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ABSTRACT

The South Shetland Islands are a Jurassic–Quaternary magmatic island arc founded on a sialic basement of schists and deformed sedimentary rocks. The schists, which are restricted to Smith Island and the Elephant and Clarence islands group, are mainly low-grade blueschists and phyllites, but include metacherts and metabasites, part of a regional high P/T metamorphic belt. The Miers Bluff Formation, a flysch sequence folded during the Gondwanian orogeny, is thought to represent part of a pre-Jurassic fore-arc complex, and the undeformed volcaniclastic Williams Point Beds are also related to the pre-arc geology since they contain a Mid to Late Triassic fossil flora. Other supposed basement correlatives, the False Bay schists of Livingston Island, have been re-interpreted as Tertiary basic dykes emplaced within and deformed by an Eocene tonalite intrusion.

Construction of the South Shetland Islands arc proper began during the latest Jurassic or earliest Cretaceous in the south-western part of the archipelago. Marine sediments with Late Jurassic–earliest Cretaceous fossil faunas are succeeded by terrestrial volcanic sandstones and conglomerates, then by basalt to dacite lavas interbedded with andesite and rhyolite ignimbrites. K–Ar dating of the extrusive sequence on Byers Peninsula has yielded mainly Early Cretaceous ages for the lavas, and ages extending into the Late Cretaceous for some intrusions.

The next identifiable arc-building phase is represented by basalt lavas and multiple intrusions between eastern Livingston Island and Robert Island (Coppermine Formation), which have yielded K–Ar ages close to 80 Ma (Late Cretaceous). By contrast, volcanic rocks on King George Island are believed to be entirely Tertiary in age: there is no clear evidence for the Jurassic or Cretaceous volcanic rocks frequently reported from the island and it seems likely that the rocks thought to be of these ages are Tertiary rocks metasomatically altered by the emplacement of later plutonic intrusions. The Fildes Formation, which consists mainly of basalt and basaltic andesite lavas, occupies much of western King George Island and is latest Palaeocene to Early Eocene in age whereas the Hennequin Formation, dominated by glassy andesite lavas, is of Eocene–Oligocene age. Possible Upper Tertiary outcrops are restricted to the south-east coast of King George Island, but they are poorly dated so far. Thus, the radiometric chronology together with the palaeontological evidence suggests a progressive north-easterly migration of intense volcanism that continued in most areas for periods of 10–20 Ma, although products from different eruptive centres overlapped in space and time.

The volcanic sequences are intruded by a varied suite of mainly small plutons, ranging in composition from gabbro to adamellite. The largest intrusions are tonalite and granodiorite of Eocene age.

The entire arc-building period, between Late Jurassic and Late Tertiary times, was characterized by emplacement and eruption of magmas intermediate between island-arc tholeiites and calc-alkaline types. During mid Tertiary times, however, there was a temporary development of intermediate calc-alkaline magmas. There is also a trend of north-easterly decreasing initial $^{87}Sr/^{86}Sr$ ratios from >0.7040, as in many calc-alkaline island arcs (and here associated with lavas of possible secondary magmatic origin), towards values of 0.7030–0.7035.

Quaternary hyaloclastites, plugs and lavas occur in patchy, isolated outcrops between eastern Livingston Island and King George Island. They include Penguin Island, a well-formed vent. Chemically, the rocks are mainly fresh olivine-basalts, but with strong alkaline affinities unique in the South Shetland Islands. This change in chemistry and the break in geographical migration occurred following the cessation of active subduction at the South Shetland trench, and probably corresponds to a switch to intra-plate tensional tectonics.

CONTENTS

I. INTRODUCTION

A. Location

The South Shetland Islands (Fig. 1) form a 550-km-long archipelago at the south-western end of the Scotia Ridge, an arcuate structure of islands and submerged continental blocks linking southern South America to the Antarctic Peninsula. They lie about 950 km south-east of Cape Horn and 100 km north-west of the Antarctic Peninsula, from which they are separated by Drake Passage and Bransfield Strait, respectively. Geophysical evidence suggests that the islands are located on a small crustal plate, which may be defined by back-arc spreading in Bransfield Strait to the east, a well-defined oceanic trench to the west (along which subduction has apparently ceased) and transverse faults to the north and south (Ashcroft, 1972; Barker and Griffiths, 1972). The island group can be divided into two geographically and geologically distinct parts (Tyrrell, 1945, p. 76):

i. Elephant and Clarence islands group, almost entirely formed of low-grade metamorphic rocks, and
ii. islands between King George and Low islands, formed largely of igneous and volcaniclastic rocks and separated from the first group by a gap of 120 km.

The present investigation (begun in 1975) is concerned only with the islands between and including King George and Low islands. Deception Island in Bransfield Strait is also excluded; it is an active volcano that erupted recently in 1967, 1969 and 1970, and has generated a detailed interest of its own (Baker and others, 1975).

B. Geological Investigations prior to 1975

The South Shetland Islands were first sighted in February 1819 by William Smith, a British merchant seaman exploring a deep southerly route round Cape Horn on a voyage from Buenos Aires to Valparaiso. He revisited the area in October of the same year and made a landing at what is probably now called North Foreland, King George Island, taking formal possession in the name of the British monarch. News of Smith's discovery was brought to Britain by Miers (1820), an engineer who was working on a copper plate mill in Concón, Chile and who had talked with Smith in Valparaiso. Miers presented a somewhat embellished account of the South Shetland Islands for, although he referred to their frequent barrenness, he reported that Smith had clearly discerned pine trees through his telescope at Williams Point, Livingston Island. At Shirreff Cove, in addition to the normal penguins and seals, he was alleged to have seen sea otters, an *Ornithorhynchus*-like animal (duck-billed platypus), and 'an abundance of wild land fowls and fresh water duck'. In view of the strategic proximity of the area to southern South America and the supposed natural resources, Miers urged that a British settlement be set up on the islands but, for reasons which are now obvious, it was never established.

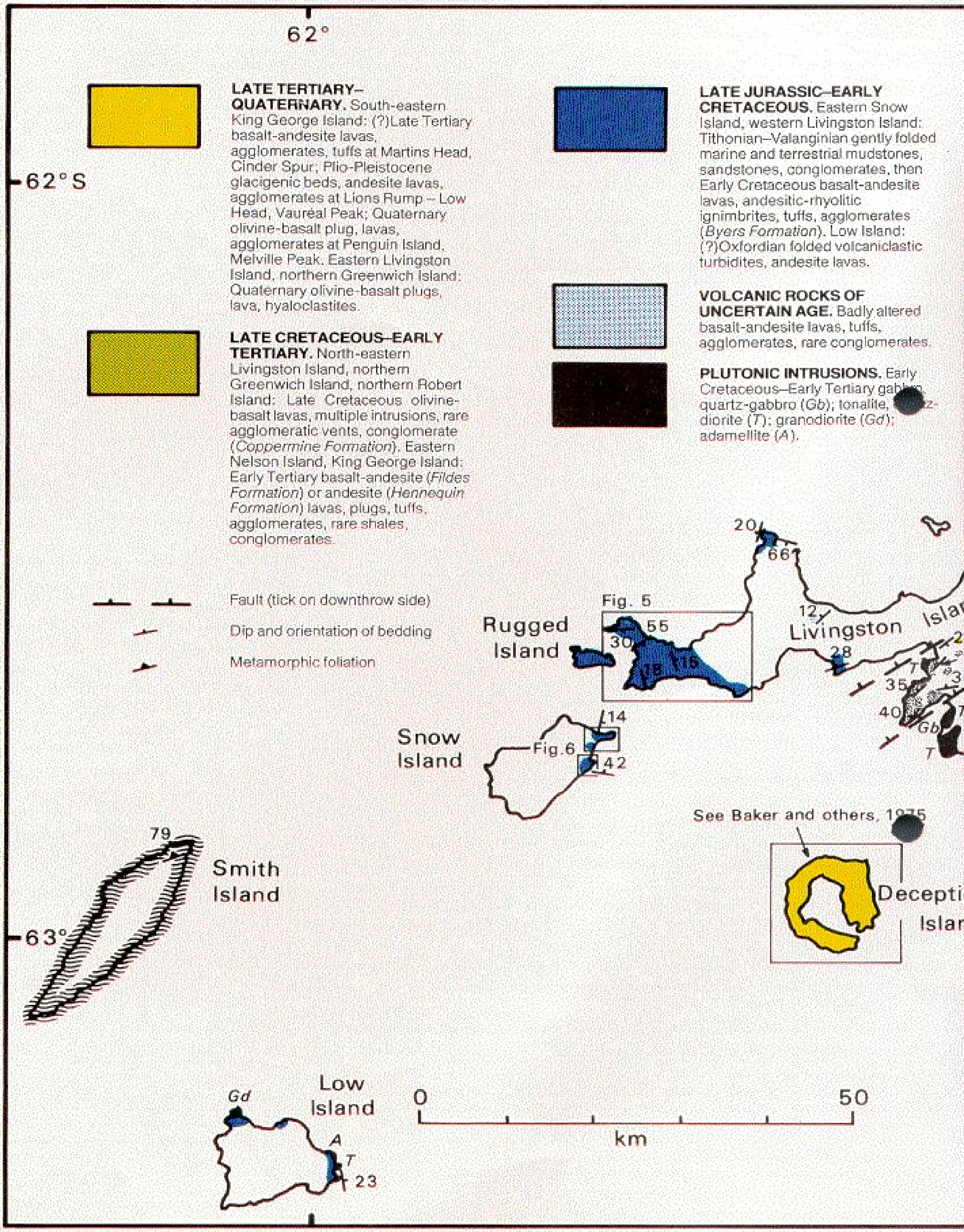
Miers (1820, p. 371) was also responsible for making the first geological deductions about the islands. On the basis of descriptions given by the ship's mate, Miers pronounced the rocks of North Foreland to be 'chlorite-slate or schistose hornblende'; subsequently he (Miers, 1820, p. 379) broadened his remarks to suggest that both the South Sandwich and the South Shetland islands were chiefly composed of 'hornblende-slate'. However, rock samples from the South Shetland Islands were soon brought back to England and their volcanic origin was correctly determined (Anon, 1821; Traill, 1822). News of the discovery of the islands and their abundant fur seals spread so rapidly through the sealing fleets that by 1822 the fur seal population of the area was virtually exterminated. Sporadic attempts at reviving the industry throughout the nineteenth century were unsuccessful. Little geological exploration was accomplished during this period of intensive activity and the only other pertinent observation is that of Eights (1833), who reported fossil wood in volcanic rock on an unspecified island. This finding has long been overlooked, probably because it was included in a paper on a new species of modern crustacean. Nevertheless, it is interesting because it is the first record of fossil remains from the Antarctic. Had it been better publicized, it would clearly have aroused considerable interest in the scientific world, as did most later findings of arborescent plant fossils in an almost entirely ice-covered land, now devoid of all but rudimentary vegetation.

Although many of the great expeditions of the nineteenth and early twentieth centuries passed through the South Shetland Islands, few stopped to make anything other than the most cursory of geological observations. Expeditions by Bellingshausen (1819–21), d'Urville (1837–40), Wilkes (1838–42), de Gerlache (1897–99) and Charcot (1908–10) all fall within this category. Nordenskjöld's 1901–04 Swedish Expedition, famous for its geological work in the Hope Bay and James Ross Island areas of northern Antarctic Peninsula, also visited Nelson, Snow and eastern Livingston islands, but the specimens collected were unfortunately lost when their ship, the *Antarctic*, sank in the Weddell Sea.

The first significant geological descriptions of the area resulted from the work of D. Ferguson, who was employed as a prospector by Messrs Salvesen's of Leith, a whaling company. In the 1913–14 whaling season he was enabled to make extensive investigations in the South Shetland Islands and Gerlache Strait area (Ferguson, 1921). The greater part of his work in the South Shetland Islands relates to King George Island, where he distinguished an earlier (? Middle Jurassic) sequence of stratified sediments with interbedded lavas from later (Cenozoic) basalts and andesites (Table I). Dioritic intrusions, which had altered the earlier sequence

Table I. Stratigraphy of the South Shetland Islands after Ferguson (1921) and Tyrell (1921 and 1945).

Olivine basalts and andesitic rocks	Quaternary–Recent
Thick andesite and pyroclastic sequence	Cenozoic
Dioritic intrusions	
Andesitic → rhyolitic lavas and pyroclastic rocks, local sedimentary intercalations	Jurassic
Basement (not exposed); crystalline schists and gneisses; sediments with cataclastic metamorphism	



LATE TERTIARY–QUATERNARY. South-eastern King George Island: (?)Late Tertiary basalt-andesite lavas, agglomerates, tuffs at Martins Head, Cinder Spur; Plio-Pleistocene glacigenic beds, andesite lavas, agglomerates at Lions Rump – Low Head, Vauréal Peak; Quaternary olivine-basalt plug, lavas, agglomerates at Penguin Island, Melville Peak. Eastern Livingston Island, northern Greenwich Island: Quaternary olivine-basalt plugs, lava, hyaloclastites.

LATE CRETACEOUS–EARLY TERTIARY. North-eastern Livingston Island, northern Greenwich Island, northern Robert Island: Late Cretaceous olivine-basalt lavas, multiple intrusions, rare agglomeratic vents, conglomerate (*Coppermine Formation*). Eastern Nelson Island, King George Island: Early Tertiary basalt-andesite (*Fildes Formation*) or andesite (*Hennequin Formation*) lavas, plugs, tuffs, agglomerates, rare shales, conglomerates.

LATE JURASSIC–EARLY CRETACEOUS. Eastern Snow Island, western Livingston Island: Tithonian–Valanginian gently folded marine and terrestrial mudstones, sandstones, conglomerates, then Early Cretaceous basalt-andesite lavas, andesitic-rhyolitic ignimbrites, tuffs, agglomerates (*Byers Formation*). Low Island: (?)Oxfordian folded volcaniclastic turbidites, andesite lavas.

VOLCANIC ROCKS OF UNCERTAIN AGE. Badly altered basalt-andesite lavas, tuffs, agglomerates, rare conglomerates.

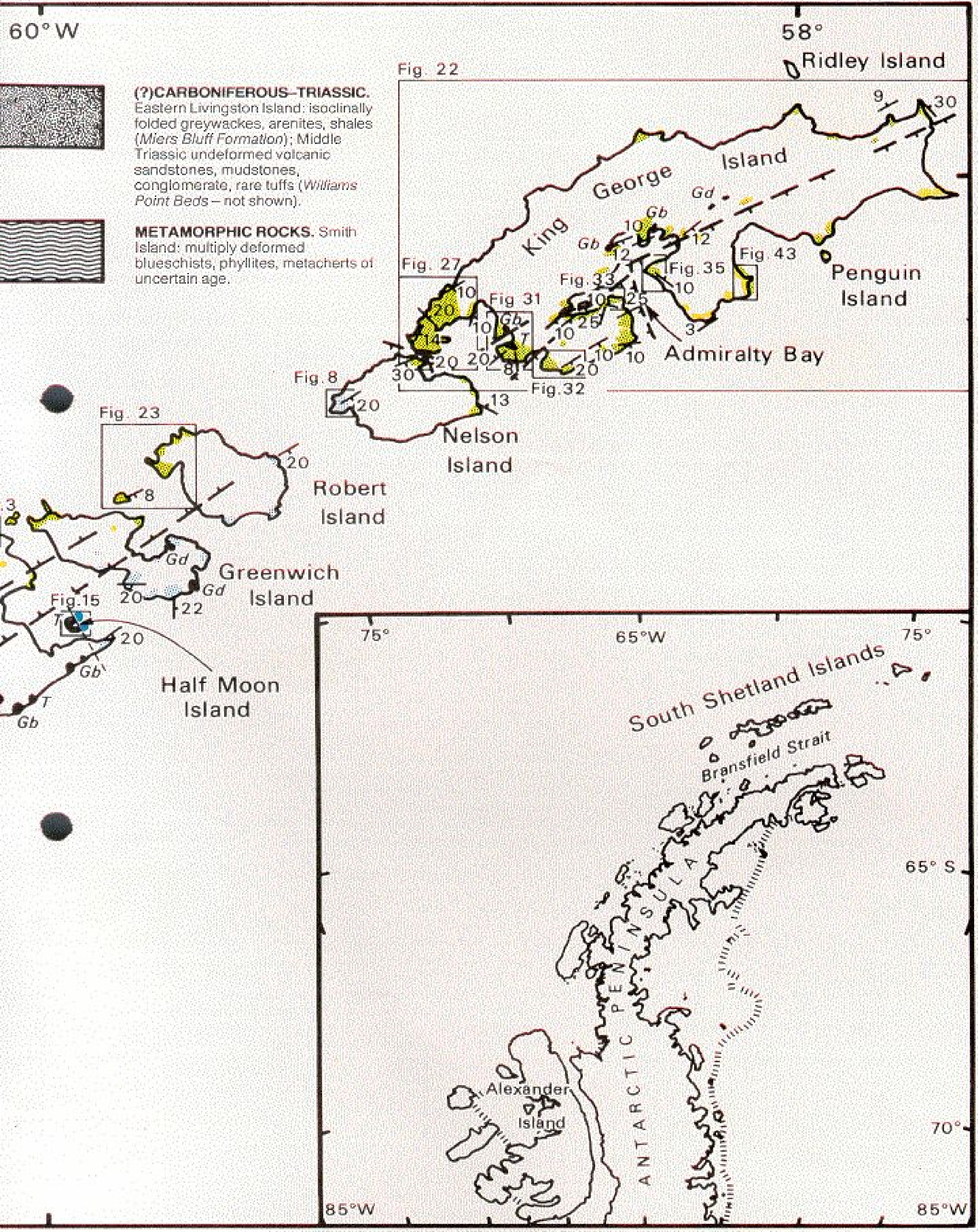
PLUTONIC INTRUSIONS. Early Cretaceous–Early Tertiary gab[illegible], quartz-gabbro (*Gb*); tonalite, [illegible]z-diorite (*T*); granodiorite (*Gd*); adamellite (*A*).

Fault (tick on downthrow side)

Dip and orientation of bedding

Metamorphic foliation

Fig. 1. Geological sketch map of the South Shetland Islands (exclu



Elephant and Clarence islands group) and their location (inset).

and caused extensive quartz-pyrite mineralization in some areas (notably Esther Harbour), were also noted. Despite Ferguson's emphasis on the high proportion of sedimentary rocks in the older sequence, Tyrrell's (1921) petrographical account showed that they figured insignificantly in his collections. He also made no petrological distinction between the two main sets of lavas, but described them as dominantly andesitic types (including bandaite) with rarer more acidic ones. However, he recognized that the basaltic rocks, then known from Bridgeman and Deception islands, and also Edinburgh Hill, Livingston Island, constituted a third and more recent phase of volcanic activity.

Rock samples from Robert Island formed part of a small collection made by J. Innes-Wilson in the 1916–17 whaling season; they were all obtained from Coppermine Cove and described as zeolitized olivine basalts by Thomas (1921).

These observations were complemented by the studies of N. A. Mackintosh and J. W. S. Marr, during the third and fourth commissions of *Discovery II* (1934 and 1937). Their collections, from King George, Nelson, Robert, Livingston and Snow islands, were described by Tyrrell (1945) within the same stratigraphical framework of three principal volcanic episodes (Table I). He pointed out that the importance of the sedimentary intercalations in the older lava sequence of Admiralty Bay had been greatly exaggerated, whereas intrusions were probably more widespread than had been previously reported. Largely on the basis of material dredged from Bransfield Strait, Tyrrell suggested that the South Shetland Islands had a basement of crystalline schists and gneisses, together with some sedimentary rocks showing cataclastic metamorphism.

The Norwegian Antarctic Expedition of 1927–28 visited the South Shetland Islands (Holtedahl, 1929) but most of its geological investigations were limited to Deception Island; two dykes from the area concerned here were described by Barth and Holmsen (1939).

During World War II, the conflicting political claims of Argentina, Britain and Chile on the Antarctic Peninsula area came to a head, and all three nations quickly established permanently-manned bases on the South Shetland Islands and elsewhere (Christie, 1951). Whatever the political justifications, this activity also had the effect of starting off a more-or-less uninterrupted programme of geological research that has continued until the present day. Other nations, notably Poland, the USA and USSR, have since taken an active interest.

The literature (Table II) is too voluminous to discuss in detail, and only the more important findings can be outlined

Table II. Geological investigations in the South Shetland Islands (King George Island to Low Island), since 1945 and prior to the present investigations.

Reference	*Area*	*Type of study*
Diaz & Terrugi, 1956	King George Island and McFarlane Strait	Local observations
Caballero & Fourcade, 1959	Robert Island	Coppermine Cove igneous petrology
Olsacher, 1959	Nelson Island	Harmony Cove igneous petrology
Quartino, 1959	Nelson Island	Harmony Cove igneous petrology
Fourcade, 1960	King George Island	Potter Cove igneous petrology
Hawkes, 1961	King George Island	Laboratory study of whole island, igneous petrology and stratigraphy
Schauer, Fourcade & Dallinger, 1961	King George Island	Fildes Peninsula, igneous petrology
Orlando, 1963, 1964	King George Island	Fildes Peninsula, Cenozoic palaeobotany
Schauer & Fourcade, 1963, 1964	King George Island	Fildes Peninsula, stratigraphy
Barton, 1964	King George Island	General review of Cenozoic palaeobotany
Araya & Hervé, 1965	Livingston & Snow islands	Local stratigraphy, summary
Barton, 1965	King George Island	Stratigraphy of whole island
Fuenzalida, 1965	Livingston & Snow islands	Mesozoic palaeobotany, summary
Araya & Hervé, 1966	Whole group	Local geological studies, stratigraphy
Villaroel, 1966	Robert, Greenwich & Half Moon islands	Mineralogy
Orlando, 1967, 1968	Livingston Island	Mesozoic palaeobotany, mainly Triassic
Grikurov & Polyakov, 1968*a*	King George Island	Fildes Peninsula, structure
Grikurov & Polyakov, 1968*b*	King George & Half Moon islands	Local geology
Hobbs, 1968	Livingston Island	Reconnaissance geology of whole island, stratigraphy
Covacevich & Lamperein, 1969, 1970, 1972	King George Island	Fildes Peninsula, Cenozoic palaeontology
Dalziel, 1969	Livingston Island	Hurd Peninsula, structure, radiometric age
Valencio & Fourcade, 1969	King George Island	Palaeomagnetism
Gonzalez-Ferran & Katsui, 1970	King George & Robert islands	Geochemical review of young volcanic rocks
Gonzalez-Ferran & others, 1970	Livingston Island	Byers Peninsula, stratigraphy & Mesozoic palaeontology
Grikurov & others, 1970	King George & Half Moon islands	Radiometric ages
Tavera, 1970	Livingston Island	Byers Peninsula, Mesozoic palaeontology
Covacevich & Hernández, 1971	King George, Livingston & Snow islands	Palaeontological review
Hernández & Azcárate, 1971	Livingston Island	Byers Peninsula, Mesozoic palaeobotany
Ashcroft, 1972	Bransfield Strait	Marine geophysics
Dalziel, 1972*a*	Livingston Island	Hurd Peninsula, structure
Davey, 1972	Bransfield Strait	Marine gravity survey
Fuenzalida & others, 1972	Snow Island	Mesozoic palaeobotany
Gusev & others, 1972	King George Island	Palaeomagnetism
Valenzuela & Hervé, 1972	Livingston Island	Byers Peninsula, stratigraphy
Caminos & others, 1973	Livingston Island	Hurd Peninsula, structure
Dalziel & others, 1973	Livingston Island	Barnard Point, radiometric age and palaeomagnetism
Schopf, 1973	Livingston Island	Hurd Peninsula palaeobotany
Del Valle & others, 1974	Livingston Island	Hurd Peninsula, economic mineralogy

here. Because of the isolated nature of the outcrops (most are situated around the coastal fringes of the ice-capped islands) logistics considerations often meant that studies had to be restricted to small areas. In this way a number of petrological surveys of headlands were carried out by Argentine geologists (e.g. Coppermine Cove (Caballero and Fourcade, 1959); Potter Cove (Fourcade, 1960)). Overland and sea-ice travel seems to have remained the domain of the British, who used this mobility to study the whole of the two major islands. From their base in Admiralty Bay, members of the Falkland Islands Dependencies Survey (F.I.D.S.) geologically surveyed and mapped King George Island (Hawkes, 1961; Barton, 1965), and a reconnaissance of Livingston Island (Hobbs, 1968) was effected during a one-season topographical survey, from a few boat landings.

Hawkes' petrological study of King George Island was based on the work of Jardine (1950) and earlier workers. It is unfortunate that Jardine's own work was never published. Whereas Hawkes described his material within the broad stratigraphical framework established by earlier workers (Table I), Jardine expressed strong doubts as to the existence of Jurassic volcanic rocks on the island, and this is more in line with the views of several recent authors (Schauer and Fourcade 1963, 1964; Grikurov and Polyakov, 1968*b*). On the basis of petrology and the geological map, Hawkes proposed a linear pattern for the distribution of Tertiary and Quaternary volcanicity on the island.

Building on Hawkes' findings, and field work by his own contemporaries, Barton (1965) carried out further work that enabled him to establish a detailed stratigraphy (Table III).

Table III. Stratigraphy of King George Island after Barton (1965).

Penguin Island Group	Pleistocene-Recent
Lions Rump Group	Pliocene
Point Hennequin Group Fildes Peninsula Group Ezcurra Inlet Group Dufayel Island Group	Late Cretaceous–Miocene
Andean Intrusive Suite	Late Cretaceous–Early Tertiary
Jurassic volcanic rocks	Late Jurassic

He erected several local subdivisions ('groups') of the Cenozoic volcanic rocks which were partly supported by the evidence of associated angiosperm floras. An important discovery was that of a *Chlamys*-bearing conglomerate ('Pecten conglomerate') similar to another deposit on Cockburn Island near James Ross Island (Andersson, 1906).

The stratigraphy established over the years for King George Island became the basis of subsequent investigations in the South Shetland Islands, sometimes with unfortunate results. Thus, a belief that the Jurassic rocks could everywhere be recognized by their alteration due to 'Andean' plutonism, led Hobbs (1968) to map relatively unaltered-looking volcanic rocks on Byers Peninsula as Cenozoic, whereas they have since yielded Late Jurassic–Early Cretaceous faunas and floras (below). However, Hobbs made two important discoveries: an earlier deformed sedimentary sequence on Hurd Peninsula, and a flora at Williams Point that was later shown to be Triassic in age (Orlando, 1967, 1968). Detailed studies of the older sedimentary rocks (Miers Bluff Formation) by Dalziel (1969) proved that much of that sequence was inverted. Poorly-preserved plant remains from the Miers Bluff Formation were studied by Schopf (1973) who considered that they favoured a post-Carboniferous, even Mesozoic age. Schlieren and xenoliths of schistose rocks in the margin of a tonalite pluton in the False Bay area were tentatively assigned by Hobbs to the Precambrian, on the basis of comparison with similar occurrences elsewhere in the region.

Palaeontological and stratigraphical studies by Chilean geologists have shown that Mesozoic rocks are widely distributed at the western end of the island group. Volcanic and volcaniclastic sequences on Livingston and Snow islands contain Middle Jurassic to Early Cretaceous floras (Hernández and Azcárate, 1971, and Fuenzalida and others, 1972) and Late Jurassic to Early Cretaceous marine molluscan faunas (González-Ferrán and others, 1970; Tavera, 1970; Covacevich, 1976). Although six Tertiary plant fossil sites had been identified on King George Island by the early 1960's (Fourcade, 1960; Barton, 1964), only one flora from Fildes Peninsula has been briefly described (Orlando, 1963, 1964) and that was assigned an Early to Middle Miocene age. From the same vicinity as this flora, Covacevich and Lamperein (1969, 1970, 1972) have reported bird tracks in tuffaceous sandstones.

A stratigraphical tool that had been little exploited in the South Shetland Islands is that of radiometric age determinations. Taken at their face value, dates reported by Grikurov and others (1970) and Dalziel and others (1973) show that, although there is some evidence for Late Cretaceous plutonic activity, plutonism also accompanied Early Tertiary volcanicity. Thus, the intrusive history of the islands appears to be more complex than was previously believed (Tables I and III). Dalziel (1972*a*) reported that a very early Jurassic date had been obtained from the Miers Bluff Formation but further details have not been published. This date probably reflects metamorphism and/or diagenesis of the sediments. A more complete survey of recent radiometric data is included in Chapter XI.

Limited land-based geophysical studies, and more extensive marine geophysical investigations in Bransfield Strait (Griffiths and others, 1964; Ashcroft, 1972; Davey, 1972), have demonstrated that the South Shetland Islands rest on a small plate that has moved away from the Antarctic Peninsula along a spreading centre in Bransfield Strait. The strait itself is graben-like in structure with strongly faulted margins (well shown on the South Shetland Islands side), and a line of volcanic centres, two of which (Bridgeman and Deception islands) project above sea level.

C. SCOPE OF THE PRESENT STUDY

The state of our geological knowledge of the South Shetland Islands (between King George and Low islands) prior to the present study has been briefly summarized above. In the past, the islands have been studied largely on an island-by-island basis and it was clear that an overall study of the whole group by a single research team was long overdue. Using the known stratigraphy of one island to interpret that of the next, and trying to fit the islands' geological history too closely to that of the Antarctic Peninsula, have both been shown to be unreliable.

From Mesozoic times the islands have had a volcanic history but the durations of the various active phases and the relative abundance of each in terms of present-day outcrop were uncertain. The old mapping criterion, that the altered volcanic rocks were Jurassic and had been metasomatized by 'Andean' plutonism, whereas the Tertiary volcanic rocks were largely post-Andean and therefore relatively unaltered, has come in for increasing criticism and needed re-investigation. Several references have been made to quartz-pyrite and copper mineralization related to this alteration but no critical assessment has been made using modern techniques. The best Tertiary macrofloras seen anywhere in the Antarctic are preserved on King George Island, and it is important that their stratigraphy be known as well as possible. Previous radiometric dating has been mostly on an *ad hoc* basis and there was clearly a need for a more comprehensive and systematic programme in conjunction with new petrological and geochemical studies of the igneous rocks of the whole island chain. Little was known of the basement to the volcanic successions, and many workers have sought evidence for Precambrian metamorphic rocks, like those supposed to exist on the Antarctic Peninsula, but with little success.

By far the greater proportion of rock exposures in the South Shetland Islands are restricted to the coastal fringes and it is possible to obtain a firm understanding of the islands' geology from the sea. Thus, with the above geological problems in mind, two summer seasons (1974/75 and 1975/76) were spent in the islands using close-ship support from *RRS Bransfield* and *John Biscoe*, and the helicopters of HMS *Endurance*. Only a few hours were spent at the smaller outcrops but parties camped for several weeks in areas of more extensive exposure and geological importance. In this way, all but the few inland exposures and the more inaccessible areas of the north-western coast were examined. During the first season a BAS party of P. D. Clarkson, R. E. S. Davies, J. L. Smellie and M. R. A. Thomson were accompanied by A. D. Saunders and S. D. Weaver of the University of Birmingham, and during the second season Davies and Smellie were joined by M. J. Littlefair of the University of Aston. Saunders and Weaver were collecting material for geochemical, radiometric and palaeomagnetic studies, whereas Littlefair was engaged in a survey of the economic mineralization. Most of their results have been, or will be, published elsewhere (e.g. Weaver and others, 1982; Tarney and others, 1982) but the radiometric age determinations made by R. J. Pankhurst on samples collected by both BAS and Birmingham geologists are assessed here.

During the preparation of this report, a large number of papers on the geology of King George Island has been published by Birkenmajer (e.g. 1979, 1980, 1982*a* and *b*), who worked from a recently-established Polish station (Arctowski) in Admiralty Bay. His papers document several important discoveries and present detailed descriptions of some of the more important volcanic successions. In addition, they introduce a large number of new stratigraphical names into the literature. For the most part, these have been omitted from the present work because its aim is to provide an overall geological interpretation of the whole volcanic history of the South Shetland Islands (except Deception Island), when a simple, widely applicable scheme is required. Many of the stratigraphical names introduced by Birkenmajer (1979, 1980) relate to rock units of limited areal extent that were probably produced by essentially instantaneous volcanic events. The broad stratigraphical scheme proposed here takes into account over 70 new radiometric age determinations (in addition to those already in the literature), over 300 chemical analyses by the authors and by Weaver and Saunders, and a petrological study of rocks from the whole island group. Reference was also made to existing rock collections made by members of the Falkland Islands Dependencies Survey, particularly to those from areas the authors were unable to visit.

II. STRATIGRAPHY

Seven major rock groups are recognized in the South Shetland Islands (Table IV; Fig. 1). Low-grade schists, which have undergone strong polyphase deformation, crop out on Smith Island. By comparison with the relatively little-deformed Upper Jurassic–Lower Cretaceous volcanic rocks, the schists might be considered pre-Jurassic, but the precise relationships with other rock groups are unknown. The MIERS BLUFF FORMATION (formerly called the Miers Bluff 'Series') of Hurd Peninsula, Livingston Island, is a thick sedimentary sequence mainly composed of arkosic arenites and greywackes. Dalziel (1972*a*) showed that much of the formation is inverted. The rocks are essentially unmetamorphosed except in narrow thermal aureoles adjacent to plutonic intrusions. An earliest Jurassic age for diagenesis and/or deformation is suggested by sparse radiometric evidence but, by comparison with lithologically and structurally similar sequences on the Antarctic Peninsula and Alexander Island, the Miers Bluff Formation itself may be (?) Carboniferous–Triassic in age. A significant structural and stratigraphical break separates the Miers Bluff Formation from rocks of younger age.

Flat-lying (?) alluvial sedimentary rocks with a well-preserved Middle to Late Triassic fossil flora crop out at Williams Point, Livingston Island, and are formally named the WILLIAMS POINT BEDS. They are remarkable in that they are essentially undeformed, and contrast sharply with possible contemporaneous sedimentary rocks of the Miers Bluff Formation.

Volcanic rocks of Late Jurassic–Early Cretaceous age form extensive outcrops south-west of King George Island (Fig. 1). They are a low-K, high-alumina calc-alkaline suite of lavas and volcaniclastic rocks, with rare rhyolites. The more mafic lavas show some of the chemical characteristics of island-arc tholeiites. Although most of these rocks were erupted subaerially, there are also thick fossiliferous marine sequences on western Livingston Island (BYERS FORMATION) and Low Island. Most of the volcanic rocks on south-eastern Robert, Greenwich and Livingston islands are grossly altered, and they may be of similar age to lithologically comparable rocks on Half Moon Island, which are intruded by a mid-Cretaceous tonalite pluton. Deformation of the volcanic rocks is typically slight and consists of open folds and faults.

Plutonic activity may have begun during the (?) Late Jurassic or Early Cretaceous and it probably reached a climax during the Early Tertiary. The intrusions vary from gabbro to micro-adamellite, but tonalites are predominant. A layered gabbro on Livingston Island is the only layered pluton known to occur in the island group.

Upper Cretaceous–Lower Tertiary lavas and volcaniclastic rocks crop out widely on Robert and King George islands. Those on Robert Island form thick sequences composed of fresh olivine-basalts, rare pyroxene-andesites and volcaniclastic rocks of Late Cretaceous age. Associated with the volcanic rocks are spectacular multiple intrusions that extend along the northern coasts of Robert, Greenwich and Livingston islands. Together, these are distinguished here as the COPPERMINE FORMATION on the basis of their age and geographical separation (Table IV). Also included here are the volcanic rocks on King George Island, which are altered by the plutonic intrusions and were formerly thought to be Jurassic in age. There is no evidence for the age of the volcanic rocks on northern and eastern Nelson Island but it is likely that they are Early Tertiary similar to nearby outcrops on King George Island. Although well-preserved fossil angiosperm floras occur locally on King George Island, they only indicate an age younger than mid Cretaceous. However, new radiometric evidence (Table XVIII) has shown that the volcanic activity on south-western King George Island was largely confined to the Early Tertiary. Contrary to an hypothesis that the Tertiary rocks on King George Island crop out in linear, petrographically distinct belts parallel to the length of the island (Hawkes, 1961), it is suggested that two broad rock units can be recognized that show no linear trends. They are formally named the FILDES and HENNEQUIN FORMATIONS and they can be distinguished lithologically and chemically: basalts and basaltic andesites with chemical affinities to both island arc tholeiites and calc-alkaline rocks predominate in the Fildes Formation, whereas calc-alkaline pyroxene-andesites are characteristic of the Hennequin Formation. At Point Thomas, andesite lavas and conglomerates of the Hennequin Formation are unconformably overlain by basalts and basaltic andesites of the upper Fildes Formation, but the two formations were at least partly contemporaneous and the volcanic activity responsible for the Hennequin Formation may have continued after volcanism in the Fildes Formation ceased (Table IV).

Volcanic rocks of (?) Late Tertiary–Quaternary age crop out in two major areas: south-eastern King George Island, and northern Greenwich and Livingston islands, and they include well-formed Recent vents at Penguin Island (Fig. 1). The outcrops on King George Island are characterized by fresh olivine-basalts and there are local occurrences of hornblende-andesites. The linear distribution of the outcrops and associated vents indicates strong structural control exerted by major longitudinal faults. Whereas subduction-related volcanism of low-K, high-alumina calc-alkaline type may have been continuous on King George Island until Late Tertiary times, there is evidence at Lions Rump for a major unconformity corresponding to much of the Oligocene, Miocene and Pliocene. At this locality, the Plio-Pleistocene Polonez Cove Formation (formerly called the *Pecten* conglomerate) unconformably overlies Upper Eocene lavas and coal-bearing sediments of the Hennequin Formation (Table IV).

The (?) Upper Tertiary–Quaternary outcrops on Greenwich and Livingston islands consist of fresh olivine-basalt lavas and hyaloclastites. All the extrusive rocks and some intrusions present are mildly alkaline in composition and are comparable with lavas on Penguin Island. This change from essentially calc-alkaline to mildly alkaline volcanism is probably related to the cessation of subduction at the South Shetland trench during the Pliocene, and it documents the regional transformation to intra-plate block tectonics.

III. METAMORPHIC ROCKS

In the area under discussion, metamorphic rocks occur *in situ* only on Livingston Island (False Bay schists) and on Smith Island (Fig. 1). Prior to their discovery, some indication of the basement rocks of the islands was sought in derived fragments occasionally found in the bed rocks of the area. Hawkes (1961, p. 2) described quartzite, hornblende–biotite–gneiss and garnetiferous granite–gneiss occurring as fragments in the 'Jurassic Volcanics and Penguin Island Group' of King George Island. However, he made no further mention of the occurrence in the 'Jurassic Volcanics' and the locality is unknown. Identical fragments of metamorphic rock occur on the present beaches as ice-rafted erratics and their inclusion in Cenozoic volcanic rocks ('Penguin Island Group') affords no indication of the nature of the metamorphic basement nor its occurrence *in situ* on King George Island (Barton, 1965, p. 7). A specimen of 'crushed sericitic quartzite of a distinctly ancient aspect' (Tyrrell, 1945, p. 51) was collected from scree on a rocky islet near Desolation Island but there are no geological observations that suggest that the specimen is representative of rocks *in situ* in the area.

A. SMITH ISLAND

Smith Island is isolated from the other islands of the South Shetland Islands by major faults trending through Boyd Strait and parallel to the island's south-eastern margin (Ashcroft, 1972, p. 39; Barker and Griffiths, 1972, fig. 11).

Table IV. Stratigraphy of the South Shetland Islands (excluding the Elephant and Clarence islands group, and Deception Islan

			SMITH ISLAND	*LOW ISLAND*	*SNOW ISLAND*	*LIVINGSTON ISLAN*	
QUATERNARY						Mildly alkaline lavas, hyalocla and plugs of north-eastern Livingston Island and possibly Desolation Island	
CENOZOIC	TERTIARY	UPPER					
		LOWER	?			Lamprophyre dykes	Tonali asi
MESOZOIC	CRETACEOUS	UPPER				Multiple intrusions and vents of the COPPERMINE FORMATION	Gabb intrus
		LOWER		Micro-adamellite, granodiorite and microtonalite intrusions		Altered volcanic rocks at Renier Point and Mount Bowles	
	JURASSIC	UPPER		Altered lavas and sediments of Cape Wallace and Cape Hooker area	Lavas and volcaniclastic rocks at President Head and Hall Peninsula	BYERS FORMATION	
		MIDDLE	Smith Island schists				
		LOWER					
	TRIASSIC					WILLIAMS POINT BED ? MIERS BLUFF FORMATION ?	
PALAEOZOIC		UPPER	?				
		LOWER					
PRECAMBRIAN							

GREENWICH ISLAND AND MACFARLANE STRAIT		*ROBERT ISLAND AND ENGLISH STRAIT*		*NELSON ISLAND*	*KING GEORGE ISLAND*	
ldly alkaline hyaloclastites and plug Mount Plymouth, Greenwich Island					Recent vents at Penguin Island.	
					Volcanic and glacigenic rocks of south-eastern King George Island (including the Polonez Cove Formation and Ternyck Needle) ? ?	
mprophyre dykes Half Moon Island	Granodiorite intrusions on Greenwich Island			Volcanic rocks of northern and eastern Nelson Island	HENNEQUIN FORMATION FILDES FORMATION ?	Granodiorite, quartz-diorite and quartz-gabbro intrusions
ltiple intrusions of the PPERMINE RMATION	Gabbro–tonalite intrusions on Half Moon Island	Volcanic rocks, conglomerates and multiple intrusions of the COPPERMINE FORMATION	Altered volcanic rocks of southern Robert Island	Altered volcanic rocks at Harmony Point		
tered volcanic rocks Half Moon and uthern Greenwich ands						

No rocks belonging to other stratigraphical groups were observed during the survey of Cape Smith (Smith Island) and Barlow Island but 'good coal' has been reported from the island (US Oceanographical Office, 1960, p. 135).* Assuming that the locality from which the coal was supposedly obtained is correct, this may record an occurrence *in situ* of coal-bearing strata on the island. However, the identification of coal may be mistaken since there exists a very strong superficial similarity between dark blue-grey Na-amphibole schist and fragments of petrified wood found on neighbouring islands.

Regionally metamorphosed rocks, which may be comparable with the Smith Island schists, crop out in the Elephant and Clarence islands group, the South Orkney Islands and on the Antarctic Peninsula. The *para*-schists of the South Orkney and South Shetland islands have been correlated lithologically by several authors (Adie, 1964*a*; Dalziel, 1972*b*; J. W. Thomson, 1974). Conversely, lithological correlation with the *ortho*-gneisses of the Antarctic Peninsula is precluded. These may well have formed at essentially the same time ((?) late Palaeozoic–early Mesozoic: see Chapter XI) but marked contrasts exist in the physical conditions of metamorphism. Low temperatures and (?) high pressures prevailed in the South Shetland and South Orkney islands, whereas high temperatures and low pressures prevailed in the Antarctic Peninsula (Smellie and Clarkson, 1975). By analogy with the 'basement complexes' of South Africa and South America, Adie (1954, p. 5) tentatively suggested a Precambrian or Early Cambrian age for all these rocks. However, the discovery of (?) Riphean acritarchs on Clarence Island (Iltchenko, 1972) is the only direct evidence for the age of any of them. It has been suggested that the blueschist-greenschist and amphibolite facies rocks of the southern Scotia arc comprise a paired metamorphic belt formed at the oceanic margin of Gondwana prior to continental break-up (Smellie and Clarkson, 1975; Dalziel, 1982). Since the *para*-schists in part, at least, probably represent ocean-floor scrapings accreted in a trench environment, the rocks examined by Iltchenko (1972) may be exotic, having been 'rafted into the region on a downgoing lithospheric plate' (Dalziel, 1982).

At present, there is no way of assigning an unequivocal maximum age to the Smith Island schists. Despite several attempts, they are undated so far. The only age constraint is that the schists are interpreted as part of an accretionary complex, which formed as a result of subduction of oceanic crust (Dalziel, 1982; Smellie, 1981), a process that has probably been roughly continuous between (?) late Palaeozoic and Tertiary times (cf. Tanner and others, 1982).

1. *Lithology and metamorphism*

Cape Smith (Smith Island) and Barlow Island are formed of grey-green schists and semi-schists that are finely banded in shades of green and dark grey-blue sub-parallel to the schistosity (Fig. 2a). The colour banding and variations in the intensity of the schistosity may correspond to original bedding features. Similar rocks crop out around the entire island and also include bands of chert and calc-silicate (Dalziel, 1976, 1982).

The rocks are mainly Na-amphibole-bearing schists which also include epidote, white mica, chlorite, quartz, albite, garnet, stilpnomelane, actinolite, calcite, sphene and minor opaque ore (Fig. 2b). Lawsonite was recorded by Rivano and Cortes (1976). Whereas petrographical studies suggested that the Na-amphibole was glaucophane (Smellie and Clarkson, 1975), electron microprobe analyses of the amphibole in specimen P.220.3 have shown it to be riebeckitic (($Fe^{+2}/(Fe^{+2} + Mn + Mg) = 0.50$, $Fe^{+3}/(Fe^{+3} + Al + Ti) = 0.80$; G. Hyden, personal communication, 1981).

Fig. 2a. Schists at Cape Smith, Smith Island, showing differences in intensity of the schistosity, possibly related to original bedding. The hammer shaft is 34 cm in length.

Fig. 2b. Radiating sheaf of ferristilpnomelane associated with prisms of Na-amphibole, granular epidote and quartz. Metachert, Cape Smith, Smith Island. (P.220.2b, ordinary light, ×125.)

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*The presence of coal in apparently appreciable quantities in the South Shetland Islands seems to have been widely believed in the early days of exploration. For example, Sherrat (1821) noted that "The westernmost island contains coals in great abundance". Although this island bears the name Cape Smith on his map (i.e. it was supposedly Smith Island), the draughting is extremely crude, and Gould (1941, p. 228) pointed out that, by the internal constitution of the map, the island is Livingston Island. Traill (1822, p. 101) was also given the same impression when given an early collection of rocks to describe.

Although the lawsonite–sodic amphibole association is diagnostic of the glaucophane–lawsonite-schist facies, lawsonite was not observed in the specimens examined here (although they were collected at the same locality (Cape Smith) as the specimens described by Rivano and Cortes). The mineral assemblages show affinities with both the glaucophane–lawsonite-schist and greenschist facies. Na-amphibole occurs in both these facies and can form over a wide temperature range (up to 800°C (Ernst, 1961)). In rocks of a basic composition, very minor amounts of actinolite and albite are typical of the glaucophane–lawsonite-schist facies (Turner, 1968, p. 291). The absence of clinozoisite may also indicate very low-grade (rather than low-grade) metamorphism (Winkler, 1974, p. 167). However, the abundance of epidote (locally comprising about 70% of the rock) is typical of the greenschist facies, and the paragenesis epidote–garnet–glaucophane (or crossite) is considered to represent conditions transitional between the two facies (Ernst, 1972, p. 658).

B. Livingston Island (False Bay Schists)

The False Bay schists are tabular enclave-like rocks that crop out in plutons of tonalite and metagabbro on the north-eastern side of False Bay, Livingston Island. Extensive injection and fragmentation of the schists by microtonalite has occurred around the margins of the tonalite pluton, and the rocks have the mineralogy and textures of metabasites metamorphosed under amphibolite or hornblende-hornfels facies conditions (Smellie, 1983). Hobbs (1968, p. 14) interpreted the schists as fragments of a (?) Precambrian metamorphic basement incorporated by the tonalite pluton during its emplacement, but new field evidence suggests that the schists are not enclaves, and may have formed as basic dykes (Smellie, 1983).

The schists occur as thin, sinuous sub-vertical sheets mainly confined to the metagabbro. They are laterally and vertically continuous, with sharply defined margins and rare enclaves of metagabbro. At one locality, a thin (12 cm) schist body cuts enclaves of metagabbro enclosed in microtonalite, a relationship that can only be explained if the schist was formed after the formation of the zone of enclaves. In addition, there is an apparent textural and mineralogical gradation between a series of unmetamorphosed, non-schistose lamprophyre dykes with prominent chilled margins, through dykes with both metamorphic and relict igneous textures and narrow schistose margins, to completely schistose and gneissose rocks (the False Bay schists (*s.s.*)). All the dykes are affected by epidote and/or metalliferous mineralization evolved at a late stage in the cooling history of the tonalite, and they were injected prior to the final consolidation of the pluton. The observed gradational relationships between the dykes and schists are best explained in terms of a hydrous basic magma injected immediately prior to, during and following the emplacement of the tonalite. The tonalite has yielded Late Eocene Rb–Sr and K–Ar whole-rock and mineral ages (Chapter XI). If this new interpretation of the origin of the False Bay schists is correct, the schists are of similar age and it is evident that they cannot be used as indicators of the 'basement' underlying the South Shetland Islands.

IV. MIERS BLUFF FORMATION

The Miers Bluff Formation (Adie, 1964*a*; Hobbs, 1968; Dalziel, 1969) is a sequence of tectonically deformed shales and greywackes that crops out only on Hurd Peninsula, Livingston Island (Fig. 1). It is fault-bounded on three sides and neither the top nor the base of the sequence is exposed. Inland of Hurd Peninsula, an upper contact with volcanic rocks of possible Cenozoic age was inferred by Hobbs (1968, fig. 2). Indurated metasomatized lapillistones (Mount Bowles agglomerate (Hobbs, 1968)), containing clasts of quartz–feldspar-rich sandstone probably derived from the Miers Bluff Formation, are faulted against the Miers Bluff Formation at the western end of the Mount Bowles ridge. The age of these rocks is also uncertain, but their altered state and field relationships led Hobbs to suggest a possible age-equivalence with Late Jurassic volcanic rocks at Hope Bay, Graham Land. He observed cataclastic effects in altered igneous rocks interbedded with the Miers Bluff Formation north-west of Huntress Glacier and he suggested that the alteration and cataclasis may have been caused by a major fault trending through Huntress Glacier. Re-examination of the specimen referred to by Hobbs failed to show any obvious cataclastic features and it is considered more likely, as Hobbs also suggested, that the effects are contact-metamorphic and related to the large Eocene plutonic intrusion that crops out on much of Livingston Island to the east and south-east of Hurd Peninsula. Del Valle and others (1974) described copper-lead mineralization in breccia zones on Hurd Peninsula and Hobbs sampled quartz veins with malachite and azurite. This mineralization is also related to the plutonic intrusion to the south-east. A tonalite apophysis that crops out north of Johnsons Dock clearly intrudes the Miers Bluff Formation and may be related to the larger pluton.

Only stratigraphically undiagnostic plant fossils and a possible shell fragment have been recovered from the rocks so far (Schopf, 1973) but Rb-Sr analysis of a cleaved mudstone layer within the formation has reportedly yielded an earliest Jurassic (197 Ma) 'apparent age', probably reflecting the time of diagenesis and/or deformation (Dalziel, 1972*a*, p. 51).

