusion probably represents a cooled high-level magma chamber, possibly formed late in the evolution of the centre, in which magma was stored prior to eruption.

f) The range of compositions in the norite and tonalite-granodiorite-granite plutonic intrusions is comparable to that in the volcanic rocks. Except for the norite, the intrusions are of relatively small size, each covering less than a few km^2, and contain locally abundant magma mixing phenomena. We suggest that the plutons were emplaced at shallow levels, perhaps into the volcanic pile that they themselves created. Many examples of such genetic relationships between volcanic complexes and plutons that intrude them are described in the literature, notably from the British Tertiary igneous province (e.g. Emeleus 1982) and the western United States (Lipman 1984, 1988). Nevertheless, intrusion of the plutons might have occurred during a much later magmatic event, unrelated to the volcanism.

Conclusions

We conclude that extensive outcrops of volcanic and related hypabyssal and plutonic rocks in north-west Palmer Land are the products of relatively large, dominantly silicic, central volcanoes. The identification of large volcanic structures within the APVG is not surprising because irregularly-spaced central volcanoes tend to dominate modern ensialic volcanic arcs. However, these are the first such structures to be identified in the Mesozoic–early Tertiary arc-related volcanic rocks of the Antarctic Peninsula, although several previous workers have suggested that parts of the APVG must be parts of large volcanoes. Ayling (1984) inferred the existence of volcanic centres in central west Palmer Land from the aspect of the volcanic rocks, and the presence of coarse of pyroclastic material in an area affected by deuteritic alteration. His interpretation of coarse, volcanic breccias as vent agglomerates gave support to the theory. Smith (1987,

p. 56) thought that one group of lavas and pyroclastic rocks cut by agglomerate in west Palmer Land represents the flanks of a volcano. Fleet (1968, p. 16) regarded the extensive ignimbrites, 610 m thick in total, of the Oscar II coast, Graham Land as having a local source, but he was unable to identify a volcanic centre. The extensive outcrop of the APVG at Mount Edgell, north-west Palmer Land, was a major factor in our recognition of the central volcanoes. In much of the Antarctic Peninsula, outcrops of volcanic rocks are smaller and more widely scattered, making the identification of volcanic structures much more difficult.

Unambiguously genetically related volcanic and plutonic rocks have not been documented from the peninsula. The common local relationship of plutonic rocks intruding the APVG led many workers to the view that the plutonic phase was later than, and separate from, the volcanic phase (e.g. Adie 1955, Dewar 1970, Davies 1984, Moyes & Hamer 1984). The relationships in the volcanic centres we describe suggests to us that the plutonic rocks are genetically related to the volcanic rocks they intrude. In particular, the presence of voluminous ignimbrites and at least one related caldera structure suggests that magma was stored prior to eruption in magma chambers in the upper crust, that are now represented in the Antarctic Peninsula by intrusions.

Acknowledgements

We are grateful to M.E. Dinn, B.J. Wilson, and J.P.A. Sweeny for their help in carrying out the fieldwork, and to Rothera base personnel and the BAS Air Unit for logistical support. We thank Drs. D.C. Armstrong, M.R.A. Thomson and R.C.R. Willan for constructive comments on earlier versions of the paper, and Drs. D. Pyle and S.D. Weaver for helpful reviews.

References

Adie, R.J. 1955. The petrology of Graham Land: II. The Andean granite-gabbro intrusive suite. *Falkland Islands Dependencies Survey Scientific Report*, No. 12, 1-39.

Ayling, M.E. 1984. The geology of parts of central west Palmer Land. *British Antarctic Survey Scientific Report*, No. 105, 1-60.

Bacon, C.R., Forster, H.L. & Smith, J.G. 1990. Rhyolitic calderas of the Yukon-Tanana terrane, east central Alaska: volcanic remnants of a mid-Cretaceous magmatic arc. *Journal of Geophysical Research*, **95**, 21451-21461.

Blake, D.H., Elwell, R.W.D., Gibson, I.L., Skelhorn, R.R. & Walker, G.P.L. 1965. Some relationships resulting from the intimate association of acid and basic magmas. *Quarterly Journal of the Geological Society of London*, **121**, 31-49.