Sedimentary sequences that have been compared with the Miers Bluff Formation crop out on the Antarctic Peninsula (Trinity Peninsula 'Series', Formation or Group (Adie, 1957*a*; Aitkenhead, 1975; Elliot, 1965, 1966; M. R. A. Thomson, 1982*a*; Hyden and Tanner, 1981), including the Legoupil Formation (Halpern, 1964; M. R. A. Thomson 1975)), Alexander Island (LeMay Formation (Grikurov and others, 1967; Bell, 1973; Edwards, 1982)) and in the South Orkney Islands (Greywacke-Shale Formation (J. W. Thomson, 1973)). On the basis of available stratigraphical, lithological, petrographical and palaeontological evidence, Adie (1957*a*, p. 22) tentatively assigned the Trinity Peninsula Group a Late Palaeozoic (? Carboniferous) age, which was confirmed by limited palynological studies (Grikurov and Dibner, 1968). Schopf (1973) reviewed and criticized this evidence, and recent palaeontological studies on rare marine fossils from the supposedly related Legoupil and LeMay formations (M. R. A. Thomson, 1975; Edwards, 1982) indicate that at least parts of the sequence are of Triassic age. The few radiometric ages obtained from these rocks are no older than Permian (Chapter XI) and have been interpreted variously in terms of diagenesis, deformation and/or metamorphism (Miller, 1960; Grikurov and others, 1967; Dalziel, 1972*a*).

1. Lithology

The Miers Bluff Formation is a sedimentary sequence, which is at least 3000 m thick, and is mainly composed of shales, siltstones, arkosic greywackes and arkosic arenites. Intra-formational conglomerates, rare polymict conglomerates and pebbly mudstones are also present. Graded bedding, current bedding and sole marks are abundant (Dalziel, 1972*a*, p. 50). Although Hobbs (1968, p. 15) noted frequent reversals in the graded bedding, he considered the rocks to be correct way up. However, a re-appraisal of the way-up criteria by Dalziel (1972*a*) showed that the rocks form the inverted limb of a large-scale isoclinal fold. In the hinterland north-east of Hurd Peninsula, metamorphosed igneous rocks are interbedded with sandstones. Hobbs suggested that the igneous rocks could be either lavas or sills but he favoured an extrusive origin. However, lava extruded into a marine environment should be finely crystalline, possibly aphanitic, whereas the specimen collected by Hobbs is relatively coarse-grained (with plagioclase crystals up to 0.3 mm in the groundmass) suggestive of a hypabyssal rather than extrusive origin for the rock.

Moderate to poorly sorted siltstones and sandstones (arkosic arenites and arkosic greywackes (Pettijohn and others, 1972, p. 158)) are prominent in the formation. They are composed of predominantly sub-angular grains of quartz, feldspar, large detrital flakes of biotite and muscovite, with accessory garnet, zircon, apatite and opaque ore (Table V). Quartz and feldspar occur in roughly equal amounts. Orthoclase and plagioclase (albite-oligoclase) are the commonest feldspars but perthite and minor microcline are also present. The amount of matrix is small and it is largely composed of chlorite and sericite. Because of difficulties in distinguishing between matrix and 'pseudomatrix' (Dickinson, 1970), the values given in Table V must be regarded as maximum figures and the rocks may have closer affinities to arenites than to wackes (Pettijohn and others, 1972, p. 158).

Table V. Modal analyses of arkosic sandstones from the Miers Bluff Formation.

	P.43.1 Arkosic greywacke	*P.47.1 Arkosic arenite*
Quartz	36.8	42.4
Feldspar*	33.6	33.4
Volcanic fragments	2.4	1.0
Plutonic fragments	–	0.4
Sedimentary fragments	0.4	0.6
Metamorphic fragments	4.6	5.2
Polycrystalline fragments	2.2	3.8
Matrix	17.0	11.0
Muscovite	0.4	0.6
Biotite	2.6	1.6
Garnet	tr	–
Zircon	tr	tr
Opaques	tr	tr

* Plagioclase and K-feldspar
tr Trace.

Lithic clasts are minor constituents of the sandstones but they form an important part of the conglomerates. They are mainly sedimentary, including shale, siltstone, sandstone and rare chert (or recrystallized (?) tuff), and it is likely that many represent reworked penecontemporaneous material. Metamorphic rock fragments, mainly quartz-rich phyllites (some like fine-grained gneiss) and polycrystalline quartz, are common but subordinate in abundance to sedimentary clasts. Muscovite is common but biotite is rare in these fragments. Volcanic rocks are uncommon. They are often completely altered to chlorite or have a recrystallized quartzo–feldspathic groundmass. In rare instances, andesitic, (?) dacitic and (?) rhyolitic compositions can be inferred from the phenocrysts present. Plutonic rocks are also uncommon and they consist of graphic-textured feldspar and pebbles of granite.

2. Provenance

Disregarding reworked penecontemporaneous sedimentary material, the commonest lithic clasts in the Miers Bluff Formation are metamorphic (quartz–muscovite–(biotite–chlorite–feldspar)–phyllites and (?) gneisses, and polycrystalline quartz). Moreover, metamorphic rocks could have supplied much of the detrital muscovite, garnet, some biotite and quartz. The plutonic fragments are granitic but are less common. They are composed of quartz, albite-oligoclase, orthoclase, perthite and biotite, which are the major mineral constituents of the formation. A plutonic provenance is also likely for grains of microcline, graphic-textured feldspar, rare euhedral zircon and some polycrystalline quartz. The abundant grains of strained quartz probably had a similar origin (cf. Dickinson, 1970, p. 699; Blatt and others, 1972, p. 271), and strained quartz occurs in many of the metamorphic clasts. Fragments of lava and other igneous detritus (e.g. 'volcanic' quartz and feldspar (Pettijohn and others, 1972, p. 264)) are scarce, as are quartz grains showing good rounding, which suggest that volcanic and sedimentary rocks probably formed only a small part of the source area.

3. Alteration

The rocks of the Miers Bluff Formation are only slightly altered. They are indurated and the shales are coarsely cleaved, although a *cleavage* is not defined in thin section. Mineralogical changes are restricted to recrystallization of the matrix to form chlorite and sericite. Although the flakes of sericite are relatively coarse, muscovite is not developed. Chlorite has grown within detrital biotite, muscovite and garnet. Plagioclase is not albitized but the feldspar grains are commonly altered to indeterminate clay and sericite (sometimes very coarse flakes). The presence of altered and unaltered feldspars in the same rocks suggests that some of these changes occurred prior to deposition.

The alteration of a sill north-west of Huntress Glacier is typical of a metamorphosed basic rock, with a mineral assemblage (plagioclase–green hornblende–actinolite–(quartz–chlorite–epidote–sphene–tremolite–biotite)) conforming to the hornblende–hornfels facies (Turner, 1968). Sandstones at this locality show considerable recrystallization, with polygonization of the clastic quartz and feldspar and growth of biotite and muscovite. North of Johnsons Dock, shales and siltstones have been contact metamorphosed by a small tonalite intrusion. The siltstones show only slight recrystallization of the smallest clastic grains of quartz, together with much sericite and minor biotite, whereas the shales are completely recrystallized and contain large (1 mm) porphyroblasts of cordierite, much sericite (notably localized within cordierite) and biotite. The grade of metamorphism conforms to a lower-temperature part of the hornblende-hornfels facies than is recorded in the rocks north-west of Huntress Glacier.

V. WILLIAMS POINT BEDS

At Williams Point, north-eastern Livingston Island, a 10–20 m sequence of thin-bedded fine-grained sandstones and mudstones (Williams Point Beds) are capped by a 20–30-m-thick basaltic sill (Figs. 3 and 4). Steep cliffs make much of this sequence difficult of access. Thicker bedded coarser sandstones and conglomerates crop out in the south-western part of the headland but are separated from the sandstones and mudstones by two pyroclastic vents of Late Cretaceous age (Chapter VIII), one of which forms Sayer Nunatak.

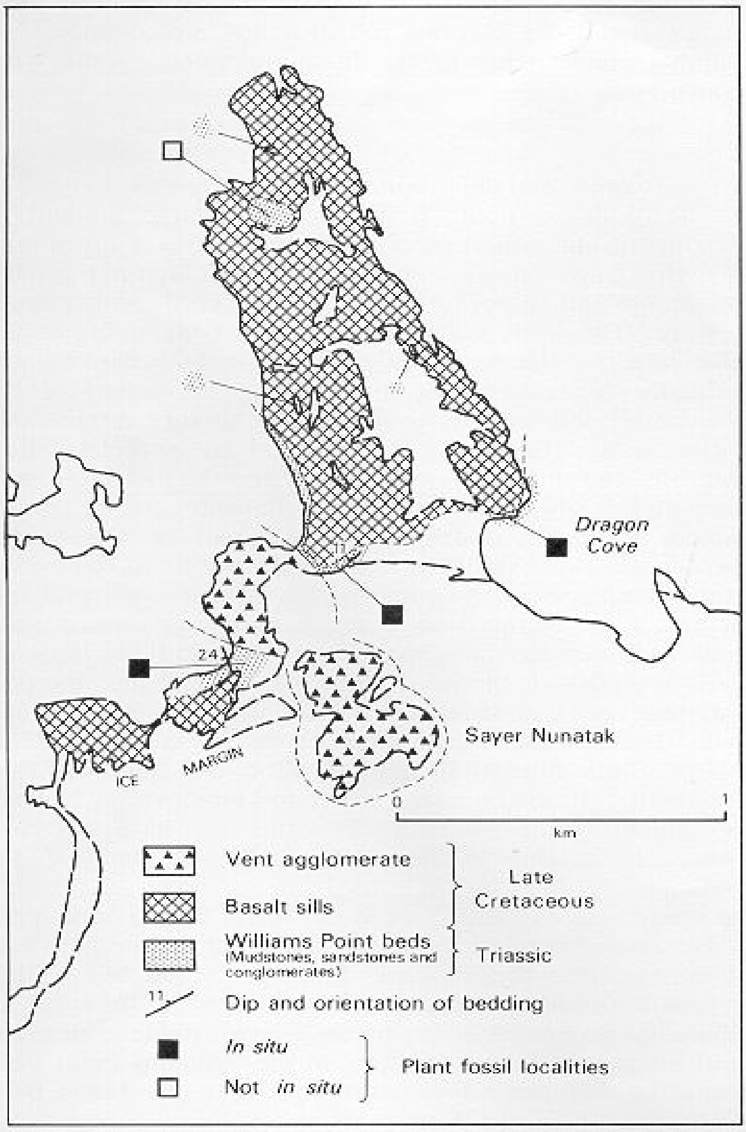

Fig. 3. Geological sketch map of Williams Point, Livingston Island.

Fig. 4. Columnar-jointed Upper Cretaceous sill intruding Triassic Williams Point Beds on the west side of Williams Point. The beds are caught up in a large-scale squeeze-up into the sill, which is a mutiple intrusion and shows faint banding perpendicular to the columnar joints. The cliffs are about 30 m high.

Concentrations of loose fragments of tuffaceous, plant-bearing sandstones, occurring on the surface of the headland, were interpreted by Hobbs (1968, p. 25) as having weathered out of boulders in the conglomerate. This conglomerate was mapped by Hobbs as part of a (?) Miocene 'Younger volcanic group', whereas Orlando (1967, 1968) assigned a Triassic age to the plant fossils. However, no boulders of comparable lithology have been found in the conglomerates and, during the present investigations, fossil leaves were found *in situ* on the north side of Dragon Cove and about 300 m north of Sayer Nunatak. Their occurrence in surface debris is believed to have resulted from giant squeeze-up structures of sedimentary beds through the capping sill. (Fig. 4). The new plant collections and those made by Hobbs have been studied by Lacey and Lucas (1981) who assigned them a Middle to Late Triassic age on the basis of the following identifications:

Thallites spp.
Equisetites sp.
E. triphyllum sp. nov.
cf. *Neocalamites* sp.
Asterotheca crassa Orlando
Conopteris distans Orlando
Rachis of Osmundaceae (? of *A. crassa*)
Frond of Dipteridacea
Thinnfeldia sp.
Dicroidium cf. *lancifolium* (Morris)
D. (*Xylopteris*) cf. *elongata* (Frenguelli)
D. (*Xylopteris*) cf. *spinifolia* (Frenguelli)
Pterophyllum dentatum sp. nov.
Pagiophyllum sp.
Ginkgoites sp.
Doratophyllum (*Taeniopteris*) cf. *tenisonwoodsi* (Etheridge)

Thus the (?) Miocene age tentatively assumed by Hobbs (1968) is no longer tenable.

The recognition of Triassic sedimentary rocks at Williams Point poses a serious stratigraphical problem. The rocks are poorly indurated and apparently undeformed. By contrast, the turbidite deposits of the Miers Bluff Formation, which could also be of Triassic age (p. 14) and crop out less than 18 km south-south-west of Williams Point, have suffered isoclinal folding. The relative proximity of these two lithologically and structurally different rock units, which could be of similar age, is enigmatic.

1. *Lithology*

The plant-bearing sequence consists of thin-bedded, crumbly grey-green volcanic sandstones, more massive-bedded brown mudstones and rare cream-coloured vitric tuffs. Some beds show normal grading and small-scale flame structures. On the north side of Dragon Cove load casts have formed at the contact with the overlying sill, which is finely brecciated within a 2–3 cm zone and includes a large (80 cm) buckled enclave derived from the sediments. About 300 m west of Sayer Nunatak (Fig. 3), well-bedded conglomerates with rounded boulders up to 0.5 m across pass up into interbedded conglomerates and fissile sandstones with rust-stained carbonized twig and log impressions. The upper 1–2 m of this sequence is stained steely blue-black near the contact with a basaltic sill.

The sandstones and sandy matrices of the conglomerates west of Sayer Nunatak are moderately well sorted, and are formed of rounded to angular quartz and plagioclase in roughly equal amounts, rare augite and chlorite-altered (?) biotite. Lithic clasts are also common and are mainly fragments of dense pilotaxitic lavas (? juvenile material), recrystallized tuffs and hypabyssal rocks, some of which contain epidote (*s.s.*). Fragments of zeolitized pumice, quartzite and quartz-feldspar-rich sandstones and siltstones with detrital biotite are also present. The rocks are cemented by (?) heulandite and/or calcite. (?) Heulandite also patchily replaces plagioclase and some grains are stained by goethite.

By contrast, the sediments north of the two vents are very muddy, with much carbonaceous matter and angular silt-sized grains of quartz, untwinned feldspar, apatite, epidote, rare biotite and clay-rich patches up to 0.2 mm across, which may represent original vitric clasts. Poorly preserved (?) spores are common in specimen P.426.8.

The rare vitric tuffs contain flattened colourless pumice up to 2.5 mm in length set in abundant yellow-brown matrix in which shard-like shapes can often be distinguished. All the vitric constituents are entirely replaced by clay minerals and microcrystalline silica, but a strong ignimbrite-like texture is evident. Silt to fine-sand-sized fragments and euhedral crystals of quartz, untwinned feldspar, opaque ore, apatite, epidote (*s.s.*) and an unidentified brown amphibole-like mineral are scattered through the rock; some of the quartz crystals have resorption textures and are clearly of volcanic origin. Sub-angular lithic clasts are uncommon and include polycrystalline (mosaic) and microcrystalline quartz, the latter possibly representing recrystallized fragments of tuff, very rare fragments of silicified lava and fine sandstone composed of angular strained quartz grains set in minor clay-rich matrix. Plant fragments, some thin-walled and preserving cell structure, are common both parallel and oblique to the fissility defined by the vitric constituents.

2. *Provenance and environment of deposition*

The Williams Point Beds contain a large amount of detritus of undoubted volcanic origin (above). Clay-altered (?) vitric fragments are common in the muddy finer-grained sediments and there are rare zeolitized clasts with pumice texture. The lithic constituents of the conglomerates are also largely volcanic (mainly lavas). In addition, reliable evidence for active volcanism during deposition of the Williams Point Beds is provided by the rare interbedded vitric tuffs. These probably formed as pyroclastic-flow deposits, but the absence of welding and the preservation of thin-walled plant fossils showing delicate cell structure, which would be destroyed by the heat of a subaerial pyroclastic flow, indicate that the final site of deposition was subaqueous; the ignimbrite-like texture was probably achieved by compaction beneath the later-formed sediments. Also present as clasts in the Williams Point Beds are rare crystals of biotite, fragments of (?) metamorphic quartzite and quartz-feldspar-rich sandstones and siltstones with detrital biotite. All these clasts are common in the Miers Bluff Formation but phyllitic and plutonic rock fragments, strained quartz, garnet and muscovite, which are prominent in the Miers Bluff Formation, have not been observed in the Williams Point Beds. Some of the sedimentary clasts in the latter bear a striking resemblance to sandstones and siltstones in the Miers Bluff Formation.

Because of similarities in clastic content and perhaps age, it appears that the Williams Point Beds and Miers Bluff Formation had a similar source, but the presence of abundant fragments of (?) juvenile lava, friable vitric clasts and interbedded ash-flow tuffs in the Williams Point Beds indicates that these rocks, in contrast to the Miers Bluff Formation, received detritus from a volcanic source active during the Middle or Late Triassic.

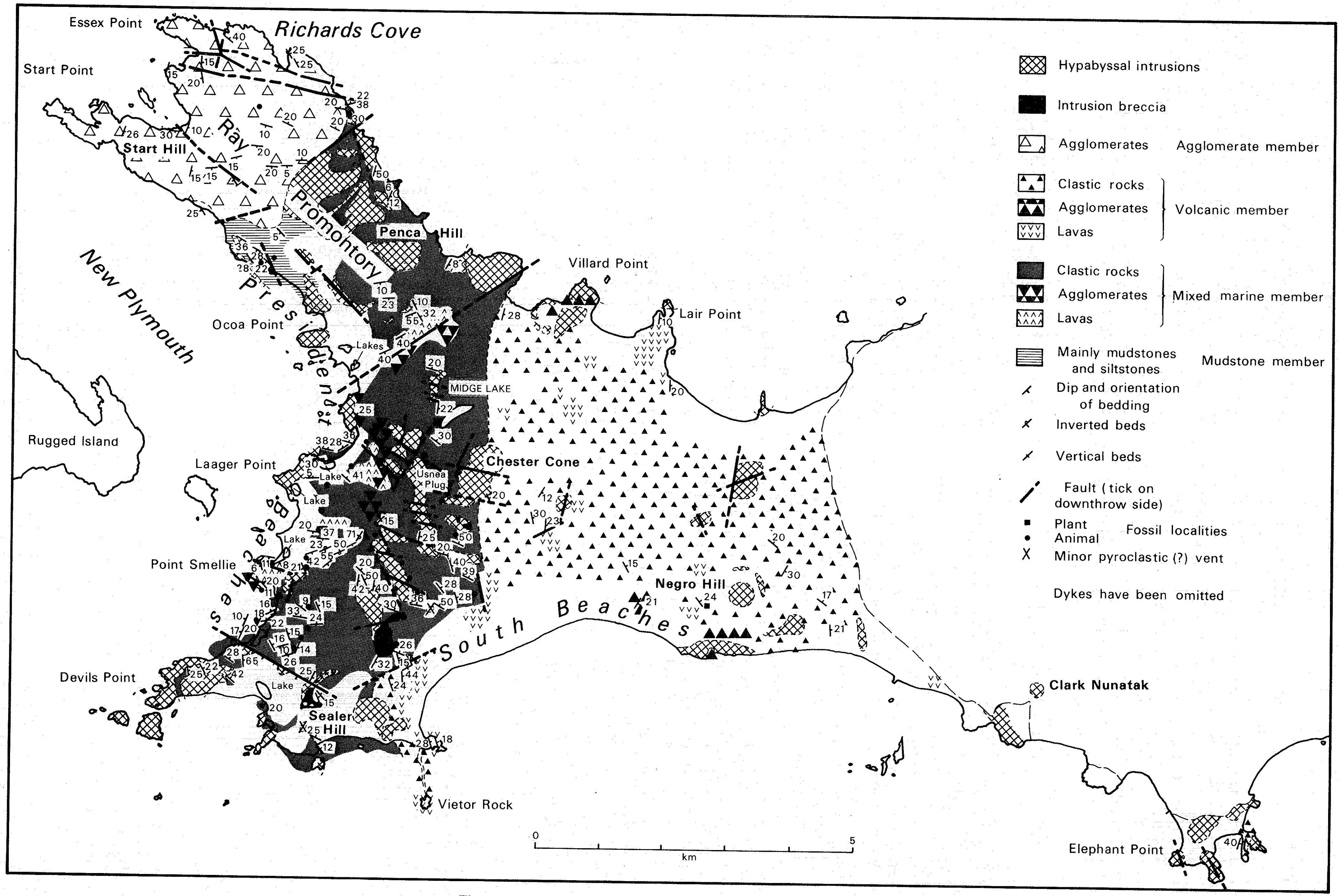

Fig. 5. Geological sketch map of Byers Peninsula, Livingston Island.

Largely on the basis of palaeobotanical evidence, Professor W. S. Lacey and Dr R. C. Lucas (University College of Wales, Bangor; written communication, 1978) suggested that the depositional environment of the Williams Point Beds was probably a system of mud banks and pools with some plants *in situ* and fragments of others washed in probably from higher land nearby. This is compatible with the petrography and field appearance of the plant-bearing sediments but the conglomerates and cleanly washed sandstones west of Sayer Nunatak, which show no evidence (such as fossils) of a marine influence and contain a large number of rounded and sub-rounded clasts, clearly indicate higher-energy conditions, possibly consistent with their formation as channel lag, point bar or alluvial fan deposits. However, this suggestion must remain tentative until more data are available.

VI. UPPER JURASSIC–LOWER CRETACEOUS VOLCANIC ROCKS

Fossiliferous rocks with ages ranging from Late Jurassic to Early Cretaceous crop out on Livingston, Snow and Low islands (Fig. 1, Table VI). On Half Moon Island, poorly exposed lavas and volcaniclastic rocks are intruded by at least three small plutons (Camacho and Villar Fabre, 1957; Araya and Hervé, 1966; Fig. 15), one of which has yielded a radiometric age of 105 Ma (Grikurov and others, 1970). Altered volcanic rocks, lithologically similar to those on Half Moon Island, also crop out extensively on Greenwich Island and form parts of Nelson, Robert and Livingston islands. The outcrops on Livingston Island (at Mount Bowles and Renier Point) and probably most of those on Greenwich Island are likely to be similar in age to the pre-mid Cretaceous rocks on Half Moon Island. However, an age assignment is more speculative for the outcrops on Nelson and Robert islands since new radiometric evidence from northern Robert Island (Chapter XI) shows that some of the less altered rocks in this area are as young as Late Cretaceous in age. At Harmony Point, Nelson Island, the rocks have suffered open 'dome and basin' folding identical to that seen at Byers Peninsula (Livingston Island) and Cape Wallace (Low Island). The extensive outcrops of metasomatically altered volcanic rocks on King George Island, previously considered to be Late Jurassic (Ferguson, 1921; Tyrrell, 1921, 1945; Diaz and Teruggi, 1956; Hawkes, 1960; Barton, 1965), are now thought to be Tertiary (Davies, 1982*a*, *b*).

Stratigraphical relationships between the Mesozoic volcanic rocks and other stratigraphical groups are obscured by the extensive cover of permanent snow and ice. However, at Mount Bowles, Livingston Island, indurated and altered volcaniclastic rocks thought to be of (?) Mesozoic age (Hobbs, 1968, p. 17) contain fragments of quartz- and feldspar-rich sandstones lithologically similar to sandstones from the Miers Bluff Formation, a short distance to the west. Although poorly exposed, deformation of the Mount Bowles rocks is apparently not as severe as that of the strongly deformed Miers Bluff Formation and, in view of the age differences between the two stratigraphical groups, it is likely that they are separated by an unconformity.

A. STRATIGRAPHY

1. *Western Livingston and eastern Snow islands*

This area contains the best known and most extensive deposits of Mesozoic age in the South Shetland Islands (Araya and Hervé, 1965, 1966; Hobbs, 1968; González-Ferrán and others, 1970; Valenzuela and Hervé, 1972). It contains the Byers Formation, which was defined on the basis of outcrops at Elephant Point, Cape Shirreff and

Table VI. Ages of the fossiliferous Mesozoic rocks of the South Shetland Islands.

AGE	LOW ISLAND Cape Wallace[1]	SNOW ISLAND President Head[2]	LIVINGSTON ISLAND Byers Peninsula[3]
EARLY CRETACEOUS		Neocomian	AGGLOMERATE MEMBER (Early Cretaceous) MIXED MARINE MEMBER (Berriasian-Valanginian) VOLCANIC MEMBER (Early Cretaceous) MUDSTONE MEMBER (Early Tithonian)
LATE JURASSIC	Oxfordian		

[1]Thomson (1982).
[2]Askin (1983).
[3]Smellie and others (1980).

Byers Peninsula (Fig. 5; Smellie and others, 1980) and it can probably be extended to include outcrops at Rugged Island, eastern Snow Island and Hannah Point. The combined sequence youngs progressively north-eastwards from Snow Island to Elephant Point, and possibly to Hannah Point. However, some repetition by faulting cannot be ruled out.

Glassy dacite lavas interbedded with fine lapillistones and tuffs constitute the base of the sequence at President Head, Snow Island. On the southern side of the headland they pass up into thick (30 m) hyalodacite lavas overlain by poorly exposed green tuff indurated by a thick andesite sheet (Fig. 6). The hyalodacites apparently pass laterally northwards into a clastic sequence composed of greenish-yellow plant-bearing tuffs (both water-lain and pyroclastic), unfossiliferous structureless fine-grained conglomerate and sandstone (Araya and Hervé, 1965), and a thick non-stratified deposit of fine brown lapillistone with rare clasts of acid plutonic rocks. Individual plant beds are 2–10 cm thick and show small-scale slumping and wash-out structures (Araya and Hervé, 1965). The eastern part of President Head is formed of basaltic andesites, some with reddened amygdaloidal surfaces, which may be lavas (Fuenzalida and others, 1972) but the field relationships are inconclusive.

Hall Peninsula, Snow Island, is composed of a thick, crudely columnar andesite sill which is locally permeated by zeolite, causing the rock to weather with a nodular effect. The low-lying promontory situated immediately to the south (Fig. 6) is formed of andesite lavas intruded by thin sills, and an isolated intrusion of highly porphyritic andesite crops out on the beach mid-way between the two promontories.

The Byers Formation on Livingston Island is a mixed sedimentary and volcanic succession that is mainly marine in the west (mudstone member), terrestrial in the east (volcanic member) and has a zone of mixed facies between the two (mixed marine member) (Smellie and others, 1980; Table VI; Fig. 5). The mudstone member is a deep-water flysch-like sequence of poorly fossiliferous black mudstones and grey siltstones with occasional thin sandstones and tuffs. It crops out principally on the shores of New Plymouth and probably passes up into a sequence of sparsely fossiliferous dark grey or greenish poorly-lithified shales with interbedded green and grey sandstones of the mixed marine member, which occur in a large area of poor exposure around Penca Hill. On the foreshore between Laager and Devils points, the mixed marine member consists of thin-bedded fossiliferous fine-grained green sandstones, grey siltstones, brown carbonaceous mudstones and rare thin conglomerates, whereas inland it is dominated by grey-green, grey-brown and rust-coloured coarse sandstones and granule to pebble conglomerates. Some of the sandstones are locally rich in fossils. Sedimentary structures

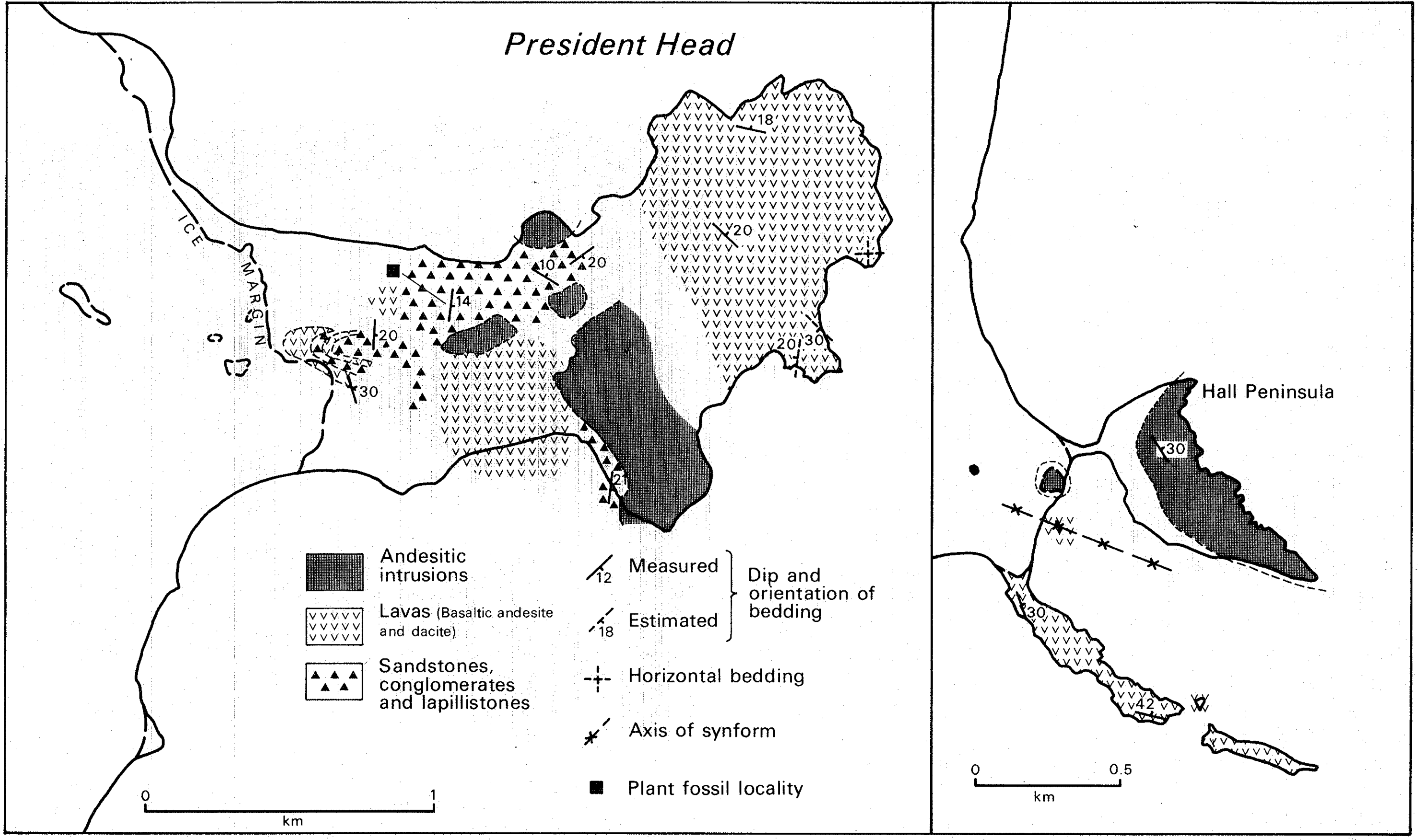

Fig. 6. Geological sketch map of President Head and Hall Peninsula, Snow Island.

in these rocks are extremely rare. Within the sandstone–conglomerate sequence there are areas of fine-grained rocks, mainly buff-green, brown or black shales but sometimes including thin sparsely fossiliferous micritic limestones or large (up to 2 m) calcareous concretions. North and south of Chester Cone, the mixed marine member intertongues with and passes up into entirely terrestrial rocks, mainly rhyolitic ash-flow tuffs and lapillistones that become finer eastwards, and interbedded basalt and basaltic andesite lavas (volcanic member), which extend east to Elephant Point and possibly north as far as Cape Shirreff. Agglomerates are present in places and there are local mudstone–siltstone sequences with occasional sandy lenses and plant fossils (Hernández and Azcárate, 1971) which probably represent lacustrine deposits.

In addition, north-western Ray Promontory is formed of coarse grey-green and brown vent breccias, agglomerates and rare basaltic andesite lavas (agglomerate member). It is thought that Rugged Island may be formed of comparable rocks. Non-erosional unconformities showing major changes in depositional angle of the beds are common and may be related to changes in location of the eruptive centres. The agglomerate member overlies both the mudstone and the mixed marine members and the contact was interpreted as an angular unconformity by Valenzuela and Hervé (1972) although no age was assigned to the agglomerates. However, Smellie and others (1980) suggested that the contact is not of major time-stratigraphical significance and the relationships can be explained by the sudden onset of volcanicity centred on the Start Point area during the Early Cretaceous. These relationships are rationalized in Table VI. This suggestion has been confirmed by radiometric data (Chapter XI).

Intrusions are common, particularly in the mixed marine member and at Elephant Point (Fig. 5). They often show intense deuteric alteration and this has affected the adjacent sediments, which frequently form conspicuous piles of pale cream-coloured debris flanking the margins of the intrusions. Some of the plugs at Byers Peninsula display spectacular columnar jointing (e.g. at Sealer Hill and Negro Hill), and the Chester Cone plug contains hornblende megacrysts up to 10 cm in diameter. A number of the intrusions are largely fragmented and form clinker-like breccias of admixed basalt and sedimentary rock fragments. They were interpreted as breccia pipes by Valenzuela and Hervé (1972) but a more plausible explanation is that they represent high-level intrusions injected into the wet sedimentary pile (Pankhurst and others, 1980). Rapid chilling of the magma was probably accompanied by gas explosions which allowed re-mobilized sediment to filter between the dispersed clasts (Smellie and others, 1980).

Hannah Point has been described in detail by Hobbs (1968, p. 23). It is composed of interbedded lavas (mainly andesites), normally graded coarse volcanic sandstones and volcaniclastic rocks, which include fine-grained thin-bedded lapillistones, coarse blocky agglomerates with carbonized logs and thin ash-flow tuffs. High-angle erosional unconformities occur locally within the volcaniclastic deposits.

2. Low Island

Two spatially separated rock groups of Late Jurassic age crop out on Low Island (Smellie, 1980). One consists of cryptically bedded (?) subaerially erupted lavas, including augite- and hornblende-andesites and rare basalts, which crop out in the Cape Hooker area and parts of Cape Wallace. The other group is formed of thin-bedded turbidite deposits, composed of primary volcanic tephra, which are sparsely fossiliferous at Cape Wallace. The sediments are mainly volcanic claystones and crystal tuffs (terminology after Fisher (1961) and Pettijohn and others (1972)) but rare lapillistones are also present and appear to form much of a rocky north-facing bluff situated approximately 10 km east of Cape Wallace. Individual beds are generally 4–30 cm thick, laterally uniform and continuous, and graded bedding was frequently observed in thin section. Other sedimentary structures are scarce but small-scale cross laminations, washouts and disrupted beds occur at Cape Wallace. All the rocks are indurated, well-jointed and pale to dark grey in colour. Epidote and, less commonly, pyrite are conspicuous on joint surfaces.

3. Eastern Livingston Island, Half Moon, Greenwich, Robert and Nelson islands

The outcrops included in this section are formed of indurated, closely-jointed, cryptically-bedded lavas (mainly andesites and basaltic andesites) and thin unfossiliferous clastic rocks. They often form areas of prominent relief (Fig. 7). Epidote and/or pyrite mineralization are usually conspicuous. The outcrop at Yankee Harbour is atypical; bedding is obvious, the rocks are less indurated and they show neither epidote nor pyrite mineralization. However, they are intruded by coarse microdiorite dykes and form an

Fig. 7. Air photograph, looking to the north-west across Greenwich, Robert and Nelson islands from above the south-east coast of Livingston Island. The areas of prominent relief are formed by plutonic intrusions and highly altered volcanic rocks.

area of moderate relief marginal to areas that possess all the characteristics listed above.

At Harmony Point (Fig. 8), the lavas vary in thickness from 4 to 20 m, but such estimates are made difficult there and elsewhere by the scarcity of recognizable primary bedding features. Scoriaceous, rarely red-coloured surfaces were observed at Triangle Point, Yankee Harbour, Harmony Point and Half Moon Island. The clastic rocks are variously green, red-brown or purple in colour and they are greatly subordinate to lavas. They usually form beds a few metres thick, but include a deposit 35 m thick at Yankee Harbour formed by dark brown fine-grained lapillistone with scattered blocks up to 30 cm. This passes laterally westwards into a sequence of lavas and thin interbedded volcaniclastic rocks. The commonest clastic rocks are fine to coarse-grained non-stratified lapillistones, but altered ash-flow tuffs crop out at Renier Point and possibly Edwards Point. Thin-bedded volcanic mudstones and fine volcanic sandstones occur locally at Harmony Point, Ferrer Point and Half Moon Island. At Harmony Point, they form beds 0.5–20 cm thick (including a 1-cm-thick bed of coal) that are locally disrupted and show cross-bedding, washout structures and normal grading. Conglomerates crop out at Ferrer, Sartorius and Harmony points and Spencer Bluff. That at Spencer Bluff is at least 17 m thick and is formed of well-rounded boulders 10–65 cm in diameter. At the other localities, coarse conglomerates form thinner beds and lenses and include pebble conglomerates that grade laterally into volcanic mudstones, shales and/or fine lapillistones at Ferrer and Harmony points. Compressed fragments of carbonized wood occur locally at Harmony Point.

Dykes and other intrusions occur at most of these localities but they are often difficult to distinguish from lavas owing to close lithological similarities. Small-scale intrusive breccias invade lavas at Triangle, Sartorius and Harmony points.

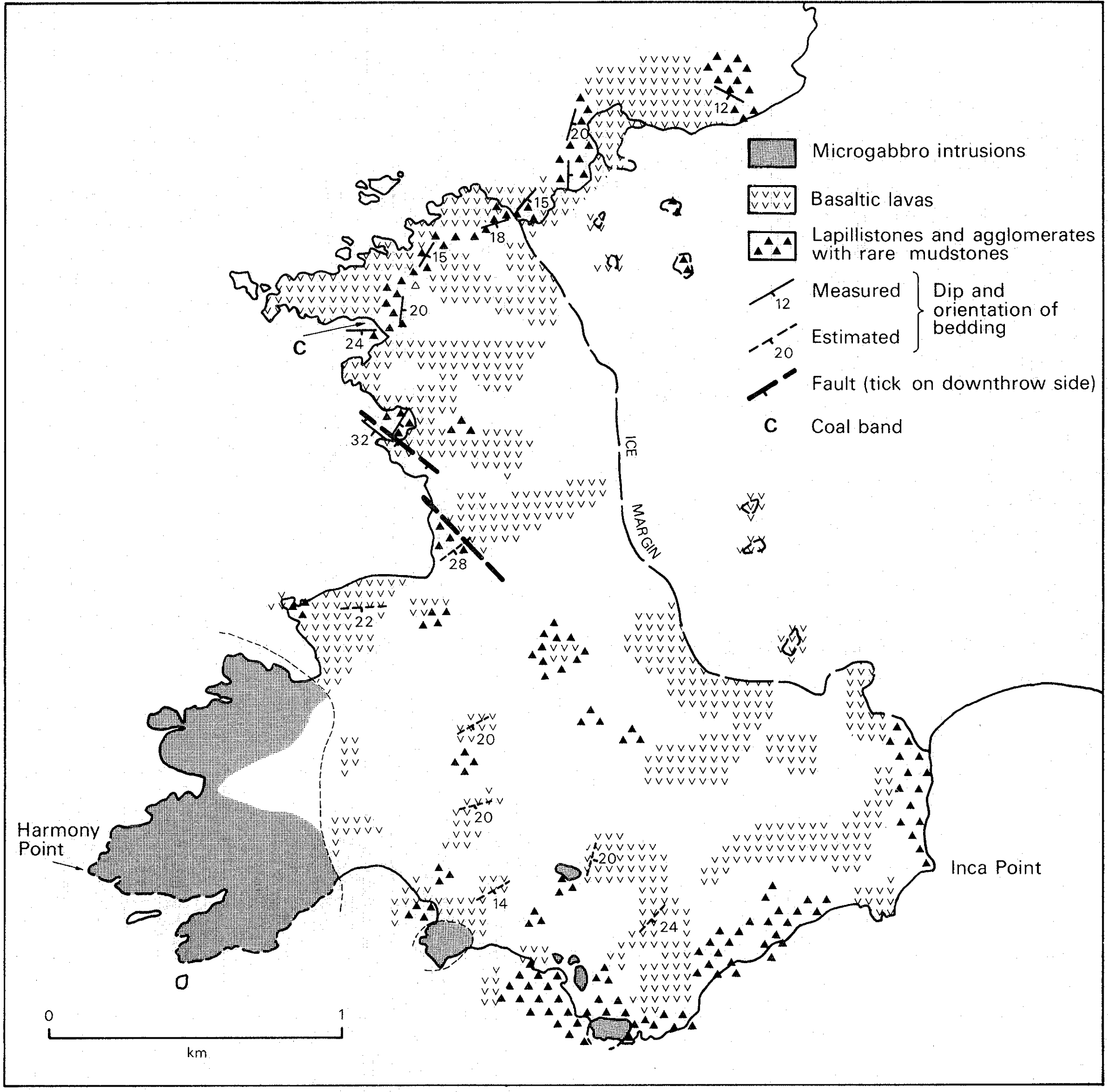

Fig. 8. Geological sketch map of Harmony Point, Nelson Island.

B. Palaeontology

Fossil marine faunas of Late Jurassic–Cretaceous age occur on Byers Peninsula and Low Island. The oldest is that of Low Island where a coarsely ribbed inoceramid of the *Retroceramus haasti* (Hochstetter) group, the ammonite *Epimayites* aff. *transiens* (Waagen) and indeterminate hibolithid belemnites were obtained. The presence of *E.* aff. *transiens* favours an Oxfordian age.

In the Byers Formation of western Livingston Island a more extensive marine sequence, ranging from Tithonian to Valanginian in age is preserved (Smellie and others, 1980). The oldest faunas occur in the marine member on the northern side of New Plymouth. These include belemnites related to *Belemnopsis stoleyi* Stevens and *Hibolithes marwicki marwicki* Stevens together with sporadic occurrences of fragmentary crushed ammonites resembling *Subplanites*, a species with close narrowly bifurcate ribbing (? *Virgatosphinctes denseplicatus* (Waagen)) and a possible body chamber of *Berriasella behrendseni* Burckhardt. Remains of buchiid bivalves in close association with some ammonite conchs may represent individuals once attached to the latter. Possible brachiopods were also found. A Late Tithonian age has been suggested for this fauna (Smellie and others, 1980).

A more extensive fauna is preserved in outcrops of the mixed marine member exposed along President Beaches. In addition to ammonites and bivalves, fragmentary remains of brachiopods, gastropods, echinoids, ophiuroids, serpulids and fish occur sporadically. The ammonites are dominated by one or two species of spiticeratid, in which the apparent lack of a bituberculate early stage favours an identification with *Negreliceras* Djanelidzé, rather than *Spiticeras* Uhlig *s.s.* Less frequent occurrences of *Himalayites hyphasis* (Blanford), *Himalayites* sp. nov. (?), *Blanfordiceras* sp. juv. (?) and *Bochianites* sp. are also present. Although the presence of *Himalayites* might be taken to indicate a Tithonian age, the more abundant spiticeratids favour a Berriasian age and it seems that the age of this fauna lies close to the Jurassic/Cretaceous boundary. Tavera (1970) suggested an Early Cretaceous age and this is also considered the more likely here.

A second fauna in the mixed marine member occurs about 1 km north of Sealer Hill (Fig. 5). It was described by Covacevich (1976) who identified the following ammonites: *Bochianites* aff. *glaber* Kitchin, *B.* aff. *gerardi* (Stoliczka), *Bochianites* sp. A, *Uhligites* sp. nov. (?), *Neocomites neocomiensis* aff. *premolica* Sayn and *Neocomites* sp. ind. Largely on the basis of *N. neocomiensis* aff. *premolica*, Covacevich assigned a Valanginian age to the fauna. Associated fossils include scaphopods, gastropods and bivalves (mainly nuculids). In a concretionary bed immediately below the main ammonite bed are robust guards similar to the belemnite *Belemnopis alexandri* Willey, first described from the Berriasian of Alexander Island (Willey, 1973, p. 37, figs. 3a–3).

A fauna that probably represents an intermediate stratigraphical position between the two latter ones occurs 2 km north of Sealer Hill. In addition to buchiid bivalves, *Nuculana, Rotularia* and crushed (?) fish remains, fragments of spiticeratid and neocomitid ammonites are also present. The neocomitid species differs from that of the last locality in possessing marked constrictions and less clearly branched ribs, and it is perhaps more closely related to the genus *Thurmanniceras* Cossman.

At least parts of the agglomerate member were erupted into the sea and at two localities it contains fragments of oysters, which probably represent shell beds overwhelmed by volcanic flows. Rare gastropods and a mytiloid bivalve occur in association with the oysters; one shell is bored by a *Lithophaga*-like bivalve.

Plant remains, mainly as woody fragments, are present in many of the Mesozoic rocks but leaf floras occur at President Head, Snow Island (Fuenzalida and others, 1972) and Negro Hill, Byers Peninsula (Hernández and Azcárate, 1971). Both of these are dominated by ferns and cycadophytes. That from President Head was dated as Middle Jurassic and that from Negro Hill as Early Cretaceous (Barremian) but recent re-examination of the former now suggests a Neocomian age (Askin, 1983). The dating of such floras in the Antarctic Peninsula with any certainty is difficult, because of the generally poor preservation of the leaves and the lack of usable associated palynofloras. Even the classic flora of Hope Bay (Halle, 1913), widely regarded as Middle Jurassic, has been variously interpreted by a number of authorities as anything from earliest Jurassic to Late Jurassic or even earliest Cretaceous (Table VII; Taylor and others, 1979). If the floras of President Head and Negro Hill have been correctly interpreted, then all the palaeontological evidence points to more or less continuous

Table VII. Palaeobotanical age of Mount Flora plant beds.

Authority	*Suggested age*	*Criteria*
Nathorst, 1907	Upper Jurassic	Broad comparison with Jurassic equivalents in Europe and India. *Upper* Jurassic only mentioned in title of paper.
Halle, 1913	Middle Jurassic	Systematic study of material and close comparison with Middle Jurassic flora of Yorkshire.
Rao, 1953; Plumstead, 1964	Lower Jurassic	Comparison with Rajmahal flora of India of supposed Lower Jurassic age.
Stipanicic and Bonetti, 1970*b*	Uppermost Jurassic-earliest Cretaceous	Critical review of Halle's determinations and the consideration that the flora shows as many Cretaceous affinities as Jurassic.
Orlando, 1971	Lower Jurassic	Comparison with South American species, with special regard to *Thinnfeldia* and *Cladophlebis*.

volcanism in the South Shetland Islands from Late Jurassic to Early Cretaceous.

C. PETROGRAPHY

In general, the lavas and hypabyssal intrusions are petrographically similar. Aphyric rocks are rare and they usually contain abundant phenocrysts, including plagioclase (andesine and labradorite, rarely bytownite), olivine, augite, hypersthene, olive-green hornblende, quartz and opaque ore. Some compositional control on these is evident and olivine occurs only in the basalts and basaltic andesites whereas hypersthene and opaque ore phenocrysts are present mainly in the andesites and some basaltic andesites. Quartz phenocrysts are restricted to dacite lavas at President Head and plugs at Chester Cone and Sealer Hill (Byers Peninsula), and hornblende only occurs in andesite and dacite lavas on Low and Snow islands and in the Chester Cone plug. Resorption effects are common in all the phenocrysts, particularly plagioclase which frequently shows 'finger-print' textures consisting of blebs of dark brown glass; hornblende megacrysts at Chester Cone are surrounded by reaction rims of granular augite, opaque ore and plagioclase. The groundmass minerals consist mainly of plagioclase laths (andesine and labradorite, rarely oligoclase), abundant inter-granular pyroxene (augite, pigeonite and/or hypersthene), granular opaque ore and rare apatite. Pigeonite is particularly common in lavas and intrusions at Byers Peninsula, Elephant Point and Hannah Point. The rocks are generally holocrystalline and sometimes pilotaxitic, but dark brown interstitial glass, with exsolved opaque ore microlites, is common in the lavas on Byers Peninsula.

Some of the thicker intrusions vary from basalt or andesite to microgabbro, microdiorite or diorite and they are common on Byers Peninsula. Although mineralogically similar to the finer-grained intrusions, they show textural differences, including ophitic augite and skeletal (?) ilmenite.

The commonest clastic rocks are lithic tuffs and lapillistones composed of sub-angular fragments derived from lavas and hypabyssal intrusions, tuffs, crystals (plagioclase, minor quartz and augite) and vitric clasts (Fig. 9a). Many of the lithic clasts contain secondary quartz or rare epidote, and much of this alteration is considered to have occurred prior to incorporation in the rock. Vesicular lithic and vitric clasts are minor constituents but they may be locally abundant (e.g. in the coarse agglomerates at north-western Ray Promontory, Byers Peninsula). The matrix varies from finely comminuted lithic fragments to vitric 'dust' and shards.

The ash- and pumice-flow deposits (terminology after Ross and Smith (1961)) are composed of pumice and glass shards, variously welded, slightly welded or non-welded (Figs. 9b and 9c). Crystal fragments are common, mainly quartz and plagioclase (oligoclase-andesine) but also including orthoclase, biotite, hornblende, augite, hypersthene and opaque ore, and similar crystals occur as phenocrysts in the pumice clasts. Lithic fragments are uncommon.

The mudstone member of the Byers Formation is mainly formed by mudstones and siltstones. They are composed of silt to fine sand-sized angular grains of plagioclase scattered in a cryptocrystalline matrix largely consisting of clay minerals and calcite (Smellie and others, 1980). Some of the laminations in these rocks are rich in carbonaceous matter and contain *Radiolaria* replaced by calcite or quartz. Calcite

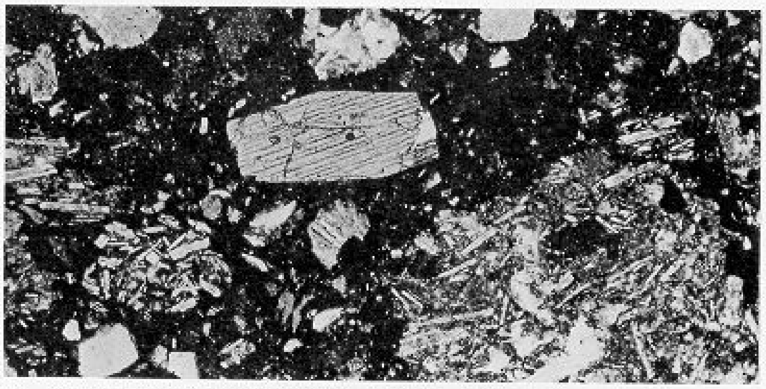

Fig. 9a. Lapilli-tuff composed of angular lithic and crystal fragments scattered in a clay-rich matrix. The euhedral crystal near the centre of the photograph is augite. Byers Peninsula, Livingston Island. (P.446.24, ordinary light, ×30.)

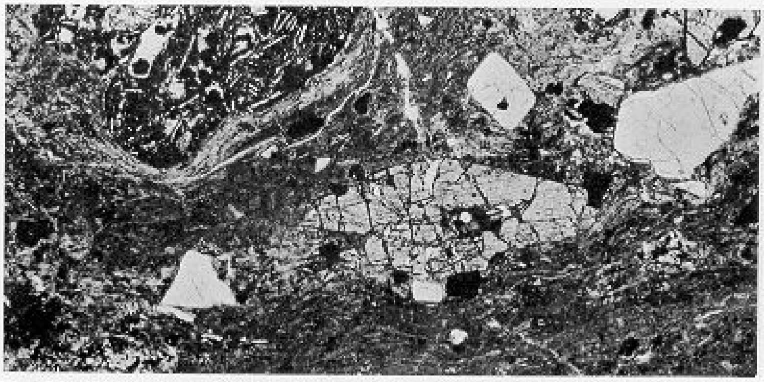

Fig. 9b. Welded andesitic ash-flow tuff, with lithic clast and crystals of plagioclase, augite and opaque ore. The dark glassy groundmass is essentially unaltered. Byers Peninsula, Livingston Island. (P.10.1, ordinary light, ×30.)

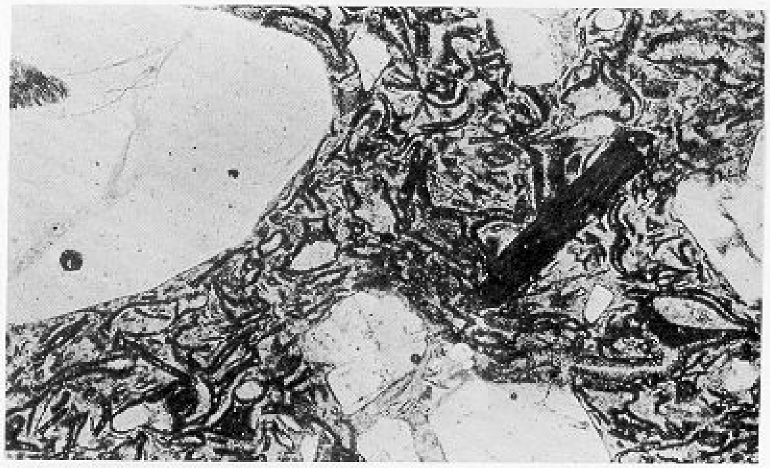

Fig. 9c. Rhyolitic ash-flow tuff showing slightly welded vitroclastic texture and crystal fragments of quartz, feldspar and biotite. Byers Peninsula, Livingston Island. (P.447.6b, ordinary light, ×30.)

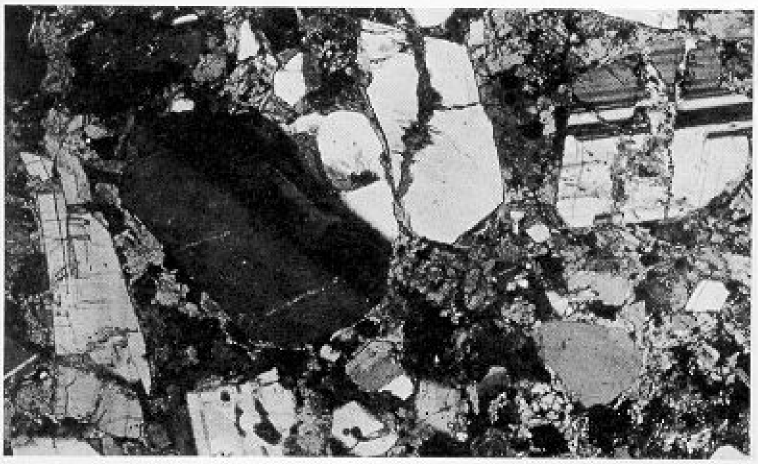

Fig. 9d. Crystal-rich sandstone from the mixed marine member, Byers Formation, Livingston Island, composed of plagioclase crystals, minor quartz and lithic fragments cemented by drusy calcite. (P.454.4, X-nicols, ×30.)

and/or chlorite-filled worm burrows are also present. Analogous deposits on Low Island are principally composed of quartz and feldspar crystals, angular to sub-rounded lithic fragments and a variable amount of fine (?) originally glassy matrix (Smellie, 1980).

The water-lain volcanic sandstones and conglomerates closely resemble the lithic tuffs and lapillistones described above, but they contain a greater number of rounded clasts, fossil fragments (including rhomb-shaped fossil seeds in specimen P.2.2) and very rare clasts of acidic plutonic rocks and polycrystalline quartz. They also have little or no matrix and typically contain blocky or drusy calcite cement (Fig. 9d). Rare limestones at Byers Peninsula are micritic with minor amounts of silt-sized angular quartz and feldspar.

D. ALTERATION

The lavas and clastic rocks of the Byers Formation, at Hannah Point, Yankee Harbour and north-eastern Snow

Table VIII. Chemical analyses of Upper Jurassic–Lower Cretaceous volcanic rocks of the South Shetland Islands. (Continued on page 25.)

	1	*2*	*3*	*4*	*5*	*6*	*7*	*8*	*9*	*10*	*11*	*12*	*13*	*14*
SiO_2	49.7	51.4	51.2	67.0	55.0	59.4	53.5	53.8	58.2	57.2	49.0	46.2	53.7	56.0
TiO_2	0.66	0.65	0.60	0.73	0.72	0.91	0.88	0.77	1.12	1.20	1.74	1.25	1.34	1.44
Al_2O_3	17.4	18.7	18.6	14.5	18.4	17.7	16.8	16.1	17.2	15.2	14.5	18.9	15.5	15.4
Fe_2O_3	2.38	2.22	2.40	1.29	2.05	2.08	2.51	2.58	2.37	2.55	4.23	3.15	3.02	2.74
FeO	5.96	5.55	6.01	3.24	5.13	5.21	6.28	6.45	5.92	6.37	10.58	7.87	7.55	6.86
MnO	0.14	0.15	0.15	0.17	nd	0.16	0.17	0.22	0.17	0.19	0.16	0.12	0.22	0.22
MgO	8.2	5.4	9.2	1.4	4.1	3.9	6.0	7.5	4.3	4.3	7.6	6.7	4.7	3.4
CaO	12.03	10.13	10.06	3.56	7.73	5.6	8.11	10.84	7.03	6.40	5.12	9.01	8.82	8.79
Na_2O	2.15	2.75	1.88	3.19	3.80	4.57	3.32	2.74	4.41	4.18	5.20	2.67	3.15	3.34
K_2O	0.40	0.20	0.58	1.88	0.69	1.16	0.72	0.24	0.88	1.27	0.14	0.15	0.75	1.21
P_2O_5	0.11	0.10	0.09	0.18	0.09	0.15	0.08	0.13	0.22	0.30	0.19	0.13	0.12	0.26
Total	99.13	97.25	100.77	97.14	97.71	100.84	98.37	101.37	101.82	99.16	98.46	96.15	98.87	99.66
TRACE ELEMENTS														
Cr	120	–	80	–	–	–	20	80	–	–	60	30	30	20
Ni	30	–	26	–	–	–	7	30	–	–	11	15	–	11
Zn	59	54	49	65	48	60	70	53	58	95	40	37	72	80
Rb	–	–	7	27	7	28	17	–	18	25	–	–	15	30
Sr	489	481	513	336	533	374	457	371	432	363	218	949	370	292
Y	13	13	13	36	19	32	21	14	30	35	23	19	21	39
Zr	67	56	58	164	67	144	69	50	118	149	67	70	85	167
Nb	–	–	–	5	6	–	–	–	4	5	–	–	–	6
Ba	161	103	116	344	178	309	158	65	347	376	100	118	158	236
La	–	–	–	9	8	17	–	–	9	24	–	–	–	12
Ce	16	10	15	27	14	26	12	14	24	34	12	9	19	33
Pb	–	–	–	10	–	–	15	–	–	–	–	–	–	–
Th	–	–	–	–	–	–	–	–	–	–	–	–	–	–
Ga	21	20	21	18	23	24	18	21	24	21	24	28	24	20
RATIOS														
K/Rb	–	–	688	578	818	344	351	–	406	422	–	–	415	335
Ba/Rb	–	–	17	13	25	11	9	–	19	15	–	–	10	8
K/Ba	21	16	41	45	32	31	38	31	21	28	12	11	39	43
Rb/Sr	–	–	0.01	0.08	0.01	0.07	0.04	–	0.04	0.07	–	–	0.04	0.10
Ba/Sr	0.3	0.2	0.2	1.0	0.3	0.8	0.3	0.2	0.8	1.0	0.5	0.1	0.4	0.8
Ca/Sr	176	151	140	76	104	107	127	209	116	126	168	68	170	215
Ce_N/Y_N	3.0	1.9	2.8	1.8	1.8	2.0	1.4	2.4	2.0	2.4	1.3	1.2	2.2	2.1
Fe*/Mg	1.3	1.8	1.1	4.0	2.2	2.3	1.8	1.5	2.4	2.6	2.4	2.0	2.8	3.5

nd – not determined

1.	P.1219.1	Basalt, Harmony Point, Nelson Island.
2.	P.1216.2	Basalt, Harmony Point, Nelson Island.
3.	P.1214.1	Basalt, Harmony Point, Nelson Island.
4.	P.1215.1	Silicified dyke rock, Harmony Point, Nelson Island.
5.	P.905.2	Andesite, Robert Point, Robert Island.
6.	P.917.1	Andesite, Edwards Point, Robert Island.
7.	P.495.1	Basaltic andesite, Edwards Point, Robert Island.
8.	P.431.3	Basaltic andesite, Ephraim Bluff, Greenwich Island.
9.	P.1251.10	Andesite, Half Moon Island.
10.	P.1251.7	Andesite, Half Moon Island.
11.	P.424.1	Basalt, Renier Point, Livingston Island.
12.	P.424.3	Basalt, Renier Point, Livingston Island.
13.	P.466.1	Basaltic andesite, Hannah Point, Livingston Island.
14.	P.476.1	Andesite, Hannah Point, Livingston Island.

Island, contain unaltered volcanic glass, plagioclase, augite and biotite and the primary igneous textures are unchanged. The commonest evidence for alteration consists of serpentine, bowlingite, iddingsite and clay minerals (mainly (?) smectite) replacing olivine, orthopyroxene, plagioclase and glass; minor amounts of zeolite minerals also replace volcanic glass. These secondary minerals are characteristic of diagenesis (Blatt and others, 1972, p. 567) and/or very low-grade metamorphism (Miyashiro, 1973). In addition, the occurrence of chlorite in rocks of the mudstone member at Byers Peninsula suggests that these rocks attained a metamorphic grade equivalent at least to the prehnite-pumpellyite facies; this is probably related to thermal effects caused by the numerous thin sills that intrude this member (Smellie and others, 1980). Many of the hypabyssal intrusions, particularly those at Byers Peninsula, contain large amounts of zeolite and clay minerals, prehnite, chlorite, calcite, and locally prominent sericite, albite, sphene and pyrite which are thought to have formed by deuteric rather than metamorphic processes (Smellie and others, 1980).

By contrast, on Low Island, virtually all the primary minerals show signs of alteration and they are often completely pseudomorphed. The commonest alteration mineral assemblage is: albite–quartz–actinolite–chlorite–epidote–sphene, and there are local occurrences of calcite, sericite, prehnite, laumontite and (?) smectite (Smellie, 1980). Moreover, biotite and/or hornblende are present in hornfelsed rocks around the margins of the plutonic intrusions on the island. Similar rocks in which actinolite is abundant also crop out east of Mount Bowles. They are typically associated with actinolite-free rocks in which the plagioclase and/or augite phenocrysts may be largely unaltered and, in some, even the groundmass minerals are unaffected (e.g. P.49.1, 4 and 1912.1). The commonest alteration mineral assemblage is albite–quartz–chlorite–epi-

Table VIII. Chemical analyses of Upper Jurassic–Lower Cretaceous volcanic rocks of the South Shetland Islands (continued).

	15	*16*	*17*	*18*	*19*	*20*	*21*	*22*	*23*	*24*	*25*	*26*	*27*
SiO_2	55.6	50.6	52.1	68.5	58.4	60.4	54.9	49.9	51.4	57.0	62.1	76.8	78.0
TiO_2	1.60	1.83	2.00	0.58	1.02	0.74	1.03	1.04	1.38	0.78	0.55	0.12	0.11
Al_2O_3	14.55	15.5	15.2	15.3	17.2	14.8	15.3	16.0	16.1	16.2	16.3	12.9	12.4
Fe_2O_3	3.19	3.56	3.65	1.43	2.31	1.71	2.72	2.40	2.68	1.96	1.58	0.28	0.06
FeO	7.98	8.91	9.12	3.57	5.76	4.27	6.80	8.01	8.94	4.89	3.94	0.71	0.14
MnO	0.21	0.23	0.23	0.09	0.13	0.11	0.20	0.20	0.23	0.21	0.26	0.02	0.01
MgO	3.6	4.7	4.4	1.9	3.4	2.1	5.9	6.8	4.9	5.4	3.6	0.3	0.2
CaO	7.44	8.97	8.28	4.32	7.72	5.34	7.55	11.79	9.81	6.03	6.45	0.56	0.27
Na_2O	3.45	2.23	3.41	4.05	3.74	4.26	2.91	2.68	3.28	4.00	3.38	3.62	2.26
K_2O	0.87	0.71	0.51	0.96	0.89	1.78	1.02	0.21	0.24	1.16	0.89	3.83	5.48
P_2O_5	0.24	0.19	0.23	0.11	0.14	0.18	0.11	0.15	0.23	0.24	0.22	0.01	0.01
Total	98.73	97.43	99.13	100.81	100.71	95.69	98.44	99.20	99.19	97.82	99.30	99.13	98.99
TRACE ELEMENTS													
Cr	–	20	–	–	10	10	20	124	27	12	11	–	–
Ni	–	–	–	–	10	–	–	27	6	4	–	–	6
Zn	96	91	98	37	65	45	104	nd	nd	nd	65	nd	nd
Rb	17	9	9	93	53	58	35	5	5	19	23	97	121
Sr	299	287	307	259	361	380	369	351	525	398	409	47	37
Y	38	26	32	20	21	33	22	18	22	25	18	30	15
Zr	125	90	111	161	103	138	78	62	70	124	140	106	102
Nb	11	–	4	4	4	3	–	–	3	6	4	8	9
Ba	206	140	153	382	312	310	154	68	150	206	218	586	665
La	18	18	16	26	15	9	–	6	6	10	13	40	19
Ce	35	19	28	39	32	25	16	15	26	23	35	32	35
Pb	–	–	–	10	10	–	–	5	8	4	4	11	9
Th	–	–	–	–	–	–	–	–	3	2	4	16	13
Ga	21	22	21	17	21	20	24	nd	nd	nd	15	nd	nd
RATIOS													
K/Rb	425	655	470	86	139	255	242	329	415	507	321	328	376
Ba/Rb	12	16	17	4	6	5	4	13	31	11	9	6	5
K/Ba	35	42	28	21	24	48	55	26	13	47	34	54	68
Rb/Sr	0.06	0.01	0.03	0.36	0.15	0.15	0.10	0.01	0.01	0.05	0.06	2.06	3.27
Ba/Sr	0.7	0.5	0.50	1.5	0.9	0.8	0.4	0.2	0.3	0.5	0.5	12.5	18.0
Ca/Sr	178	223	193	119	153	100	146	240	134	108	113	85	52
Ce_N/Y_N	2.3	1.8	2.1	4.8	3.7	1.8	1.8	2.0	2.9	2.2	4.7	2.6	5.7
Fe*/Mg	3.9	3.3	3.6	3.3	3.0	3.6	2.0	1.9	3.0	1.6	1.9	4.8	1.2

nd – not determined.

15.	P.901.3	Basaltic andesite, Elephant Point, Livingston Island.
16.	P.904.1	Basalt, Elephant Point, Livingston Island.
17.	P.903.4	Basalt, Elephant Point, Livingston Island.
18.	P.417.2	Dacite, President Head, Snow Island.
19.	P.411.3	Andesite, President Head, Snow Island.
20.	P.404.3	Andesite, Cape Hooker, Low Island.
21.	P.405.6	Basaltic andesite, Low Island.
22.	15468	Basalt, Negro Hill, Byers Peninsula, Livingston Island.
23.	15461	Basalt, Byers Peninsula, Livingston Island.
24.	15452	Andesite, Chester Cone, Byers Peninsula, Livingston Island.
25.	16572	Dacite, Chester Cone, Byers Peninsula, Livingston Island.
26.	15455	Rhyolite, Byers Peninsula, Livingston Island.
27.	15454	Rhyolite, Byers Peninsula, Livingston Island.

22–27: Representative analyses provided by A. D. Saunders and S. D. Weaver.

dote ± actinolite; sphene is a ubiquitous but minor constituent and clinozoisite occurs in specimens P.546.1 and 905.3. Biotite-bearing hornfelsed rocks crop out at Fort Point and Half Moon Island and the latter include amygdales filled by crystalline mosaics of twinned labradorite (P.1252.2).

The conspicuous epidote and pyrite mineralization on Low Island is largely restricted to fissures and the major alteration has been ascribed to low-pressure, very low-grade burial metamorphism or to large-scale, low-grade contact metamorphism caused by plutonic intrusions (Smellie, 1980). In the rocks east of Mount Bowles, metasomatism has occurred at Triangle, Ferrer and Ash points (calcite mineralization situated along a major fault trending through Yankee Harbour and Discovery Bay), and Half Moon Island (epidosite veins and metalliferous mineralization (Camacho and Villar Fabre, 1957, p. 51; Araya and Hervé, 1966, p. 48)). On a much smaller scale, metasomatic activity has resulted in the formation of K-feldspar in lavas at Spencer Bluff and Robert Point, grey-blue (?) pumpellyite in Sartorius Point, and veins of quartz–andesine/oligoclase–epidote–sphene, epidote–quartz–chlorite and actinolite–epidote–quartz at Mount Bowles, Renier Point, Spencer Bluff and Half Moon Island. However, there is little geochemical evidence to support the suggestion that widespread *substantial* introduction of material has occurred (below) and it is considered that the major alteration in the rocks east of Mount Bowles is a form of large-scale thermal metamorphism caused by the high-level emplacement and hydrothermal activity of acidic plutons; at Harmony Point, a large intrusion of porphyritic microgabbro is probably responsible for much of the alteration. In general, the mineral assemblages are those of the prehnite-pumpellyite facies. The more restricted occurrence of actinolite compared with the abundance of this mineral on Low Island suggests that both lower and upper prehnite-pumpellyite facies conditions are represented in the rocks east of Mount Bowles, whereas metamorphism on Low Island apparently did not fall below the upper prehnite-pumpellyite facies.

E. GEOCHEMISTRY

Major oxides and 14 trace elements were determined for 21 volcanic rocks of Late Jurassic–Early Cretaceous age (Table VIII) at the University of Birmingham (Department of Geological Sciences) using a Philips PW 1450 automatic X-ray spectrometer. Only seven analyses are from areas of unaltered rocks but these are supplemented by analyses of rocks from Byers Peninsula supplied by A. D. Saunders and S. D. Weaver (University of Birmingham). The rocks are classified by their silica content (raw analyses recalculated to 100% anhydrous): basalt <53%, basaltic andesite 53–56%, andesite 56–62%, dacite 62–68%, rhyodacite 68–72% and rhyolite >72% (Weaver and others, 1982).

When plotted against SiO_2, most of the altered rocks appear to have slightly to markedly low contents of K_2O, Na_2O, TiO_2, P_2O_5, Rb, Ba, La and Ce compared with the unaltered rocks, and analyses from Ephraim Bluff and Harmony Point are conspicuously rich in Ni and Cr. Although some of this variation may be attributed to alteration, the inclusion of TiO_2, P_2O_5, La and Ce, all of which are normally considered immobile (Pearce and Cann, 1973; Floyd and Winchester, 1975), and Ni and Cr which are relatively immobile, suggests that the use of SiO_2 as a fractionation index is suspect. Zr is highly incompatible in rocks of basic to intermediate composition (Tarney and others, 1977) and it is a well-known immobile element. Therefore, plots using Zr as an index of fractionation could be more meaningful. The differences in TiO_2, P_2O_5, La, Ce, Ni and Cr disappear when plotted against Zr, whereas enrichment in K_2O and Ba relative to the unaltered rocks is evident, and the Low Island lavas are also enriched in Rb. From the spread of data points, it is also likely that movement of Fe and Ca has occurred. Because these differences are largely restricted to the altered rocks, they may be attributed to metasomatic hydrothermal activity associated with the acidic plutonic rocks. Similar geochemical variation is shown by some of the deuterically altered hypabyssal intrusions at Byers Peninsula. However, because the chemical differences are generally small, inter-element ratios such as K/Rb and K/Ba may still have some significance, and La, Ce, Y and Zr are notably unaffected.

Weaver and others (1982) suggested that the Mesozoic volcanic rocks in the South Shetland Islands (Byers Peninsula) and Graham Land have definite calc-alkaline characteristics, which is in agreement with views expressed by other workers (e.g. Adie, 1972; Baker, 1972). It was also suggested that the more mafic lavas, which occur principally at Byers Peninsula and western Graham Land, are plagioclase-phyric high-alumina rocks with low Rb/Sr and Ba/Sr, and high K/Rb ratios typical of island-arc tholeiites (Jakes and Gill, 1970). By contrast, the contents of Sr, Zr, Ba, Cr and Ni are as high as those of calc-alkaline rocks, only moderate Fe-enrichment occurs on an AFM diagram, and the Ce_N/Y_N ratios (generally 1.5–3.5) suggest moderate light rare earth enrichment contrary to the flat or light rare earth depleted patterns typical of most island arc tholeiites. These conflicting affinities are particularly well shown by the Byers Peninsula data, in which the mafic rocks (basalts, basaltic andesites and silica-poor andesites) have high Fe*/Mg ratios similar to tholeiites, whereas the K_2O contents are typical of calc-alkaline rocks (Figs. 10 and 11).

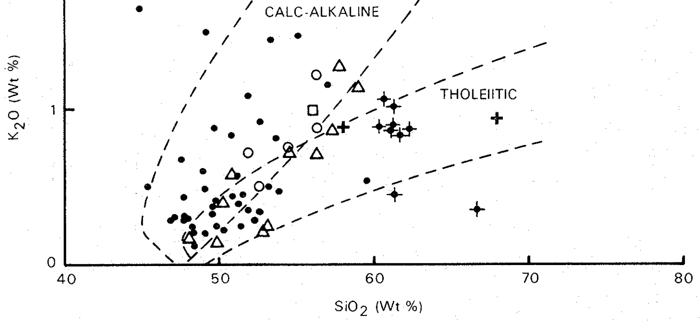

Fig. 10. Plot of K_2O against SiO_2 for Upper Jurassic–Lower Cretaceous volcanic rocks of the South Shetland Islands. (Symbols: □ = Low Island; + = President Head; ● = Byers Peninsula (✦ = Byers Peninsula, low-Y rocks); ○ = Elephant and Hannah points; △ = Renier Point, Half Moon Island, Ephraim Bluff, Edwards Point, Robert Point and Harmony Point.)

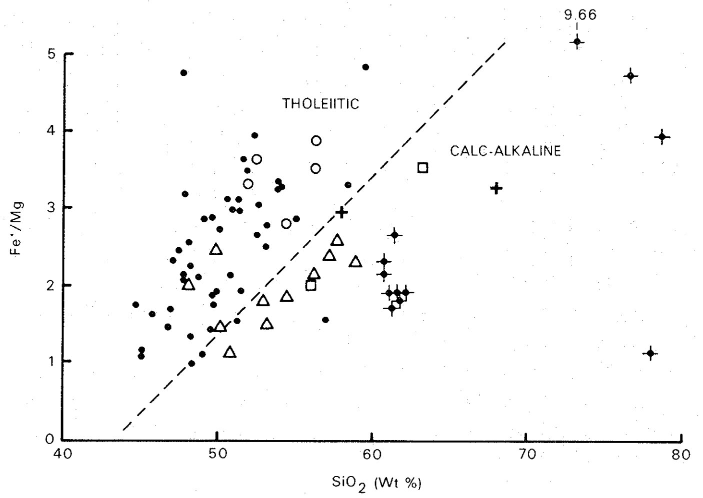

Fig. 11. Plot of Fe*/Mg against SiO_2; Upper Jurassic–Lower Cretaceous volcanic rocks of the South Shetland Islands. (Fe* = total iron as Fe^{2+}; other symbols as in Figure 10.)

The new data presented here confirm the suggestions of Weaver and others (1982) and extend them to include other localities in the South Shetland Islands. The new analyses are of basalts, basaltic andesites and andesites which are chemically indistinguishable from the majority of the Byers Peninsula analyses. However, it is now evident that the rhyolitic ignimbrites of Byers Peninsula are more evolved in terms of oxide and element contents, Ba/Rb and Rb/Sr than any other extrusive rocks encountered during this investigation. Moreover, together with analyses of the Chester Cone andesite plug and a hyalodacite lava (P.417.2) from President Head, they are chemically distinctive, having high Ce/Y and low Y/Zr (due to low absolute amounts of Y), low La and Ce relative to silica, and uniformly low Fe*/Mg ratios (Figs. 11 and 12).

The two analysed rocks from President Head have K/Rb ratios conspicuously low (by a factor of three) compared with other Upper Jurassic–Lower Cretaceous rocks of similar silica content. Given the other trace element contents present, this is difficult to account for using models of crystal fractionation or partial melting and it could be due to alkali mobility. In general, uncertainty regarding alkali mobility also influences interpretation of the geochemical relationships between the lavas and plutonic intrusions, some of the latter possibly having acted as magma reservoirs for the volcanicity. At present, there are too few analyses of lavas from Low Island to demonstrate unambiguously any relationship with the plutonic intrusions, although there are chemical similarities, particularly the K/Ba, Ba/Rb, K/Rb and Ce_N/Y_N ratios. However, the intrusions on the island have yielded K-Ar ages of *c.* 120 Ma (Chapter XI) significantly younger than the Upper Jurassic sequence that they intrude. Analyses of a hornfelsed lava (P.1251.10) and intrusive hornblende-andesite (P.1251.7) from Half Moon Island are strikingly similar. Moreover, they have K/Ba, K/Rb, Ba/Rb and Rb/Sr ratios comparable with gabbro–tonalite plutons on the island and a cogenetic relationship is possible. The analysed rocks from Greenwich and Livingston islands (Renier Point and Ephraim Bluff) are geochemically dissimilar to those from Half Moon Island, and it has also not been possible to demonstrate any close relationship with the Livingston Island gabbro. Moreover, the striking enrichment in most oxides and elements in the Greenwich Island granodiorite (p. 32) is not shared by any of the Upper Jurassic–Lower Cretaceous volcanic rocks analysed and this pluton is unlikely to have acted as a magma reservoir for any of these rocks.

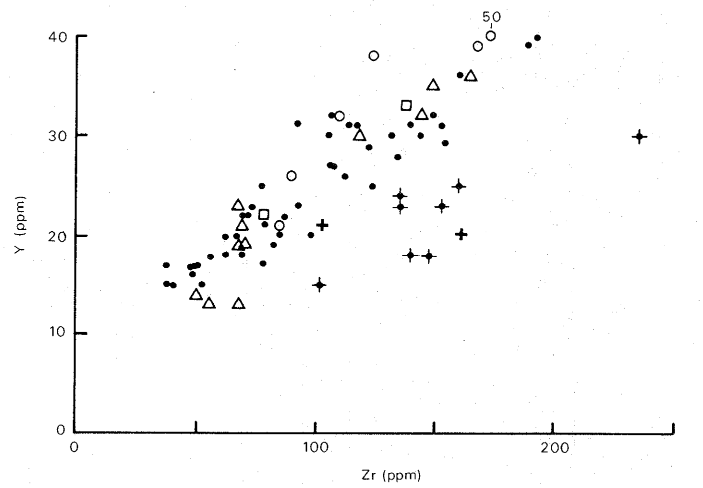

Fig. 12. Plot of Y against Zr; Upper Jurassic–Lower Cretaceous volcanic rocks of the South Shetland Islands. (Symbols as in Figure 10.)

Tarney and others (1982) presented rare earth element (REE) analyses for the Byers Peninsula volcanic rocks. These showed slight light REE-enrichment, and Ce_N/Yb_N increasing from 1.8 to 3.0 through a four-fold increase in REE content. Only slight negative Eu anomalies were observed in the andesites. It was suggested that both fractional crystallization and variable partial melting of the source region were involved in the petrogenesis of these rocks. Available $^{87}Sr/^{86}Sr$ data are given in Table XVII (p. 74), some samples having been re-analysed subsequent to the data published by Tarney and others (1982). The extrusive volcanic rocks have a narrow range of initial $^{87}Sr/^{86}Sr$ ratios: 0.7040–0.7044. The Late Cretaceous intrusions in the east of the peninsula (e.g. Negro Hill) also have values within this range, which is typical of many rocks of the Andean belt in South America (e.g. Francis and others, 1977; Hawkesworth and others, 1979), considered to be either derived from a mantle source region more enriched in the lithophile elements than the sub-oceanic mantle, or else to be contaminated with more radiogenic Sr from the oceanic or continental crust. The Chester Cone andesite plug has lower initial $^{87}Sr/^{86}Sr$ ratios of 0.7033–0.7039, indicating either a source region with a low Rb/Sr ratio or less contamination with crustal Sr.

F. DISCUSSION

In their review of the geochemical characteristics of volcanism in Graham Land and the South Shetland Islands, Weaver and others (1982) described trends of westerly decreasing K_2O, Rb, Th and possibly Ba in the Mesozoic rocks. Ba/Sr, Rb/Sr and Ce_N/Y_N ratios are generally lower and K/Rb ratios higher in the South Shetland Islands (Byers

Peninsula) consistent with the partial tholeiitic affinities of the South Shetland Islands rocks. It was shown that crystal fractionation can explain most of the trends shown on the element variation diagrams and/or depth-related variations in the composition of the source material (e.g. participation or non-participation of garnet). Elsewhere in the region, data are only available for the Mesozoic volcanic rocks in western Palmer Land. These rocks are very similar geochemically to those of western Graham Land (West, 1974; T. G. Davies, 1976; Smith, 1977). Tholeiitic characteristics have been recognized in the basalts whereas the basaltic andesites and more acidic rocks can be divided into low-K and high-K calc-alkaline groups with the characteristics of rocks formed in island arcs and at continental margins respectively (Smith, 1977, p. 88).

The conclusions reached here on the basis of new data are in agreement with views expressed by Weaver and others (1982). Furthermore, although the basalts show considerable compositional overlap with those in western Graham Land and Palmer Land, it can now be shown that K_2O, Rb, Ba and possibly Th contents in the Mesozoic volcanic rocks of the South Shetland Islands are the lowest, whereas K/Rb ratios are highest in the Antarctic Peninsula region. The South Shetland rocks also have the low trace element abundances, low K_2O/Na_2O ratios and silica range typical of rocks of island arcs in contrast to a continental margin setting for Mesozoic volcanism in the Antarctic Peninsula (cf. Jakes and White, 1970). La and Ce contents are slightly high relative to other island arcs but are similar to Mesozoic rocks in the Antarctic Peninsula. This enrichment appears to be a characteristic feature of the region (West, 1974, p. 32).

VII. PLUTONIC ROCKS

Isolated outcrops of plutonic intrusions occur on many of the islands, particularly King George, Livingston and Low islands (Fig. 1). They vary petrographically from gabbro to microgranite but tonalite (or quartz-diorite) is the commonest and diorites are apparently absent. The thick hypabyssal intrusions, which are coarse-grained (gabbroic or dioritic) in part, are excluded from this discussion.

A. Lithologies and Field Relationships

1. Gabbro

On Livingston Island, a gabbro pluton of possible batholithic dimensions crops out between False Bay and Renier Point. It shows well-developed rhythmic layering at one locality and is differentiated to (?) ferrodiorite near Renier Point (Smellie, 1983). Thermal metamorphism of the gabbro has occurred, mainly in the False Bay area, such that these rocks are dioritic in appearance (cf. Hobbs, 1968, p. 22). However, they were referred to as metagabbro by Smellie (1983) and their chemistry is indistinguishable from that of the gabbro. Textures in the less altered rocks vary from adcumulate (P.419.3, 5a, 7) and heteradcumulate (P.419.8) to mesocumulate (P.1253.11a, 1256.2). The cumulus phases consist of plagioclase (mainly labradorite, ranging from andesine to bytownite), augite, forsteritic olivine, opaque ore and rare tiny apatite subhedra; intercumulus minerals are absent. In the metagabbro, petrographical evidence of a gabbroic origin includes rare relict labradorite-bytownite, augite and olivine. The identification of ferrodiorite near Renier Point is tentative. Texturally, the rock (P.422.3) is an ortho- or mesocumulate formed of cumulus andesine, augite, hypersthene and rare serpentinized (?) olivine; the intercumulus minerals include plagioclase (composition unknown), augite, hypersthene, opaque ore, micrographic quartz and K-feldspar, apatite and rare allanite; secondary (? metamorphic) biotite and amphibole are also present.

Gabbro also occurs on Half Moon Island (Fig. 13). It intrudes locally scoriaceous lavas, which are thermally metamorphosed and occasionally injected by thin gabbroic stringers. The intrusion is grey-green in colour and is formed of labradorite laths, generally fibrous actinolite replacing augite, and opaque ore. Thin actinolite (± chlorite) veins are also present.

2. Quartz-gabbro

At Wegger Peak, King George Island, specimens of quartz-gabbro and quartz-diorite have been described by Tyrrell (1921, p. 62) and Hawkes (1961, p. 12). Barton (1965, p. 14) suggested that the pluton is heterogeneous but that the lithologies are genetically related. Comparison of

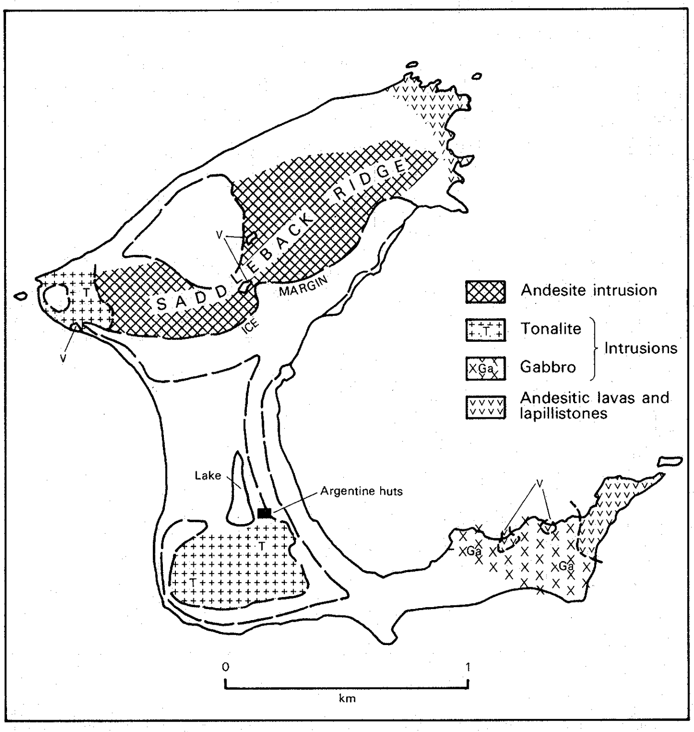

Fig. 13. Geological sketch map of Half Moon Island.

the petrographical descriptions shows that the rocks are not significantly different and, in view of the dominantly labradoritic plagioclase composition, it is considered that the name used by Tyrrell (quartz-gabbro) is more consistent with current petrographical terminology. Similarly, the 'quartz-diorite' at Stenhouse Bluff (Hawkes, 1961, p. 12) is referred to here as quartz-gabbro. Quartz-gabbro also crops out at Weaver Peninsula (Davies, 1982a) and Tyrrell (1945, p. 56) described a specimen of 'feldspathic quartz-gabbro of a type identical with other occurrences in the South Shetland Islands' collected *in situ* on eastern Snow Island; there are no field observations of the Snow Island occurrence and the locality is unknown.

Contacts are generally obscured but at Wegger Peak the contact is steeply discordant and gabbroic veins, up to 1 m thick, intrude the surrounding Tertiary lavas. Close to the contact, the lavas are hornfelsed (Hawkes, 1961, p. 8). Enclaves were observed only at Wegger Peak, where they are rare and appear to be cognate. Some of the small exposures of lavas close to the quartz-gabbro at Stenhouse Bluff may be roof pendants.

The quartz-gabbros have hypidiomorphic-granular textures and sometimes show flow-alignment. They are formed of plagioclase (mainly labradorite, rarely andesine), augite, hypersthene, opaque ore, interstitial quartz and K-feldspar, and accessory apatite. Hypersthene is usually altered to fibrous green actinolite (bastite pseudomorphs (Tyrrell, 1921; Davies, 1982*a*)) or (?) serpentine and calcite. Epidote mineralization is locally conspicuous (e.g. P.17.1).

3. *Tonalite (quartz-diorite)*

Tonalite intrusions crop out widely on King George, Half Moon, Livingston and Low islands. At Noel Hill, King George Island, the intrusion is fault-bounded along its south-western margin and appears to dip beneath altered volcanic rocks to the north-east (Davies, 1982*a*). The intrusion is predominantly quartz-diorite in composition but it becomes granodioritic along the north-eastern margin. Similar petrographical variation is shown by the intrusion at Rose Peak, and Davies (1982*a*) suggested that these and possibly related intrusions at Wegger Peak, Stenhouse Bluff and Weaver Peninsula may be surface expressions of the same pluton, an idea similar to that proposed by Hawkes (1961, p. 10) and now supported geochemically (p. 32).

Tonalite also crops out on Half Moon Island (Fig. 13). It is intruded by a hornblende-andesite pluton that contains blocks of tonalite measuring up to 6 m in diameter; the andesite is itself locally intruded by 'granodioritic' (*s.l.*) dykes.

On Livingston Island, a large (? batholithic) tonalite intrusion crops out between False Bay and Renier Point; a much smaller apophysis of this pluton intrudes and has thermally metamorphosed sediments of the Miers Bluff Formation north of Johnsons Dock, Hurd Peninsula (Hobbs, 1968, p. 19). In the crags north of Charity Glacier, tonalite intrudes and has fragmented a gabbro pluton. Screens of metagabbro alternate with foliated microtonalite and zones of metagabbro enclaves in a protoclastic contact zone up to 200 m wide (Smellie, 1983). Aplite and pegmatite veins are conspicuous in the metagabbro and microtonalite but they are practically absent from the tonalite. Veins of pyrite, chalcopyrite, molybdenite, malachite and siderite are also conspicuous in the rocks north of Charity Glacier, and the tonalite probably caused the copper-lead mineralization on Hurd Peninsula described by del Valle and others (1974).

On Low Island, microtonalite occurs as a small pluton intruding altered lavas, and as dark grey dykes intruding a micro-adamellite pluton (Smellie, 1980).

The essential constituents of the tonalites are plagioclase (oligoclase–andesine) and green hornblende, associated with minor brown biotite, quartz, K-feldspar, augite and opaque ore. Accessory minerals include apatite, zircon and sphene; tourmaline (schorlite) occurs in specimen P.22.3 (Hobbs, 1968, p. 20) and apple-green–yellow optically negative (?) pumpellyite in specimen P.1250.2 (Half Moon Island).

4. *Granodiorite*

Granodiorite rocks form part of the zoned intrusions at Noel Hill and Rose Peak, King George Island (Hawkes, 1961; Davies, 1982*a*). Granodiorite also crops out on Greenwich Island, at Guesalaga Peninsula (Fuenzalida, 1964, fig. 1; Araya and Hervé, 1966, p. 42) and on the tombolo at Fort Point. On Low Island, the Cape Wallace granodiorite is characterized by abundant fine-grained dark grey enclaves derived from the surrounding lavas, against which it shows steep intrusive contacts (Smellie, 1980).

The granodiorites are medium to pale grey rocks, ranging to pale pink at Cape Wallace, and they contain slightly more K-feldspar and quartz relative to the tonalites which they closely resemble in other respects.

5. *Micro-adamellite and microgranite*

The principal occurrence of these rocks is as late-stage veins and dykes associated with the coarse-grained plutonic intrusions. On Half Moon Island, micro-adamellite veins have brecciated the country rock at the south-eastern extremity of the island and on Saddleback Ridge. The clasts in the breccia zones are up to 4 m wide and are generally sub-angular. They vary lithologically from mainly fine-grained lava types, to rarer fragments of gabbro and tonalite. In addition, a small micro-adamellite pluton crops out on Low Island (Smellie, 1980).

The rocks are pink in colour, and contain quartz, plagioclase (? albite–oligoclase) and K-feldspar as essential constituents invariably associated with traces of brown biotite and opaque ore; olive-green hornblende occurs in specimens P.407.3 and 215.2 (in which it is common but highly chloritized). Accessory minerals are varied and include apatite, sphene, allanite and tourmaline (schorlite (P.433.2)).

B. AGE RELATIONSHIPS

The oldest intrusions dated so far are the Lower Cretaceous plutons on Low Island (120 Ma: Chapter XI), despite some petrographical evidence for a Late Jurassic/earliest Cretaceous age (Smellie, 1980). A tonalite on Half Moon Island has yielded a K–Ar radiometric age of 105 Ma (Grikurov and others, 1970). There is little direct evidence for the age of the layered gabbro on Livingston Island, but it post-dates altered (?) pre-mid Cretaceous volcanic rocks at Mount Bowles and Renier Point and it is intruded and fragmented by the Barnard Point tonalite, which has yielded Rb–Sr and K–Ar whole-rock and mineral ages of 40 Ma (Dalziel and others, 1973; del Valle and others, 1974; but see also Chapter XI of this report). An apophysis of the Barnard Point tonalite intrudes the (?) Carboniferous–Triassic Miers Bluff Formation on Hurd Peninsula. The granodiorites at Fort Point and Guesalaga Peninsula, Greenwich Island, also intrude altered volcanic rocks of (?) pre-mid Cretaceous age but there is otherwise no age control on these intrusions. K–Ar radiometric ages ranging from 47 to 53 Ma have been obtained from the quartz-diorite at Noel Hill (Grikurov and others, 1970; Watts, 1982), which is dated more precisely at 47 ± 1 Ma in this report. It has been suggested that the several outcrops of plutonic rocks on King George Island may form part of a zoned intrusion (p. 29). They intrude heavily altered volcanic rocks whose age is controversial but which is now considered to be Tertiary (Davies, 1982*a*, *b*).

In summary, plutonic activity had already begun by Early Cretaceous times on Low Island and continued during the mid-Cretaceous on Half Moon and possibly Livingston islands, producing magmas of comparable types repeatedly. However, the major phase of plutonic activity occurred in the Early Tertiary and is represented, in particular, by major intrusions (of (?) batholithic size) on Livingston and possibly King George islands.

C. GEOCHEMISTRY

Thirty-five plutonic rocks were analysed for major oxides and 14 trace elements (Table IX). The major oxide compositions are typical of a calc-alkaline suite (Nockolds and Allen, 1953; Best, 1969; Fig. 14). In particular, the rocks are characterized by high alumina and moderate alkali contents, and no iron enrichment in the intermediate members. With increasing silica content, the major oxides show regular trends of increasing K_2O and decreasing CaO, Fe_2O_3* (total iron oxides as Fe_2O_3), MgO, Al_2O_3, MnO and TiO_2; Na_2O and P_2O_5 first increase then decrease in the more acid members. Among the trace elements, the patterns are less well defined and they are complicated by small but consistent differences characteristic of each pluton or related group of plutons. In general, with increasing silica content, Rb, Ce, Y, Pb and Th show a gradual increase whereas Sr, Cr and Ni decrease; Ba, Zr, La and Ga increase then decrease similar to Na_2O and P_2O_5. Zn and Nb show no obvious overall pattern but Zn contents tend to be higher in rocks of intermediate compositions.

1. *Gabbroic rocks of Livingston and Half Moon islands*

Five specimens of gabbro from Livingston and Half Moon islands were analysed (Table IX). When plotted against indices of fractionation (SiO_2, Zr and modified Larsen factor (Nockolds and Allen, 1953; Tarney and others, 1977)), the major oxides and trace elements show regular curvilinear trends. The two specimens of metagabbro analysed are geochemically indistinguishable from the gabbro analyses. Although ferrodiorite is normally considered to be a product of the differentiation of a tholeiitic magma, the only other 'tholeiitic' characteristics of the Livingston Island gabbro are its low K_2O content (generally less than 0.8%) and low K_2O/Na_2O ratio (less than 0.35) (Jakes and White, 1972; Fig. 14). In other characteristics, particularly increasing silica and decreasing total Fe with increasing fractionation, high alumina and moderate total alkalis, it is typically calc-alkaline. In view of this the gabbro is regarded here as calc-alkaline with mild tholeiitic affinities.

Chemical variation in these rocks is seen to be related to their cumulus mineralogy. The high MgO and Ni contents in specimen P.419.3 directly reflect the large amount of forsteritic olivine in this rock and this is probably also true for metagabbro specimen P.1256.2 in which olivine is preserved only as scattered talc pseudomorphs. The other gabbros have much lower MgO values. They contain considerable Ni and Cr but only moderate total Fe which support the petrographical evidence that the major ferromagnesian cumulus phase was a diopsidic augite. Specimen P.1256.2 is also anomalously low in Al_2O_3 and Sr, consistent with low plagioclase content. High P_2O_5 in the ferrodiorite (P.422.3) is attributed to the volume of intercumulus and possibly cumulus apatite present. Similarly, the low values of Fe_2O_3, TiO_2 and MnO in the Half Moon Island gabbro can be related to the small amount of opaque ore in the rock. The close geochemical similarity between the Half Moon Island gabbro and the cumulate rocks on Livingston Island (particularly specimens P.419.3 and 1256.2) suggests that it may also have had a cumulate origin. However, there is no petrographical evidence for this and the geochemical similarity need not indicate a comagmatic relationship. Significantly, both gabbros (and the metagabbro) have consistently lower K/Ba ratios than other plutonic intrusions in the South Shetland Islands (Table IX).

2. *Tonalitic rocks of Livingston and Half Moon islands*

The tonalite intrusions on Livingston and Half Moon islands have similar major oxide compositions with the exception of unusually high TiO_2, Fe_2O_3 and MnO and low Al_2O_3 in the Half Moon Island rocks (Table IX). More differences are apparent among the trace elements. In general, the Half Moon Island tonalite is richer in La, Y and Zn, poorer in Sr and has higher Ba/Sr, Rb/Sr and Ba/Rb ratios. Conversely, specimens P.1251.1 (from Half Moon Island) and P.1259.2 (from Livingston Island) have similar Ce, Ba and Zr contents. Because only three specimens have been analysed, it is not known how representative the analyses are, but the geochemical differences observed are not surprising in view of the widely different ages of the two tonalite intrusions (Chapter XI).

The aplitic micro-adamellite veins associated with the intrusions have low Sr, Ni, Cr and Zn, and high Zr, Ba, Rb, La, Ce and Y contents. Relative to the other South Shetland plutonic rocks analysed, they are greatly enriched in Ba and Zr and they have anomalously high K/Rb and Ba/Rb ratios. The trend of increasing K/Rb and Ba/Rb during fractionation is contrary to the predicted and observed behaviour of most differentiating magmas (e.g. Philpotts and Schnetzler, 1970; Kuryvial, 1976). Anomalously high K/Rb ratios in aplites from the Louis Lake batholith (Wyoming, USA) were interpreted in terms of Rb concentrating into late-stage fluids (chiefly water) and the

Table IX. Chemical analyses of plutonic rocks of the South Shetland Islands. (Continued on page 32 and 33.)

	1	2	3	4	5	6	7	8	9	10	11	12	13	14
SiO_2	44.7	47.6	51.2	52.8	53.2	54.9	48.2	54.7	53.5	54.9	54.1	49.1	58.2	60.0
TiO_2	0.98	1.44	1.11	0.96	0.97	0.84	0.39	0.79	0.74	0.80	0.75	1.09	0.77	0.59
Al_2O_3	15.6	9.0	18.5	17.4	16.9	16.2	18.7	15.7	16.5	16.8	17.3	21.13	16.9	16.0
Fe_2O_3	3.27	2.90	2.42	2.47	2.49	2.33	2.08	2.15	2.42	2.29	2.32	2.40	2.24	1.84
FeO	8.18	7.25	6.05	6.17	6.23	5.84	5.19	5.39	6.05	5.72	5.80	8.00	5.61	4.59
MnO	0.18	0.20	0.15	0.15	0.16	0.10	0.13	0.13	0.16	0.14	0.14	0.19	0.21	0.16
MgO	12.2	14.8	5.0	5.2	6.2	5.8	8.7	5.3	6.9	5.8	6.4	7.43	4.1	5.6
CaO	14.61	13.47	10.83	8.37	9.70	8.44	13.90	8.43	7.93	7.29	8.39	5.27	7.72	5.58
Na_2O	0.95	1.81	3.36	4.66	3.14	4.20	2.19	2.71	3.37	3.46	3.30	2.82	3.33	3.82
K_2O	0.11	0.39	0.65	0.82	0.72	0.42	0.20	2.15	1.42	1.74	1.41	2.14	2.18	1.59
P_2O_5	0.01	0.03	0.63	0.23	0.17	0.16	0.04	0.23	0.20	0.24	0.17	0.16	0.21	0.19
Total	100.79	98.89	99.90	99.23	99.88	99.23	99.72	97.68	99.19	99.18	100.08	99.73	101.47	99.94
TRACE ELEMENTS														
Cr	50	570	20	–	80	–	150	30	20	10	20	29	–	45
Ni	18	123	15	–	–	–	40	16	7	11	11	14	–	18
Zn	57	62	63	44	67	27	59	64	68	69	70	77	86	84
Rb	–	4	9	14	20	4	–	36	32	37	34	61	38	42
Sr	424	226	511	459	390	508	480	533	616	631	597	517	719	414
Y	5	26	26	27	18	19	7	21	18	20	19	19	24	18
Zr	16	45	80	144	83	119	21	206	137	148	127	216	253	183
Nb	–	–	–	5	3	–	–	–	–	5	–	4	3	5
Ba	30	85	217	258	184	132	62	374	265	323	262	637	407	334
La	7	8	12	13	10	11	–	20	11	20	19	22	29	16
Ce	10	15	30	34	28	25	–	44	32	43	33	52	52	36
Pb	–	–	–	–	–	–	–	10	–	10	–	15	–	10
Th	–	–	–	–	–	–	–	–	–	–	–	–	–	–
Ga	17	13	22	25	20	23	21	23	25	23	24	20	25	–
RATIOS														
K/Rb	–	809	599	486	299	872	–	496	368	390	344	291	476	314
Ba/Rb	–	21	24	18	9	33	–	10	8	9	8	10	11	8
K/Ba	30	38	25	26	33	26	27	48	44	45	45	28	44	39
Rb/Sr	–	0.02	0.02	0.03	0.05	0.01	–	0.07	0.05	0.06	0.06	0.12	0.05	0.10
Ba/Sr	0.1	0.4	0.4	0.6	0.5	0.3	0.1	0.7	0.4	0.5	0.4	1.2	0.6	0.8
Ca/Sr	246	426	152	130	178	119	207	113	92	83	100	73	77	96
Ce_N/Y_N	4.9	1.4	2.8	3.1	3.8	3.2	–	5.1	4.3	5.2	4.2	6.7	5.3	4.9
Fe*/Mg	1.2	0.9	2.1	2.1	1.8	1.8	1.0	1.8	1.5	1.7	1.6	1.8	2.4	1.4

nd – not determined

1. P.419.3 Gabbro, east of Brunow Bay, Livingston Island.
2. P.1256.2 Metagabbro, north-eastern False Bay, Livingston Island.
3. P.422.3 (?) Ferrodiorite, near Renier Point, Livingston Island.
4. P.419.2 Gabbro, east of Brunow Bay, Livingston Island.
5. P.1253.5 Metagabbro, north-eastern False Bay, Livingston Island.
6. P.419.1 Gabbro, east of Brunow Bay, Livingston Island.
7. P.1252.4 Gabbro, Half Moon Island.
8. P.1189.1 Quartz-gabbro, Stenhouse Bluff, King George Island.
9. G.23.6 Quartz-gabbro, Wegger Peak, King George Island.
10. P.1192.1 Quartz-gabbro, Wegger Peak, King George Island.
11. P.1192.5 Quartz-gabbro, Wegger Peak, King George Island.
12. P.679.1 Noel Hill quartz-diorite (marginal facies), King George Island.
13. P.1430.1 Noel Hill quartz-diorite, King George Island.
14. P.680.1 Noel Hill quartz-diorite, King George Island.

subsequent loss of these fluids from the pluton (Condie and Lo, 1971). The same process was used to explain anomalously low Ba in some of the rocks, whereas Ba is concentrated in the aplites discussed here. By contrast to these alkali-rich late-stage veins, many of the aplites and pegmatites in the False Bay area of Livingston Island are trondhjemitic. In specimen P.1253.18, the absence of K-feldspar is reflected in unusually low K_2O, Rb, Ba and Y, high CaO, Na_2O and Sr, and a low K/Ba ratio.