Davies, T.G. 1971. The geology of the Mount Edgell area and south side of the Fleming Glacier. *British Antarctic Survey Interim Report*, No. G6/1970/E. [Unpublished].

Davies, T.G. 1984. The geology of part of northern Palmer Land. *British Antarctic Survey Scientific Report*, No. 103, 1-46.

Dewar, G.J. 1970. The geology of Adelaide Island. *British Antarctic Survey Scientific Report*, No. 57, 1-66.

Dickin, A.P. & Exley, R.A. 1981. Isotopic evidence for magma mixing in the petrogenesis of the Coire Uaigneich granophyre, Isle of Skye, N.W. Scotland. *Contributions to Mineralogy and Petrology*, **76**, 98-108.

Druitt, T.H. 1985. Vent evolution and lag breccia formation during the Cape Riva eruption of Santorini, Greece. *Journal of Geology*, **93**, 439-454.

Druitt, T.H. & Bacon, C.R. 1986. Lithic breccia and ignimbrite erupted during the collapse of Crater Lake, Oregon. *Journal of Volcanology and Geothermal Research*, **29**, 1-32.

Druitt, T.H. & Sparks, R.S.J. 1982. A proximal ignimbrite breccia facies on Santorini, Greece. *Journal of Volcanology and Geothermal Research*, **13**, 147-171.

Emeleus, C.H. 1982. The central complexes. *In* Sutherland, D.S. *ed. Igneous rocks of the British Isles*. Chichester: Wiley, 369-414.

Fleet, M. 1968. The geology of the Oscar II coast, Graham Land. *British Antarctic Survey Report*, No. 59, 46pp.

Garrett, S.W. 1990. Interpretation of reconnaissance gravity and aeromagnetic surveys of the Antarctic Peninsula. *Journal of Geophysical Research*, **95**, 6759-6777.

Hackett, W.R. & Houghton, B.F. 1989. A facies model for a Quaternary andesitic composite volcano: Ruapehu, New Zealand. *Bulletin of Volcanology*, **51**, 51-68.

Howells, M.F., Reedman, A.J. & Cambell, S.D.G. 1991. *Ordovician (Caradoc) marginal basin volcanism in Snowdonia (North-West Wales)*. London: HMSO for the British Geological Survey, 191pp.

Lipman, P.W. 1976. Caldera-collapse breccias in the western San Juan Mountains, Colorado. *Bulletin of the Geological Society of America*, **87**, 1397-1410.

Lipman, P.W. 1984. The roots of ash-flow calderas in western North America: windows into the tops of granitic batholiths. *Journal of Geophysical Research*, **89**, 8801-8841.

Lipman. P.W. 1988. Evolution of silicic magma in the upper crust: the mid-Tertiary Latir volcanic field and its cogenetic granitic batholith, northern New Mexico, U.S.A. *Transactions of the Royal Society of Edinburgh: Earth Sciences*, **79**, 265-288.

Lipman, P.W., Mutschler, F.E., Bryant, B. & Steven, T.A. 1969. Similarity of Cenozoic igneous activity in the San Juan and Elk Mountains, and its regional significance. *United States Geological Survey Professional Paper*, No. 650-D, 33-42.

Maslanyj, S.W., Garrett, S.W., Johnson, A.C., Renner, R.G.B. & Smith, A.M. 1991. *Aeromagnetic anomaly map of West Antarctica (Weddell Sea sector), 1:2 500 000*. Cambridge: British Antarctic Survey.

Matthews, D.W. 1983a. The geology of Pourquoi Pas? Island, northern Marguerite Bay, Graham Land. *British Antarctic Survey Bulletin*, No. 52, 1-20.

Matthews, D.W. 1983b. The geology of Horseshoe and Lagotellerie Islands, Marguerite Bay, Graham Land. *British Antarctic Survey Bulletin*, No. 52, 125-154.