Araya and Hervé (1966, p. 47) suggested that the plutonic intrusions on Half Moon Island are largely dioritic but grade to tonalite in places. This is broadly compatible with the geochemistry presented here, although the 'dioritic' rocks are now shown to be gabbro and it is believed that at least two intrusive phases are present. In particular, all the Half Moon Island rocks have low K/Ba ratios (Table IX) which are likely to be of petrogenetic importance since these elements are not fractionated from each other in basic and intermediate magmas. Large differences in the opaque ore content of the specimens analysed are the probable cause of the striking differences in TiO_2, MnO and total Fe observed. Although the range of K/Ba ratios in the Livingston Island gabbro includes those of the Half Moon Island intrusions, the rocks of the two areas have apparently differentiated to ferrodiorite and tonalite respectively, and micro-adamellite veins are associated with the rocks on Half Moon Island. Therefore, it appears that the fractionation histories of the two gabbroic magmas were largely separate, although they may have shared a common origin.

3. *Quartz-gabbro, quartz-diorite and granodiorite rocks of King George and Greenwich islands*

Mineralogically, the plutonic rocks at Stenhouse Bluff and Wegger Peak are quartz-gabbros. Chemically, especially in their high silica contents, they are closer to diorites. No geochemical data are presently available for the Weaver

Table IX. Chemical analyses of plutonic rocks of the South Shetland Islands (continued).

	15	*16*	*17*	*18*	*19*	*20*	*21*	*22*	*23*	*24*	*25*	*26*	*27*	*28*
SiO_2	61.2	61.4	61.7	61.7	62.1	63.1	63.2	61.1	55.0	56.0	54.8	57.3	58.6	59.7
TiO_2	0.65	0.66	0.58	0.57	0.60	0.58	0.58	0.59	1.10	1.26	0.69	0.79	0.66	0.90
Al_2O_3	15.9	16.0	16.5	15.3	16.2	16.5	16.1	16.3	16.3	15.2	16.0	16.6	17.4	16.7
Fe_2O_3	1.46	1.55	1.52	1.29	1.48	1.40	1.44	1.49	2.62	2.74	2.32	2.08	1.85	2.13
FeO	3.65	3.88	3.79	3.22	3.69	3.50	3.59	3.73	6.56	6.84	5.81	5.20	4.64	5.31
MnO	0.12	0.15	0.14	0.13	0.14	0.11	0.14	0.11	0.19	0.20	0.19	0.14	0.10	0.15
MgO	3.0	4.0	4.0	2.9	3.5	2.5	3.2	2.6	5.5	4.8	6.2	6.1	5.0	4.0
CaO	5.12	5.24	5.43	4.60	4.76	4.95	4.94	6.19	8.09	7.60	8.68	6.89	6.42	6.20
Na_2O	4.05	3.93	4.23	4.00	4.17	4.20	3.91	3.97	3.56	3.57	2.96	3.92	4.53	3.70
K_2O	2.59	2.23	2.28	2.50	2.69	2.72	2.68	1.53	0.92	1.12	0.74	1.75	1.99	2.38
P_2O_5	0.19	0.20	0.16	0.19	0.19	0.16	0.15	0.15	0.28	0.26	0.11	0.25	0.19	0.21
Total	97.93	99.30	100.29	96.40	99.49	99.72	100.01	97.76	100.12	99.59	98.50	101.02	101.38	101.38
TRACE ELEMENTS														
Cr	–	21	24	–	21	–	19	–	–	–	70	nd	40	–
Ni	7	10	7	6	8	–	7	–	–	–	14	nd	17	–
Zn	67	111	86	66	90	51	90	43	84	95	124	75	47	68
Rb	53	51	57	46	58	56	62	32	17	25	29	36	40	65
Sr	403	372	400	374	362	374	358	487	408	372	303	521	709	390
Y	28	22	23	26	22	27	21	24	28	32	19	24	16	31
Zr	214	208	190	219	215	218	216	142	85	133	127	nd	165	197
Nb	4	5	4	–	5	–	5	–	–	3	–	nd	4	4
Ba	440	452	447	436	497	400	466	307	266	311	105	425	356	392
La	19	21	20	25	21	25	20	15	15	17	10	nd	16	27
Ce	44	47	46	44	51	46	46	32	31	31	23	nd	40	50
Pb	15	15	15	20	15	15	15	–	–	10	25	10	–	10
Th	–	–	15	–	10	10	10	–	–	–	–	–	–	–
Ga	23	16	17	21	17	19	16	23	23	23	19	22	25	21
RATIOS														
K/Rb	406	363	332	451	385	403	359	397	449	372	212	403	413	304
Ba/Rb	8	9	8	9	9	7	7	10	16	12	4	–	9	6
K/Ba	49	41	42	48	45	56	48	41	29	30	58	–	46	50
Rb/Sr	0.13	0.14	0.14	0.12	0.16	0.15	0.17	0.07	0.04	0.07	0.10	0.07	0.06	0.17
Ba/Sr	1.1	1.2	1.1	1.2	1.3	1.1	1.3	0.6	0.6	0.8	0.3	–	0.5	1.0
Ca/Sr	91	101	97	88	94	95	99	91	142	146	205	95	65	114
Ce_N/Y_N	3.8	5.2	4.9	4.1	5.7	4.2	5.3	3.3	2.7	2.4	3.0	–	6.1	3.9
Fe*/Mg	2.1	1.7	1.7	1.9	1.8	2.5	1.9	2.5	2.1	2.5	1.6	1.5	1.6	2.3

nd – not determined

15.	P.681.3	Noel Hill quartz-diorite, King George Island.
16.	P.681.3	Noel Hill quartz-diorite, King George Island.
17.	P.676.1	Noel Hill quartz-diorite, King George Island.
18.	P.535.3	Noel Hill quartz-diorite, King George Island.
19.	P.681.1	Noel Hill quartz-diorite, King George Island.
20.	P.535.2	Noel Hill quartz-diorite, King George Island.
21.	P.682.1	Noel Hill quartz-diorite, King George Island.
22.	P.1259.2	Tonalite, north-eastern False Bay, Livingston Island.
23.	P.1250.2	Tonalite, Half Moon Island.
24.	P.1251.1	Tonalite, Half Moon Island.
25.	P.215.3	Microtonalite, Half Moon Island.
26.	G.490.1	Granodiorite, Rose Peak, King George Island.
27.	G.25.4	Granodiorite, Rose Peak, King George Island.
28.	P.433.5	Granodiorite, Fort Point, Greenwich Island.

Peninsula quartz-gabbro. On the other hand, the plutonic intrusions at Rose and Rea Peaks, which are granodiorites in mineralogy, show geochemical characteristics intermediate between the quartz-gabbros and the Noel Hill quartz-diorite. Problems in terminology such as these are not unique and similar rocks in British Columbia (Canada) have also been described using their mineralogical names (Richards and McTaggart, 1976, p. 946).

Among the major oxides, only enrichment in K_2O (Fig. 14) and slight depletion in Fe_2O_3* distinguish the plutonic rocks of King George and Greenwich islands from the other plutonic rocks analysed. More striking differences are evident among the trace elements. The intrusions on these two islands show enrichment in Rb, Ba, Zr, Ce, Ni, Cr and probably La and Zn; Y is slightly depleted in the King George Island rocks whereas Sr is enriched in the more basic members. Separation is also well achieved on plots of the inter-element ratios. Slight differences between King George and Greenwich islands are sometimes evident on these, and low values of Ba/Rb and K/Rb, and high Fe*/Mg, K/Ba and Rb/Sr in the Greenwich Island analysis relative to King George Island can be demonstrated (Table IX). As only one analysis from Greenwich Island is available, these differences are of uncertain significance.

The very strong geochemical coherence shown by the rocks from King George Island supports the suggestion that they are all related and may be the surface expressions of a larger pluton (Hawkes, 1961; Davies, 1982*a*). Alternatively, the rocks may have been emplaced as a series of cupolas similar to those observed in eastern Palmer Land (Williams and others, 1972; Singleton, 1980, p. 114) and Rothschild Island (Care, 1980).

4. *Granodiorite and micro-adamellite rocks of Low Island*

In major oxide and trace element contents, the granodiorite and micro-adamellite intrusions on Low Island plot

Table IX. Chemical analyses of plutonic rocks of the South Shetland Islands (continued).

	29	*30*	*31*	*32*	*33*	*34*	*35*
SiO_2	64.0	71.4	77.1	75.1	69.2	67.7	77.5
TiO_2	0.54	0.39	0.16	0.13	0.43	0.39	0.05
Al_2O_3	15.2	14.4	13.5	13.6	15.3	16.4	14.5
Fe_2O_3	1.62	0.86	0.29	0.46	1.16	0.84	0.04
FeO	4.05	2.15	0.72	1.16	2.90	2.09	0.09
MnO	0.12	0.09	0.04	0.04	0.12	0.02	0.00
MgO	1.9	1.1	0.2	0.3	0.4	0.8	0.1
CaO	4.44	2.40	0.45	0.73	2.07	2.22	3.19
Na_2O	4.12	4.60	4.24	3.56	6.21	5.14	5.28
K_2O	1.82	2.52	4.85	5.60	2.41	3.67	0.19
P_2O_5	0.12	0.05	0.04	0.03	0.13	0.09	0.01
Total	97.93	99.96	101.56	100.71	100.33	99.36	100.95
TRACE ELEMENTS							
Cr	–	–	–	–	–	–	–
Ni	–	–	–	–	–	–	–
Zn	30	46	14	16	33	–	–
Rb	54	61	103	108	38	43	–
Sr	200	200	27	60	255	217	371
Y	36	27	57	29	45	27	7
Zr	140	168	209	100	267	342	93
Nb	5	–	6	3	8	4	–
Ba	319	318	407	421	544	661	110
La	19	18	22	23	25	23	21
Ce	37	34	43	37	44	34	32
Pb	–	35	15	15	10	–	–
Th	–	10	15	20	–	10	35
Ga	19	15	14	14	24	21	9
RATIOS							
K/Rb	280	343	391	430	526	708	–
Ba/Rb	6	5	5	4	14	15	–
K/Ba	47	66	99	110	37	46	14
Rb/Sr	0.27	0.30	3.81	1.80	0.15	0.20	–
Ba/Sr	1.6	1.6	15.1	7.0	2.1	3.0	0.3
Ca/Sr	159	86	119	87	58	73	61
Ce_N/Y_N	2.5	3.1	1.8	3.1	2.4	3.1	11.2
Fe*/Mg	3.7	3.4	7.4	6.8	12.7	4.6	1.6

nd – not determined.

29.	P.407.4	Granodiorite, Cape Wallace, Low Island.
30.	P.215.1	Micro-adamellite, Low Island.
31.	P.219.2	Late-stage vein, islet off Cape Wallace, Low Island.
32.	P.407.3	Late-stage vein, Cape Wallace, Low Island.
33.	P.1251.8	Late-stage vein, Half Moon Island.
34.	P.419.4	Late-stage vein, east of Brunow Bay, Livingston Island.
35.	P.1253.18	Late-stage vein, north-eastern False Bay, Livingston Island.

along the differentiation trend defined by the other plutonic intrusions of the South Shetland Islands (excluding King George and Greenwich islands). The few exceptions include Rb which is noticeably enriched in the granodiorite (P.407.4), and Ba, La and Zr which are slightly depleted in the micro-adamellite (P.215.1). The late-stage veins associated with the granodiorite are rich in K_2O and Rb, poor in Na_2O, Ba, La and Zr, and one vein (P.219.2) is greatly enriched in Y.

Separation of the Low Island analyses from the other plutonic rocks is often achieved on plots of the inter-element ratios. In particular, Low Island is characterized by high Fe*/Mg, Rb/Sr and Ba/Sr, and low Ba/Rb; in addition, the micro-adamellite and late-stage veins have high K/Ba ratios (Table IX). Plots of Ba/Rb and K/Rb against SiO_2 are strikingly linear and the latter has a pronounced positive slope contrary to normal differentiation trends but similar to late-stage veins trends associated with the tonalites of Livingston and Half Moon islands (see above). This was tentatively explained in terms of Rb dissolving into late-stage fluids which were subsequently lost from the plutons. However, the process is inadequate here because it should not discriminate between chemically similar elements such as Ba and Rb, which are depleted and enriched respectively in the Low Island rocks. Y commonly, but not invariably, behaves as if it were a heavy rare earth element (Lambert and Holland, 1974; Drake and Weill, 1975) and its enrichment in one of the late-stage veins (P.219.2) may be explained by the ease with which the heavy rare earths relative to the light rare earths form stable complexes in late-stage fluids (Buma and others, 1971).

D. Discussion

The *progressive* increase in SiO_2, Na_2O and K_2O, together with a general decrease in TiO_2, Al_2O_3, CaO, MgO, MnO and Fe_2O_3*, suggests that fractionation has occurred in the plutonic rocks, but the geographical separation and age differences argue against their evolution as one series from a basic magma. Of interest are the unusually

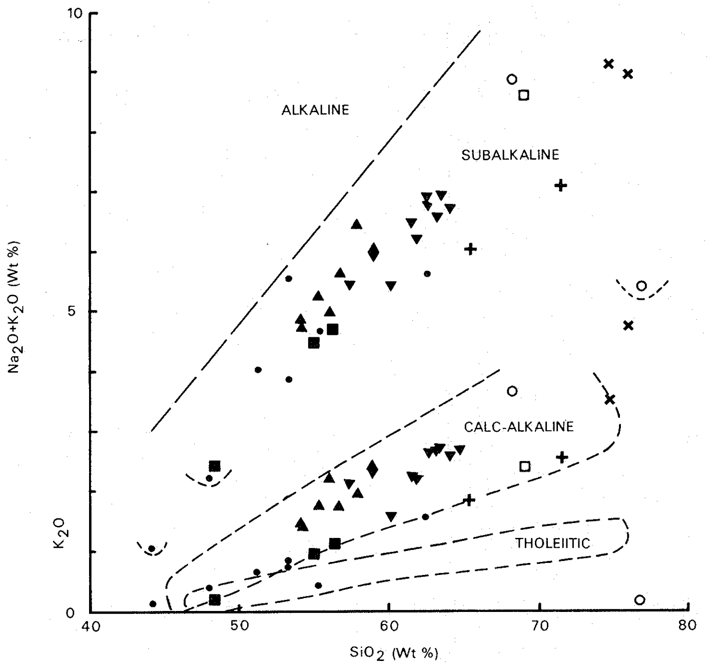

Fig. 14. Plot of total alkalis and K_2O against SiO_2 for plutonic rocks of the South Shetland Islands. (Symbols: ▲ = King George Island (excluding Noel Hill); ▼ = King George Island (Noel Hill); ◆ = Greenwich Island; ■ = Half Moon Island; □ = Half Moon Island, late-stage veins; ● = Livingston Island; ○ = Livingston Island, late-stage veins; + = Low Island; × = Low Island, late-stage veins.)

high Ca/Sr ratios in all the Low Island analyses, suggesting that plagioclase fractionation was less prolonged in these magmas than in any of the other plutons analysed. Moreover, on King George Island, a decrease in Ca/Sr occurs from the quartz-gabbros to the granodiorites whereas Ca/Sr rises again in the Noel Hill quartz-diorite. This highlights a difference in the fractionation histories of these specimens and supports the suggestion that at least some of the plutons were emplaced separately, possibly as cupolas. Y is also strikingly low in plutonic intrusions on King George Island, with Y contents lower in the King George Island 'granodiorites' than in some of the gabbros on Livingston and Half Moon islands (Fig. 15). All the South Shetland plutons have Ce_N/Y_N ratios between 2.37 and 6.11 indicating slight light rare earth enrichment.

In a regional context, the plutonic intrusions of the South Shetland Islands are geochemically similar to the extensive calc-alkaline plutonic suite that forms much of the Antarctic Peninsula. In particular, a close chemical affinity with the plutonic intrusions of the Danco Coast, western Graham Land (West, 1974), is evident. Moreover, the general trend of westerly decreasing K_2O and Rb in Graham Land postulated by Saunders and others (1982) is confirmed by the new data from the South Shetland Islands, which have the lowest Rb contents in the region. An interesting reversal of this trend occurs in the plutonic rocks of King George and Greenwich islands, which are relatively enriched in K_2O and Rb. Geochemical data for Palmer Land (Davies, 1976; Singleton, 1980; Smith, 1977) also show westerly decreasing K_2O in the intrusions but the trend is not as well defined as in Graham Land and there is no complementary trend for Rb. However, intrusions on Rothschild Island (west of Alexander Island) have greater K_2O contents than rocks in Palmer Land (Care, 1980) suggesting a situation analogous to that between King George Island and Graham Land.

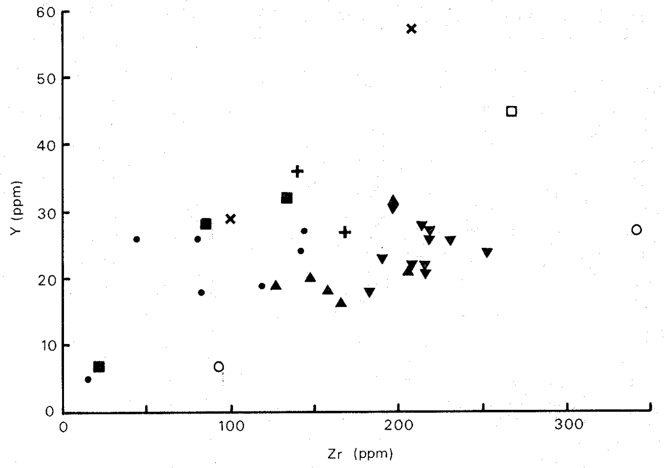

Fig. 15. Plot of Y against Zr; plutonic rocks of the South Shetland Islands. (Symbols as in Figure 14.)

La and Ce contents in plutons on the east coast of Graham Land are similar to those in King George and Greenwich islands and together they are slightly enriched relative to other intrusions in the South Shetland Islands; La and Ce data from western Graham Land show considerable scatter that encompasses the data from eastern Graham Land and the South Shetland Islands. There is little evidence for spatial differences in the other elements within the general scatter of data points.

K/Rb ratios for most continental plutonic rocks vary between quite narrow limits, generally 160 to 300 (Culbert, 1972). Most of the K/Rb ratios in the plutonic rocks of the Antarctic Peninsula also fall within this range and they have the K_2O/Na_2O (0.60 to 1.1) and $(FeO + Fe_2O_3)/MgO$ (greater than 2.0) ratios characteristic of calc-alkaline rocks at continental margins (Jakes and White, 1972; Singleton, 1980, p. 109). By contrast, K/Rb ratios in plutons in the South Shetland Islands are significantly higher than is considered normal for continental rocks, especially the gabbros (Table IX) and, in general, they have the chemical characteristics of calc-alkaline rocks in island arcs (cf. Jakes and White, 1972).

Culbert (1972) attributed high K/Rb ratios in the Coast Mountains batholith (British Columbia, Canada) to direct destruction of alkali-poor oceanic crust or to removal of alkalis by a volatile phase. Both explanations were considered consistent with suspected subduction of an oceanic crustal plate in conjunction with the formation of the plutonic suite, and either explanation is compatible with the prolonged history of subduction in the South Shetland Islands envisaged here.

VIII. UPPER CRETACEOUS–LOWER TERTIARY VOLCANIC ROCKS

Rocks of Late Cretaceous–Early Tertiary age crop out most extensively on King George Island (Fig. 1). Smaller outcrops also occur to the west as far as north-eastern Livingston Island, and some of the altered volcanic rocks described in a previous section (p. 17) may be of comparable age. Together, they comprise a basalt–andesite suite of lavas and interbedded clastic rocks intruded by columnar-jointed plugs and/or coarse vent breccias, which may represent the contemporaneous eruptive centres (Tyrrell, 1921; Hawkes, 1961; Barton, 1965), and spectacular multiple sills. Known eruptive centres occur principally at Fildes Peninsula (King George Island) and Stansbury Peninsula (Nelson Island) but include plugs at Three Brothers Hill, Jardine Peak and Esther Nunatak (Figs. 16 and 17). Florence Nunatak and Pawson Peak are also tentatively included here. Neither of these nunataks has been examined geologically, but Hawkes (1961, fig. 2) placed Pawson Peak on his 'line of hypersthene–augite–andesites'. Viewed from the north at a distance of 0.4 km, the nunatak has a plug-like appearance, with well-defined columnar jointing. The morphology and isolated position of Florence Nunatak are reminiscent of plugs elsewhere (e.g. Ternyck Needle and Esther Nunatak), but the inclusion of these nunataks in this section must remain speculative at present. In addition, (?) Lower Tertiary lamprophyric dykes intrude plutonic rocks on the east side of False Bay, Livingston Island (Smellie, 1983), and Half Moon Island.

Owing to the obscuring effects of the permanent ice cover, little is known of the geological relationships with other stratigraphical rock groups. However, at Lions Rump, King George Island, Lower Tertiary andesite lavas and coal-bearing shales are unconformably overlain by the Plio-Pleistocene Polonez Cove Formation (p. 59) (formerly called the *Pecten* conglomerate (Barton, 1965)), and at Williams Point, Livingston Island, Upper Cretaceous sills and vents intrude the Middle–Upper Triassic Williams Point Beds.

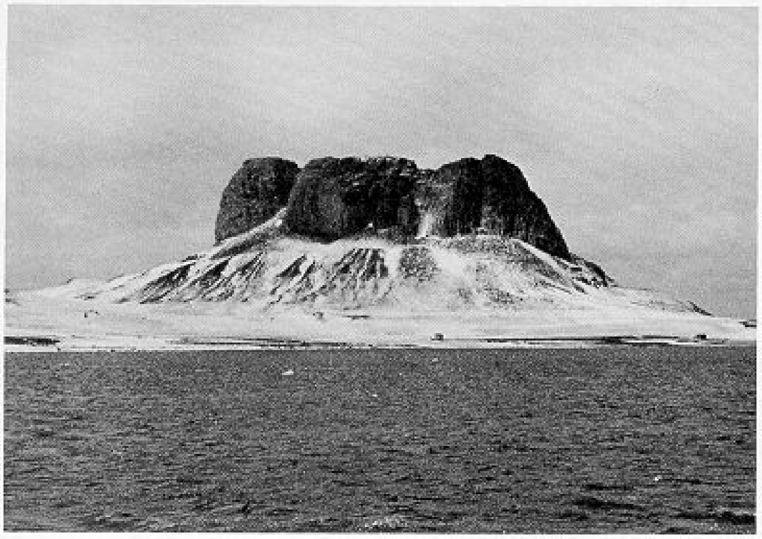

Fig. 16. Three Brothers Hill (196 m), Potter Peninsula, King George Island; looking south from Potter Cove.

Rocks at Turret and Three Sisters points, King George Island, were previously assigned to the Pliocene–Recent 'Penguin Island Group' (Hawkes, 1961; Barton, 1965), but there is no direct evidence for their age. Although a lava described by Hawkes (1961, p. 22) is formed of fresh olivine–basalt that can be correlated lithologically (and probably in age) with practically identical rocks on Penguin Island, its outcrop is restricted to the south-westernmost promontory at Turret Point (not Three Sisters Point (Barton, 1965, p. 27)) and no contacts are exposed. The remainder of the area, extending to Three Sisters Point, is formed of pyroxene–andesite lavas in which marine terraces have been cut (González-Ferrán and Katsui, 1970, p. 153); this contrasts with the relatively little-dissected state of the cone at Penguin Island. Lithologically and in their alteration these pyroxene–andesites closely resemble Lower Tertiary lavas, and geochemical evidence is presented later that supports a correlation between the two.

Well-preserved plant fossils occur at several localities on King George Island (Barton, 1965; Fourcade, 1960), and a new plant fossil locality was discovered during the present investigation in a medial moraine extending eastwards from the base of Anvil Crag, from which the plant-bearing detritus may have been derived. Carbonized and petrified

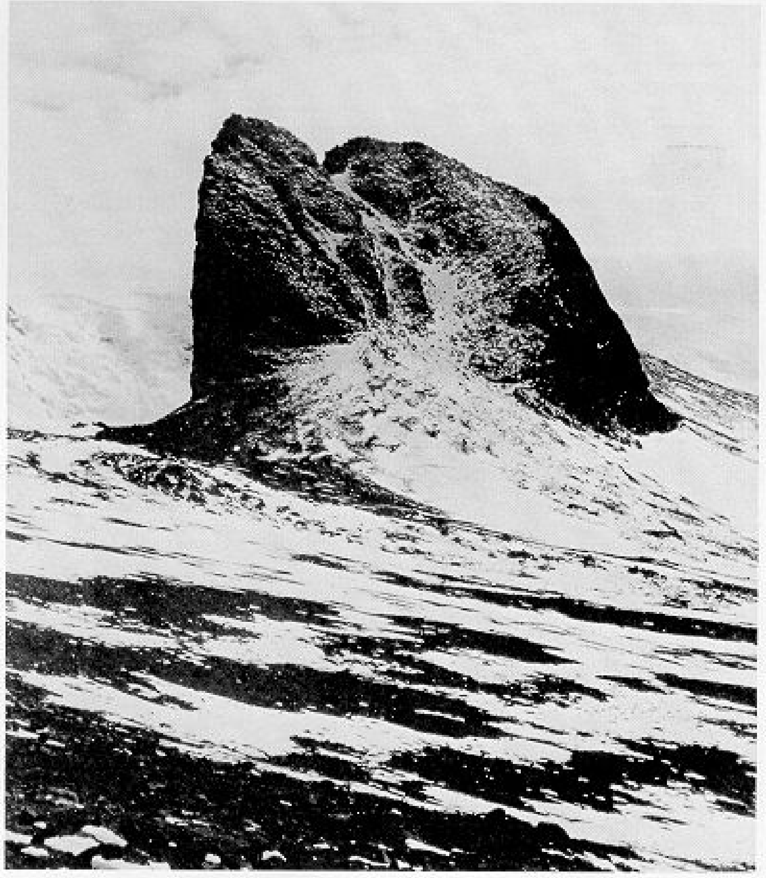

Fig. 17. Jardine Peak (approximately 230 m), Port Thomas, King George Island; looking south-west from Point Thomas.

wood and indeterminate plant fragments occur in most of the Upper Cretaceous–Lower Tertiary outcrops on King George and Nelson islands. They have not been observed *in situ* in the Upper Cretaceous rocks west of Nelson Island but the moraine south of Catharina Point, Robert Island, contains khaki-coloured volcanic sandstone detritus with poorly preserved plants. The plants on King George Island were initially assigned an Early to Middle Miocene age (Hawkes, 1961; Orlando, 1964) but a broader (?) Late Cretaceous–Miocene age was suggested by Barton (1965). At present, the major stratigraphical importance of the fossil plants is that, where present, they provide a clear method of distinguishing between the Upper Jurassic–Lower Cretaceous and Upper Cretaceous–Lower Tertiary groups of rocks.

Altered volcanic rocks characterized by abundant calcite, silica and/or pyrite crop out extensively King George Island. Conspicuous quartz-pyrite 'lodes' (*s.l.*) are locally present (Pyrites Island, Keller Peninsula and Barton Peninsula (Ferguson, 1921; Barton, 1965)). The alteration has generally been ascribed to metasomatism related to the felsic plutons on King George Island and the rocks were assigned a Late Jurassic age (Ferguson, 1921, p. 53; Hawkes, 1961, p. 4; Barton, 1965, p. 8). However, there is now considerable evidence to suggest that the recognition of Jurassic rocks on King George Island is no longer justifiable:

i. In terms of primary textures and mineralogy, the 'Jurassic' and Tertiary rocks are indistinguishable.
ii. Unconformities between 'Jurassic' and Tertiary rocks were inferred (but not shown) by Ferguson (1921, p. 37) and mapped by Barton (1965) at Fildes Peninsula and Admiralen Peak. Subsequent workers have failed to find evidence for these unconformities (e.g. Schauer and Fourcade, 1964; Grikurov and Polyakov, 1968*a*, *b*; Davies, 1982*b*) and their existence is now in some doubt.
iii. Barton (1965, p. 29) suggested that the altered 'Jurassic' and unaltered Tertiary rocks are separated by a major fault which trends through Potter Cove, Ezcurra Inlet and Martel Inlet. Petrographical examination of specimens from both sides of the fault has shown that local areas of Tertiary rocks are altered in an identical manner to the 'Jurassic' rocks. Significantly, all the altered Tertiary rocks crop out within 2.5 km of the major fault (Fig. 18). It is possible that the juxtaposition of different stratigraphical levels by the fault has masked what may be a simple northward increase in alteration.
iv. The presence of 'pebbles of granite and quartz-pyrite in the lavas of Fildes Peninsula and Point Hennequin' was used by Barton (1965, p. 16) as 'conclusive evidence that these rocks post-date the plutonic

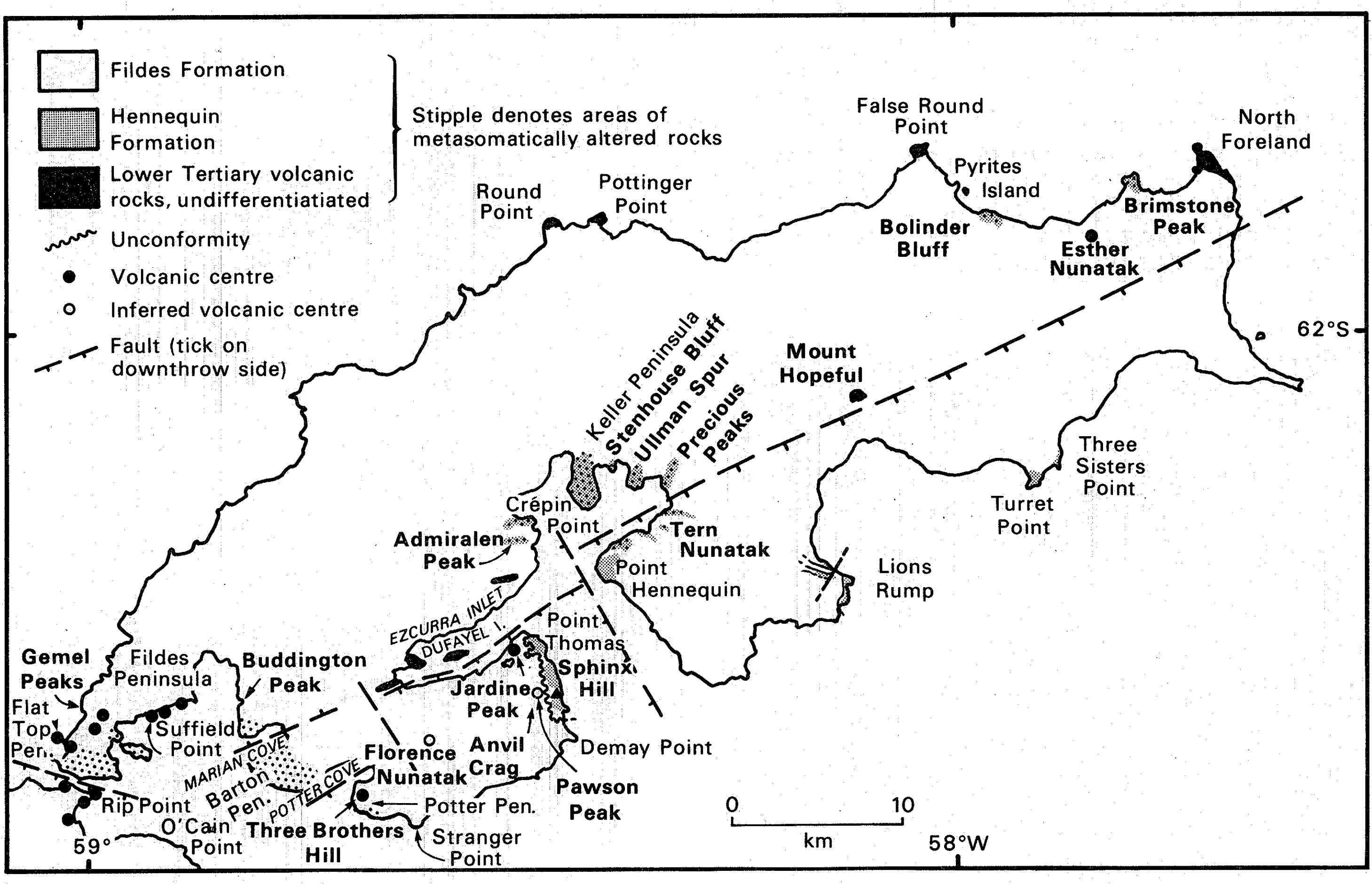

Fig. 18. Geological sketch map showing the distribution of the Fildes and Hennequin Formations on King George and north-eastern Nelson islands.

intrusions'. However, fragments of acidic plutonic rocks occur in an Upper Jurassic lapillistone at President Head (Snow Island) and on Barton Peninsula (King George Island (Davies, 1982*a*)) and clasts of quartz-pyrite occur at Ullmann Spur (Jardine, 1950, p. 5) and Weaver Peninsula (Davies, 1982*a*) in altered agglomerates previously thought to be Jurassic. The presence of quartz-pyrite clasts in altered volcanic rocks indicates that eruption and alteration were penecontemporaneous processes (cf. Low Island (Smellie, 1980; Davies, 1982*a*)).

v. Because of the close relationship between metasomatism and the plutonic intrusions, the altered rocks on King George Island were assigned a pre-plutonic, most likely Late Jurassic age (e.g. Ferguson, 1921, p. 53; Hawkes, 1961, p. 4). Conversely, the unaltered outcrops were assumed to post-date the plutonic intrusions and were assigned an Early Tertiary (usually Miocene) age (Hawkes, 1961, p. 4). However, the presence of fossil angiosperm leaves in altered rocks on Dufayel Island is evidence that volcanism and plutonism overlapped at least in part (Barton, 1965, p. 18) and this has been confirmed recently by radiometric dating of the Noel Hill quartz-diorite which has yielded a K–Ar age of 47 ± 1 Ma (Chapter XI). Furthermore, if the plutonic intrusions of King George Island are related to a single pluton of (?) batholithic proportions, the age of the Noel Hill pluton may provide an approximate (minimum) age for the volcanic period represented by the altered rocks on King George Island. Some of the plutons may have acted as magma reservoirs for the Lower Tertiary vents.

Arguments based on radiometric data are considered in Chapter XI.

A. STRATIGRAPHY

The outcrops between Livingston and Robert islands are geographically isolated from other Upper Cretaceous–Lower Tertiary rocks (Fig. 1). Moreover, they are of Late Cretaceous age in contrast to the mainly Lower Tertiary rocks on King George and probably Nelson islands (Table XVIII; Fig. 49). In view of these differences, it is proposed that the several outcrops of lavas, clastic rocks and intrusions of Late Cretaceous age in these western outcrops be distinguished as a separate lithostratigraphical unit, the COPPERMINE FORMATION, named after the type locality in the Coppermine Cove area, western Robert Island. This formation includes the 'Copper Mine Formation' of González-Ferrán and Katsui (1970), although these authors believed the rocks to be Early Tertiary.

Volcanic activity occurred approximately synchronously on different parts of King George Island during the Early Tertiary (Table XVIII; Fig. 49) and the rocks do not form the temporally and spatially isolated stratigraphical 'groups' envisaged by Barton (1965). However, detailed examination of the Lower Tertiary rocks suggests that a broad, two-fold *lithological* division can be made (Fig. 18). East of Admiralty Bay, the rocks (for which data are available) form a distinctive petrographical province composed almost exclusively of very fine-grained and glassy hypersthene–augite-andesites. These rocks are named the HENNEQUIN FORMATION after the type locality at Point Hennequin. At Point Thomas, rocks correlated lithologically with those at Point Hennequin (cf. Tyrrell, 1921, p. 69) are unconformably overlain by holocrystalline olivine-bearing basalts and basaltic andesites, with subordinate pyroxene–andesites. Similar rocks crop out extensively to the west and south, possibly extending as far as eastern Nelson Island, and they are named the FILDES FORMATION after the type area at Fildes Peninsula. The radiometric data suggest that the two formations were partly contemporaneous, with the oldest known volcanicity on King George Island actually represented by the base of the Fildes Formation in the type area, and it is likely that the unconformity at Point Thomas is of no great time-stratigraphical significance.

1. Coppermine Formation

Extrusive rocks of the Coppermine Formation are best exposed in the type area between Fort William and Mitchell Cove, western Robert Island, but smaller isolated outcrops also occur to the north-east as far as Hammer Point, in the Kitchen Point area and on Dee Island (Fig. 19). In the type area, the rocks are mainly olivine–basalt lavas generally 5–7 m thick, with prominent red-coloured scoriaceous interfaces. Clastic rocks, originally described as conglomerates (Caballero and Foucade, 1959), are relatively minor and they are largely restricted to south-eastern Coppermine Peninsula. They form a volcaniclastic sequence at least 40 m thick, composed of coarse polymict lapillistones with sub-rounded–sub-angular lava lapilli and scattered blocks ranging up to 2.5 m across. Sag structures are evident at the base of some of the larger blocks and are consistent with deposition by air-fall.

Coarse green polymict agglomerates with sub-rounded blocks up to 1 m across are interbedded with basaltic andesite and andesite lavas in the Kitchen Point area, whereas coarse conglomerates form a thick sequence on Dee Island (Fig. 20). The conglomerates contain well-rounded boulders of lava generally 0.3 m in diameter set in minor gritty (0.5–3 mm) matrix, some of which is replaced by orange-coloured (?) heulandite. An irregular (?) water-worn junction between very coarse (up to 1 m) conglomerate above and brick-red pebbly granule-conglomerate below is exposed at station P.492, east of Dee Island.

Two vents filled by non-stratified, dark grey-green and red-brown, essentially monomict agglomerate crop out at Sayer Nunatak and the prominent bluff 0.5 km to the north-west (Fig. 3). The agglomerate is fine-grained and composed of basaltic fragments with conspicuous phenocrysts of augite and altered olivine. The marked contrasts in lithology in the Williams Point Beds to the north and south of the vents (p. 16) suggests that the vents are located on a fault.

Intrusions are widespread and are characterized by prominent alternating pairs of parallel pale and dark brown bands, with the colours often corresponding to differences in hardness (Fig. 21). The softer bands, which are often twice as thick as the adjacent hard parts, contain abundant clay minerals and/or zeolite. This alteration is probably

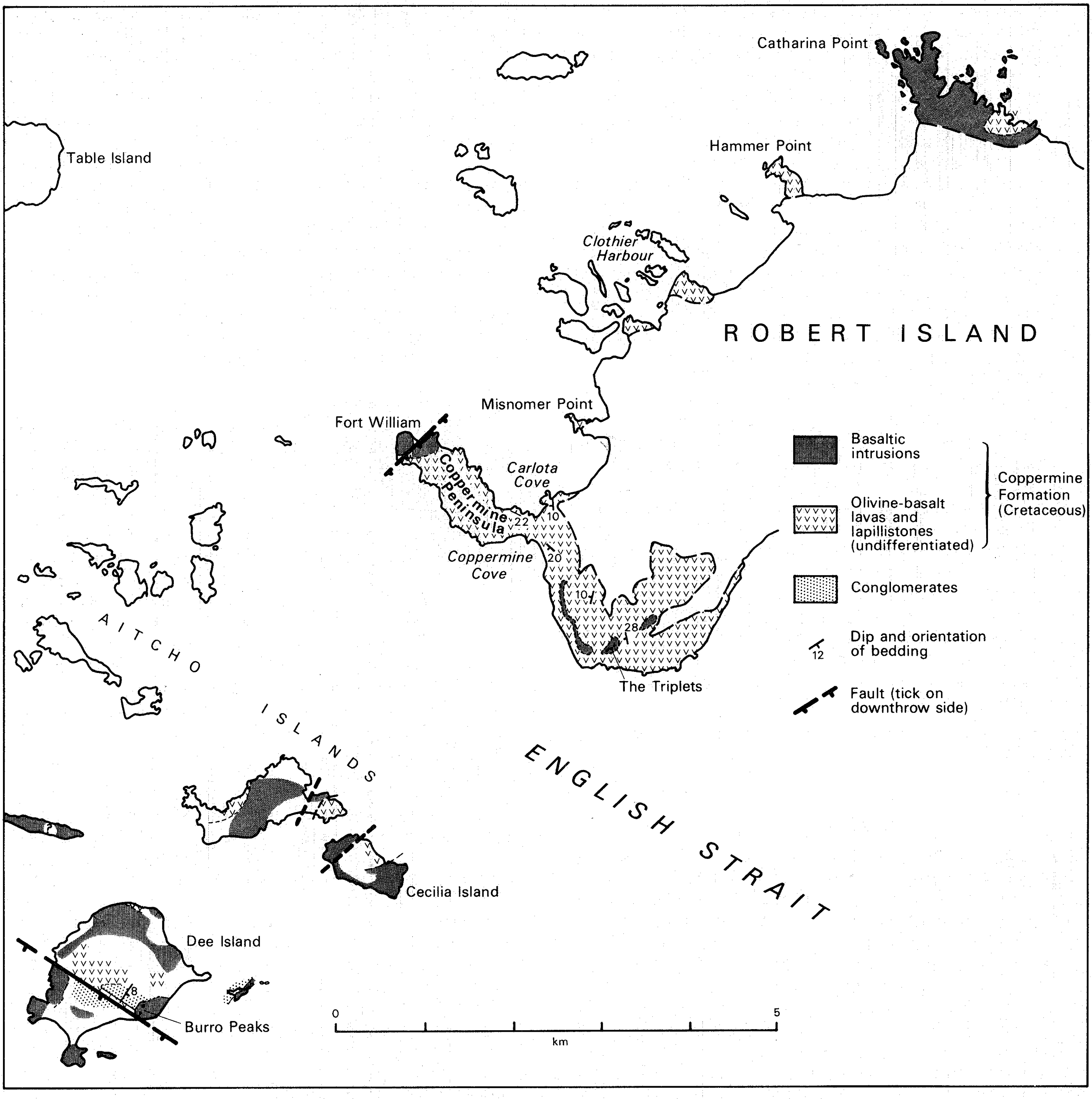

Fig. 19. Geological sketch map of the area between Dee Island and northern Robert Island.

deuteric and zeolite-filled amygdales occur in some soft bands, flanked by harder non-amygdaloidal bands. Together, the pairs of colour bands form layers or couplets, usually 1 or 2 m thick, that are laterally continuous sub-parallel to the margins of the intrusions, where these can be seen. The use of the term 'layer' is descriptive only, and neither cumulate textures nor major changes in the primary mineralogy were observed. Comparable structures also occur in intrusions of other ages in the South Shetland Islands but they are particularly characteristic of the Coppermine Formation.

Layers are most conspicuous around the margins of the intrusions and there is usually a massive, non-layered interior. Because the hard bands weather proud of the rock

Fig. 20. Boulder conglomerate on Dee Island. The hammer shaft is 54 cm in length.

Fig. 21. Upper Cretaceous sill at Williams Point, Livingston Island, showing prominent sub-horizontal banding caused by multiple intrusion. Weathering has accentuated hardness differences within the layers. The hammer shaft is 34 cm in length.

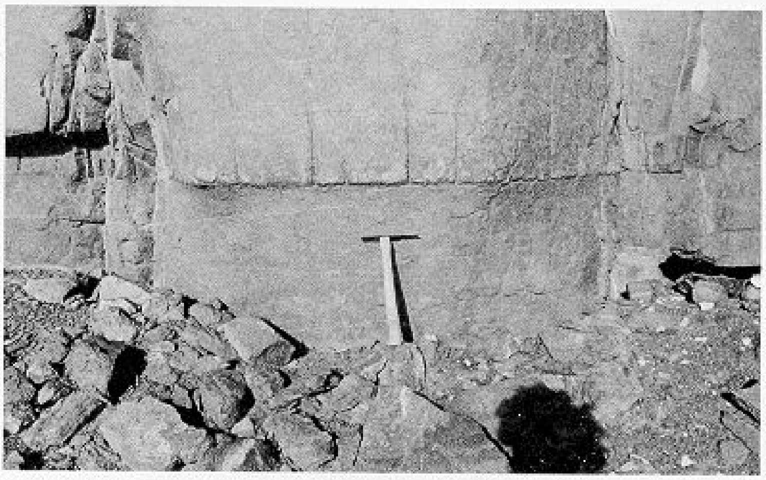

Fig. 22. Part of the multiple intrusion at Fort William, Coppermine Peninsula, Robert Island, showing fractures probably caused by shrinkage during cooling of the upper chilled margin against the lower. The hammer shaft is 34 cm in length.

surface, a kind of way-up criterion is produced and, in a fold-like structure in the intrusion at Spark Point, Greenwich Island, the couplets above the massive interior are mirror images of their counterparts below. In some intrusions, the junction between adjacent couplets is marked by a planar (?) cooling joint. At Fort William, Robert Island, the presence of small vertical fractures at contacts between couplets, but on *one side* only, strongly suggests chilling and contraction of one couplet against the other (Fig. 22). However, at nearby localities, this same intrusive sheet displays prominent columnar cooling joints which pass perpendicularly through well-developed layering (cf. González-Ferrán and Katsui, 1970, fig. 7) demonstrating that the time-lag between the formation of the layers was probably small. Comparable structures also occur in rare dykes, many of which are compositionally and probably genetically related to the thicker intrusive sheets. Such features in dykes are commonly attributed to multiple intrusion (*s.s.*) and this is probably a reasonable explanation for all of the structures described above.

2. *Fildes Formation*

The volcanic rocks of Fildes Peninsula can be divided into three members (Table XI; Fig. 23). Although minor unconformities are common within each member, no evidence was found for the major unconformities mapped by Barton (1965, fig. 7) and it is now believed that all the rocks are of Early Tertiary age and young progressively from south-west

Table X. Stratigraphy of the Upper Cretaceous–Lower Tertiary volcanic rocks.

Unit	*Location*	*Type area*	*Major lithological characteristics*	*Age*
Hennequin Formation	King George Island, mainly east of Admiralty Bay	Point Hennequin, King George Island	Fine-grained and glassy hypersthene-augite-andesites; rare basaltic andesites and dacites	Early Tertiary (Eocene–Oligocene)
Fildes Formation	Mainly King George Island, west of Admiralty Bay; also Stansbury Peninsula and other outcrops on eastern Nelson Island	Fildes Peninsula, King George Island	Weathered olivine-basalts and basaltic andesites; rare pyroxene-andesites and dacites	Early Tertiary (Palaeocene–Eocene)
Coppermine Formation	North-eastern Livingston Island to Robert Island; possibly includes some of the outcrops of altered volcanic rocks on southern Robert and Greenwich islands	Coppermine Peninsula, Robert Island	Usually fresh olivine-basalt lavas; rare basaltic andesites and pyroxene-andesites; multiple intrusions	Late Cretaceous

Table XI. Stratigraphical succession for Fildes Peninsula, King George Island.

Member	*Description*	*Field Relationships*
Upper Member	Fine-grained aphyric and micro-porphyritic andesite and dacite lavas	Top of sequence not exposed; conformably overlies the middle member
Middle Member	Mainly volcaniclastic rocks (locally plant-bearing) with a few basalt and basaltic andesite lavas	Base of sequence not exposed; down-faulted against the lower member
Lower Member	Coarsely porphyritic basalt and basaltic andesite lavas interbedded with laterally impersistent volcaniclastic rocks (some with plant fossils)	Neither base nor top of sequence exposed

to north-east. However, the stratigraphical succession described by Barton (1965, table V) is upside down and this clearly contributed to his incorrect interpretation of the local stratigraphy.

The lower member crops out over much of Fildes Peninsula and can probably be extended to include Stansbury Peninsula (Nelson Island (Fig. 23)). It is not easily divisible into smaller units and is largely formed of conspicuously porphyritic basalt and basaltic andesite lavas mainly 1–7 m thick, but ranging up to 25 m. The thinner lavas (1–2 m), best seen in cliff exposures on the north-west coast, are formed almost entirely of scoriaceous fragments variably grey, purple or red-coloured. It is likely that these are the 'clastic lavas' mapped by Grikurov and Polyakov (1968, fig. 1). In some, lenses of non-brecciated lava form brown-coloured pod-like and lenticular shapes totally enclosed by scoria, a feature also common in the thicker lavas (>2 m) in which scoriaceous surfaces form at least half the thickness of each flow. The rocks are more weathered and mineralized (including calcite, zeolites, agate and quartz in veins and amygdales) than lavas of the upper member, but a few fine-grained, fissile micro-porphyritic flows similar to those of the upper member also occur.