Moyes, A.B. & Hamer, R.D. 1984. The geology of Arrowsmith Peninsula and Blaiklock Island, Graham Land, Antarctica. *British Antarctic Survey Bulletin*, No. 65, 41-55.

Pankhurst, R.J. 1982. Rb-Sr geochronology of Graham Land, Antarctica. *Journal of the Geological Society of London*, **139**, 701-711.

Pankhurst, R.J. 1990. The Paleozoic and Andean magmatic arcs of West Antarctica and southern South America. *Geological Society of America Special Paper*, No. 241, 1-7.

Procter, N.A.A. 1959. The geology of northern Marguerite Bay and the Mount Edgell area. *Falkland Islands Dependencies Survey Preliminary Geological Report*, No. 4, 1-18. [Unpublished].

Rex, D.C. 1976. Geochronology in relation to the stratigraphy of the Antarctic Peninsula. *British Antarctic Survey Bulletin*, No. 43, 49-58.

Saunders, A.D. & Tarney, J. 1982. Igneous activity in the southern Andes and northern Antarctic Peninsula: a review. *Journal of the Geological Society of London*, **139**, 691-700.

Smellie, J.L. 1991. Middle-late Jurassic volcanism on Jason Peninsula, Antarctic Peninsula, and its relationship to the break-up of Gondwana. *In* Ulbrich, H. & Rocha Campos, A.C. *eds. Gondwana Seven Proceedings*. Sao Paulo: Universidade de Sao Paulo, 685-699.

SMELLIE, J.L., HOLE, M.J. & NELL, P.A.R. 1993. Late Miocene valley-confined subglacial volcanism in northern Alexander Island, Antarctic Peninsula. *Bulletin of Volcanology*, **55**, 273-288.

SMELLIE, J.L., PANKHURST, R.J., THOMSON, M.R.A. & DAVIES, R.E.S. 1984. The geology of the South Shetland Islands: VI. Stratigraphy, geochemistry and evolution. *British Antarctic Survey Scientific Report*, No. 87, 85pp.

SMITH, C.G. 1987. The geology of parts of the west coast of Palmer Land. *British Antarctic Survey Scientific Report*, No. 112, 101pp.

SMITH, G.A. 1986. Coarse-grained nonmarine volcaniclastic sediment: terminology and depositional process. *Bulletin of the Geological Society of America*, **97**, 1-10.

SMITH R.L. 1960. Ash flows. *Bulletin of the Geological Society of America*, **71**, 795-842.

SUÁREZ, M. 1976. Plate-tectonic model for southern Antarctic Peninsula and its relation to southern Andes. *Geology*, **4**, 211-214.

THOMSON, M.R.A. 1982. Mesozoic paleogeography of West Antarctica. *In* CRADDOCK, C. *ed. Antarctic geoscience*. Madison: University of Wisconsin Press, 331-337.

THOMSON, M.R.A. & PANKHURST, R.J. 1983. Age of Post-Gondwanian calc-alkaline volcanism in the Antarctic Peninsula region. *In* OLIVER, R.L., JAMES, P.R. & JAGO, J.B. *eds. Antarctic earth science*. Canberra: Australian Academy of Science, 328-333.

WALKER, G.P.L. 1985. Origin of coarse lithic breccias near ignimbrite source vents. *Journal of Volcanology and Geothermal Research*, **25**, 157-171.

WARESBACK, D.B. & TURBEVILLE, B.N. 1990. Evolution of a Plio-Pleistocene volcanogenic-alluvial fan: the Puye Formation, Jemez Mountains, New Mexico. *Bulletin of the Geological Society of America*, **102**, 298-314.

WEAVER, S.D., SAUNDERS, A.D. & TARNEY, J. 1982. Mesozoic-Cenozoic volcanism in the South Shetland Islands and the Antarctic Peninsula: geochemical nature and plate tectonic significance. *In* CRADDOCK, C. *ed. Antarctic geoscience*. Madison: University of Wisconsin Press, 263-273.

WEST, S.M. 1974. The geology of the Danco Coast, Graham Land. *British Antarctic Survey Scientific Report*, No. 84, 1-58.