The clastic rocks are mainly thin, laterally impersistent lapillistones and agglomerates, lithologically similar to those in the middle member (see below). Some of the deposits are very coarse-grained (with clasts up to 3 m (Fig. 24)) and unconformities are common. The lapillistones that crop out on the south side of Bothy Bay form well-mixed heterogeneous units, 10 cm to 1.5 m thick, that show both normal and reversed grading in fine-grained zones 2–3 cm thick along the bedding surfaces. They are unconformably overlain by coarse agglomerate and thin sub-horizontal lavas which rest in hollows eroded across the steeply dipping lapillistones. Normal grading and possible washout structures were observed in stratified agglomerates and lapillistones with pebbly clasts on the foreshore 1.5 km north-north-east of Bothy Bay, and some pyroclastic deposits show sag structures and mantle bedding. The large area of poor exposure west of Clement Hill is largely covered by coarse red-brown volcanic sandstone debris. Thin-bedded, purple-grey and green volcanic mudstones and sandstones with bird tracks, invertebrate trails and well-preserved plant fossils are exposed *in situ* on the north side of Saunders Valley (Barton, 1964; Covacevich and Lamperein, 1972; Covacevich and Rich, 1982). They are interbedded with fine lapillistones and coarse tuffs and show millimetre-scale scour and fill structures, grading and rare ripples; some beds are disrupted. Grey-brown shales with carbonized plant fragments are locally present elsewhere on Fildes Peninsula and there are local deposits of coarse conglomerate in beds up to 20 m thick. The conglomerates contain sub-rounded–sub-angular boulders 10 cm to 3 m in diameter set in a gritty matrix with rounded pebbles and crystals of pyroxene and feldspar. Ash-flow tuffs, some black and glassy, are interbedded with conglomerates on eastern Stansbury Peninsula.

The middle and upper members are restricted to northern Fildes Peninsula and the small headlands fringing the ice cap on the west side of Collins Harbour (Fig. 23). The former is composed of grey, brown, buff and green volcaniclastic rocks interbedded (mainly in the upper part of the sequence) with a few thin basalt and basaltic andesite lavas. Plant-bearing tuffs and fine lapillistones crop out extensively around Rocky Cove, passing up north-eastwards into coarse lapillistones and agglomerates. Fissile green pumice-flow lapillistones crop out around Profound Lake. Rocks exposed at sea level at the north-east corner of Norma Cove show good stratification, with beds 60 cm to 2 m thick, graded normally and showing faint (?) cross-bedding. Stratification is rarely seen elsewhere but this may be a function of the poor exposure. The agglomerates contain sub-angular–sub-rounded fragments 5–20 cm in diameter, and scattered blocks up to 2 m, which locally form coarse concentrations. They are polymict, dominated by fragments of coarsely porphyritic lavas. Fine-grained fissile micro-porphyritic lava clasts and fragments of petrified wood also occur. Ochre-coloured pumice is conspicuous in a thick poorly stratified pyroclastic deposit about 750 m north-north-west of Rocky Cove. The interbedded lavas on Davies Heights and at Lapidary Point are locally shattered into angular fragments, mainly non-vesicular but with minor admixed scoria. Veins of zeolite, quartz and agate are common. Usually only the basal parts of the lavas are affected but, near Lapidary Point, a lava is brecciated through its entire thickness (10 m); near here, the underlying volcaniclastic rocks form intrusive wedges squeezed up into the lavas.

The upper member largely conforms to Barton's (1965, table V) lowest group of andesite lavas. It is formed of fresh, fine-grained aphyric and sparsely micro-porphyritic grey and brown-coloured andesite–dacite lavas that vary in thickness from 2 to 8 m at eastern Davies Heights, to 35 m near Nebles Point. Closely spaced curvi-planar cooling joints are well developed (Fig. 25) but no other primary structures were observed *in situ*; elliptical amygdales were seen in fissile debris at one locality. One of the lavas about 1.5 km east of Jasper Point has pillow-like structures between which fine-grained blue-green and brown sediment with cross-laminations has filtered.

Plug-like intrusions, some displaying well-developed columnar jointing, crop out at Flat Top Peninsula, Horatio Stump, Clement Hill, 1 km south-east of Exotic Point and western Stansbury Peninsula, and some of these may have acted as vents for much of the volcanism in the area

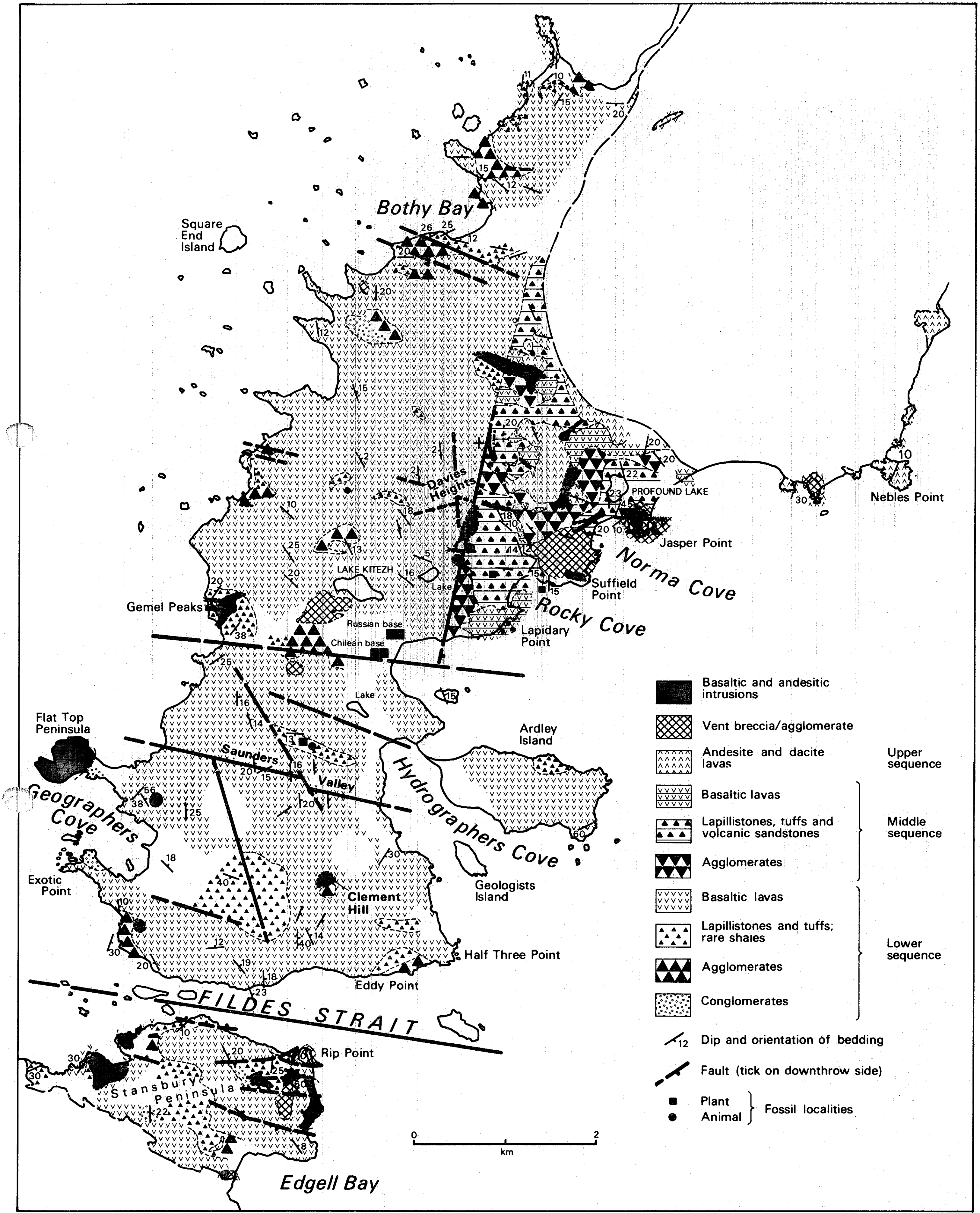

Fig. 23. Geological sketch map of Fildes Peninsula, King George Island, and Stansbury Peninsula, Nelson Island.

Fig. 24. Coarse agglomerate in the lower member on Fildes Peninsula, King George Island. The agglomerate rests unconformably on shales. The exposed face is about 8 m in height.

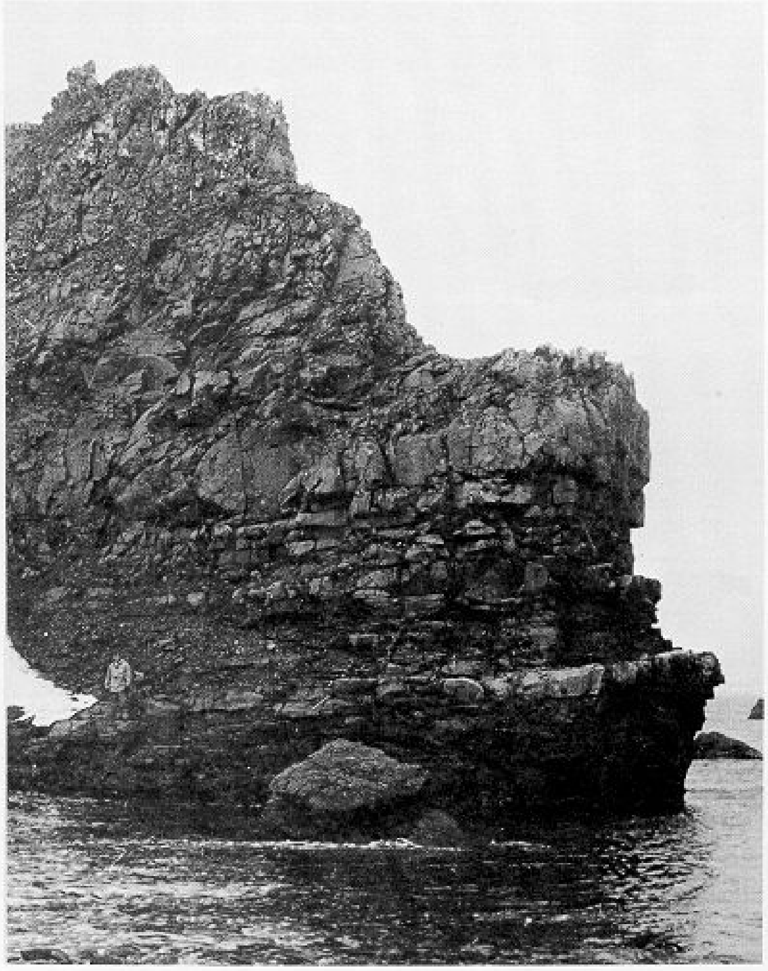

Fig. 25. Well-developed planar cooling joints in a thick lava at Nebles Point, King George Island.

(Jardine, 1950; Hawkes, 1961; Barton, 1965). Vents containing agglomerate or vent breccia are also common. At Suffield and Jasper points, two related vents filled by buff-coloured, non-stratified monomict breccia are intruded by columnar-jointed plugs and sills. Veins of red and green jasper, agate and quartz are common. The breccia is composed of angular to sub-rounded blocks and bombs of glassy basaltic andesite generally 10–25 cm in diameter but including bombs up to 3 m across with twisted shapes and sinuous columnar cooling joints. A log-sized fragment of petrified wood was also observed near Suffield Point. The country rocks generally dip in toward the two vents suggesting a conformable relationship. However, an intrusive contact is exposed on the west side of Norma Cove and another can be inferred on the east side. Chaotic (?) vent agglomerate formed of angular to sub-rounded polymict fragments of coarsely porphyritic lavas, some with twisted bomb-like shapes, and intruded by several thick dykes and irregular sheets form a 27-m-high bluff about 0.9 km west of Nebles Point (Fig. 23). A thick pile of non-stratified polymict (?) vent agglomerate is also present 1 km east of Gemel Peaks. It contains coarsely porphyritic blocks and bombs, generally about 10 cm across but ranging up to 2 m, and it is intruded into and partly interbedded with the surrounding lavas. Grey monomict vent agglomerate intrudes a lava sequence 1 km south-east of Gemel Peaks, but the deposit may be interbedded with lavas to the east.

Three minor co-linear vents crop out on eastern Stansbury Peninsula (Fig. 23). That situated about 1.7 km south-west of Rip Point is formed of polymict green-brown agglomerate with sub-angular–sub-rounded lava fragments 2–10 cm in diameter, but includes blocks and bombs up to 1.6 m. The deposit is about 63 m thick and it is intruded by a central plug. Rip Point is formed by a vent composed of angular monomict breccia and thick (17 m) lavas with prominent scoriaceous surfaces. The third vent (Fig. 26) is filled by non-stratified dark brown monomict agglomerate with scoriaceous bombs 2–4 cm in diameter, ranging up to 20 cm.

Andesite–dacite lavas and small intrusions, some showing pyrite mineralization, crop out at O'Cain Point, Nelson Island, and Duthoit Point is formed of prehnite-bearing andesite lavas intruded by a major basalt dyke.

Weaver Peninsula (Fig. 27) is formed of altered, non-stratified polymict clastic rocks that vary in a northerly

Fig. 26. View of eastern Stansbury Peninsula, Nelson Island, looking south-west. The hill on the right is formed of vent agglomerate, which intrudes a gently dipping sequence of lavas and volcaniclastic rocks. A thick sill forms the low cliff on the left of the photograph.

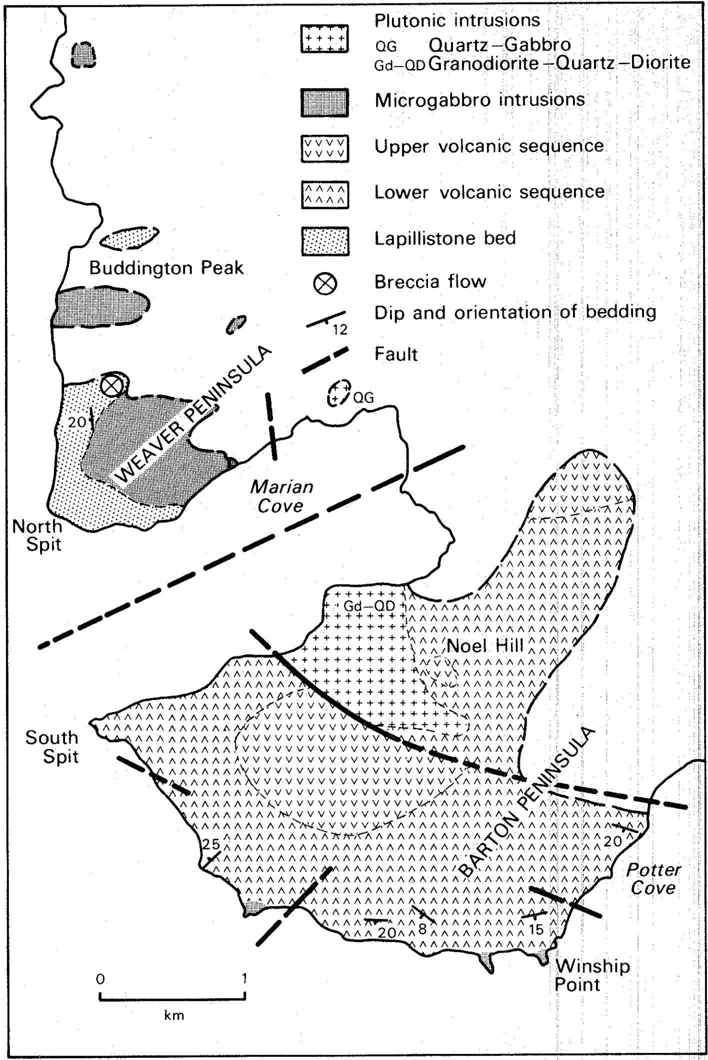

Fig. 27. Geological sketch map of Weaver and Barton peninsulas, King George Island.

direction from fine-grained agglomerate to tuff and volcanic siltstone (Davies, 1982*a*). The rocks are notable for the presence of clasts of 'quartz-pyrite rock' and they are intruded by sheets of microgabbro and a high-level microgabbro pluton at Buddington Peak.

Two sequences of altered volcanic rocks separated by an unconformity crop out at Barton Peninsula (Davies 1982*a*). They are formed of lavas (mainly basalts and basaltic andesites but including pyroxene andesites similar to those of the Hennequin Formation), lapillistones, some with clasts of acidic plutonic rocks, and rare volcanic mudstones. The lower sequence dips at about 20° to the south whereas the upper sequence is sub-horizontal.

South of Potter Cove, a sequence of poorly stratified dark brown fine-grained lapillistones interbedded with a few basalt and basaltic andesite lavas is unconformably overlain by similar lavas and rare interbedded lapillistones (Fig. 28). The unconformity is not planar and on Potter Peninsula it reveals a highly irregular topographical surface. The lower sequence dips predominantly to the north and north-west whereas the upper sequence dips regularly to the south-east. An altered, red-brown andesitic ash-flow tuff crops out north-east of Three Brothers Hill and fragments of green ash-flow tuff occur in moraines on the south-eastern part of the peninsula, associated with dark brown tuff debris with accretionary lapilli. Purple-brown volcanic sandstones with fern and angiosperm fossils occur *in situ* (Fourcade, 1960, p. 94) and in piled scree 1.25 km north-east of Three Brothers Hill.

West of Monsimet Cove, southern Ezcurra Inlet, at least 150 m of thick (7–18 m) hypersthene–augite–andesite lavas and thin impersistent green, brown and purple tuffs and lapillistones with plant fossils (Bibby, 1961, p. 5; Barton, 1964, p. 604) pass abruptly up into a sequence of thinner (3–7 m) basalt and basaltic andesite lavas with prominent red-coloured scoriaceous surfaces*. The upper sequence also crops out extensively at Point Thomas and extends south to Demay Point. At western Point Thomas, the lavas contain conspicuous plagioclase and pyroxene phenocrysts up to 1.5 cm and 5 mm, respectively. The beds show a pronounced radial distribution of steep dips (26–48°) apparently centred on a steep-sided horst-like structure composed of thick (15–20 m) gently-dipping lavas and conglomerate of the Hennequin Formation (Figs. 29 and 30). Coarse and fine-grained green-brown, reddish and yellow-brown crystal-rich lapillistones crop out 1 km south-south-west of Jardine Peak. They are intruded by a basaltic dyke swarm which also crops out on the foreshore and in crags facing Ezcurra Inlet, but not apparently in intervening outcrops. The lapillistones are locally graded normally in beds a few millimetres to centimetres thick showing *lit-par-lit* relationships, but stratification is usually poor. Coarse grey-green and purple-grey non-stratified agglomerates crop out in the crags east of Hervé Cove and are formed of sub-angular–sub-rounded lava fragments generally 3–30 cm in diameter, ranging up to 3.5 m. The agglomerates crop out above and below a prominent unconformity that probably represents a change in the location of the contemporaneous eruption centre.

Sphinx Hill is a minor plug sheathed in baked, fissile pale purple-grey ash-flow tuff of the Hennequin Formation. Plant fossils preserved in brown-grey and red-brown tuff occur in moraines 1 km to the south-west. Basalt and basaltic andesite lavas up to 35 m thick, and thin interbedded volcaniclastic rocks crop out in the Demay Point area, whereas Demay Point itself is composed of an indurated pale grey and grey-brown colour-banded rock lithologically similar to the ash-flow tuff at Sphinx Hill. It forms a structureless unit at least 100 m thick unconformably overlain by friable green pumice-lapillistones. Soft red-brown tuff occurs in places at the contact between the two lithologies. Thick piles of cream-coloured ash-flow tuff with lithophysae are present about 2 km west of Demay Point, but the rocks were not observed *in situ*.

*Note added in proof: Based on its field appearance, lithology and two geochemical analyses, the lower sequence of thick, andesite lavas and tuffs with plant fossils probably should be assigned to the Hennequin Formation. The upper contact with the thinner-bedded basalt and basaltic andesite lavas of the Fildes Formation is approximately planar and trends obliquely eastwards down the southern side of Ezcurra Inlet, probably reaching sea-level at the base of the first bluff west of Monsimet Cove.

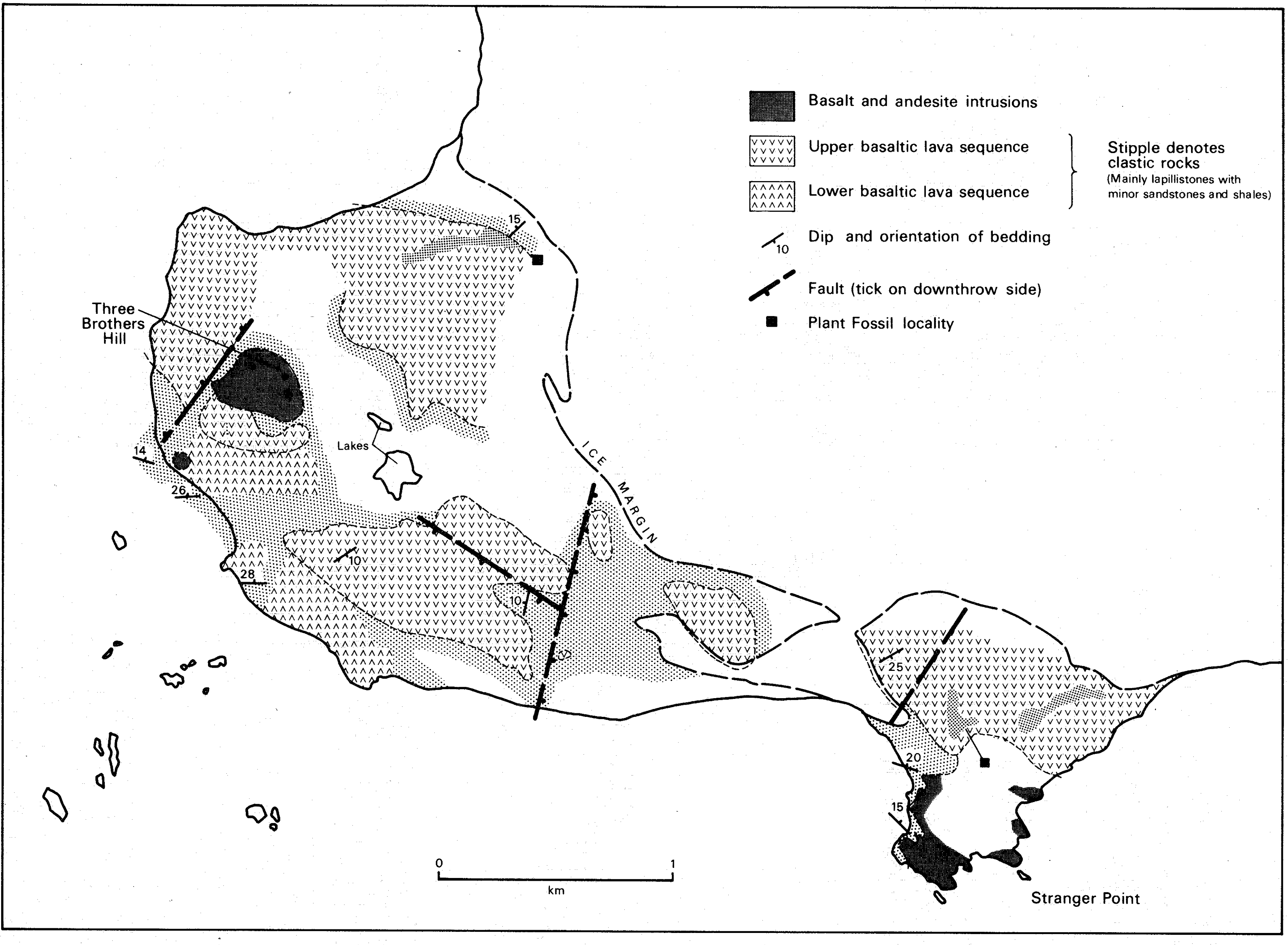

Fig. 28. Geological sketch map of Potter Peninsula and Stranger Point, King George Island.

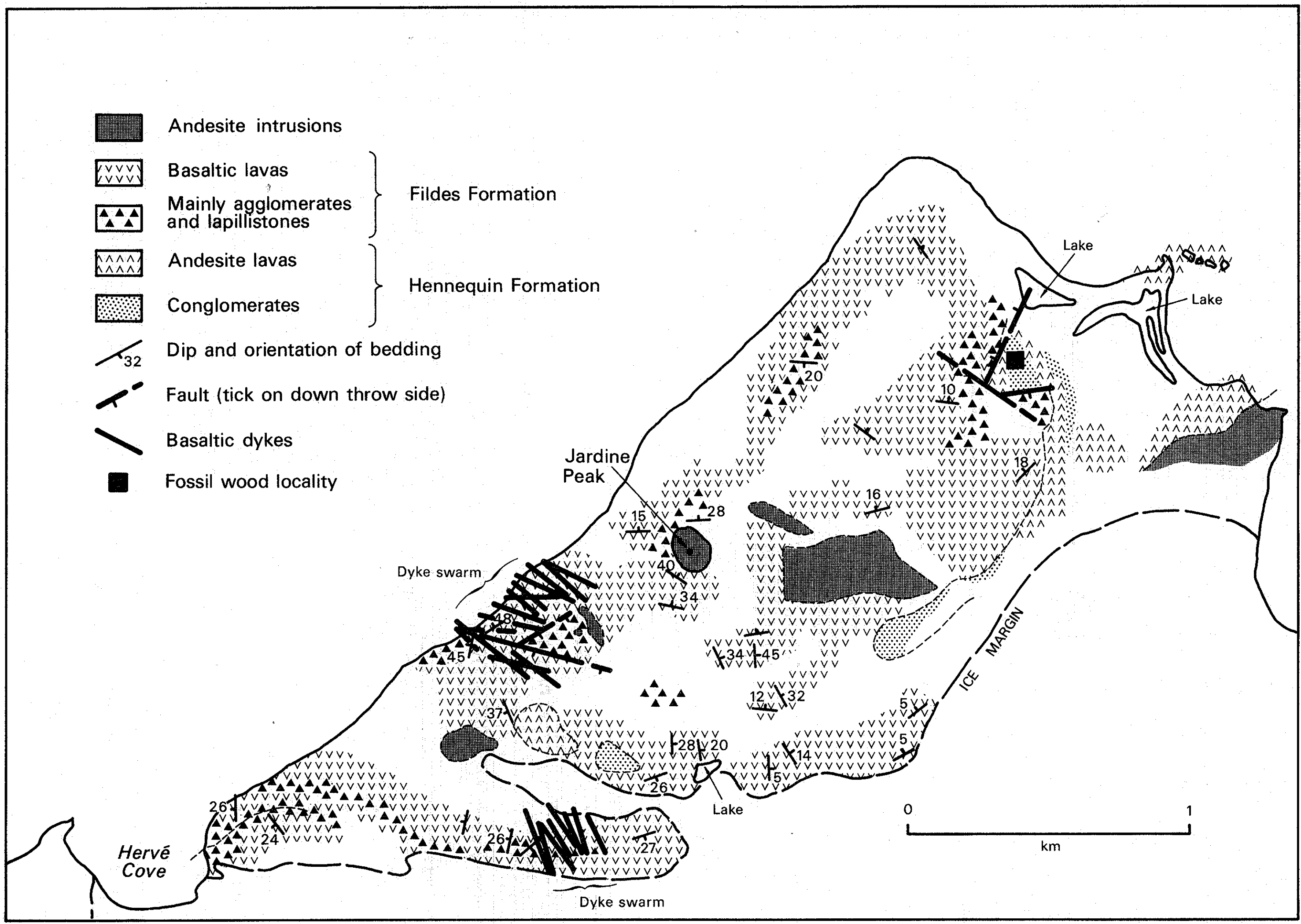

Fig. 29. Geological sketch map of Point Thomas, King George Island.

Extensively altered lavas and rarer ash-flow tuffs crop out on Dufayel Island and plant fossils occur in flaggy tuffs at its eastern end (Bibby, 1961, p. 4). Rhyolite Point contains a thick (190 m) sequence of altered, indurated ash-flow tuffs; conglomerate, with rounded boulders up to 2 m across, crops out at the eastern tip of the headland. The fissile green and rust-coloured 'rhyolite intrusion' described by Bibby (1961) is an altered andesite in thin section. It shows close petrographical similarities to the altered ash-flow tuffs at Sphinx Hill and Demay Point.

3. Hennequin Formation

Thick (25–35 m) andesite and hyalo-andesite lavas interbedded with agglomerate, thin laterally impersistent tuffs and fine green and brown lapillistones crop out at Point Hennequin (Barton, 1965, table IV; Fig. 31). Some of the tuffs contain indeterminable carbonized plant fragments whereas well-preserved fossil leaves occur in moraines on the northern side of Point Hennequin. The latter occur in grey-coloured coarse and fine volcanic sandstones, siltstones, shales and tuffs which show rare mud cracks and ripple marks (Jardine, 1950, p. 3).

Thick (15–20 m) lavas similar to those at Point Hennequin also crop out at Point Thomas and extend south almost as far as Sphinx Hill (Fig. 29). They are interbedded with grey-green conglomerates and rare crystal-rich sandstones and lapillistones. The conglomerates contain sub-angular fragments 0.5–3.0 cm in diameter and rounded boulders, generally 15–65 cm across but ranging up to 2 m. The clasts are almost exclusively composed of Hennequin-type lavas but they include conspicuous log-sized fragments of rust-coloured petrified wood. The conglomerate that crops out about 0.7 km south-south-east of Point Thomas (Fig. 29) fills deep hollows eroded in the underlying lava and it is locally up to 17 m thick. The underlying lava shows no red discolouration but it is frequently stained copper-green. The conglomerate is overstepped to the south and west by fissile grey-green pumice lapillistone, agglomerate and lavas of the Fildes Formation.

Barton (1965, p. 24) described a conglomerate with 'large water-worn pebbles' on the south-west side of Lussich Cove, whereas the other isolated exposures east-north-east of Point Hennequin are formed of lavas 5–15 m thick. The rocks have a similar structural attitude to those at Point

Hennequin and apparently form part of the same sequence. Fragments of fawn-coloured tuffs with poorly preserved carbonized plant stems and wood are present in moraines and on rock ledges at the bluff about 2.5 km south-west of Ternyck Needle.

Lions Rump is formed of two thick (20 and 40 m) columnar-jointed andesite lavas separated by soft, fissile grey and grey-brown shales which wedge out southwards (Fig. 39). The shales contain scattered rounded boulders up to 15 cm in diameter, carbonized plant remains and thin (2–7 cm) beds and lenses of coal. The lower lava crops out on the foreshore south towards Low Head and displays prominent colonnade and entablature columnar jointing. Pale purple and fawn-coloured lapilli-tuffs crop out 1 km west of Lions Rump. Similar pyroxene-andesite lavas also crop out at Three Sisters and Turret points. They are up to 33 m thick and are separated by reddish-coloured scoriaceous surfaces.

Interbedded altered andesite lavas and volcaniclastic rocks (largely pyroclastic) occur between Precious Peaks and Admiralen Peak (Jardine, 1950; Barton, 1965; Davies, 1982*b*). The western outcrops (Stenhouse Bluff to Admiralen Peak) are largely composed of lavas, whereas volcaniclastic rocks are more important at Ullmann Spur and Precious Peaks. The lavas (mainly fine-grained hypersthene–augite–andesites) are apparently up to 93 m thick (Barton, 1965, fig. 5) but they are usually less than 10 m. Acidic lavas, including latite or trachyandesite and dacite, were described by Tyrrell (1921) and Hawkes (1961). These were regarded by Hawkes (1961, p. 5) as primary derivatives of a normal calc-alkaline magma, but petrographical examination of many specimens from this area suggests that these are secondary products of metasomatic alteration and should not be regarded as primary lithologies. This explanation may also apply to the trachyandesite that crops out at Point Hennequin (Hawkes, 1961, p. 19). Poorly stratified polymict agglomerates up to 68 m thick crop out at Precious Peaks, Ullmann Spur and Keller Peninsula. They contain scattered fragments of carbonized and petrified wood and sub-rounded blocks of lava up to 2 m across. Lapillistones are less common. They are variably grey-purple, cream, purple-brown and green in colour. At Precious Peaks, lapillistone beds 1–17 m thick grade laterally into a massive unit with scattered sub-rounded blocks up to 30 cm in diameter. The blocks also form a laterally discontinuous concentration at the base of the unit. Plant-bearing laminated tuffs and tuffaceous sandstones crop out at Admiralen Peak (Barton, 1964, p. 604) and thin-bedded tuffs occur at Precious Peaks and Ullmann Spur. A silicified and pyritized ash-flow tuff at Keller Peninsula is the 'quartz-pyrite lode' referred to by previous authors (Jardine, 1950; Barton, 1965).

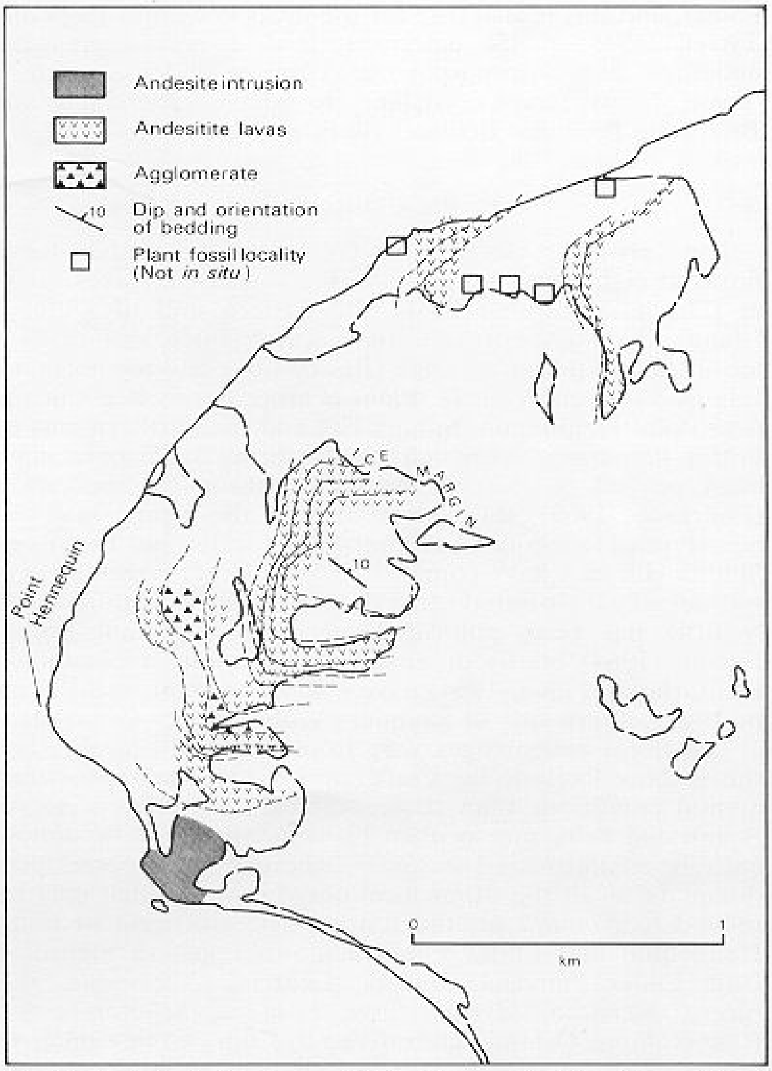

Fig. 31. Geological sketch map of Point Hennequin, King George Island. (Based on a field map made by C. M. Barton, with modifications.)

Fig. 30. Thick, gently dipping lavas of the Hennequin Formation flanked (on the west side) by thin, steeply dipping lavas of the Fildes Formation. Western Point Thomas, King George Island, looking north. The lava in the centre of the photograph is about 20 m thick.

The outcrops of (?) Lower Tertiary rocks on the north coast of King George Island are poorly known. They were mapped by Jardine (1950) and Barton (1965) as altered andesite (*s.l.*) lavas locally veined by quartz and pyrite. Petrographical data are either absent (False Round Point, North Foreland) or the rocks are extremely altered, thus obscuring the primary mineralogy (Tartar Island, Pottinger

Point), and this is also true for the lavas at Mount Hopeful. Tyrrell (1945, p. 45) described 'fresh hypersthene-augite–andesite' and microporphyritic 'enstatite–andesite' with a 'dense brown cryptocrystalline to glassy groundmass' at Brimstone Peak and Bolinder Bluff, respectively.

B. Palaeontology

The Tertiary rocks of King George island contain fossil floras at eight localities at least (Fig. 1). Fossil leaves occur *in situ* at Admiralen Peak, the eastern end of Dufayel Island, the southern side of Ezcurra Inlet and at two localities on Fildes Peninsula (Rocky Cove and the northern side of Saunders Valley). Plant-bearing debris is abundant near Point Hennequin, Sphinx Hill and the northern part of Potter Peninsula. Although plant-bearing sandstones have been proved *in situ* on Potter Peninsula by excavation (Fourcade, 1960), the source beds of the erratic material near Point Hennequin have not been located but that from Sphinx Hill may have come from Anvil Crag. Fossil wood is sporadically distributed through the sequence. Unfortunately little has been published on these important floras. Barton (1964) briefly discussed their climatic implications, and Orlando (1963, 1964) gave a short account of the flora on the northern side of Saunders Valley, Fildes Peninsula.

The floral assemblages vary from locality to locality but this is more likely to be a reflection of local palaeoenvironmental conditions than stratigraphical age differences. At Admiralen Peak macro plant remains appear to be almost entirely coniferous (*Araucaria*), whereas angiosperms predominate at all the other localities. Leaves, which may be related to *Nothofagus*, the southern beech, occur at Point Hennequin and Fildes Peninsula; other genera identified from Fildes Peninsula include *Laurelia, Nectandra, Tetracera, Sterculia, Myrtiphyllum, Lomatia, Schinopsis* and *Rhamnidium*. Orlando considered this flora to be similar to others in South America of 'Magellanian' or Miocene age. However, the radiometric age data now available from Fildes Peninsula suggest that it is much older – Early Tertiary.

C. Petrography

In the lavas and hypabyssal intrusions, porphyritic rocks are prodominant but aphyric rocks are also present. Despite the thickness of many of the intrusions, only a few are as coarse as microgabbro. The basalt lavas which are abundant in the Coppermine Formation contain fresh subhedral–anhedral phenocrysts of augite, olivine and labradorite set in a coarse holocrystalline groundmass of plagioclase (mainly labradorite), augite, hypersthene and opaque ore (Fig. 32). Rare hypersthene phenocrysts may also be present and all the phenocryst minerals show signs of magmatic resorption. Concentric zoning and hour-glass structure, rare in the lavas, are prominent in augite phenocrysts of the intrusions. Glomeroporphyritic clusters are common. In basalts and basaltic andesites of the Fildes Formation, unaltered olivine is only preserved as rare relics in some of the plugs. The basaltic andesites resemble the basalts but lack groundmass hypersthene, pigeonite is rarely present and there may be a small number of opaque ore micro-phenocrysts; dark brown glass sometimes occurs interstitially. These rocks, and the rare interbedded pyroxene andesites, are typically coarsely crystalline (Fig. 33). By contrast, the pyroxene andesites characteristic of the Hennequin Formation are generally fine-grained or glassy (Fig. 34), with euhedral–subhedral

Fig. 32. Typical olivine–basalt lava of the Coppermine Formation, with phenocrysts of unaltered olivine, diopsidic augite (showing pronounced oscillatory zoning) and plagioclase. (P.840.5, X-nicols, × 30.)

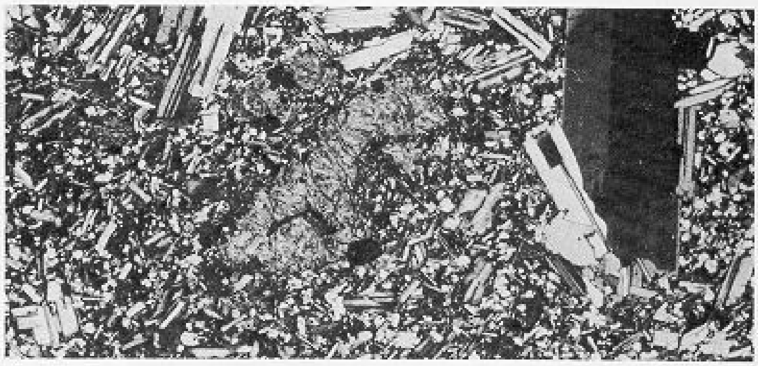

Fig. 33. Typical coarse-grained basalt lava of the Fildes Formation, with phenocrysts of altered olivine, augite (not shown) and plagioclase. (P.1162.5, X-nicols, ×30.)

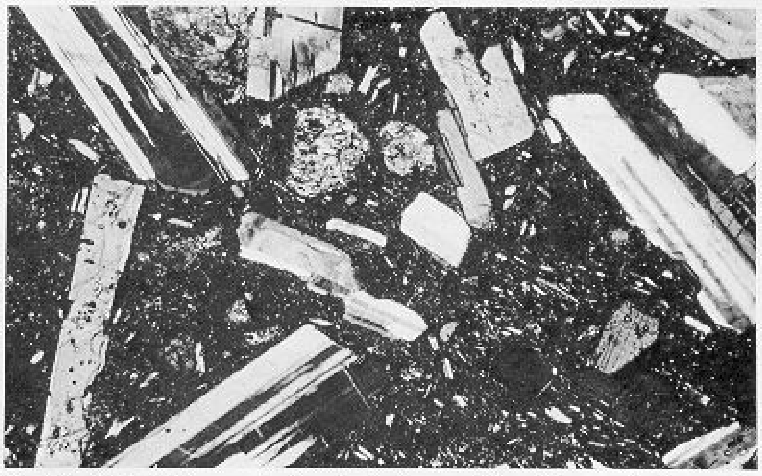

Fig. 34. Typical fine-grained andesite lava of the Hennequin Formation, with phenocrysts of lathy plagioclase, augite, hypersthene and opaque ore. (G.28.1, X-nicols, ×40.)

Table XII. Chemical analyses of Upper Cretaceous–Lower Tertiary volcanic rocks of the South Shetland Islands. (Continued on pp 50–56.)
1–14: Coppermine Formation.

	1	2	3	4	5	6	7	8	9	10	11	12	13	14
SiO_2	49.8	51.5	51.7	50.3	50.8	51.8	50.9	52.1	47.9	50.3	47.5	49.5	49.2	53.4
TiO_2	0.67	0.66	1.06	1.10	0.88	1.07	0.75	0.76	0.86	1.05	0.75	0.99	0.91	0.88
Al_2O_3	17.1	18.4	16.7	16.5	14.4	17.6	16.9	17.5	13.90	17.40	14.10	17.28	15.50	18.40
Fe_2O_3	2.46	2.37	2.59	2.57	2.56	2.60	2.46	2.36	2.67	2.21	2.57	2.29	2.64	2.38
FeO	6.14	5.94	6.48	6.43	6.41	6.51	6.16	5.90	6.68	5.52	6.43	5.73	6.59	5.94
MnO	0.14	0.14	0.15	0.17	0.16	0.16	0.15	0.17	0.15	0.12	0.15	0.13	0.16	0.14
MgO	9.8	7.9	8.8	8.9	12.2	8.3	8.3	7.5	11.7	5.4	12.2	6.1	10.2	6.4
CaO	11.39	11.03	10.63	10.48	9.05	10.55	12.06	11.31	9.66	8.64	9.93	8.65	10.08	9.37
Na_2O	2.24	2.73	2.59	2.56	2.73	2.56	2.30	2.65	2.03	4.97	2.76	4.34	2.42	3.38
K_2O	0.34	0.69	0.69	0.54	0.49	0.71	0.21	1.00	0.63	1.59	0.52	1.76	0.33	0.94
P_2O_5	0.12	0.11	0.34	0.48	0.37	0.34	0.02	0.15	0.26	0.30	0.20	0.25	0.14	0.22
Total	100.20	101.47	101.73	100.03	100.05	102.20	100.21	101.40	96.44	97.50	97.11	97.02	98.17	101.45
TRACE ELEMENTS														
Cr	360	246	230	200	210	210	290	200	360	89	360	80	291	140
Ni	142	83	70	67	70	72	84	46	130	26	112	23	88	88
Zn	54	56	75	71	66	74	58	65	54	51	52	47	59	69
Rb	–	6	9	–	–	10	3	9	10	29	7	25	–	7
Sr	670	675	681	704	545	621	555	737	540	693	582	991	475	830
Y	10	10	20	19	16	19	11	12	14	17	12	16	15	12
Zr	58	59	112	112	108	127	57	89	72	108	79	108	56	59
Nb	–	–	–	4	3	–	–	4	–	3	–	–	–	4
Ba	157	156	229	224	206	233	–	–	265	373	240	859	120	240
La	–	–	12	12	23	24	13	24	8	11	7	9	–	10
Ce	16	12	31	33	27	32	15	31	23	27	20	26	15	17
Pb	–	–	–	–	–	–	–	–	–	–	–	–	–	10
Th	–	–	–	–	–	–	–	–	–	–	–	–	–	–
Ga	20	20	21	21	21	21	18	18	22	25	21	22	23	25
RATIOS														
K/Rb	–	955	636	–	–	589	581	922	523	455	617	584	–	1115
Ba/Rb	–	26	25	–	–	23	–	–	26	13	34	34	–	34
K/Ba	18	37	25	20	20	25	–	–	20	35	18	17	23	33
Rb/Sr	–	0.01	0.01	–	–	0.02	0.01	0.01	0.19	0.04	0.01	0.02	–	0.01
Ba/Sr	0.2	0.2	0.3	0.3	0.4	0.4	–	–	0.5	0.5	0.4	0.9	0.2	0.3
Ca/Sr	121	117	112	106	119	121	155	110	128	89	121	62	152	81
Ce_N/Y_N	3.9	2.9	3.8	4.2	4.1	4.1	3.3	6.3	4.0	3.9	4.1	4.0	2.4	3.5
Fe*/Mg	1.1	1.3	1.3	1.3	0.9	1.4	1.3	1.4	1.0	1.8	0.9	1.6	1.1	1.6

1.	P.840.3	Basalt, Coppermine Peninsula, Robert Island.
2.	P.841.12	Basalt, Coppermine Peninsula, Robert Island.
3.	P.842.4	Basalt, Coppermine Peninsula, Robert Island.
4.	P.842.9	Basalt, Coppermine Peninsula, Robert Island.
5.	P.1607.1	Basalt, Coppermine Peninsula, Robert Island.
6.	P.1494.2	Basalt, Coppermine Peninsula, Robert Island.
7.	P.1492.2	Basalt, Coppermine Peninsula, Robert Island.
8.	P.1484.1	Basalt, Coppermine Peninsula, Robert Island.
9.	P.841.2	Basalt, Coppermine Peninsula, Robert Island.
10.	P.841.6	Basalt, Coppermine Peninsula, Robert Island.
11.	P.841.7	Basalt, Coppermine Peninsula, Robert Island.
12.	P.841.9	Basalt, Coppermine Peninsula, Robert Island.
13.	P.843.1	Basalt, the Triplets, Robert Island.
14.	P.1603.1	Microgabbro, Catharina Point, Robert Island.

phenocrysts of plagioclase (andesine–labradorite), augite, hypersthene, opaque ore and rare distinctive microphenocrysts of apatite with abundant grey to grey–blue rod-like inclusions. Some augite phenocrysts have poorly defined hour-glass structure and may show concentric zoning, occasionally oscillatory. The hypersthene phenocrysts may be mantled by augite (e.g. G.34.2 and P.540.1). Tyrrell (1945, p. 45) described a 'single crystal of magnetite-rimmed brown hornblende' in a hypersthene–augite–andesite from Brimstone Peak and hornblende also occurs in a dyke at Gemel Peaks, Fildes Peninsula, and as crystal relics largely pseudomorphed by granular augite, magnetite and plagioclase (cf. Chester Cone, p. 23) in a large intrusion 2 km west-north-west of Demay Point. Quartz xenocrysts with narrow reaction rims of prismatic augite also occur in the intrusion near Demay Point and in the Jardine Peak plug.

In general, the clastic rocks are entirely composed of igneous fragments, mainly dense or glassy, often vesicular juvenile clasts but including angular–sub-angular more coarsely crystalline fragments of the surrounding lavas and crystals of plagioclase and pyroxene. Clasts of 'quartz-pyrite rock' and plutonic rocks occur in volcaniclastic rocks at Point Hennequin, Ullmann Spur and Weaver and Barton peninsulas. The composition of the matrix is often difficult to distinguish due to olive-green clay alteration, staining by hematite or partial replacement by zeolite, each of which also affects the lithic clasts. In the metasomatized rocks, the matrix is invariably recrystallized and its original nature is usually indeterminable. Prior to this alteration and recrystallization, matrices were probably formed of finely comminuted lithic, crystal and vitric fragments. The ash-flow tuffs are predominantly composed of wispy fiamme, crystals of plagioclase, augite and opaque ore, and rare lithic fragments, set in a matrix of clay- or zeolite-altered glass shards and dust. These rocks are easily recognized in the field by

Table XII. Chemical analyses of Upper Cretaceous–Lower Tertiary volcanic rocks of the South Shetland Islands (continued).
15–18: Coppermine Formation; 19–28: Fildes Formation.

	15	*16*	*17*	*18*	*19*	*20*	*21*	*22*	*23*	*24*	*25*	*26*	*27*	*28*
SiO_2	51.1	48.3	50.4	49.6	55.2	63.7	64.5	49.6	57.9	50.7	53.1	55.9	62.2	62.0
TiO_2	0.80	1.18	0.86	0.89	1.35	0.92	0.92	0.50	0.92	0.87	1.06	0.87	0.86	0.85
Al_2O_3	16.90	18.20	19.10	17.70	16.2	15.4	15.5	19.6	15.9	19.9	17.6	18.9	16.3	16.2
Fe_2O_3	2.57	2.57	2.60	2.57	2.87	1.56	1.45	2.33	2.26	2.74	2.82	2.28	1.68	1.61
FeO	6.42	6.43	6.50	6.42	7.18	3.90	3.63	5.84	5.64	6.85	7.06	5.71	4.20	4.02
MnO	0.16	0.16	0.16	0.14	0.21	0.20	0.20	0.14	0.19	0.17	0.18	0.15	0.17	0.15
MgO	9.6	7.0	6.3	6.5	3.4	1.4	1.2	7.4	3.2	3.9	4.8	3.9	1.1	1.2
CaO	10.43	11.18	11.35	10.73	7.47	3.61	3.46	12.22	7.32	11.57	9.69	8.00	5.14	5.54
Na_2O	2.93	3.51	2.89	2.76	4.48	5.37	5.48	2.04	4.21	3.38	3.81	3.74	4.95	3.92
K_2O	0.87	0.92	0.43	0.76	0.79	2.04	2.13	0.38	0.50	0.32	0.57	0.87	1.36	1.38
P_2O_5	0.23	0.29	0.13	0.20	0.25	0.24	0.24	0.08	0.14	0.12	0.14	0.16	0.29	0.28
Total	102.01	99.74	100.72	98.27	99.40	98.34	98.71	100.13	98.18	100.52	100.83	100.48	98.25	97.15
TRACE ELEMENTS														
Cr	350	180	90	90	–	–	–	40	–	–	30	30	–	–
Ni	98	59	13	44	–	–	–	28	–	–	12	11	–	–
Zn	59	61	57	58	92	79	83	58	82	69	76	64	70	63
Rb	13	15	–	8	23	39	40	–	4	–	13	25	44	50
Sr	480	500	394	617	481	347	339	572	476	609	439	523	433	494
Y	15	16	11	14	25	35	37	9	21	13	17	18	27	27
Zr	104	140	49	60	120	221	225	62	108	57	81	121	183	182
Nb	3	–	3	–	–	4	–	–	–	–	–	–	8	–
Ba	308	248	85	226	293	492	518	122	268	149	192	319	450	540
La	19	26	11	15	15	27	26	–	–	–	–	16	25	24
Ce	28	41	10	21	41	58	57	20	28	17	21	32	53	47
Pb	–	–	–	–	–	10	10	–	–	–	–	–	10	–
Th	–	–	–	–	–	–	–	–	–	–	–	–	–	–
Ga	19	21	19	23	23	23	22	19	25	24	23	22	21	22
RATIOS														
K/Rb	555	309	–	789	285	434	442	–	1038	–	364	289	257	229
Ba/Rb	24	17	–	28	13	13	13	–	67	–	15	13	10	11
K/Ba	23	31	42	28	22	34	34	26	15	18	25	23	25	21
Rb/Sr	0.03	0.03	–	0.01	0.05	0.11	0.12	–	0.01	–	0.03	0.05	0.10	0.10
Ba/Sr	0.6	0.5	0.2	0.4	0.6	1.4	1.5	0.2	0.6	0.2	0.4	0.6	1.0	1.1
Ca/Sr	155	160	206	124	111	74	73	153	110	136	158	109	85	80
Ce_N/Y_N	4.6	6.3	2.2	3.7	4.0	4.0	3.8	5.4	3.3	3.2	3.0	4.3	4.8	4.2
Fe*/Mg	1.2	1.6	1.8	1.7	3.7	4.9	5.3	1.4	3.1	3.1	2.6	2.6	6.7	5.9

15.	P.1613.1	Microgabbro, Fort William, Robert Island.
16.	P.1487.1	Basalt, Coppermine Peninsula, Robert Island.
17.	P.926.7	Microgabbro, Express Island.
18.	P.922.2	Microgabbro, Duff Point, Greenwich Island.
19.	P.1125.1	Basaltic andesite, Fildes Peninsula, King George Island.
20.	P.1182.1	Dacite, Fildes Peninsula, King George Island.
21.	P.1183.2	Dacite, Fildes Peninsula, King George Island.
22.	P.1147.3	Basalt, Fildes Peninsula, King George Island.
23.	P.1149.1	Andesite, Fildes Peninsula, King George Island.
24.	P.1162.5	Basalt, Fildes Peninsula, King George Island.
25.	P.1166.7	Basalt, Fildes Peninsula, King George Island.
26.	P.1114.1	Basaltic andesite, Suffield Point, Fildes Peninsula, King George Island.
27.	P.1136.1	Dacite, Jasper Point, Fildes Peninsula, King George Island.
28.	P.1181.3	Dacite, Jasper Point, Fildes Peninsula, King George Island.

their fissile nature which is caused by the flattened pumice. Despite hand-specimen similarities to rocks at Sphinx Hill, the (?) ash-flow tuffs at Demay and Rhyolite points preserve no vitroclastic texture. However, 'snowflake texture', signifying devitrification of volcanic glass (Anderson, 1969, 1970*a*, *b*; Lofgren, 1971), is conspicuous in the microlithic groundmass. Nevertheless, the identification of these rocks as ash-flow tuffs must remain highly tentative at present.

D. ALTERATION

Away from the plutonic intrusions, the only signs of alteration in the Upper Cretaceous–Lower Tertiary rocks consist of clay minerals (including iddingsite or bowlingite) and serpentinization of orthopyroxene and olivine, (?) smectite and/or sericite partial alteration of plagioclase, and replacement of glass by zeolite, silica and/or (?) smectite. Most of these effects occur to some extent throughout the area and can probably be attributed to normal weathering processes.

Thermal metamorphism has occurred adjacent to some plutonic intrusions, resulting in rocks with fine-grained granoblastic textures composed of twinned recrystallized plagioclase (generally andesine), hypersthene, augite, apatite and opaque ore, and scattered partially polygonized plagioclase phenocrysts. The mineral parageneses correspond to the pyroxene–hornfels facies of low-pressure contact metamorphism (Turner, 1968). The presence of bastite pseudomorphs after hypersthene, and red-brown biotite (localized around crystals of opaque ore) are evidence of slight retrograde metamorphism (Hawkes, 1961, p. 9)

Table XII. Chemical analyses of Upper Cretaceous–Lower Tertiary volcanic rocks of the South Shetland Islands (continued). 29–42: Fildes Formation.

	29	*30*	*31*	*32*	*33*	*34*	*35*	*36*	*37*	*38*	*39*	*40*	*41*	*42*
SiO_2	51.8	52.9	50.2	49.3	66.1	51.1	51.7	50.3	50.6	49.9	53.1	55.6	52.3	49.3
TiO_2	0.78	0.67	0.53	0.47	0.78	0.53	0.80	0.84	0.82	1.00	1.37	1.44	1.49	1.05
Al_2O_3	18.3	21.2	19.2	20.1	14.9	19.2	16.2	18.9	20.1	18.2	16.4	14.4	14.9	17.9
Fe_2O_3	2.66	2.38	2.26	2.29	1.23	2.22	2.39	2.51	2.45	2.50	2.76	2.74	2.93	2.65
FeO	6.66	5.94	8.66	5.72	3.08	5.56	5.98	6.29	6.13	6.25	6.90	6.84	7.32	9.63
MnO	0.18	0.13	0.13	0.11	0.14	0.14	0.15	0.15	0.16	0.26	0.18	0.22	0.18	0.16
MgO	5.0	5.2	6.7	6.0	1.0	6.4	8.3	5.4	4.6	5.6	3.8	3.5	4.0	6.3
CaO	9.46	10.70	12.06	13.22	3.52	11.20	9.79	11.44	10.10	10.75	8.98	7.71	8.10	10.71
Na_2O	3.14	3.30	2.58	2.29	4.80	2.97	3.04	2.81	3.20	3.39	3.60	3.52	3.17	2.90
K_2O	0.93	0.82	0.56	0.61	1.85	0.87	0.51	0.50	0.66	0.31	0.38	1.25	0.63	0.33
P_2O_5	0.13	0.10	0.08	0.08	0.13	0.08	0.14	0.14	0.11	0.22	0.22	0.30	0.28	0.20
Total	99.04	103.34	102.96	100.19	97.53	100.27	99.00	99.28	98.93	98.38	97.69	97.52	95.30	98.13
TRACE ELEMENTS														
Cr	–	20	90	20	–	50	30	10	10	30	–	–	–	40
Ni	–	8	43	25	–	23	15	12	11	14	–	–	–	30
Zn	61	62	55	49	64	46	64	62	63	67	82	93	92	76
Rb	9	8	4	4	37	6	7	8	5	–	–	11	6	–
Sr	532	568	549	771	391	586	527	479	611	756	562	470	496	676
Y	14	12	11	7	38	8	13	15	13	16	25	29	28	17
Zr	67	63	69	58	308	59	61	62	68	69	103	132	127	73
Nb	–	–	–	4	7	5	–	6	4	4	3	3	4	–
Ba	162	147	129	109	602	151	154	142	209	205	242	318	297	179
La	8	7	11	11	25	11	7	6	11	16	18	19	23	15
Ce	17	15	16	15	57	15	19	17	15	31	17	36	35	28
Pb	–	–	–	–	15	–	–	–	–	–	–	10	–	–
Th	–	–	–	–	–	–	–	–	–	–	–	–	–	–
Ga	22	22	22	20	22	21	25	22	22	23	23	25	23	22
RATIOS														
K/Rb	858	851	1162	1266	415	1204	605	519	1096	–	–	943	872	–
Ba/Rb	18	18	32	27	16	25	22	18	42	–	–	29	49	–
K/Ba	48	46	36	46	26	48	27	29	26	13	13	33	18	15
Rb/Sr	0.02	0.01	0.01	0.01	0.09	0.01	0.01	0.02	0.01	–	–	0.02	0.01	–
Ba/Sr	0.3	0.3	0.2	0.1	1.5	0.3	0.3	0.3	0.3	0.3	0.4	0.7	0.6	0.3
Ca/Sr	127	135	157	123	64	137	133	171	118	102	114	117	117	113
Ce_N/Y_N	3.0	3.0	3.5	5.2	3.7	4.6	3.6	2.8	2.8	4.7	1.7	3.0	3.0	4.0
Fe*/Mg	2.3	2.0	2.0	1.7	5.4	1.5	1.3	2.0	2.3	2.0	3.2	3.4	3.2	1.8

29.	P.1177.1	Basalt, Gemel Peaks, Fildes Peninsula, King George Island.
30.	P.1177.2	Basalt, Gemel Peaks, Fildes Peninsula, King George Island.
31.	P.1129.1	Basalt, Fildes Peninsula, King George Island.
32.	P.1205.1	Basalt, Stansbury Peninsula, Nelson Island.
33.	P.1198.1	Basalt, Stansbury Peninsula, Nelson Island.
34.	P.1224.1	Basalt, Rip Point, Stansbury Peninsula, Nelson Island.
35.	P.1198.5	Basalt, Stansbury Peninsula, Nelson Island.
36.	P.1203.1	Microgabbro, Stansbury Peninsula, Nelson Island.
37.	P.232.1	Basalt, Potter Peninsula, King George Island.
38.	P.232.6	Basalt, Potter Peninsula, King George Island.
39.	P.754.2	Basaltic andesite, Potter Peninsula, King George Island.
40.	P.757.2	Andesite, Potter Peninsula, King George Island.
41.	P.758.1	Basaltic andesite, Potter Peninsula, King George Island.
42.	P.760.1	Basalt, Potter Peninsula, King George Island.

Green actinolite pseudomorphs after pyroxene occur in a specimen metamorphosed by the Noel Hill quartz-diorite (G.526.1). Minor epidote, sphene, brown biotite and (?) albite in this rock suggest that albite–epidote–hornfels or greenschist facies metamorphism has occurred and this is confirmed by the co-existence of actinolite, Fe-rich epidote and chlorite in veins (Turner, 1968; Winkler, 1974, p. 165).

The major alteration that has affected the Lower Tertiary rocks on King George and Nelson islands is metasomatic and it is related to the plutonic intrusions (Ferguson, 1921; Hawkes, 1961). According to Hawkes (1961, p. 9), the alteration is characterized by epidote and pyrite mineralization accompanied by widespread albitization of plagioclase. He related the additional calcite mineralization to fumarolic activity associated with Tertiary vents (Hawkes, 1961, p. 10). This could explain the occurrence of calcitized rocks in the areas of otherwise unaltered Tertiary rocks (e.g. at Point Hennequin and Potter Peninsula), although the effects are most pronounced in areas of 'Jurassic' rocks. However, since there is no reason to suspect that the areas of altered ('Jurassic') and unaltered rocks differ significantly in age (p. 36), it is possible that calcite mineralization is another aspect of the metasomatic activity related to the plutonic intrusions. It was also suggested that pyrite mineralization is localized near the larger quartz-pyrite 'lodes' (*s.l.*) (Hawkes, 1961, p. 9) that occur at Pyrites Island and Keller and Barton peninsulas, but subsequent investigation has revealed a more widespread distribution, including most of the 'Jurassic' outcrops and restricted occurrences in areas of 'unaltered' Tertiary rocks.

Calcite is the commonest and most conspicuous alteration mineral. It forms ragged plates in phenocrysts of plagioclase and pyroxene and it is usually abundant in the groundmass. Chlorite is largely restricted to pseudomorphs after

Table XII. Chemical analyses of Upper Cretaceous–Lower Tertiary volcanic rocks of the South Shetland Islands (continued).
43–56: Fildes Formation.

	43	*44*	*45*	*46*	*47*	*48*	*49*	*50*	*51*	*52*	*53*	*54*	*55*	*56*
SiO_2	51.0	51.1	53.1	56.5	53.5	55.2	49.4	55.7	54.3	50.5	52.6	52.4	50.8	51.6
TiO_2	1.03	1.15	0.97	0.77	0.63	0.61	1.01	1.31	1.02	0.83	0.84	0.74	1.36	1.67
Al_2O_3	17.6	15.5	17.2	17.8	16.1	17.2	18.0	18.1	21.2	18.2	20.6	15.7	14.7	13.9
Fe_2O_3	2.56	2.86	2.46	2.15	2.20	2.15	2.62	2.63	2.28	2.67	2.46	2.23	2.86	3.25
FeO	6.41	7.16	6.15	5.39	5.49	5.38	6.54	6.57	5.70	6.66	6.14	5.57	7.15	8.13
MnO	0.18	0.20	0.16	0.13	0.14	0.13	0.20	0.17	0.17	0.14	0.15	0.15	0.23	0.21
MgO	6.4	7.1	5.7	4.3	6.6	6.2	5.5	3.8	3.4	6.7	4.6	6.7	5.8	5.8
CaO	9.62	8.27	8.00	6.90	9.31	7.92	11.29	7.99	9.35	11.78	9.67	7.51	8.94	8.73
Na_2O	3.13	2.93	3.36	3.65	2.48	3.04	2.91	3.85	4.13	2.50	3.40	2.68	3.00	3.15
K_2O	0.47	0.75	1.00	2.05	0.36	1.15	0.20	1.36	0.82	0.26	0.91	1.44	0.18	0.20
P_2O_5	0.25	0.22	0.22	0.18	0.17	0.18	0.18	0.29	0.22	0.13	0.22	0.20	0.31	0.29
Total	98.65	97.24	98.32	99.82	96.98	99.16	97.85	101.77	102.59	100.37	101.59	95.32	95.33	96.93
TRACE ELEMENTS														
Cr	50	20	20	20	20	20	20	–	–	160	20	nd	17	–
Ni	27	14	16	17	19	20	12	–	–	40	11	nd	–	–
Zn	73	83	66	52	64	60	72	72	67	61	60	63	94	102
Rb	–	13	14	40	4	14	–	22	10	–	14	16	–	–
Sr	636	638	563	547	802	786	597	492	610	623	629	686	762	605
Y	20	23	23	22	14	13	15	27	18	12	15	14	27	28
Zr	83	90	93	172	124	97	65	159	98	73	76	nd	174	130
Nb	5	5	–	4	–	–	5	4	5	–	–	nd	3	5
Ba	314	197	333	354	173	294	134	328	240	138	238	nd	131	166
La	13	13	16	20	14	15	13	27	15	17	15	nd	15	13
Ce	17	21	20	51	35	22	18	46	23	19	33	nd	47	40
Pb	–	–	–	10	–	–	–	–	–	–	–	–	–	–
Th	–	–	–	–	–	–	–	–	–	–	–	–	–	–
Ga	24	22	21	22	23	24	22	21	24	22	25	24	27	25
RATIOS														
K/Rb	–	479	593	425	747	682	–	513	681	–	540	747	–	–
Ba/Rb	–	15	24	9	43	21	–	15	24	–	17	–	–	–
K/Ba	12	32	25	48	17	32	12	34	28	16	32	–	11	10
Rb/Sr	–	0.02	0.02	0.07	0.01	0.02	–	0.45	0.02	–	0.02	0.02	–	–
Ba/Sr	0.5	0.3	0.6	0.6	0.2	0.4	0.2	0.7	0.4	0.2	0.4	–	0.2	0.3
Ca/Sr	108	93	102	90	83	72	135	116	110	135	110	78	84	103
Ce_N/Y_N	2.1	2.2	2.1	5.7	6.1	4.1	2.9	4.2	3.1	3.9	5.4	–	4.2	3.5
Fe*/Mg	1.8	1.8	1.9	2.2	1.5	1.5	2.1	3.0	2.9	1.7	2.3	1.5	2.2	2.5

nd = not determined

43. P.693.1 Basalt, Potter Peninsula, King George Island.
44. P.694.2 Basalt, Potter Peninsula, King George Island.
45. P.697.2 Basaltic andesite, Potter Peninsula, King George Island.
46. P.685.4 Andesite, Three Brothers Hill, King George Island.
47. P.696.1 Basaltic andesite, Potter Peninsula, King George Island.
48. P.696.2 Basaltic andesite, Potter Peninsula, King George Island.
49. P.751.1 Basalt, Potter Peninsula, King George Island.
50. P.1236.1 Basaltic andesite, Demay Point, King George Island.
51. P.1240.1 Basalt, Demay Point, King George Island.
52. P.1241.1 Basalt, Demay Point, King George Island.
53. P.1246.1 Basalt, Anvil Crag, King George Island.
54. P.662.1 Basaltic andesite, Barton Peninsula, King George Island.
55. P.663.1 Basaltic andesite, Barton Peninsula, King George Island.
56. P.669.1 Basaltic andesite, Barton Peninsula, King George Island.

pyroxene. Silica is invariably present, as patchy interstitial quartz or indiscriminately replacing large areas of rock (e.g. G.220.2). Tiny spherulitic aggregates of silica occasionally occur in plagioclase phenocrysts and may form the cores of pseudomorphs (rimmed by serpentine) after pyroxene (e.g. P.1195.1). Calcite-replacement of plagioclase is often accompanied by albite and minor flakes of sericite, but albitization is a minor process and is frequently absent. Epidote is also a minor constituent. It is usually bright yellow (Fe-rich) pistacite but radiating crystals of clinozoisite occur in specimen G.62.3. Nodule-like masses of granular pistacite occur rarely in pseudomorphs after pyroxene (e.g. G.21.1). Granular sphene is ubiquitous in the groundmass and also occurs in some pyroxene pseudomorphs. Prehnite rarely replaces plagioclase (e.g. P.232.4, 1195.2 and G.10.1) and Hawkes (1961, p. 9) described pale yellow isotropic (?) grossular in a lava from Barton Peninsula (G.67.3). Similar crystals of (?) grossular, showing weak birefringence, occur in lavas on Dufayel Island (G.21.1, 218.3). The (?) grossular occurs in parageneses with epidote–chlorite–(quartz–actinolite).

E. GEOCHEMISTRY

Major oxides and 14 trace elements were determined for 110 volcanic rocks of Late Cretaceous–Early Tertiary age, including 16 from the Coppermine Formation, 65 from the Fildes Formation and 29 from the Hennequin Formation (Table XII). In addition, 57 analyses (comprising 36 from Fildes Peninsula, 6 from Point Hennequin, 3 from Three Brothers Hill, 2 from Lions Rump and 10 from Turret Point) were supplied by A. D. Saunders and S. D. Weaver (University of Birmingham).

Using SiO_2 as a fractionation index, there is little

Table XII. Chemical analyses of Upper Cretaceous–Lower Tertiary volcanic rocks of the South Shetland Islands (continued).
57–70: Fildes Formation.

	57	*58*	*59*	*60*	*61*	*62*	*63*	*64*	*65*	*66*	*67*	*68*	*69*	*70*
SiO_2	53.8	48.7	47.5	56.7	51.3	51.9	57.4	57.8	54.2	55.9	53.4	47.8	47.3	54.9
TiO_2	0.76	1.17	0.71	0.77	1.66	1.58	0.87	1.05	0.84	0.78	0.93	0.61	0.76	0.51
Al_2O_3	15.8	21.1	16.9	17.0	13.9	14.8	17.9	17.8	19.8	16.2	17.5	20.3	16.3	17.6
Fe_2O_3	2.38	2.71	2.51	2.22	3.31	3.17	2.29	2.42	2.44	2.38	2.58	2.46	2.56	2.40
FeO	5.96	6.78	6.29	5.54	8.27	7.93	5.73	6.05	6.10	5.95	6.44	6.16	6.40	6.00
MnO	0.15	0.17	0.21	0.14	0.22	0.20	0.15	0.17	0.15	nd	0.16	0.15	0.12	0.18
MgO	6.0	7.1	8.5	5.36	5.8	5.5	6.2	5.35	3.9	7.0	6.1	7.6	9.78	5.76
CaO	8.78	4.56	9.90	6.89	8.63	8.20	8.39	4.95	8.39	9.47	8.08	10.52	12.32	8.23
Na_2O	2.38	2.77	3.02	3.75	3.18	2.79	3.01	2.64	3.69	2.50	3.48	2.85	1.37	3.07
K_2O	0.99	2.77	0.53	2.03	0.21	1.30	1.10	1.68	0.27	0.42	1.07	0.43	0.45	0.64
P_2O_5	0.17	0.15	0.11	0.22	0.29	0.30	0.18	0.21	0.25	0.18	0.21	0.09	0.10	0.13
Total	97.17	97.98	96.18	100.62	96.77	97.67	103.22	100.13	100.03	100.78	99.95	98.97	97.46	99.42
TRACE ELEMENTS														
Cr	10	20	30	10	–	–	–	10	10	40	20	40	20	–
Ni	8	10	22	11	–	–	–	–	–	22	9	20	29	–
Zn	68	56	57	64	105	104	82	86	82	76	76	57	70	50
Rb	17	75	7	41	–	15	20	40	–	7	16	–	4	7
Sr	770	530	715	537	601	490	583	579	500	578	664	618	645	610
Y	18	27	14	25	29	30	19	24	22	20	20	10	10	13
Zr	166	210	63	200	120	119	184	196	192	135	156	64	87	80
Nb	3	–	–	4	9	11	5	–	4	–	–	–	4	3
Ba	323	686	145	378	152	373	244	377	178	140	330	155	177	206
La	13	17	–	21	19	17	22	25	28	17	25	14	22	14
Ce	37	49	15	42	43	31	36	43	43	27	39	11	20	18
Pb	10	15	–	10	–	–	10	–	10	–	–	–	–	–
Th	–	–	–	10	–	–	–	–	–	–	–	–	–	–
Ga	22	32	24	23	24	25	23	23	22	24	23	22	21	25
RATIOS														
K/Rb	483	307	628	411	–	719	457	351	–	498	555	–	934	759
Ba/Rb	19	9	21	9	–	25	12	9	–	20	21	–	44	29
K/Ba	25	34	30	45	11	29	37	37	13	25	27	23	21	26
Rb/Sr	0.02	0.14	0.01	0.08	–	0.03	0.03	0.07	–	0.01	0.02	–	0.01	0.01
Ba/Sr	0.4	1.3	0.2	0.7	0.2	0.8	0.4	0.6	0.4	0.2	0.5	0.2	0.3	0.3
Ca/Sr	82	62	99	92	103	120	103	61	120	117	87	122	137	96
Ce_N/Y_N	5.0	4.4	2.6	4.1	3.6	2.5	4.6	4.4	4.8	3.3	4.8	2.7	4.9	3.4
Fe*/Mg	1.7	1.7	1.3	1.8	2.5	2.5	1.6	2.0	2.7	1.5	1.9	1.4	1.1	1.8

57. P.674.1 Basaltic andesite, Barton Peninsula, King George Island.
58. P.679.1 Basalt, Barton Peninsula, King George Island.
59. P.683.4 Basalt, Barton Peninsula, King George Island.
60. P.318.2 Andesite, Barton Peninsula, King George Island.
61. P.321.2 Basalt, Barton Peninsula, King George Island.
62. P.328.2 Basaltic andesite, Barton Peninsula, King George Island.
63. P.535.4 Basaltic andesite, Barton Peninsula, King George Island.
64. P.1427.1 Andesite, Barton Peninsula, King George Island.
65. P.1435.1 Basaltic andesite, Barton Peninsula, King George Island.
66. P.1431.1 Basaltic andesite, Barton Peninsula, King George Island.
67. P.1443.1 Basaltic andesite, Barton Peninsula, King George Island.
68. P.1440.1 Basalt, Barton Peninsula, King George Island.
69. P.1481.1 Basalt, Weaver Peninsula, King George Island.
70. P.1480.1 Basaltic andesite, Weaver Peninsula, King George Island.

evidence for the mobility of silica observed in the Upper Jurassic–Lower Cretaceous rocks (p. 26), although petrographical criteria suggest that silica may have been mobile in some of the rocks that were not analysed. However, in view of the possible unreliability of SiO_2 when dealing with altered rocks, the data were also plotted using Zr as the ordinate (p. 26). From the spread of data points, it is evident that some rocks from the altered areas have undergone movement of Ca, Fe, Rb and Ba, but the significance of this is uncertain since many of the rocks from unaltered areas (particularly in the Hennequin Formation) show a broadly similar scatter. In general, the movements indicated are of a comparable magnitude to altered rocks in the Upper Jurassic–Lower Cretaceous outcrops and, similarly, it is thought that inter-element ratios using these elements may still have some significance.

Chemically (Table XII), the Coppermine Formation has low K and high Ni and Cr contents, moderate to high K/Rb, Fe*/Mg and low Rb/Sr ratios characteristic of island arc tholeiites. Calc-alkaline features are also present and include high contents of La, Sr, Rb and Ba, and moderate Ce_N/Y_N ratios (3–4.2). The Fildes Formation also shows tholeiitic and calc-alkaline characteristics. The basalts and basaltic andesites, which largely comprise the formation, have low K, Rb, Ba and Cr contents, moderate to high K/Rb, Fe*/Mg and Na_2O/K_2O ratios, and low Rb/Sr ratios similar to tholeiites. Conversely, only slight Fe-enrichment is evident on AFM and Fe–Mg diagrams, La and Sr contents are high and the Ce_N/Y_N ratios (2–5.5) suggest moderate light rare earth enrichment, which are features of calc-alkaline rocks. Although the rare andesites and dacites in the formation retain the high Fe/Mg ratios and low Cr contents of tholeiites, they are calc-alkaline in all other respects. The Hennequin Formation is entirely calc-alkaline. It shares the low K_2O and high Al_2O_3 contents of the Coppermine and Fildes formations and together they

Table XII. Chemical analyses of Upper Cretaceous–Lower Tertiary volcanic rocks of the South Shetland Islands (continued).
71–83: Fildes Formation; 84: Hennequin Formation.

	71	*72*	*73*	*74*	*75*	*76*	*77*	*78*	*79*	*80*	*81*	*82*	*83*	*84*
SiO_2	55.9	50.9	48.5	50.0	53.6	45.1	66.2	66.2	54.1	50.0	59.0	56.9	48.9	54.2
TiO_2	1.18	0.72	0.59	0.55	0.69	0.51	1.00	1.00	1.71	1.09	0.84	0.78	0.96	0.77
Al_2O_3	15.9	19.7	19.9	23.4	18.3	19.5	14.7	14.7	15.5	15.3	18.3	17.7	15.8	18.7
Fe_2O_3	2.67	2.29	2.27	1.93	2.35	2.10	1.58	1.60	2.99	2.71	2.13	2.22	2.71	2.46
FeO	6.68	5.73	5.68	4.82	5.88	5.25	3.95	4.00	7.47	6.77	5.33	5.54	6.78	6.16
MnO	0.18	0.14	0.14	0.09	0.15	0.11	0.20	0.18	0.18	0.18	0.15	0.16	0.25	0.15
MgO	4.1	7.1	5.9	5.0	5.7	8.5	0.7	0.7	5.2	8.7	4.3	5.0	9.3	5.5
CaO	6.65	10.49	11.99	12.70	8.37	13.78	4.27	3.81	8.23	8.54	6.53	7.50	9.78	8.70
Na_2O	3.06	2.82	1.81	2.23	2.96	1.49	5.11	5.36	3.58	3.03	3.84	3.36	2.61	3.54
K_2O	1.62	0.53	0.99	0.49	1.33	0.19	1.15	1.63	0.88	0.35	2.24	1.64	0.24	1.20
P_2O_5	0.41	0.12	0.07	0.10	0.16	0.07	0.26	0.27	0.24	0.17	0.19	0.18	0.23	0.16
Total	98.35	100.52	97.84	101.31	99.49	96.60	99.12	99.45	100.08	96.84	102.85	100.98	97.56	101.54
TRACE ELEMENTS														
Cr	–	21	20	20	10	30	–	–	20	150	–	20	62	20
Ni	–	10	8	10	6	17	–	–	8	67	–	8	36	–
Zn	94	68	43	126	60	44	76	81	86	72	64	61	68	67
Rb	14	4	12	3	15	3	52	40	17	–	49	32	–	19
Sr	512	626	620	675	699	558	387	345	381	486	498	560	834	638
Y	31	10	8	8	17	7	38	39	35	24	23	21	14	15
Zr	247	72	62	74	138	54	294	294	133	118	187	164	74	104
Nb	5	–	–	–	–	–	7	5	6	5	–	–	3	–
Ba	439	154	175	126	294	53	436	479	268	204	352	274	149	229
La	39	12	12	13	23	8	35	34	17	17	30	25	14	13
Ce	65	18	13	12	35	12	56	59	27	20	49	48	25	30
Pb	10	–	–	–	–	–	15	15	–	10	10	10	–	–
Th	–	–	–	–	–	–	–	–	–	–	–	–	–	–
Ga	22	25	20	24	23	21	22	22	20	19	22	24	29	26
RATIOS														
K/Rb	960	1100	685	1356	736	526	184	338	430	–	380	425	–	524
Ba/Rb	31	38	15	42	20	18	8	12	16	–	7	9	–	12
K/Ba	31	29	47	32	38	30	22	28	27	14	53	50	13	43
Rb/Sr	0.03	0.01	0.02	0.01	0.02	0.01	0.13	0.12	0.04	–	0.10	0.06	–	0.03
Ba/Sr	0.9	0.2	0.3	0.2	0.4	0.1	1.1	1.4	0.7	0.4	0.7	0.5	0.2	0.4
Ca/Sr	93	120	138	135	86	177	79	79	154	126	94	96	84	97
Ce_N/Y_N	5.1	4.4	4.0	3.7	5.0	4.2	3.6	3.7	1.9	2.0	5.2	5.6	4.4	4.9
Fe*/Mg	2.9	1.4	1.7	1.7	1.8	1.1	9.9	0.0	2.5	1.4	2.2	1.9	1.3	2.0

71.	P.1475.7	Andesite, Weaver Peninsula, King George Island.
72.	P.1473.4	Basalt, Weaver Peninsula, King George Island.
73.	P.1480.2	Basalt, Weaver Peninsula, King George Island.
74.	P.1473.5	Basalt, Weaver Peninsula, King George Island.
75.	P.1473.2	Basaltic andesite, Weaver Peninsula, King George Island.
76.	P.1472.7	Basalt, Weaver Peninsula, King George Island.
77.	P.1421.1	Dacite, O'Cain Point, Nelson Island.
78.	P.1418.2	Dacite, O'Cain Point, Nelson Island.
79.	P.1195.2	Basaltic andesite, Duthoit Point, Nelson Island.
80.	P.1195.9	Basalt, Duthoit Point, Nelson Island.
81.	P.1411.1	Andesite, Ezcurra Inlet, King George Island.*
82.	P.1187.4	Andesite, Ezcurra Inlet, King George Island.*
83.	P.1416.1	Basalt, Ezcurra Inlet, King George Island.
84.	P.444.10	Basaltic andesite, Point Thomas, King George Island.

* Note added in proof: Now assigned to the Hennequin Formation.

are best regarded as Low-K, high-alumina calc-alkaline sequences with tholeiitic affinities in the basic members.

Lithologically and chemically in many respects, the Coppermine Formation is similar to the basalts and basaltic andesites of the Fildes Formation. By contrast, the high Zr contents are closer to those of the Hennequin Formation, and the Coppermine Formation rocks are distinguished from all others by their high MgO and exceptionally high Cr and Ni contents (Table XII). However, because of the small number of analyses available and their low silica mode (50.6%), a more detailed comparison of the Coppermine Formation with the formations on King George and Nelson islands is not possible at present.

The geochemical data presented here confirm the separation of the Lower Tertiary rocks on King George and Nelson islands into at least two formations. Recognition of these is primarily based on lithology, but the geochemical data are consistent with the petrographical evidence and show that the Fildes Formation is formed almost entirely of basalts and basaltic andesites, with rare andesites and dacites, whereas the Hennequin Formation is mainly formed of andesites, with subordinate basaltic andesites and rare dacites. The pyroxene–andesites at Turret Point, and probably Three Sisters Point for which data are lacking, are included in the Hennequin Formation. They show conspicuous differences (mainly MgO, Y, Sr, Ni and Cr contents, and K_2O/Na_2O, Fe*/Mg, Ba/Sr and Ce/Y ratios) compared with the (?) Upper Tertiary–Quaternary volcanic rocks with which they were previously correlated. Conversely, with the exception of slightly low CaO and total Fe contents and low Ca/Sr ratios, they are very similar to rocks of the Hennequin Formation and they show all the chemical characteristics that distinguish these rocks from those of the Fildes Formation (see below).

Table XII. Chemical analyses of Upper Cretaceous–Lower Tertiary volcanic rocks of the South Shetland Islands (continued).
85–98: Hennequin Formation.

	85	*86*	*87*	*88*	*89*	*90*	*91*	*92*	*93*	*94*	*95*	*96*	*97*	*98*
SiO_2	58.0	64.7	58.5	56.7	55.7	52.6	55.7	53.2	53.2	56.3	56.4	49.8	56.5	57.6
TiO_2	0.91	0.85	0.79	1.00	1.18	0.79	1.02	0.94	0.88	0.76	1.05	0.79	0.86	0.70
Al_2O_3	17.7	15.1	17.5	20.1	14.9	16.9	16.1	18.5	15.9	6.1	16.0	15.3	15.6	16.8
Fe_2O_3	2.28	1.55	2.06	2.15	2.66	2.49	2.54	2.27	2.29	2.22	2.26	2.44	2.23	2.04
FeO	5.71	3.86	5.15	5.37	6.66	6.22	6.36	5.67	5.73	5.55	5.64	6.11	5.58	5.10
MnO	0.15	0.14	0.11	0.15	0.15	0.18	0.15	0.15	0.14	0.12	0.17	0.15	0.18	0.11
MgO	3.4	0.9	6.4	3.4	5.4	6.9	6.6	3.4	5.3	6.4	3.5	7.4	4.8	6.0
CaO	7.25	3.96	7.69	7.28	4.66	9.27	5.38	9.95	8.13	6.38	6.58	9.39	6.28	5.01
Na_2O	3.61	4.52	3.85	4.36	3.40	2.55	3.27	3.69	3.54	3.53	3.83	2.67	2.57	3.66
K_2O	1.26	2.6	1.13	1.78	3.16	0.50	1.59	0.34	0.92	2.04	2.05	0.20	1.83	2.33
P_2O_5	0.22	0.23	0.13	0.32	0.26	0.19	0.20	0.25	0.18	0.23	0.38	0.20	0.22	0.13
Total	100.49	98.07	103.31	102.61	98.13	98.59	98.90	98.36	96.21	99.63	97.86	94.47	97.65	99.48
TRACE ELEMENTS														
Cr	10	–	120	–	–	30	10	–	40	30	–	30	–	20
Ni	–	–	30	–	–	8	15	–	18	18	–	18	–	9
Zn	63	64	57	69	88	72	74	66	62	55	78	61	63	53
Rb	14	84	17	23	74	5	29	4	14	39	34	–	24	47
Sr	588	379	414	566	494	698	794	754	637	541	642	707	556	661
Y	22	32	14	29	28	16	29	22	21	23	30	18	25	23
Zr	191	342	110	183	200	149	233	147	186	182	158	122	159	212
Nb	4	5	–	–	3	–	4	6	10	6	4	–	–	–
Ba	266	543	278	437	384	273	596	294	406	349	461	129	376	452
La	26	37	18	34	20	12	25	18	24	22	26	17	21	20
Ce	56	69	21	59	43	35	43	43	58	48	62	37	45	49
Pb	–	15	–	–	10	–	–	10	–	10	10	10	–	9
Th	–	10	–	–	–	–	–	–	10	10	–	–	10	10
Ga	24	21	20	23	26	25	22	23	27	24	24	23	24	23
RATIOS														
K/Rb	747	223	552	642	354	830	455	706	545	434	500	–	633	411
Ba/Rb	19	6	16	19	5	55	21	73	29	9	14	–	16	10
K/Ba	39	37	34	34	68	15	22	10	19	49	37	13	40	43
Rb/Sr	0.02	0.22	0.04	0.04	0.15	0.01	0.04	0.01	0.02	0.07	0.05	–	0.04	0.07
Ba/Sr	0.4	1.3	0.7	0.8	0.8	0.4	0.7	0.4	0.6	0.6	0.7	0.2	0.7	0.7
Ca/Sr	88	75	133	92	67	95	48	94	91	84	73	95	81	54
Ce_N/Y_N	6.2	5.3	3.7	5.0	3.8	5.3	3.6	4.8	6.7	5.1	5.0	5.0	4.4	5.2
Fe*/Mg	2.9	7.5	1.4	2.8	2.2	1.6	1.7	2.9	1.9	1.5	2.8	1.4	2.0	1.5

85.	P.443.16	Andesite, Point Thomas, King George Island.
86.	P.443.11	Dacite, Point Thomas, King George Island.
87.	P.443.5	Andesite, Jardine Peak, King George Island.
88.	P.547.2	Basaltic andesite, north of Sphinx Hill, King George Island.
89.	P.440.1	Basaltic andesite, Dufayel Island.
90.	P.1192.1	Basaltic andesite, Crepin Point, King George Island.
91.	P.1415.1	Andesite, Admiralen Peak, King George Island.
92.	P.363.1	Basaltic andesite, Keller Peninsula, King George Island.
93.	P.363.3	Basaltic andesite, Keller Peninsula, King George Island.
94.	P.1452.2	Andesite, Keller Peninsula, King George Island.
95.	P.1458.3	Andesite, Keller Peninsula, King George Island.
96.	P.1463.1	Basalt, Keller Peninsula, King George Island.
97.	P.1464.2	Andesite, Keller Peninsula, King George Island.
98.	P.1465.1	Andesite, Keller Peninsula, King George Island.

Using SiO_2 as a differentiation index, the two formations are largely indistinguishable, the Fildes Formation grading into the Hennequin Formation with increasing silica content. However, two diverging trends can be distinguished on a Zr–SiO_2 diagram (Fig. 35): a high-Zr series, which includes the entire Hennequin Formation, and a low-Zr series composed of Fildes Formation rocks from Fildes, Stansbury and Potter peninsulas, Stranger Point, Demay Point and Anvil Crag. Most of the rocks from Barton and Weaver peninsulas, southern Ezcurra Inlet and eastern Nelson Island, which are assigned to the Fildes Formation using petrographical criteria, also form part of the high-Zr series. Using other chemical parameters, these areas were found to be composed of rocks that show characteristics of both Fildes (low-Zr) and Hennequin formations; very few analyses show consistent affinities to either formation. Although it is possible that these rocks may constitute a separate formation, they are best regarded as part of the Fildes Formation until more supporting evidence is obtained.

Plotted against SiO_2, the low-Zr rocks of the Fildes Formation generally have lower contents of K_2O (Fig. 36), La, Ce, Cr, Ni and Sr, and slightly higher total Fe compared with the Hennequin Formation. Using Zr as the differentiation index, there are *no* significant differences in K_2O, La or Ce contents (except for rocks at Turret Point, which are low in La and Ce), but MgO, CaO, total Fe, Sr, Cr and Ni are depleted in the Fildes Formation relative to the Hennequin Formation, whereas Y and possibly Na_2O, Ba and Rb are enriched (Fig. 37; Table XII). None of these differences is apparent in the high-Zr rocks of the Fildes Formation, which either resemble the Hennequin Formation or have intermediate values. Better separation of the two formations is achieved using plots of selected trace

Table XII. Chemical analyses of Upper Cretaceous–Lower Tertiary volcanic rocks of the South Shetland Islands (continued).
99–112: Hennequin Formation.

	99	*100*	*101*	*102*	*103*	*104*	*105*	*106*	*107*	*108*	*109*	*110*	*111*	*112*
SiO_2	57.9	55.2	56.8	50.5	54.7	55.1	53.6	54.1	51.7	56.0	57.2	57.2	54.8	58.6
TiO_2	1.06	0.85	0.86	0.91	0.81	0.83	0.83	0.75	0.81	0.74	0.73	0.68	0.66	0.64
Al_2O_3	17.0	16.6	17.8	19.2	18.9	15.9	15.7	17.4	16.4	16.1	16.2	17.1	17.1	17.7
Fe_2O_3	2.28	2.22	2.27	2.10	2.18	2.24	2.38	2.21	2.54	1.98	1.97	1.85	2.04	1.75
FeO	5.71	5.54	5.67	5.24	5.45	5.60	5.96	5.53	6.35	4.95	4.92	4.63	5.10	4.37
MnO	0.17	0.20	0.14	0.18	0.14	0.13	0.14	0.13	0.15	0.10	0.21	0.09	0.16	0.11
MgO	3.6	5.8	5.2	4.9	4.1	6.2	6.5	4.8	5.0	4.9	6.5	5.4	8.1	4.8
CaO	6.35	8.50	4.98	8.40	7.27	7.09	6.78	8.88	6.85	8.10	7.04	7.59	3.91	6.39
Na_2O	3.94	3.12	3.33	3.61	2.58	3.10	3.02	2.76	2.09	2.81	3.71	4.23	3.79	4.53
K_2O	1.72	1.23	3.19	0.60	2.42	2.28	2.24	1.78	2.51	1.19	1.75	1.56	0.21	1.69
P_2O_5	0.40	0.18	0.18	0.32	0.24	0.20	0.29	0.22	0.16	0.17	0.15	0.21	0.19	0.20
Total	100.08	99.45	100.42	95.96	98.79	98.66	97.44	98.56	94.56	97.04	100.38	100.54	96.06	100.78
TRACE ELEMENTS														
Cr	–	30	–	30	–	40	30	20	10	nd	nd	nd	nd	nd
Ni	–	12	6	–	–	19	14	13	10	nd	nd	nd	nd	nd
Zn	76	59	66	67	61	62	61	62	71	57	65	53	101	54
Rb	29	17	56	11	42	42	48	28	57	21	26	25	–	27
Sr	552	524	608	820	511	506	584	575	529	661	540	557	627	582
Y	30	19	24	22	22	22	23	20	18	18	19	17	18	19
Zr	193	233	216	189	195	213	200	123	122	nd	nd	nd	nd	nd
Nb	6	3	4	–	–	5	–	–	7	nd	nd	nd	nd	nd
Ba	458	304	559	390	391	407	496	309	343	nd	nd	nd	nd	nd
La	38	29	27	28	26	21	19	19	17	nd	nd	nd	nd	nd
Ce	63	48	46	49	45	47	51	40	33	nd	nd	nd	nd	nd
Pb	10	–	10	–	–	–	15	10	10	10	–	–	–	–
Th	–	–	–	–	–	–	–	–	–	10	–	–	–	–
Ga	24	24	23	20	22	24	25	24	22	24	22	25	26	24
RATIOS														
K/Rb	492	601	473	453	478	398	387	528	365	470	559	518	–	520
Ba/Rb	16	18	10	35	9	9	10	11	6	–	–	–	–	–
K/Ba	31	34	47	13	51	46	37	48	61	–	–	–	–	–
Rb/Sr	0.05	0.03	0.09	0.01	0.08	0.05	0.08	0.05	0.11	0.03	0.05	0.04	–	0.05
Ba/Sr	0.8	0.6	0.9	0.5	0.8	0.4	0.8	0.5	0.6	–	–	–	–	–
Ca/Sr	82	116	59	73	102	98	83	110	93	88	93	97	45	78
Ce_N/Y_N	5.1	6.1	4.7	5.4	5.0	4.7	5.4	4.9	4.5	–	–	–	–	–
Fe*/Mg	2.8	1.7	1.9	1.9	2.3	1.9	1.6	2.0	2.2	1.8	1.3	1.5	1.1	1.6

nd – not determined.

99.	P.1458.2	Andesite, Keller Peninsula, King George Island.
100.	P.1454.1	Basaltic andesite, Keller Peninsula, King George Island.
101.	P.1409.1	Andesite, Ullmann Spur, King George Island.
102.	P.1408.1	Basalt, Ullmann Spur, King George Island.
103.	P.1406.1	Basaltic andesite, Ullmann Spur, King George Island.
104.	G.14.2	Basaltic andesite, Precious Peaks, King George Island.
105.	P.1188.1	Basaltic andesite, Precious Peaks, King George Island.
106.	P.317.2	Basaltic andesite, Pottinger Point, King George Island.
107.	P.317.12	Basaltic andesite, Pottinger Point, King George Island.
108.	G.26.1	Andesite, False Round Point, King George Island.
109.	G.28.1	Andesite, Esther Nunatak, King George Island.
110.	G.29.1	Andesite, Brimstone Peak, King George Island.
111.	G.30.3	Microdiorite, North Foreland, King George Island.
112.	G.30.7	Andesite, North Foreland, King George Island.

elements and inter-element ratios. In general, the Fildes Formation has lower K/Ba, K/Rb, Ba/Rb and possibly Ca/Sr ratios, and higher values of Rb/Sr, Ba/Sr and Fe*/Mg (Fig. 38; Table XII). Separation is also achieved on Ce–Y and K_2O–Na_2O diagrams. The conflicting affinities of the high-Zr rocks of the Fildes Formation are evident in all these diagrams.

In general, it is likely that some of the major oxide and trace element differences between the formations can be explained by crystal fractionation of the phenocrysts present. Thus the high MgO, CaO, total Fe, Ni and Cr in the Hennequin Formation probably reflect the high proportion of pyroxene (including abundant magnesian orthopyroxene) and magnetite phenocrysts compared with the Fildes Formation, in which magnetite phenocrysts are scarce and the major ferromagnesian phenocrysts are olivine and magnesian-poor clinopyroxene. The differences in Y cannot be explained so easily since orthopyroxene, which accepts Y in greater amounts than any of the other phenocrysts present (Lambert and Holland, 1974), is most abundant in the Hennequin Formation, in which Y contents are lowest. The data show a progressive increase in Y and decrease in Ce_N/Y_N ratios passing from the Hennequin Formation to the Fildes Formation, with Y contents greatest and Ce_N/Y_N ratios least in the rocks of the Potter Peninsula–Stranger Point area (Fig. 37; Table XII); K/Rb ratios are also very high in this latter area (Table XII). These changes would occur if hornblende was present in the magmatic source material (hydrated, amphibolitized oceanic crust subducted at the South Shetland trench?) and melted in increasing amounts, reaching a maximum in the magmas of the Potter Peninsula–Stranger Point area. Moreover, the low Ca/Sr ratios shown by Hennequin Formation rocks at Turret Point and northern Admiralty Bay (Table XII) cannot be attri-

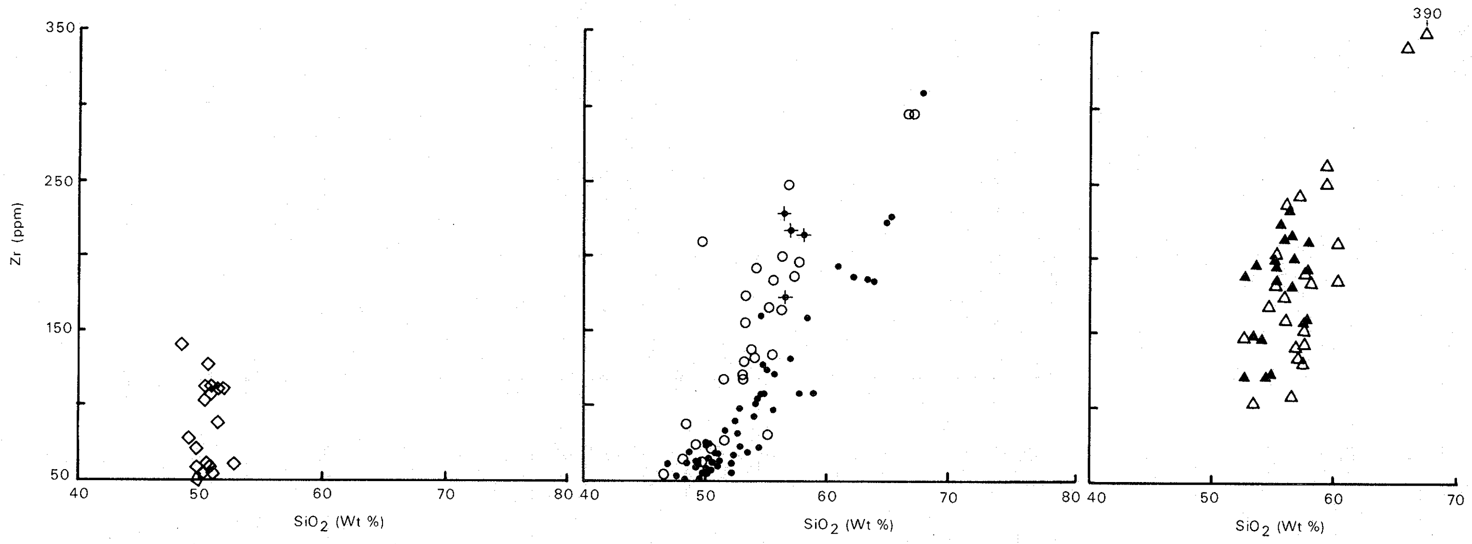

Fig. 35. Plot of Zr against SiO_2 for Upper Cretaceous–Lower Tertiary volcanic rocks of the South Shetland Islands. (Symbols: ◇ = Coppermine Formation; ● = Fildes Formation (low-Zr); ○ = Fildes Formation (high-Zr); △ = Hennequin Formation (▲ = altered rocks); ✦ = Three Brothers Hill.)

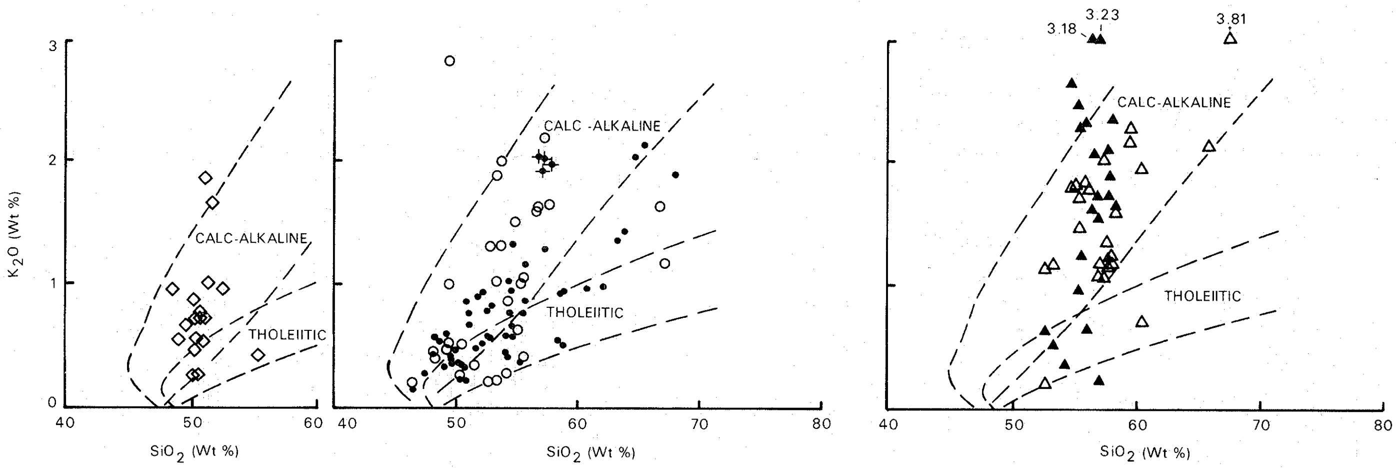

Fig. 36. Plot of K_2O against SiO_2; Upper Cretaceous–Lower Tertiary volcanic rocks of the South Shetland Islands. (Symbols as in Figure 35.)

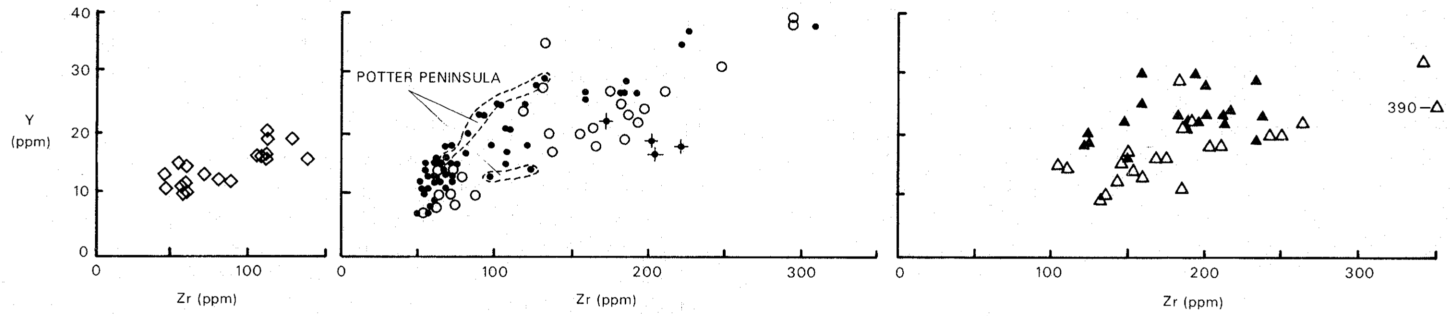

Fig. 37. Plot of Y against Zr; Upper Cretaceous–Lower Tertiary volcanic rocks of the South Shetland Islands. (Symbols as in Figure 35.)

buted to extensive plagioclase fractionation because a corresponding decrease in Sr would occur, which is not observed. However, fractionation of augite, probably accompanied by some plagioclase, may explain the observed chemical effects since augite is generally richer in Ca but extracts less Sr than plagioclase, leading to low Ca/Sr ratios without a large decrease in Sr.

All the geochemical data available for the widely scattered outcrops of the Hennequin Formation are strikingly similar, suggesting that they share a common petrogenesis and are of comparable age (? Early Tertiary). Similar reasoning can be applied to the low-Zr rocks of the Fildes Formation, which are now known to be early Tertiary at Fildes and Potter peninsulas (Table XVIII). Since the

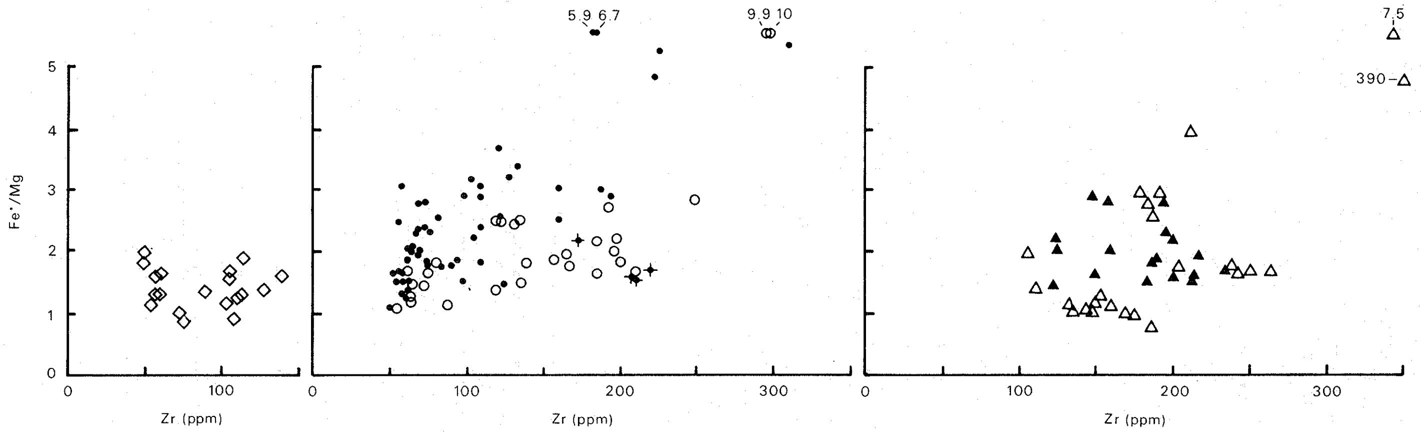

Fig. 38. Plot of Fe*/Mg against SiO_2; Upper Cretaceous–Lower Tertiary volcanic rocks. (Fe* = total iron as Fe^{2+}; other symbols as in Figure 35.)

high-Zr rocks at Barton and Weaver peninsulas, southern Ezcurra Inlet and eastern Nelson Island are very similar geochemically to both the Fildes and Hennequin formations, they too are likely to be of Early Tertiary age. Furthermore, there are small but consistent geochemical differences between the Lower Tertiary rocks and those of Late Jurassic–Early Cretaceous age (see below). Thus, the geochemical data support the suggestions made by Jardine (1950), Grikurov and Polyakov (1968*b*) and Davies (1982*a, b*) that no Mesozoic rocks are presently exposed on King George Island.

If these age and petrogenetic relationships are true, it is possible that the fresh hypersthene–augite–andesite plug at Esther Nunatak acted as a vent for some of the altered volcanic rocks in this area (Brimstone Peak and Bolinder Bluff). Similarly, the lavas and plugs at Fildes Peninsula are chemically indistinguishable, which is consistent with the radiometric age data (Chapter XI) and shows that the plugs may represent the vents responsible for much of the volcanism in the area. Conversely, the plug at Three Brothers Hill, which was previously considered to be the source vent for the surrounding lavas on Potter Peninsula (Jardine, 1950, p. 12; Diaz and Teruggi, 1956, p. 106; Fourcade, 1960, p. 28; Barton, 1965, p. 20), shows all the geochemical characteristics of the Hennequin Formation (cf. Figs 35–38) whereas the lavas clearly belong to the Fildes Formation; this is also true for some dykes at Potter Peninsula. The lavas at Barton Peninsula show many similarities to rocks of the Hennequin Formation (p. 55) and it is possible that some were erupted from the vent at Three Brothers Hill.

F. Discussion

Excluding the South Shetland Islands, there are few outcrops of Upper Cretaceous–Lower Tertiary volcanic rocks in the Antarctic Peninsula region. Isolated outcrops of Palaeogene (35–63 Ma) basalts occur on Tower and Two Hummock islands, Palmer Archipelago (Rex, 1972). They are poorly described so far but apparently have a tholeiitic chemistry (Baker and others, 1977). Despite meagre field evidence, Hooper (1962, p. 65) correlated post-plutonic volcanic rocks at north-eastern Anvers Island with the Lower Tertiary rocks on King George Island. The same rocks were assigned a Pleistocene age by Alarcón and others (1976), and a Miocene–Recent age was suggested by Gledhill and others (1982). These rocks, and volcanic sediments of possible mid to Late Tertiary age on Brabant Island (Alarcón and others, 1976), are younger than any of the rocks on King George Island dated so far and they may be more closely related to the Late Tertiary–Quaternary volcanism of the region. Volcanic rocks with a poorly preserved fossil flora similar to that on King George Island are present in the Elgar Uplands, northern Alexander Island (Thomson and Burn, 1977). They have yielded Early Tertiary K–Ar whole-rock ages (Chapter XI), and a late Cretaceous (70 Ma) K–Ar mineral age has been obtained from a supposedly related tuff sequence in the Colbert Mountains of central Alexander Island (Grikurov and others, 1967). However, the Alexander Island outcrops comprise andesites, dacites and rhyolites regarded as part of a high-K, calc-alkaline suite not closely comparable with the South Shetland Islands (Burn, 1981).

Comparisons with the Upper Jurassic–Lower Cretaceous volcanic rocks of the South Shetland Islands show that they are compositionally very similar to the Upper Cretaceous–Lower Tertiary rocks, indicating 'steady-state subduction-related magmatism in the area' (Weaver and others, 1982). However, several differences are apparent in the new geochemical data presented here. TiO_2 contents are higher in the Mesozoic rocks of Byers Peninsula and Elephant Point than in any others and there is a striking enrichment of Cr and Ni in the Coppermine Formation. MgO is also enriched in the Coppermine Formation and the high-Zr rocks of Barton and Weaver peninsulas, and Al_2O_3 contents are generally higher in all the basic rocks of Late Cretaceous–Early Tertiary age, accompanied by high Sr contents. Furthermore, Y contents and Ce_N/Y_N ratios are consistently lower and higher, respectively (except in the rocks at Potter Peninsula and Stranger Point), compared with the Upper Jurassic–Lower Cretaceous rocks. Low Y contents and high Ce_N/Y_N ratios are also characteristic of the plutonic intrusions of King George Island and this may indicate a genetic relationship between intrusive and extrusive rocks on this island. Conversely, none of the volcanic rocks show the pronounced enrichment in trace elements (other than Sr) that distinguishes these plutons from others in the island group. Moreover, K/Ba ratios are much higher (40–50) in the King George and Greenwich islands plutons compared with lavas in the Coppermine and Fildes formations (generally less than 30), although they are similar to those of the Hennequin Formation (30–50).

Four samples of the Fildes Formation were analysed for rare earth element contents by Tarney and others (1982). Ce_N/Yb_N ratios were found to be significantly higher (2.5–6.1) than in the Byers Peninsula volcanic rocks, largely due to lower relative Yb contents. Slight negative Ce anomalies were present in two of the samples, a characteristic only found previously in oceanic ophiolite complexes and andesites in New Guinea (Heming and Rankin, 1980), and attributable to the involvement of altered sea-floor basalts in their parentage. Initial $^{87}Sr/^{86}Sr$ ratios for the Tertiary volcanic rocks (Table XVII) also show a clear distinction from the Upper Jurassic–Lower Cretaceous samples and fall in the range 0.7032–0.7036. There is no obvious difference in this ratio between the Fildes and Hennequin formations, although, on the basis of only two samples, it appears that the Coppermine Formation may have intermediate values between the Mesozoic and Tertiary volcanic rocks.

No *regular* trends of increasing or decreasing oxide or element contents were observed across King George Island, but this may be due to the relatively small separation of the outcrops (reaching a maximum of 27 km in the Hennequin Formation between Pottinger Point and Lions Rump). However, the rocks young in a north-easterly direction, and north-easterly trends of increasing Ce_N/Y_N, K_2O/Na_2O and K_2O, and decreasing Y are apparent. Moreover, the Coppermine and Fildes formations show tholeiitic features whereas the Hennequin Formation is entirely calc-alkaline. These variations are apparently associated with a trend of increasing silica mode, varying from 50.6% in the Coppermine Formation, through 53.3% in the Fildes Formation (low and high-Zr rocks) to 57.0% in the Hennequin Formation. However, this last suggestion cannot be tested until more data are available for the Coppermine Formation and the chemical (and stratigraphical) affinities of the high-Zr rocks of the Fildes Formation are known.

IX. (?) UPPER TERTIARY–QUATERNARY VOLCANIC ROCKS

A. Field Relationships and Age

(?) Upper Tertiary and Quaternary volcanic rocks crop out principally on King George Island; other occurrences are isolated and uncommon (Fig. 1).

Sedimentary rocks within volcanic sequences near Lions Rump, King George Island, contain marine fossils of probable Pliocene age. Originally referred to as the *Pecten* conglomerate (Barton, 1965), they have been the subject of investigations further to those described here, and have been redefined as part of the Polonez Cove [Polonaise Cove] Formation (Birkenmajer, 1982*a*), based on a type locality about 1.5 km south of the original reported occurrence. The conglomerates are notable for their content of a wide variety of clast types, which vary in size from small pebbles to large blocks. Some (e.g. green and red sandstones, limestones, fossiliferous mudstones and gneisses with blue quartz) are exotic to the Antarctic Peninsula area and were transported presumably from a different region. A likely explanation is that they were ice-rafted and that the rocks represent marine tillites, a thesis developed in detail by Birkenmajer (1982*a*). A cool environment for the waters in which they accumulated is suggested by the presence of bivalves similar to *Laternula elliptica* and *Adamusium colbecki*, both of which are restricted to present-day Antarctic waters. However, *Chlamys* (the so-called *Pecten* of earlier papers) now ranges no farther south than the sub-Antarctic.

The age of these beds is still imprecisely known. Barton (1965, p. 25) suggested that they were Pliocene on the basis of enclosed Foraminifera, but the data on which this assessment was based have never been published. Close similarities of some of the bivalves with recent species (above) could indicate a relatively young age. Birkenmajer (1982*a*) preferred a Pliocene age on the basis of a comparison with another so-called *Pecten* conglomerate on Cockburn Island, north-eastern Antarctic Peninsula. However, the age of the latter has been variously assessed as Pliocene or Pleistocene and, in any case, identity of the *Chlamys* species from King George Island with *C. anderssoni* (Hennig, 1911) from Cockburn Island has yet to be demonstrated. At present it is probably unreasonable to attribute an age more precise than Plio-Pleistocene to the '*Pecten*' conglomerate of King George Island.

The Polonez Cove Formation rests unconformably on Lower Tertiary lavas with interbedded coal-bearing sediments. The latter are suggestive of a relatively warm and humid climate and indicate a significant climatic cooling during Late Tertiary times.

Exotic clasts are also present in a thick sequence of volcanic sandstones forming most of Cape Melville promontory. They also contain green hornblende, which is an uncommon constituent in volcanic rocks of any age in the South Shetland Islands, except in the conglomerates, tuffs and lavas of the Lions Rump area. This suggests a rough stratigraphical equivalence between the fossiliferous marine tillites of the Lions Rump area and the rocks of Cape Melville. However, Birkenmajer (1982*b*) reported the occurrence of a varied marine fauna from Cape Melville, including belemnites, and suggested a (?) Late Cretaceous age for those rocks. If the sequence there is also a glacio-marine sequence, this would be surprising since the highly fossiliferous Late Cretaceous rocks of James Ross Island (e.g. references in Thomson, 1977) have yet to yield any evidence of glacial conditions. Investigations made during the course of the present study were limited to a short visit by helicopter. The only fossils obtained were a number of indeterminate crustacean fragments, and some nuculanid bivalves that most closely resemble *Nuculana (?) volckmanni* (Phillipi) from the (?) Upper Miocene of Chile (Phillipi, 1887, p. 194, pl. 41, fig. 9). Clearly there is an important stratigraphical problem to be resolved here. Glacial conditions in Antarctica during the Miocene would be acceptable to many geologists but the implications of a Late Cretaceous glaciation are more far-reaching.

In a comprehensive review of the geomorphology of the South Shetland Islands, John and Sugden (1971, p. 66) suggested that the raised marine platforms and/or surfaces are all pre-glacial features (i.e. pre-Pleistocene). On King George Island, platforms and surfaces have been cut in virtually all the coastal exposures of (?) Upper Tertiary–Quaternary rocks, and this suggests that most of the latter are also pre-Pleistocene. Moreover, the lavas at Martins Head and Cinder Spur are geochemically very similar to those erupted during the Mesozoic and Early Tertiary (p. 63). indicating that they are also subduction-related. Because subduction ceased at the South Shetland trench about 4 Ma ago, the rocks at these two localities are likely to be Pliocene or older in age.

A fresh lava of Quaternary age may overlie the Miers Bluff Formation at Gleaner Heights, eastern Livingston Island, but no contacts are exposed (Hobbs, 1968, fig. 2). Similarly a Quaternary plug at Mount Plymouth, Greenwich Island is only seen to intrude a distinctive hyaloclastite vent deposit, believed to be of similar age to the plug. Hyaloclastites at Mount Plymouth, Inott Point and the un-named nunatak north-west of Sharp Peak are similar to hyaloclastites that form widely separated outcrops elsewhere in Lesser Antarctica, including the James Ross Island Volcanic Group (Nelson, 1975), Alexander Island (Bell, 1973*a*; Burn and Thomson, 1981), Ellsworth Land (Rutford and others, 1972) and Marie Byrd Land (LeMasurier, 1972). Whereas some of the these are of undoubted marine origin (Nelson, 1975), most were probably erupted sub-glacially (LeMasurier, 1972; LeMasurier and Rex, 1982; Burn and Thomson, 1981). In the South Shetland Islands, marine geomorphological features are only present up to about 200 m (John and Sugden, 1971, table I) whereas the hyaloclastites north-west of Sharp Peak and at Mount Plymouth crop out above 300 and 500 m, respectively, suggesting that they were also erupted sub-glacially and may be of Pleistocene age or younger. A minimum age for the hyaloclastites on Greenwich Island is suggested by the plug at Mount Plymouth, now known to be Recent (p. 77).

At present, there is no unequivocal way of assigning a lower age limit to these rocks. On King George Island, there is evidence at Lions Rump for a considerable unconformity corresponding to much of the Oligocene, Miocene and Pliocene but this cannot be shown to be present elsewhere. Moreover, there is no geophysical evidence for a significant hiatus in subduction during the Tertiary (cf. Barker, 1972, fig. 3) and volcanic activity may have been roughly continuous on King George Island until the Late Tertiary. Conversely, lavas in the outcrops on Greenwich and Livingston islands are lithologically and geochemically comparable with Penguin Island, a Recent vent. Together, they represent a distinctive phase of volcanicity essentially unrelated to subduction (p. 65) and probably of Quaternary age.

B. STRATIGRAPHY

The (?) Upper Tertiary–Quarternary rocks on King George Island crop out principally on the coast between Admiralty Bay and Cape Melville. Ternyck Needle, previously considered to be of Middle Miocene age (Hawkes, 1961, p. 16), is also included as are isolated outcrops on Greenwich and Livingston islands (Fig. 1). Although Three Sisters and Turret points are now thought to be largely Early Tertiary (p. 00), a small outcrop of fresh vesicular olivine-basalt occurs at the south-western extremity of Turret Point and was probably derived from a vent on Penguin Island. A Pliocene–Recent age was assigned to the outcrops at Vauréal Peak, Martins Head and Cinder Spur (Barton, 1965) but evidence for the age of these rocks is minimal; Hawkes (1961) equated these rocks with his Hennequin Formation ('Middle Miocene'). Many of the lavas show a degree of weathering comparable with those of Early Tertiary age. Lithologically, they most closely resemble basaltic rocks of the Fildes Formation but they occur within the general outcrop area of the Hennequin Formation. The presence of rare, highly resorbed magnetite-rich pseudomorphs after (?) hornblende in lavas at Martins Head and Cinder Spur suggests that they have affinities with the Plio-Pleistocene hornblende–andesite lavas between Lions Rump and Low Head since hornblende is very rare in the Lower Tertiary rocks and occurs mainly in intrusions. The geochemical evidence is ambiguous but it broadly supports the distinction of these rocks from those of Early Tertiary age (p. 65).

The rocks are mainly olivine-basalt lavas, although hornblende–andesite lavas crop out above the '*Pecten* conglomerate' between Lions Rump and Low Head. Major dykes at western Cinder Spur and near Low Head are formed of hornblende- and pyroxene-andesite, respectively. Pyroclastic rocks, including hyaloclastites on Greenwich and Livingston islands, are often interbedded with the lavas, whereas water-lain volcaniclastic rocks form a thick sequence at Cape Melville. Conglomerates are present at Lions Rump (Polonez Cove Formation), Vauréal Peak and Three Sisters Point. Eruptive centres are represented by olivine-basalt plugs at Trowbridge Island, Melville Peak, Low Head, Vauréal Peak, Ternyck Needle, Edinburgh Hill and Mount Plymouth, and Chabrier Rock is a minor (?) basalt plug that intrudes agglomerate at its eastern margin. Small pyroclastic cones are present at Cinder Spur (Barton, 1965) and Penguin Island. Only the relevant outcrops between Lions Rump and Low Head, and forming Cape Melville promontory are described here; other outcrops were visited only briefly or not at all by the authors. More detailed accounts are presented in Ferguson (1921), Tyrrell (1921 and 1945), Diaz and Terrugi (1956), Hobbs (1968) and Birkenmajer (1982*a*).

Cape Melville is a narrow, east-south-east trending peninsula mainly formed of sub-horizontally bedded volcaniclastic rocks. Contrary to previous descriptions (Jardine, 1950; Hawkes, 1961; Barton, 1965), lavas are uncommon and may be restricted to the western end. A columnar-jointed intrusion forms the bastion-like eastern extremity. There are several dykes and they appear to be apophyses of this intrusion. The clastic rocks include pyroclastic layers but they are mainly volcanic sandstones, which are locally fossiliferous. They also contain scattered blocks (up to 1 m in diameter) of coarse garnetiferous biotite-schist, garnet-

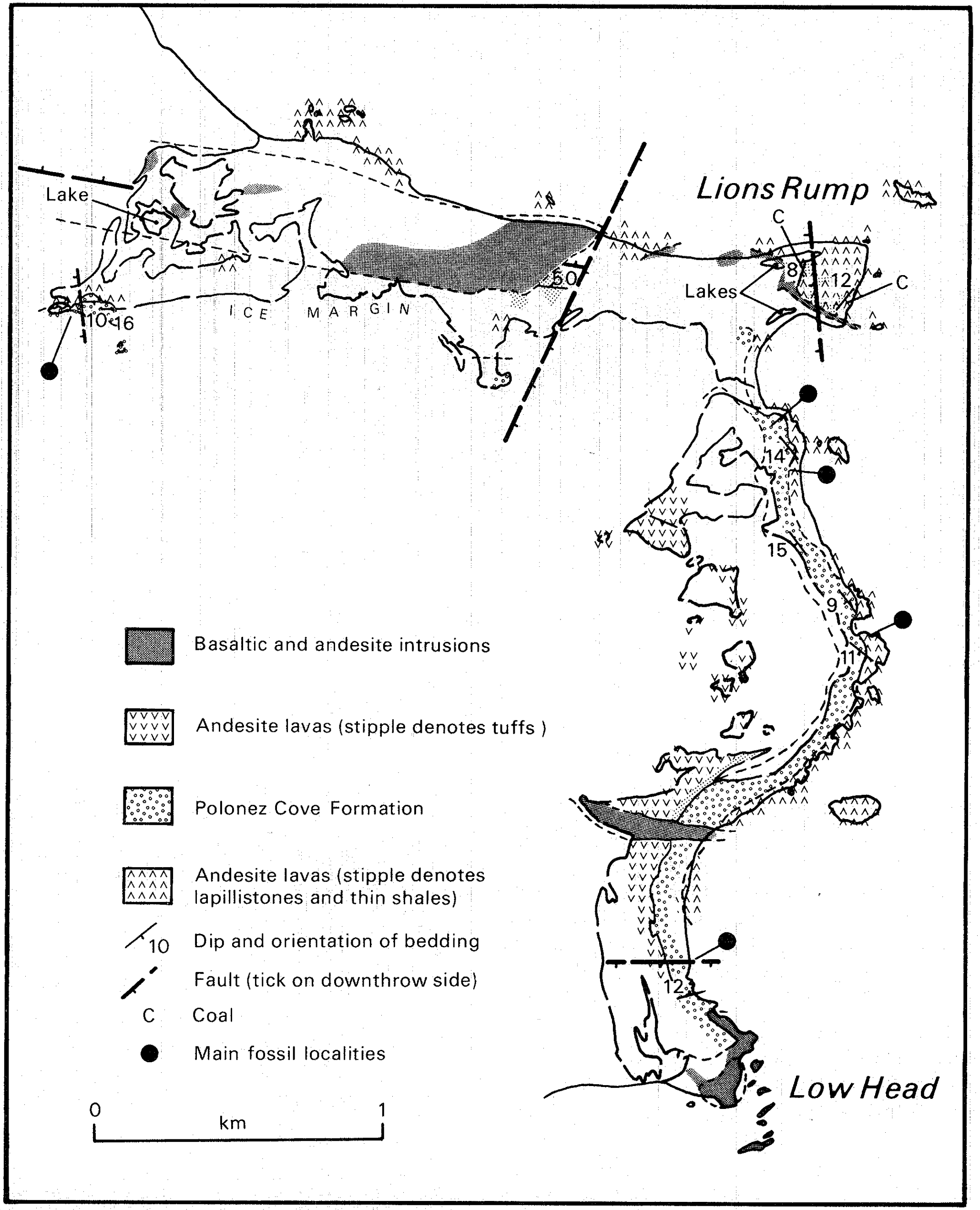

Fig. 39. Geological sketch map of the Lions Rump–Low Head area of King George Island.

gneiss, potash-granite and micro-adamellite thought to represent ice-rafted material (Jardine, 1950, p. 23); these occasionally form entire beds. A more detailed description is presented in Birkenmajer (1982*b*).

Lions Rump is formed of Lower Tertiary lavas interbedded with coal-bearing sediments of the Hennequin Formation (p. 47). The lowest lava also crops out in cliffs to the south and forms the foreshore towards Low Head (Figs. 39 and 40). It is overlain, with planar unconformity, by conglomerates of the Polonez Cove Formation, which also fill local depressions up to 2 m deep cut in the amygdaloidal lava surface. The contact is usually sharp, and specimen G.337.1 shows microscopical fractures in the lava filled by matrix from the overlying conglomerate. In places, a thin layer of friable weathered lava separates the two lithologies but the extent of weathering prior to the formation of the surface is uncertain. In particular, it does not show the red discolouration commonly found in lavas weathered subaerially, and it is possible that the unconformity was formed by marine or glacial action (Birkenmajer, 1982*a*). Moreover, unless a fault is present on the south side of Lions Rump (cf. Barton, 1965, fig. 3), the Lower Tertiary sequence forming the Rump itself may be a residual feature, possibly a small island in the Late Tertiary landscape.

The conglomeratic sediments that comprise the Polonez Cove Formation have been studied in great detail by Birkenmajer (1982*a*) who has subdivided them into named members, documenting a number of complex stratigraphical relationships within the sequence and suggested correlations

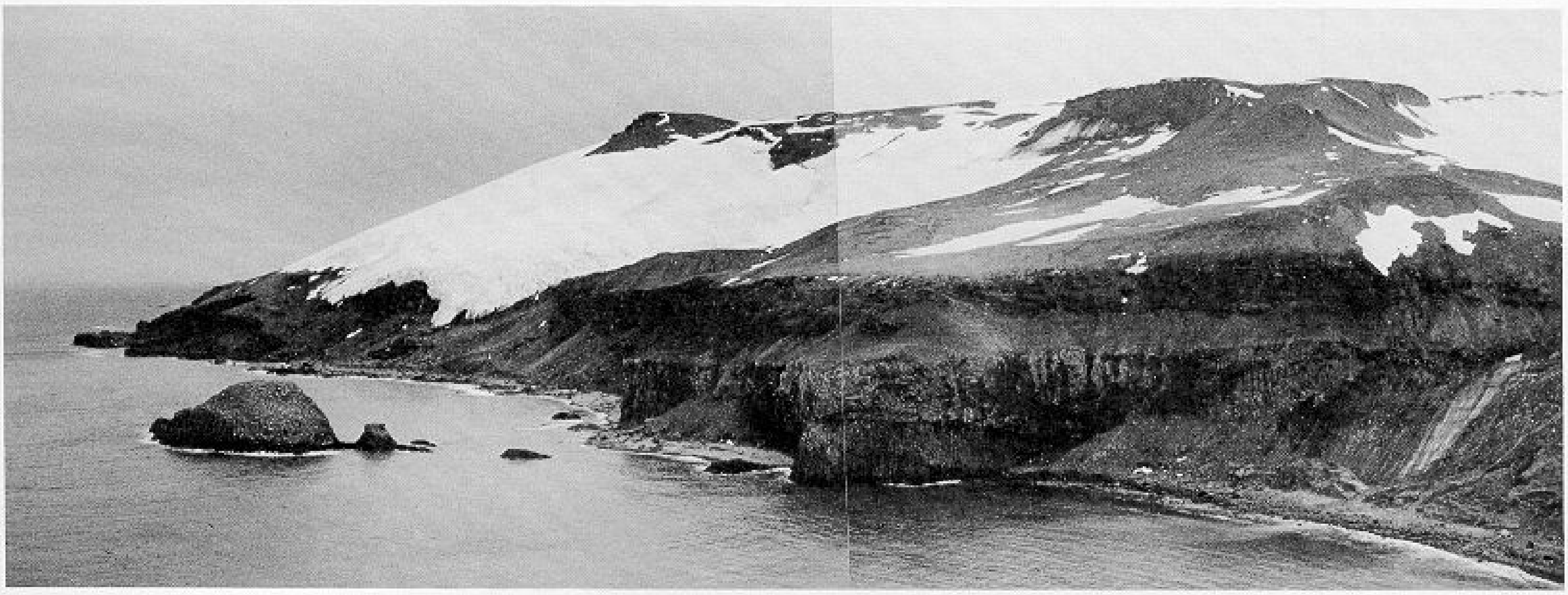

Fig. 40. Panoramic view of the cliffs and succession south from Lions Rump, King George Island. A Lower Tertiary lava of the Hennequin Formation forms the prominent cliff face (with spectacular colonnade and entablature columnar jointing) and low foreshore, overlain by conglomerates of the Polonez Cove Formation (subdued cliff face). These are succeeded by poorly exposed tuffs in the scree slope which leads up into brecciated lavas forming the low crags on the skyline.

with isolated outcrops of conglomerate at Vauréal Peak, Cinder Spur and Three Sisters Point. No further discussion is warranted here.

At least 100 m of tuffs and hornblende–andesite lavas conformably overlie the Polonez Cove Formation. In the cliffs near Low Head the lavas overlie and apparently overstep the tuffs. They are pale purple-grey, friable and autobrecciated, with dark-coloured permeations which contain clasts lithologically unlike the enclosing lava. No amygdaloidal surfaces were observed, but the presence of a strongly red-coloured pile of debris, lithologically similar to the lavas, suggests that eruption was at least partly subaerial. The lowest lava exposed is 15 m thick.

A small columnar-jointed neck mantled by monomict agglomeratic breccia crops out at Low Head. The breccia is non-stratified and forms a gently sloping surface against which the conglomerates of the Polonez Cove Formation have passively onlapped. The neck probably represents a minor Upper Tertiary vent that pre-dated the conglomerates.

A thick intrusive sheet, lithologically similar to the neck at Low Head, crops out 1 km west of Lions Rump, and a minor apophysis of the same sheet intrudes the lavas at Lions Rump. The sheet appears to be a multiple intrusion and it shows well-developed 'layer-like structures' (cf. (p. 39), spaced about 2 m apart, and dipping at 22–44° to the north-north-west. It has apparently intruded a normal fault with this orientation and is truncated by a major, north-east trending fault with a downthrow of about 60–70 m to the east (Fig. 39). Other intrusions are uncommon and include a major dyke that cuts the cliffs north of Low Head. The dyke is columnar jointed and 40 m thick at the base of the cliffs, increasing upwards to 70 m.

C. Petrography

The lavas vary petrographically from basalt to andesite. Typically, they are highly porphyritic whereas aphyric rocks are rare. The intrusions are mainly basalts and basaltic andesites but rarer more acidic rocks are also present and they are described here together with the lavas.

The commonest rocks are olivine-basalts, characterized by conspicuous phenocrysts of olivine (Fo_{70-95}) and diopsidic augite that often form nodule-like glomeroporphyritic aggregates, sometimes associated with minor plagioclase. The augite phenocrysts often show hour-glass structure and

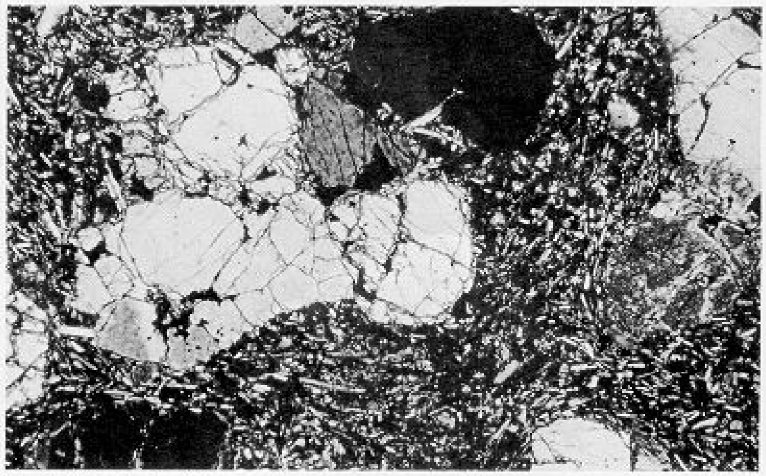

Fig. 41. Typical olivine–augite-rich, plagioclase-free mildly alkaline basalt from the plug at Mount Plymouth, Greenwich Island. (P.54.1, X-nicols, ×40.)

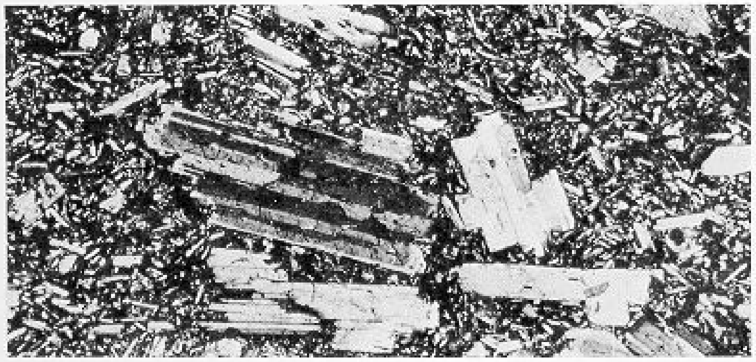

Fig. 42. Typical plagioclase-rich basalt lava from south-eastern King George Island (near Vauréal Peak). (P.545.1, X-nicols, ×30.)

striking oscillatory zoning. Plagioclase phenocrysts (An_{30-70}) are present in only minor amounts in the youngest rocks (i.e. those on Greenwich, Livingston and Penguin islands) and they may be absent in the very fine-grained or glassy specimens (e.g. G.32.1 and P.54.1) (Fig. 41). They are noticeably smaller than the olivine and augite phenocrysts and they show little evidence of resorption, which contrasts with the strong resorption seen in olivine and sometimes augite crystals. Conversely, plagioclase phenocrysts similar in size to olivine and augite are abundant in the (?) Upper Tertiary rocks on King George Island and they commonly show 'fingerprint' textures (Fig. 42). The fine-grained pilotaxitic or hyalopilitic groundmass is formed of plagioclase laths (usually calcic andesine, rarely oligoclase or labradorite), augite, pigeonite (Hawkes, 1961, p. 21), minor opaque ore and accessory apatite. Groundmass olivine is a characteristic feature of most of the youngest rocks.

Olivine is gradually replaced by hypersthene in the basaltic andesites. If hypersthene is present, olivine occurs only as a phenocryst phase and it may be mantled by hypersthene.

The andesites contain rarely glomeroporphyritic phenocrysts of plagioclase, augite, hypersthene, opaque ore and rare hornblende. Faint oscillatory zoning is developed in some augite phenocrysts but they are much less distinctive than those in the basalts. The hornblende phenocrysts are variably olive-green (P.439.1) or red-brown (P.439.4). They show marked evidence of magmatic resorption and are largely pseudomorphed by magnetite.

In general, alteration is slight in most of the lavas and some intrusions. It consists of serpentine, talc, bowlingite and/or calcite replacement of olivine and hypersthene, and (?) smectite in the groundmass. In addition, some of the intrusions and lavas (notably the hornblende–andesites between Cinder Spur and Lions Rump) contain considerable amounts of zeolites, and calcite is sometimes present (G.41.1).

The most distinctive clastic rocks are the palagonitized breccias (hyaloclastites), which are composed of loosely cemented, angular, monomict fragments of glassy vesicular lava with abundant unaltered phenocrysts of olivine and diopsidic augite. The glass varies from sub-opaque (due to exsolved opaque ore granules) to bright yellow and orange (palagonite). There is a weak fringing cement formed by tiny elongate crystals of an unidentified (?) zeolite.

With the exception of exotic lithologies (p. 59), the conglomerates of the Polonez Cove Formation are formed of sub-rounded–sub-angular clasts of weathered lava. They are holocrystalline pyroxene-andesites which are sometimes vesicular. Calcite forms a blocky cement and fills vesicles. A discontinuous sandy layer at the base of the formation is formed of poorly sorted fragments of little-altered lava, metamorphic and sedimentary rocks (including some similar to rocks of the Miers Bluff Formation). A few clasts are composed of feldspar microlites and devitrified (?) glass, suggesting penecontemporaneous volcanism. Angular to sub-rounded crystals of plagioclase and quartz are common, and there are minor clasts of augite, green hornblende, epidote and opaque ore. Matrix is abundant, formed of finely comminuted lithic and crystal fragments, and much clay.

The tuffs above the Polonez Cove Formation have a similar clastic content to fossil-bearing sediments at Cape Melville. They are fine-grained rocks mainly formed of clay-rich matrix which, at Cape Melville, has formed by alteration of glass shards. Scattered angular lava clasts are also present and are common in the coarser sandy rocks at Cape Melville, but the majority of the clasts are largely unaltered crystal fragments of plagioclase, olive-green hornblende (some euhedral), augite and opaque ore. Irregularly shaped pumice may be present and is common at Cape Melville. Poorly formed (?) accretionary lapilli were also observed in the Lions Rump rocks.

D. GEOCHEMISTRY

Although only four (?) Upper Tertiary–Quaternary volcanic rocks were analysed during this investigation (Table XIII), twenty-four additional analyses from King George Island (comprising 14 from Cinder Spur, 9 from Martins Head and 1 from Lions Rump) were made available by A. D. Saunders and S. D. Weaver (University of Birmingham).

The (?) Upper Tertiary rocks of King George Island are mainly basalts and basaltic andesites, with rare silica-poor andesites. They have high Ni and Cr contents, moderate Fe*/Mg, K/Rb and Na_2O/K_2O, and low Rb/Sr ratios similar to island arc tholeiites, whereas the high contents of K_2O, Rb, Ba and Sr are those of calc-alkaline rocks. Moreover, only slight Fe-enrichment is evident on an AFM diagram, and the Ce_N/Y_N ratios suggest slight enrichment of the light rare earths (Table XIII). In general, the rocks may be regarded as a low-K, high-alumina calc-alkaline suite created due to subduction at the South Shetland trench. Despite the lack of reliable evidence for the age of the outcrops at Vauréal Peak, Martins Head and Cinder Spur (p. 60), rocks from these localities show many lithological similarities to the Lower Tertiary Fildes Formation. However, analyses of rocks from Martins Head and Cinder Spur have consistently lower Rb, Ce and possibly La contents, and higher Cr and Ni, and these chemical differences may justify their separation from the Fildes Formation. The age and affinities of the fresh olivine-basalt plug at Ternyck Needle are also uncertain. Although lithologically similar to

Table XIII. Chemical analyses of (?) Upper Tertiary–Quaternary volcanic rocks of the South Shetland Islands.

	1	*2*	*3*	*4*	*5*	*6*	*7*	*8*	*9*	*10*	*11*	*12*	*13*	*14*
SiO_2	49.8	50.2	51.5	52.7	57.2	50.8	51.4	52.6	53.7	54.1	55.4	48.4	48.2	50.3
TiO_2	0.81	0.75	0.75	0.73	0.59	0.78	0.87	0.82	0.86	0.85	0.70	1.26	1.31	1.08
Al_2O_3	18.1	16.5	17.7	18.2	18.2	22.0	19.8	17.7	24.0	18.0	18.70	17.1	15.5	18.1
Fe_2O_3	1.93	2.00	2.00	1.96	1.71	1.48	1.71	1.52	0.82	1.58	2.15	2.74	2.81	2.55
FeO	6.44	6.66	6.65	6.54	4.28	4.94	5.69	5.06	2.74	5.27	5.39	6.84	7.02	6.38
MnO	0.21	0.37	0.19	0.18	0.17	0.31	0.14	0.14	0.13	0.16	0.13	0.16	0.16	0.15
MgO	5.9	5.3	5.2	4.0	4.2	4.4	4.1	5.7	1.8	5.4	4.9	8.2	10.2	5.0
CaO	10.27	11.36	9.53	9.24	7.06	7.96	9.90	9.66	10.35	7.84	8.92	11.45	10.79	11.27
Na_2O	3.33	3.37	3.71	3.69	4.36	4.91	3.74	3.42	4.16	3.70	3.82	3.96	3.62	4.15
K_2O	0.58	0.64	0.80	0.82	0.94	0.88	0.81	0.95	0.66	1.02	1.44	0.42	0.49	0.56
P_2O_5	0.14	0.24	0.22	0.23	0.26	0.24	0.20	0.14	0.20	0.14	0.14	0.18	0.19	0.17
Total	97.51	97.39	98.25	98.29	98.97	98.70	98.36	97.71	99.42	98.06	101.69	100.71	100.29	99.71
TRACE ELEMENTS														
Cr	57	212	43	46	20	27	23	43	19	28	60	470	700	110
Ni	26	77	25	23	9	24	14	18	12	16	19	206	367	35
Zn	74	125	83	96	86	91	88	66	99	67	58	66	68	76
Rb	10	7	14	15	16	13	12	11	10	11	30	4	–	7
Sr	388	402	467	484	535	503	486	449	462	640	650	470	477	590
Y	18	22	20	21	14	22	23	23	23	15	14	14	12	16
Zr	95	123	114	124	140	123	115	100	129	113	114	58	77	50
Nb	1	3	3	4	1	1	–	1	1	–	3	3	4	3
Ba	177	215	234	259	408	421	223	214	246	325	258	124	143	175
La	7	13	12	11	13	9	11	9	10	8	12	12	14	9
Ce	21	25	25	26	31	22	26	20	21	19	27	14	20	8
Pb	3	8	9	10	7	6	12	8	3	6	–	–	–	–
Th	–	3	2	2	–	1	2	2	2	3	–	–	–	–
Ga	25	23	24	26	25	28	28	25	24	26	26	21	19	24
RATIOS														
K/Rb	491	770	474	454	488	562	560	717	559	770	398	872	–	664
Ba/Rb	18	31	17	17	25	32	19	19	25	30	9	31	–	25
K/Ba	27	25	28	26	19	17	30	37	22	26	46	28	28	27
Rb/Sr	0.02	0.02	0.03	0.03	0.03	0.03	0.02	0.02	0.02	0.02	0.46	0.01	–	0.01
Ba/Sr	0.5	0.5	0.5	0.5	0.8	0.8	0.5	0.5	0.5	0.5	0.4	0.3	0.3	0.3
Ca/Sr	189	202	146	136	94	113	146	154	160	88	98	174	162	137
Ce_N/Y_N	2.8	2.8	3.0	3.0	5.4	2.4	2.8	2.1	2.2	3.1	4.7	2.4	4	1.2
Fe*/Mg	1.8	2.1	2.1	2.7	1.8	1.8	2.3	1.4	2.5	1.6	1.9	1.5	1.2	2.2

1.	16136	Basalt, Martins Head, King George Island.
2.	16138	Basalt, Martins Head, King George Island.
3.	16137	Basalt, Martins Head, King George Island.
4.	16135	Basaltic andesite, Martins Head, King George Island.
5.	16131	Andesite, Martins Head, King George Island.
6.	16153	Basalt, Cinder Spur, King George Island.
7.	16147	Basalt, Cinder Spur, King George Island.
8.	16145	Basaltic andesite, Cinder Spur, King George Island.
9.	16148	Basaltic andesite, Cinder Spur, King George Island.
10.	16144	Basaltic andesite, Cinder Spur, King George Island.
11.	G.13.1	Basaltic andesite, Ternyck Needle, King George Island.
12.	P.54.1	Basalt, Mount Plymouth, Greenwich Island.
13.	P.55.1	Basalt, Mount Plymouth, Greenwich Island.
14.	P.51.1	Basalt, Gleaner Heights, Livingston Island.

1–10: Representative analyses provided by A. D. Saunders and S. D. Weaver.

many of the Quaternary rocks, it does not have comparably high Na_2O contents (see below) and, by contrast, its low K/Rb and Ba/Rb ratios and high Rb/Sr fall within the range for Scotia Sea-floor basalts, suggestive of a subduction-related origin similar to that envisaged for the (?) Upper Tertiary lavas. However, only one analysis from Ternyck Needle is currently available and it is not known how representative the sample was.

Only three Quaternary rocks were analysed during the present survey, but analyses of Quaternary basalts from Penguin Island were included in comparisons with the (?) Upper Tertiary volcanic rocks (data from Weaver and others, 1979). The Quaternary rocks, characterized by fresh olivine-basalts, are broadly similar geochemically to those of (?) Late Tertiary age. Small trace element differences are, however, evident, principally in La/Zr and Ce/Zr ratios, and absolute contents of Cr and Ni which are higher and much higher, respectively, in the Quaternary analyses (Fig. 43; Table XIII). Moreover, the Quaternary rocks are mildly alkaline. Because of their freshness, this is demonstrably not an alteration effect. The analyses contain up to 6.3% *ne* (Table XIII) and they plot close to and within the field of alkaline rocks on a total alkalis–silica diagram (Fig. 44), although Zr/Nb ratios in *ne*-normative lavas on Penguin Island are appreciably higher than in typical alkaline rocks (Weaver and others, 1982). The increase in total alkalis is mainly caused by high Na_2O contents (Table XIII); K_2O is not appreciably higher within the general data scatter.

E. Discussion

The striking geochemical similarity between the Lower and (?) Upper Tertiary volcanic rocks on King George Island strongly suggests that subduction-related magmatism continued until (?) Late Tertiary times on this island. This is supported by geophysical evidence for sea-floor spreading in western Drake Passage, which probably ceased around 4 Ma (Barker, 1976). However, following the cessation of

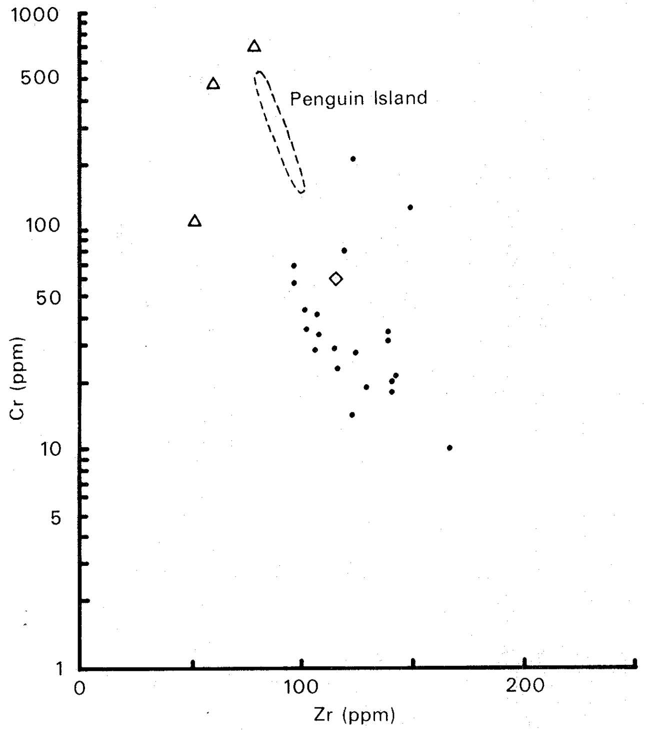

Fig. 43. Plot of Cr against Zr for (?) Upper Tertiary–Quaternary volcanic rocks of the South Shetland Islands. Data for Penguin Island from Weaver and others (1979). (Symbols: ● = south-eastern King George Island (Martins Head, Cinder Spur and Lions Rump); ◇ = Ternyck Needle; △ = Mount Plymouth (Greenwich Island) and Gleaner Heights (Livingston Island).)

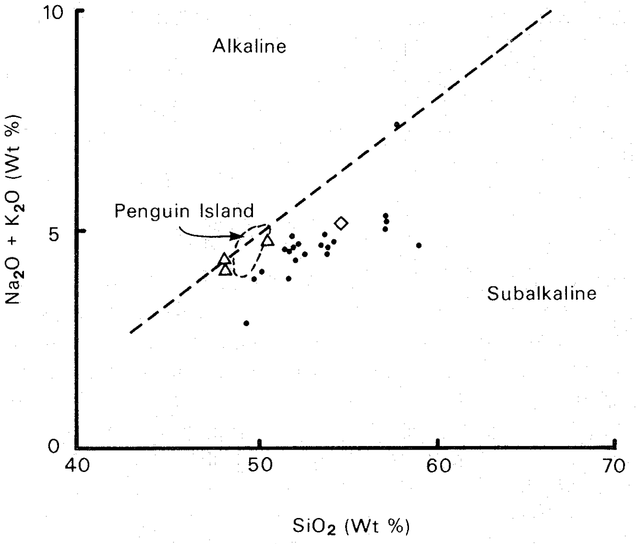

Fig. 44. Plot of total alkalis against SiO_2; (?) Upper Tertiary–Quaternary volcanic rocks of the South Shetland Islands. (Symbols as in Figure 43.)

subduction at the South Shetland trench in the Early Pliocene, the character of the volcanic activity changed and mildly alkaline lavas were erupted, principally during the Quaternary. Tarney and others (1977, p. 374) suggested that the Penguin (and Deception) Island magmas are unlikely to have been derived by melting of subducted Scotia Sea oceanic crust 'since Rb/Sr ratios are lower and K/Rb and Ba/Rb ratios are higher in the volcanics than in the subducting oceanic crust' and this is also true for the three new Quaternary analyses. The very high Cr and Ni contents of all the Quaternary lavas also support this suggestion, although basalts in the Upper Cretaceous Coppermine Formation share this characteristic (p. 54). This is consistent with the status of the Quaternary volcanism as an intra-plate phenomenon (cf. Barker, 1976).

Because of its age, position close to the fault-bounded northern margin of Bransfield Strait, and supposed enrichment in the incompatible elements, the (?) Late Tertiary volcanism on King George Island was related by Weaver and others (1982) to processes connected with the initial stages of rifting open of Bransfield Strait as a marginal basin. Conversely, Penguin Island was regarded as an off-axis volcano erupting mildly alkaline basalts with high Ce_N/Y_N ratios indicative of a deep (garnet-bearing) mantle source. However, these suggestions were based on data for the (?) Upper Tertiary rocks which included analyses from Turret Point, and comparisons were made only with Lower Tertiary rocks at Fildes Peninsula. The thick andesite lavas at Turret Point are now considered to be Early Tertiary and they have the typical calc-alkaline characteristics of the Hennequin Formation (p. 53), in contrast to the mixed tholeiitic and calc-alkaline characteristics of the Fildes Formation (p. 53). There is little evidence in the Quaternary rocks now recognized (i.e. those on Greenwich, Livingston and Penguin islands) for any significant enrichment of the incompatible elements. Moreover, the geographical position of the Quaternary outcrops on Greenwich and Livingston islands, situated well away from Bransfield Strait, suggests that magmatism in these areas is less likely to be causally related to the opening of Bransfield Strait and they have low Ce_N/Y_N ratios indicative of a shallower melting source than the Penguin Island magmas.

X. STRUCTURE AND TECTONICS

A. SMITH ISLAND

The most conspicuous structural feature of the rocks at Cape Smith and on Barlow Island is a strong schistosity within which tight asymmetrical folds with a wavelength of several centimetres are locally present. On Barlow Island, some folds are ptygmatic and have greatly attenuated limbs. Kink bands spaced about 2 cm apart occur in groups of two or three at irregular intervals and develop a strain-slip cleavage on Barlow Island. A mineral lineation is also present and is deformed by the kink bands and possibly small folds, although Dalziel (1982) suggested that the lineation and small folds are related.

From the meagre structural data available, the steeply dipping small fold axial planes have a general east-north-easterly strike, with hinges plunging at about 30° towards

057°N. This agrees well with data obtained by Dalziel (1982) during a structural study of the entire island. Dalziel (1982) described a main phase of deformation represented by tight asymmetrical folds trending towards 070°N, 'pre-dated by isoclinal folds and post-dated by various conjugate folds and kink bands'.

B. Miers Bluff Formation and Williams Point Beds

The Miers Bluff Formation dips predominantly to the north-west and it has a north-easterly strike (Hobbs, 1968, p. 30). Whereas Hobbs (1968) suggested that the rocks form the western limb of a major anticline which plunges to the south-west, an interpretation consistent with a north-westerly younging direction, Dalziel (1972*a*, p. 50) recognized that the strata are dominantly downward-facing, and they form the inverted limb of a nappe-like recumbent fold. The axial plane of the fold dips at 10–30° to the north-west, with a hinge plunging to the south-west or south-south-west. The sense of overturning is from north-west to south-east. The limb is locally re-inverted by smaller-scale asymmetrical folds with hinges which plunge at low angles to the north-east and south-west.

Deformation of the Miers Bluff Formation must have occurred prior to the deposition of the Upper Jurassic–Lower Cretaceous volcanic rocks, which are only affected by open folds and faults (see below). Moreover, if the Miers Bluff Formation can be correlated with lithologically and structurally similar sequences on the Antarctic Peninsula and Alexander Island, the presence of Triassic marine fossils in these (M. R. A. Thomson, 1975; Edwards, 1982) indicates that at least some of the deformation occurred during the Late Triassic–Early Jurassic. However, the depositional age of the Miers Bluff Formation is uncertain (? Carboniferous–Triassic) and earlier deformations may also have occurred. These suggestions are supported by Rb–Sr radiometric ages of 197 and 242 Ma obtained from the Miers Bluff Formation and Trinity Peninsula Group, respectively, which are thought to represent times of diagenesis and/or deformation (Dalziel, 1972*a*). More recently Pankhurst (1982) obtained a Rb–Sr isochron age of 281 ± 16 Ma from shales in the Trinity Peninsula Group at Hope Bay.

By contrast, the Middle–Upper Triassic Williams Point Beds are apparently undeformed. They are poorly indurated and roughly flat-lying, except where they are caught up in large squeeze-up structures into an overlying (?) Upper Cretaceous sill. Moreover, there is no pervasive cleavage and it is unlikely that the beds have suffered any major deformation. However, because of the small outcrop area, gentle folding cannot be excluded.

C. Upper Jurassic–Lower Cretaceous Volcanic Rocks

Because of the alteration of the Mesozoic rocks east of Mount Bowles, Livingston Island, bedding is usually difficult to distinguish and data from this area are virtually absent. This does not include Harmony Point, Nelson Island, from which several measurements were obtained. In general, the Upper Jurassic–Lower Cretaceous volcanic rocks show mild deformation in the form of open folds and

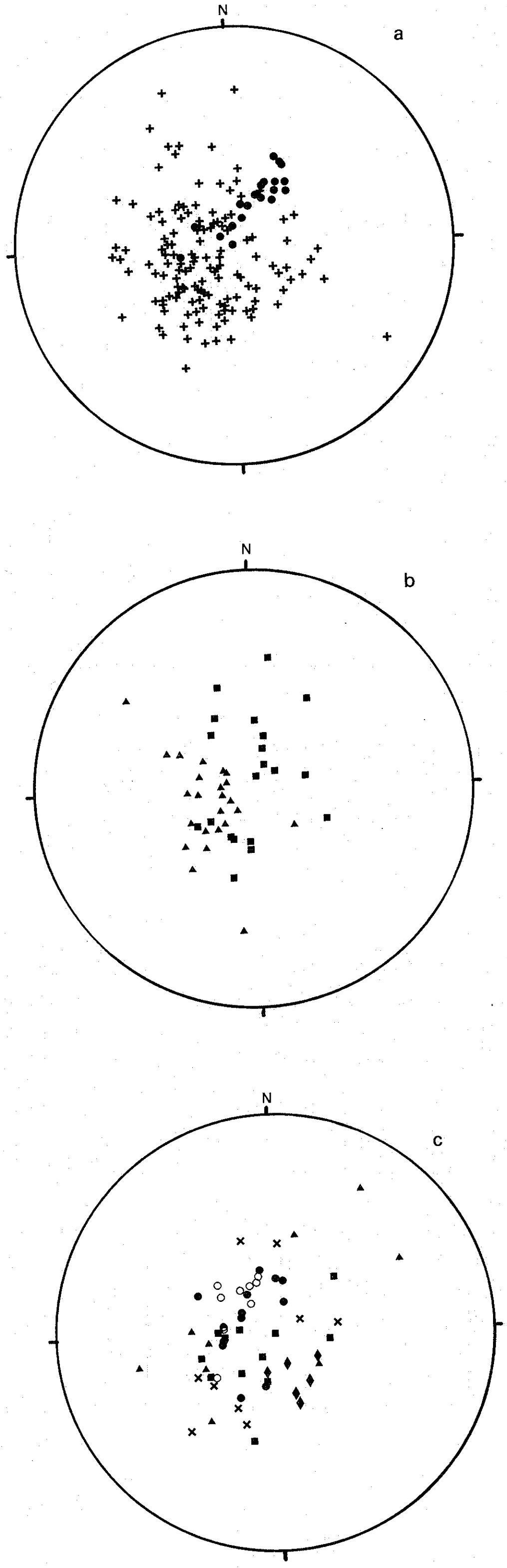

Fig. 45. Stereograms of poles to bedding for Upper Jurassic–Lower Cretaceous rocks of the South Shetland Islands: a. Mudstone (●) and mixed marine (+) members, Byers Formation. b. Volcanic (▲) and agglomerate (■) members, Byers Formation. c. Other outcrops (● = Harmony Point (bedding planes); ○ = Harmony Point (fissility in volcaniclastic rocks); ▲ = Cape Shirreff; ■ = President Head and Hall Peninsula; × = Cape Wallace and Cape Hooker area. Data for Cape Shirreff from Hobbs, 1958, unpublished field notes.

faulting. The interpretation of poles to bedding on a stereographic projection (Fig. 45) is particularly difficult since the rocks are largely coarse-bedded and of volcanic origin, and many of the bedding variations may simply reflect irregularities in the terrain on to which the rocks were deposited (e.g. mantle bedding in pyroclastic rocks). Moreover, deposits that accumulated in vent or near-vent locations may show anomalously steep dips due to their incorporation in the cone structure of the vent, and overlapping of adjacent vents may produce thick sequences of lavas and pyroclastic rocks with very different bedding orientations. This has been observed in coarse vent-facies agglomerates at north-western Ray Promontory, Byers Peninsula (agglomerate member of the Byers Formation (Smellie and others, 1980)). However, undoubted folding of dome and basin type was observed in well-bedded sedimentary sequences on Low Island (Cape Wallace), Livingston Island (Byers Peninsula and probably Cape Shirreff) and Nelson Island (Harmony Point) (Hobbs, 1958, unpublished field notes; Smellie, 1980; Smellie and others, 1980), and it is likely that the other outcrops of Late Jurassic–Early Cretaceous age have suffered similar deformation. No pervasive cleavage is developed. Furthermore, about 45% of all the poles to bedding plot within the south-western quadrant (Fig. 45), indicating that the rocks dip generally towards the north-east. Conversely, north to north-westerly dips are comparatively rare. The significance of the predominantly south-easterly dips in rocks at Harmony Point (Fig. 45) is uncertain because many of the data were obtained using fissility in volcaniclastic rocks as a bedding indicator and the number of measurements is large compared with the relatively small size of the headland.

Minor kink-like folds, formed during the emplacement of some intrusions, and small-scale monoclinal to tight anticlinal folds of uncertain origin that locally invert beds, are present at Byers Peninsula and have been described by Smellie and others (1980).

Fault and/or joint trends were obtained mainly at Byers Peninsula and Harmony Point. Dyke trends were also measured and provide additional information on the fracture systems in these areas. In general, it is assumed that most of the faults and dykes are not much younger than their host rocks.

Despite the wide total range of orientations, dykes at Byers Peninsula have mainly south-east to east-south-east orientations, which are similar to the major fault trend for the peninsula (Fig. 46a). However, the prominent east-north-easterly trend of dykes and faults suggested by Valenzuela and Hervé (1972, p. 88) is not supported by the data presented here, which show only a very subsidiary trend in this direction; this may be due to the paucity or selectivity of the data obtained. Dykes at Harmony Point are also structurally controlled and their orientations vary mainly between east-north-east and south-east (Fig. 46b). Despite slight evidence for a weak subsidiary trend to the north or north-north-east at both Harmony Point and Byers Peninsula, a conspicuous feature of the data, including measurements obtained from other localities (southern Greenwich and Robert islands, and Low Island), is the rarity of dykes or fractures with orientations between north-west and north-east; these amount to only about 15% of all the measurements.

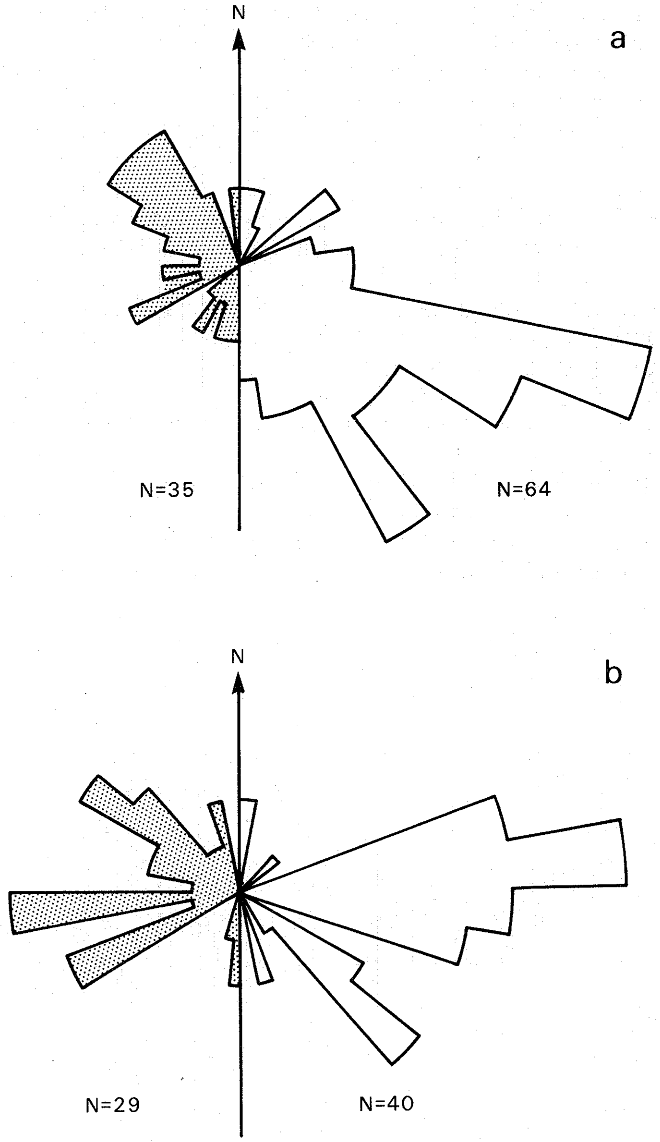

Fig. 46. Rose diagrams of dyke (unshaded), fault and joint (shaded) trends in Upper Jurassic–Lower Cretaceous volcanic rocks of the South Shetland Islands: a. Byers Formation, b. Harmony Point, Nelson Island.

Whereas there is little evidence in the South Shetland Islands for the age of the deformation of the Upper Jurassic–Lower Cretaceous volcanic rocks, regional studies carried out in southern South America and the Antarctic Peninsula suggest that it occurred mainly during the Late Cretaceous (Andean orogeny) (Dalziel, 1974, p. 572).

D. Upper Cretaceous–Lower Tertiary Volcanic Rocks

Barton (1965, p. 17) described rocks at southern Ezcurra Inlet (Point Thomas) as 'folded into a dome and syncline with limbs dipping at 35–40°', and related the deformation to a major fault along Ezcurra Inlet. Although folding in this manner could also be caused by the buoyant uprise of a major intrusion not exposed at the surface, no thermal or metasomatic effects were observed in the rocks. Moreover, the anomalously steep dips occur only in thin-bedded scoriaceous lavas and volcaniclastic rocks of the Fildes Formation, which are radially distributed around a 'core' of flat-lying, undeformed thick lavas and conglomerate of the Hennequin Formation (Fig. 33; p. 44). At eastern Point Thomas, the Hennequin Formation is uncomformably overlain by the Fildes Formation and a similar relationship may exist at western Point Thomas. If the structure is a horst, it must have been uplifted prior to the extrusion of the Fildes Formation because, despite the presence of considerable faulting in the area, no faults appear to relate specifically to the 'horst'. Alternatively, the structure may represent a steep-sided fossil hill over which lavas of the Fildes Formation were draped.

In general, no deformation other than major faulting is known to have occurred following the (?) Late Cretaceous Andean orogeny. Although this may have affected the Coppermine Formation, it cannot be demonstrated here owing to the difficulties of interpreting data obtained from coarse-bedded volcanic deposits (see above).

A large number of dyke orientations were obtained from the Lower Tertiary rocks at Fildes, Stansbury, Weaver and Barton peninsulas and Point Thomas (Fig. 47). Measurements of fault and/or joint trends are fewer and have only been compiled for three areas (Fildes Peninsula, Barton and Weaver peninsulas, and Demay Point) (Fig. 47). The trends show a great total range of orientations. This variation is particularly obvious in measurements obtained at Fildes Peninsula and it contrasts with the more restricted ranges of orientations encountered in individual outcrops of Late Jurassic–Early Cretaceous age. The reasons for this are unknown at present. However, most of the measurements show a predominance of easterly orientations, varying from north-east to south-south-east. Northerly trends are apparently only important at Demay Point and possibly Barton and Weaver peninsulas, but they are subsidiary to the main easterly trends at these localities. Few data were obtained at other localities but, in general, they are

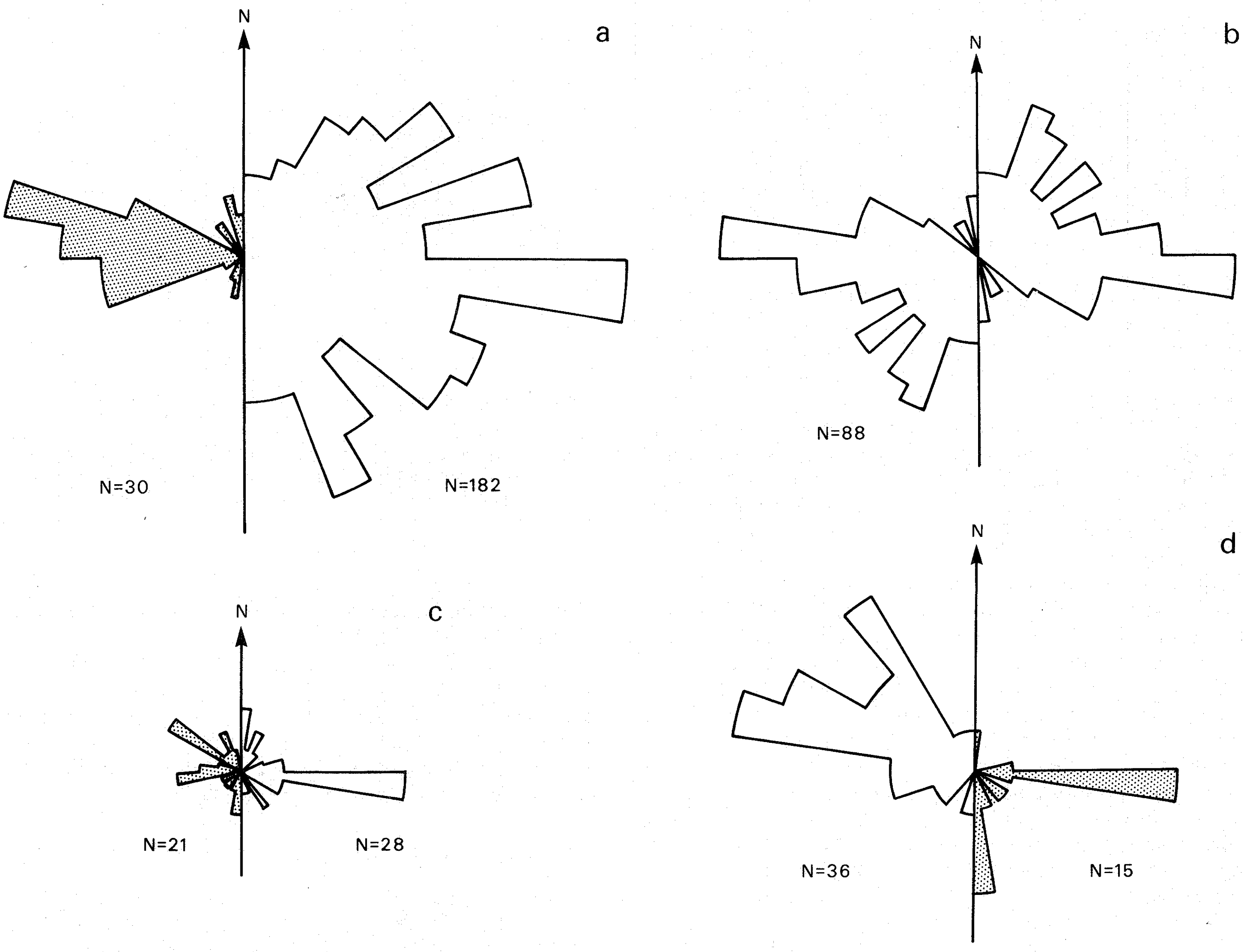

Fig. 47. Rose diagrams of dyke (unshaded), fault and joint (shaded) trends in Upper Cretaceous–Lower Tertiary volcanic rocks of the South Shetland Islands: a. Fildes Peninsula, King George Island, b. Stansbury Peninsula, Nelson Island, c. Barton and Weaver peninsulas, King George Island, d. Point Thomas and Demay Point, King George Island.

consistent with a regional dyke/fault orientation varying between north-east and south-east. This includes limited measurements from the Upper Cretaceous Coppermine Formation.

E. (?) UPPER TERTIARY–QUATERNARY VOLCANIC ROCKS

Deformation of the (?) Upper Tertiary–Quaternary volcanic rocks is restricted to faulting. Longitudinal east-north-east trending faults are responsible for the uplift of the centre of King George Island and south-eastern Robert, Greenwich and Livingston islands, and multiple step-faults flank the islands to the south-east, with downthrows of 2.5 to 4 km into Bransfield Strait (Griffiths and others, 1964; Ashcroft, 1972). The faults cut Lower Tertiary volcanic and plutonic rocks on King George Island and a Lower Tertiary pluton on Livingston Island. Moreover, the distribution of the Lower Tertiary formations and eruptive centres shows no obvious fault control, contrary to the hypothesis proposed by Hawkes (1961). It is suggested therefore that the faults are mid Tertiary or younger in age and this is supported by dyke-trend data from Point Thomas and Barton and Weaver peninsulas (Fig. 47), which show few east-north-east trends comparable with the major faults passing through Ezcurra Inlet and Marian and Potter coves.

Complementary transverse faults are probably present in most of the major straits and bays in the island group. That in Admiralty Bay, King George Island, may have caused sinistral displacement of 2 or 3 km with a likely downthrow to the west. Similar dislocations may have occurred on the other faults but they cannot be shown at present. The longitudinal faults on Livingston, Greenwich and Robert islands do not appear to have been off-set across Macfarlane and English Straits.

The strong linearity expressed by the outcrops and eruptive centres of (?) Late Tertiary–Quaternary age on south-eastern King George Island is likely to be fault-related. Moreover, it is possible that the isolated co-linear outcrops of Quaternary rocks on northern Livingston and Greenwich islands (Gleaner Heights, Edinburgh Hill, Inott Point and Mount Plymouth) are located on a major fault which may be that mapped by Hobbs (1968, fig. 2; Fig. 1) through South Bay.

F. DISCUSSION

The axes of the main-phase folds on Smith Island are parallel to the length of the island group whereas folds in the Miers Bluff Formation are aligned at about 25° to the island trend. The significance of the Miers Bluff Formation structural trends are uncertain but they are associated with south-easterly over-thrusting.

Dyke and fault trends in the Mesozoic and Early Tertiary volcanic rocks are predominantly between east-north-east and south-east; conversely, north-north-west to north-north-east orientations are generally rare. The dyke trends commonly show two maxima intersecting at an acute angle (approximately 40–80°). This is suggestive of patterns formed by conjugate structures with the principal axis of compressive stress directed to the east-south-east, and it may be causally related to subduction in this direction during the Mesozoic and Early Tertiary. However, with the present data, it cannot be demonstrated that the fractures now occupied by the dykes were formed simultaneously. Furthermore, data from the Tertiary outcrops characteristically show a great total range of orientations. Maxima, where present, may be poorly defined or multiple (e.g. at Fildes Peninsula; Fig. 47a) and data from Stansbury Peninsula apparently define an unlikely axis of maximum compression towards the east-north-east (Fig. 47b). Because of these uncertainties, too much speculation seems unjustified at present, but it is interesting that magnetic anomaly patterns in Drake Passage (Barker, 1971, 1972) are not parallel to the trend of the islands and indicate oblique subduction at the South Shetland trench during the Tertiary at least.

The major longitudinal faults of the island group have been attributed to uplift in response to the emplacement of Tertiary plutonic intrusions (Ashcroft, 1972, p. 37) or to the development of the Bransfield Strait graben during Pliocene–Recent times (Barker and Griffiths, 1972; Barker, 1976). Alternatively, it may have been the cessation of subduction at the South Shetland trench during the Pliocene that initiated isostatic recovery of the light continental crust beneath the islands. Block faulting and associated mildly alkaline volcanism are essentially intra-plate phenomena and the situation in the South Shetland Islands is broadly comparable with volcano-tectonic relationships observed in Marie Byrd Land (e.g. González-Ferrán, 1972).

Davey (1972) interpreted the Bransfield Strait graben as a marginal basin. Whereas the north-eastern limit is poorly defined, a prominent sinistral wrench fault passes through Boyd Strait to the south-west and may be causally related to the spreading in Bransfield Strait (Ashcroft, 1972, p. 39).

XI. GEOCHRONOLOGY

1. Previous work

Until recently very little has been published on the radiometric dating of rocks from the South Shetland Islands (Table XIV). Thus much of the local chronology has been based on a small amount of palaeontological evidence and by comparison with radiometric data from the Palmer Archipelago and Antarctic Peninsula.

The oldest rocks in the South Shetland Islands are those of the blueschist metamorphic complex of Elephant and Clarence islands and Smith Island. They are probably of comparable age to the similarly low-grade metamorphic complex of the South Orkney Islands (J. W. Thomson, 1968, 1974) and perhaps also with the higher-grade gneissic rocks of Graham Land (Adie, 1954; Hoskins, 1963). The blueschist facies rocks are not readily amenable to radiometric dating and biotite/hornblende K-Ar ages obtained from the mica schists and amphibolites do not exceed 200 Ma (Miller, 1960; Tanner and others, 1982), which is generally considered to be the age of the Gondwanian metamorphism (e.g. Gledhill and others, 1982). Rex

Table XIV. Previously published radiometric ages for rocks from the South Shetland Islands.

Locality	*Rock type*	*Sample No. and type**		*% K*	*^{40}Ar rad. (nl/g)*	*% Atmos.*	*Age (Ma)*	*Reference*
(a) LIVINGSTON ISLAND								
Johnsons Dock	Altered porphyry	101/1	WR	3.18	7.0	–	56	1
Ray Promontory	Basalt sill	P.862.4	WR	0.417	2.075	44	123 ± 5	2
Ray Promontory	Andesite dyke	P.862.3	WR	1.531	7.883	14	128 ± 4	2
Chester Cone	Andesite plug	P.848.1	WR	0.933	4.111	42	110 ± 4	2
Chester Cone	Andesite plug	P.848.5	WR	0.808	3.591	25	113 ± 4	2
Chester Cone	Andesite plug	P.848.7	amphibole	0.290	1.540	22	132 ± 5	2
Chester Cone	Rhyolite lava	P.848.14	WR	4.96	21.624	9	109 ± 4	2
Vietor Rock	Basalt lava	P.845.1b	WR	0.529	2.232	55	106 ± 4	2
Vietor Rock	Basaltic andesite lava	P.845.2c	WR	1.004	4.325	38	108 ± 4	2
Vietor Rock	Basaltic andesite lava	P.845.3a	WR	0.488	1.672	48	86 ± 3	2
Sealer Hill	Dolerite plug	P.845.8	WR	0.257	1.110	40	108 ± 4	2
Sealer Hill	Dolerite plug	P.845.9	WR	0.271	1.180	53	109 ± 4	2
Eastern Byers Peninsula	Basalt lava	P.850.8	WR	0.195	0.733	56	94 ± 3	2
Eastern Byers Peninsula	Basalt lava	P.850.11	WR	0.295	0.929	58	79 ± 3	2
Eastern Byers Peninsula	Basalt sill	P.850.5	WR	0.221	0.660	71	76 ± 3	2
Eastern Byers Peninsula	Basalt sill	P.864.1a	WR	0.500	1.508	47	77 ± 3	2
Eastern Byers Peninsula	Basalt sill	P.864.1c	WR	0.532	1.545	51	74 ± 3	2
Negro Hill	Dolerite plug	P.864.2	WR	0.191	0.675	72	89 ± 4	2
Negro Hill	Dolerite plug	P.864.4	WR	0.194	0.736	76	95 ± 5	2
(b) HALF MOON ISLAND								
	Quartz diorite	4a	WR	0.64	2.6	–	102	1
(c) KING GEORGE ISLAND								
Southern Fildes Peninsula	Basalt lava	20a	WR	0.78	2.6	–	84	1
Southern Fildes Peninsula	Andesite plug	134	WR	0.66	1.2	–	46	1
Southern Fildes Peninsula	Basalt lava	7	WR (acid	0.2487	0.650	29	66 ± 2	3
			leached)	0.2403	1.044	36	109 ± 2	3
Southern Fildes Peninsula	Basaltic dyke	8	WR (acid leached)	0.6423	2.070	56	81 ± 5	3
Southern Fildes Peninsula	Andesite lava	A23	WR	0.20	0.875	84	109 ± 10	4
Southern Fildes Peninsula	Andesite lava	All	WR	0.54	1.887	61	88 ± 5	4
Southern Fildes Peninsula	Andesite lava	A24	WR	0.28	0.676	23	61 ± 3	4
Southern Fildes Peninsula	Andesite lava	A6	WR	0.30	0.313	68	27 ± 2	4
Horatio Stump	Dolerite plug	5	WR	0.3598	0.751	49	56 ± 1	3
Potter Cove	"Upper" lava	1	WR	0.3324	0.659	52	50 ± 2	3
Potter Cove	"Middle" lava	2	WR	0.4640	1.088	41	59 ± 2	3
Potter Cove	"Lower" lava	3	WR	0.4701	0.944	30	51 ± 3	3
Three Brothers Hill	Andesite plug	4	WR	1.796	3.673	62	52 ± 1	3
Marian Cove	Granodiorite intrusion	276	WR	2.01	4.5	–	57	1
Noel Hill	Granodiorite intrusion	6#1	WR	2.320	4.307	56	47 ± 1	3
		6#2	WR	2.173	4.307	41	52 ± 1	3

*WR = whole rock.

References:

1. Grikurov and others, 1970.
2. Pankhurst and others, 1979.
3. Watts, 1982.
4. Valencio and others, 1979.

All the above ages have been recalculated from concentrations of K and ^{40}Ar given in the references, using the constants recommended by Steiger and Jäger (1977). Replicate analyses have been averaged where in reasonable agreement.

A number of radiometric ages for which no experimental data have been given are referred to in publications on the South Shetland Islands. These are summarized below:

Locality	*Rock-type*	*Method*	*Age (Ma)*	*Reference*
False Bay, Livingston Island	Tonalite	Rb-Sr biotite (average of 3)	40 ± 10	Dalziel and others, 1973.
False Bay, Livingston Island	Tonalite	K-Ar biotite	40 ± 5	del Valle and others, 1974.
False Bay, Livingston Island	Tonalite	K-Ar amphibole	25 ± 5	del Valle and others, 1974.
Miers Bluff, Livingston Island	Mudstones	Rb-Sr isochron WR	197	Dalziel, 1972.

For the last of these, Dr I. W. D. Dalziel has kindly made available the following analytical data:

Sample No.	*Rb ppm*	*Sr ppm*	$^{87}Rb/^{86}Sr$	$^{87}Sr/^{86}Sr$
LI–60–6A	58.3	4.0	15.0	0.7408
LI–60–6B	58.8	16.5	3.65	0.7198
LI–60–6C	48.4	13.7	3.60	0.7198
LI–60–6D	58.5	12.9	4.65	0.7228
LI–60–6E	55.4	24.4	2.32	0.7155
LI–60–6F	65.2	10.8	6.21	0.7268

(Analyses by M. Halpern, University of Texas at Dallas; specimens collected by I. W. D. Dalziel, Lamont-Doherty Geological Observatory of Columbia University; work supported by U.S. National Science Foundation, Division of Polar Programs under NSF Grant No. GV 19543 to Dalziel).

Assuming errors of 1% and 0.05% in Rb/Sr and $^{87}Sr/^{86}Sr$ ratios respectively, and excluding the data for sample LI–60–6A, an isochron age of 205 ± 19 Ma is obtained ($\lambda^{Rb} = 1.42 \times 10^{-11}\ y^{-1}$), with an initial $^{87}Sr/^{86}Sr$ ratio of 0.709 ± 0.001.

(1976) reported a Rb-Sr whole-rock isochron age of 280 ± 55 Ma* for amphibolite schists from Signy Island, South Orkney Islands. However, there is considerable scatter in the data points obtained, and the Antarctic Peninsula gneisses from Marguerite Bay yielded Rb-Sr whole-rock ages of only 170–200 Ma (Halpern, 1972; Gledhill and others, 1982). Acid gneisses on the east coast of Graham Land (Rex, 1976) have yielded two K-Ar hornblende ages 237 ± 9 and 243 ± 10 Ma.

Dalziel (1972*a*) indicated that unpublished Rb-Sr whole-rock data for shales from the sedimentary Miers Bluff Formation gave an apparent age of 192 Ma (but see Table XIV), which may again relate to the effects of the Gondwanian deformation. Similar analyses from the Trinity Peninsula Group at Hope Bay gave a Permian age of *c.* 235 Ma. Rb-Sr analyses on samples recently collected by BAS (Hamer and Pankhurst, new data) effectively refute another Palaeozoic age obtained in the area – that of *c.* 360–390 Ma for an intrusion at Lizard Hill, northernmost Antarctic Peninsula (Rex, 1976). This now appears to be no older than mid-Cretaceous. Thus there is no definitive evidence to suggest that the basement beneath the South Shetland Islands arc need be significantly older than latest Palaeozoic. Smellie (1981) proposed that a (?) Carboniferous–Triassic magmatic arc existed to the east of the Mesozoic arc centred on the Antarctic Peninsula.

The oldest known post-Gondwanian rocks in the arc occur at the south-western end of the island group. On President Head, Snow Island, and on Byers Peninsula, Livingston Island, volcanic rocks are associated with fossiliferous Upper Jurassic–Lower Cretaceous sediments. A minimum age for the volcanic rocks near the middle of the South Shetland Islands is given by a tonalite intrusion on Half Moon Island, dated at 102 Ma (Grikurov and others, 1970). Predominantly Cretaceous volcanic rocks (63–98 Ma) have been dated at Cierva Point [Cape Spring] (west coast of Graham Land) by Codignoto and others (1978). By contrast, the volcanic and plutonic rocks of King George Island have yielded mostly Tertiary ages in the range 45–66 Ma (Grikurov and others, 1970; Watts, 1982). However, Hawkes (1961) and Barton (1965) postulated the existence of an older (? Jurassic) group of rocks on southern Fildes Peninsula, Barton Peninsula and in Admiralty Bay on the basis of their more intense alteration and a supposed unconformable relationship with the Tertiary Lavas. Ages of 90, 106 and 113 Ma have been reported from such altered rocks on southern Fildes Peninsula (Grikurov and others, 1970; Valencio and others, 1979; Watts, 1982) but their very altered nature and, in particular, the presence of zeolites in this area leave their age open to doubt. The present work has failed to confirm the existence of pre-Tertiary ages from King George Island.

Tertiary volcanic rocks are also known from the Palmer Archipelago, Rex (1976) having reported K-Ar ages of *c.* 60 Ma and 36 Ma from Tower and Two Hummock islands, respectively. Gledhill and others (1982) have dated a hybrid intrusion at Arthur Harbour, Anvers Island at 36 ± 6 Ma. An age of 68 Ma from Alexander Island (Grikurov and others, 1966), supplemented by unpublished BAS ages of 50–60 Ma, confirm the probable extension of Tertiary volcanism throughout much of the Antarctic Peninsula. This is also indicated by the discovery of fossil angiosperm leaves in volcanic rocks in northern Alexander Island (Thomson and Burn, 1977) and in a previously supposed Jurassic volcaniclastic sequence on Adelaide Island (Jefferson, 1980). Late Tertiary intrusive rocks are known by a 40 Ma Rb-Sr biotite age for the Barnard Point tonalite of Livingston Island (Dalziel and others, 1973) re-analysed in the present work.

Finally, the preservation of volcanic cones at Penguin and Deception islands and a cone remnant at Bridgeman Island in Bransfield Strait bear witness to the continuation of recent volcanism in the South Shetland Islands area. Deception Island is still active (Baker and others, 1975).

In conjunction with the comprehensive field, petrological and geochemical study of the igneous rocks of the South Shetland Islands on which this report is based, a detailed geochronological investigation was also undertaken. The first part of this progamme, K-Ar whole-rock dating of samples from Byers Peninsula, Livingston Island, has been published elsewhere (Pankhurst and others, 1980) but it is reconsidered here along with some new Rb-Sr data from the same area. The remaining data given in Tables XV–XX is new.

2. *Upper Jurassic–Lower Cretaceous volcanic rocks*

As noted in Chapter II, previous authors believed volcanic rocks of Jurassic–Early Cretaceous age occurred in two areas in the South Shetland Islands: at the western end of

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*All previously published ages have been recalculated with the decay constants recommended by Steiger and Jäger (1977).

Table XV. K-Ar age data for Late Jurassic–Early Cretaceous sequence of Byers Peninsula.

Sample Number	*Description*	*Locality*	*% K*	*^{40}Ar rad (nl/g)*	*% Atmos.*	*Age (Ma)*
P.862.3	Andesite dyke	Ray Promontory	1.531	7.884	14	128 ± 3
P.862.4	Basalt sill	Ray Promontory	0.417	2.075	44	123 ± 4
P.848.1	Andesite plug	Chester Cone	0.933	4.111	42	110 ± 3
P.848.5	Andesite plug	Chester Cone	0.804	3.592	25	113 ± 3
P.848.7	Hornblende megacryst	From P.848.5	0.290	1.540	22	132 ± 4
P.848.14	Rhyolite lava	Chester Cone	4.96	21.62	9	109 ± 4
P.845.1b	Basalt lava	Sealer Hill area	0.529	2.232	55	106 ± 3
P.845.2c	Basaltic andesite	Sealer Hill area	1.004	4.322	38	108 ± 3
P.845.3a	Basaltic andesite	Sealer Hill area	0.485	1.672	48	86 ± 2
P.845.3b	Basaltic andesite	Sealer Hill area	0.397	1.156	56	74 ± 2
P.845.8	Microgabbro plug	Sealer Hill	0.257	1.110	40	108 ± 4
P.845.9	Microgabbro plug	Sealer Hill	0.271	1.180	53	109 ± 4
P.850.8	Basalt lava	2 km east of Chester Cone	0.195	0.733	56	95 ± 3
P.850.11	Basalt lava	2 km east of Chester Cone	0.295	0.929	58	80 ± 3
P.850.5	Basalt sill	2 km east of Chester Cone	0.221	0.660	71	76 ± 3
P.864.1a	Basalt sill	0.5 km south-west of Negro Hill	0.500	1.508	47	76 ± 2
P.864.1c	Basalt sill	0.5 km south-west of Negro Hill	0.532	1.545	51	74 ± 2
P.864.2	Microgabbro plug	Negro Hill	0.191	0.675	72	89 ± 4
P.864.4	Microgabbro plug	Negro Hill	0.194	0.736	76	95 ± 5

Data averaged from replicate analyses on MS10, given by Pankhurst and others (1980).

the island group, and in association with the Tertiary volcanic rocks on King George Island. K–Ar dating by Watts (1982) and later in this report cast serious doubt on the antiquity of the latter group. However, a Late Jurassic–Early Cretaceous age is established by palaeontological evidence for mainly volcaniclastic successions on Low and Snow islands and Byers Peninsula, Livingston Island. It has not been possible to date radiometrically the volcanic sequences of the first two islands, although a granodiorite intruding them at Cape Wallace gave a K-Ar age of 121 Ma, and a hornblende concentrate from a microadamellite north of Cape Hooker gave 120 Ma (Table XIX).

The results of K-Ar dating on 18 whole-rock samples and one hornblende separate from Byers Peninsula, published by Pankhurst and others (1980), are reproduced in Table XV. Ignoring the hornblende age for the moment, the oldest ages on the rocks are 128 and 123 Ma for minor intrusions in an agglomerate sequence forming Ray Promontory. This is the 'younger unit' of Valenzuela and Hervé (1972), which overlies a sequence of marine shales and sandstones occupying the rest of the western half of Byers Peninsula. These rocks contain invertebrate faunas with ammonites indicative of Tithonian–Valanginian ages (latest Jurassic–Early Cretaceous)*. Since the top of the Valanginian most probably corresponds to a radiometric age of 125–130 Ma, the geochronological and palaeontological evidence seem to be in good agreement in this area. No samples suitable for dating have been obtained from the lavas and intrusions in the marine sequence. The remaining dates were obtained from relatively fresh lavas (basalt-rhyolite) in the non-marine sequence to the east, and andesite and microgabbro intrusions within it (e.g. Chester Cone and Negro Hill). These range from 113 Ma to 74 Ma, with a general trend of decreasing age updip from west to east. However, in this case there is a significant discrepancy with the sparse palaeontological evidence, since plant fossils from volcaniclastic sediments near Negro Hill suggest a Barremian age (Hernández and Azcárate, 1972), i.e. *c.* 115 Ma. However, lavas sampled within a 300-m traverse near Sealer Hill yielded ages of 74, 85, 108 and 106 Ma from *west to east.* Most of the 70–80 Ma ages elsewhere are from sills, which could be significantly younger than the lavas. The fresh microgabbro plug at Negro Hill gave ages of 89 ± 4 and 95 ± 5 Ma, confirming a pre-Cenomanian age for the top of the non-marine succession. It seems most likely that some of the lavas at least have lost radiogenic Ar, perhaps during a late hypabyssal intrusive phase some 20–30 Ma after cessation of extrusive volcanism. Some doubt is thus cast on the validity of the whole-rock K-Ar ages even where they are concordant, as at Chester Cone where ages of *c.* 110 Ma were obtained for the andesitic cone and a rhyolite lava, but a single hornblende megacryst within the andesite gave an age of 132 ± 5 Ma. In an attempt to resolve this doubt, Rb-Sr analyses (Table XVI) were carried out on the dacite–rhyolite–ignimbrite sequence around Chester Cone – the most chemically evolved flows found in the whole of the present survey of the South Shetland Islands. The results are shown in an Rb-Sr isochron diagram (Fig. 48), which gives a very reasonable straight line corresponding to an age of 111 ± 4 Ma, in excellent agreement with the K-Ar results on the whole rocks.

Clearly both chemical systems are recording the same, discrete geological event, which may be either igneous crystallization or complete subsequent isotopic resetting and

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*Note added in proof: A six-point, whole-rock, Rb-Sr isochron for samples from the lowermost mudstone member of the Byers Formation gives an age of 163 ± 16 Ma (initial ^{87}Sr/^{86}Sr 0.7053) in accordance with the Late Jurassic age suggested by the palaeontology (p. 22).

Table XVI. Rb-Sr isochron data, South Shetland Islands.

Sample Number	*Rb*	*Sr*	*Sample description*	*^{87}Rb/^{86}Sr*	*^{87}Sr/^{86}Sr**
Acid volcanic rocks, Chester Cone, Byers Peninsula					
P.848.9	91	67	Pale-coloured ignimbrite	3.93 ± 0.02	0.71098 ± 11
P.848.10	99	53	Pale-coloured ignimbrite	5.40 ± 0.04	0.71339 ± 11
P.848.11	3	46	Pale-coloured ignimbrite	0.205 ± 0.012	0.70560 ± 7
P.848.13	8	102	Flinty red rhyolite	0.229 ± 0.007	0.70541 ± 7
P.848.14A	145	35	Rhyolite	12.08 ± 0.12	0.72413 ± 11
P.848.14B	142	35	Rhyolite	11.87 ± 0.12	0.72405 ± 11
P.848.15	116	41	Green rhyolite	8.14 ± 0.08	0.71832 ± 11
P.848.16	133	45	Green rhyolite	8.64 ± 0.09	0.71890 ± 11
P.848.18	48	257	Veined obsidian	0.543 ± 0.005	0.70564 ± 7
P.848.20	40	560	Coarse dark ignimbrite	0.205 ± 0.002	0.70562 ± 7
An isochron fit to the above data shows slight excess scatter (MSWD = 6.5). Allowing for this, an age of 111 ± 4 Ma is obtained, with an initial ^{87}Sr/^{86}Sr ratio of 0.7051 ± 0.0002.					
Barnard Point tonalite					
P.1259.2	312	7.71	Biotite	117.8	0.77084 ± 2
P.1259.2	8.39	38.7	Hornblende	0.627	0.70435 ± 11
These two points give an intersection age of 40.0 ± 0.4 Ma, with an initial ^{87}Sr/^{86}Sr ratio of 0.7040 ± 0.0001.					

*Errors shown with respect to last digit.

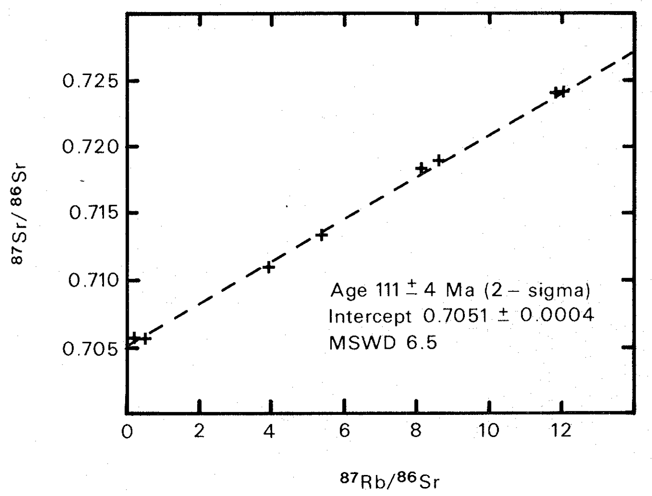

Fig. 48. Rubidium–strontium isochron plot for acid volcanic rocks from Chester Cone, Byers Peninsula, Livingston Island (see Table XIX for data). The points reasonably define a straight line corresponding to an Early Cretaceous age for crystallization or subsequent hydrothermal activity. The errors include uncertainty due to scatter in the data outside analytical precision.

rehomogenization. Acid volcanic whole-rock systems are often considered subject to resetting; the initial ^{87}Sr/^{86}Sr ratio of 0.7051 on the isochron (Fig. 48) is significantly higher than the values of 0.7032–0.7043, characteristic of other South Shetland Islands rocks (Table XVII). This relationship is consistent with the idea of rehomogenization after a period of say 10–20 Ma, during which some radiogenic Sr would have accumulated. However, these acid volcanic rocks at Chester Cone are geochemically quite unlike other volcanic rocks on Byers Peninsula (or elsewhere in the South Shetland Islands). Their very high SiO$_2$ and low Ca and Sr contents suggest either extreme differentiation or a different source mechanism of magma generation from the calc-alkaline rocks, e.g. melting of crustal sediments or refusion of earlier volcanic rocks. The latter interpretation would also adequately explain a rather higher initial ^{87}Sr/^{86}Sr ratio, and is considered a more likely possibility than complete rehomogenization once the lava pile had erupted. There is no trace of isotopic exchange for example with the Chester Cone plug, which has initial ^{87}Sr/^{86}Sr ratios in the normal range. It is concluded that the radiometric ages obtained do record the volcanic events during which the rocks were formed, and this in turn suggests that many of the other K-Ar ages from Byers Peninsula are reliable. The anomalous older age of 132 Ma for the hornblende megacryst remains to be explained. Important factors here are its very low K content (0.29% as against 0.80% for the whole rock), and its apparent chemical instability indicated by resorption and exsolution in thin section. One possibility is that there has been significant K-loss by metasomatism (Pankhurst and others, 1980). Alternatively, it may even be xenocrystal hornblende, picked up by the andesite magma from a genuinely older crustal rock, without complete outgassing during emplacement.

This interpretation implies an interval of about 15–20 Ma between the deposition of the latest fossiliferous marine rocks (Valanginian) and that of the non-marine succession, despite the fact that no stratigraphical breaks have been observed, and possibly a further 20 Ma for the accumulation of the non-marine sequences to the east.

3. *Upper Cretaceous–Lower Tertiary volcanic rocks*

Although it might be anticipated that the general sense of younging eastwards seen in the succession on Byers Peninsula would continue through eastern Livingston Island and the adjacent islands, there has, until now, been no clear evidence of the existence of Upper Cretaceous rocks in the area. The next youngest fossiliferous strata are Tertiary in age and are known from King George Island only. Thus the K-Ar ages of 78–83 Ma for the lavas and sills from Copper-

Table XVII. Sr isotope data for the South Shetland Islands.

Sample Number	*Rb*	*Sr*	$^{87}Sr/^{86}Sr$	*Assumed age (Ma)*	$(^{87}Sr/^{86}Sr)_0$
BYERS PENINSULA					
*P.862.3	39	302	0.70493	125	0.70427
P.862.4	6	366	0.70409	125	0.70401
P.845.1b	9	422	0.70434	110	0.70424
P.845.2c	28	409	0.70452	110	0.70421
P.845.3a	7	502	0.70433	110	0.70427
P.845.3b	7	516	0.70421	110	0.70415
*P.848.1	26	565	0.70369	110	0.70348
*P.848.5	22	433	0.70364	110	0.70331
*P.848.6	22	409	0.70400	110	0.70376
*P.848.7	22	442	0.70401	110	0.70378
*P.848.8	20	437	0.70394	110	0.70386
P.850.8	2	559	0.70410†	90	0.70409
*P.864.1a	10	402	0.70431†	75	0.70423
*P.864.2	5	367	0.70424	90	0.70419
*P.864.4	5	366	0.70433	90	0.70428
P.725.1	31	411	0.70465	(100)	~0.70435
COPPERMINE FORMATION					
P.840.6			0.70389	80	
P.842.4	9	681	0.70405	80	0.70401
FILDES FORMATION					
P.615.1	4	713	0.70320	58	0.70319
P.608.5a	2	513	0.70358	58	0.70357
P.1149.1	5	508	0.70358	58	0.70356
P.1166.7	14	461	0.70357	58	0.70350
P.1147.3	4	616	0.70337	58	0.70335
P.1147.4	4	612	0.70337	58	0.70335
P.1162.5	3	647	0.70344	58	0.70343
*P.611.1	46	446	0.70376	45	0.70357
*P.619.1	7	508	0.70355	50	0.70352
P.1125.1	27	514	0.70360	45	0.70350
P.1182.1/2	43	371	0.70384	45	0.70363
P.1183.2/7	46	363	0.70384	45	0.70361
P.1478.5	5	699	0.70351	45	0.70349
P.438.1	44	511	0.70402	42	0.70387
HENNEQUIN FORMATION					
P.831.3	3	839	0.70360	(27)	0.70357

Rb and Sr determined by XRF to ±1%; $^{87}Sr/^{86}Sr$ ratios ± 0.01%.
*Intrusive rocks in specified formations.
†From Pankhurst and others (1980); all other values newly determined.

mine Cove, Robert Island (Table XVIII) are the first direct indication of the age of the rocks in the central part of the South Shetland Islands arc. The observed range is small, almost within analytical error, and there is therefore no reason to suspect disturbance of the K-Ar systems. This volcanism is dated as Senonian and it is essentially contemporaneous with the minor intrusions on Byers Peninsula (above). The extent of Late Cretaceous activity in the intervening ground is evidenced by other data shown in Table XVIII. In the Williams Point area, Livingston Island, a sill west of Sayer Nunatak (P.225.1 a and b), gave ages of 79 and 74 Ma. There is also an age of 81 ± 2 Ma for a lava clast within a volcanic vent forming the nunatak itself. Since this would most likely have suffered complete outgassing on incorporation into the vent, it should date the emplacement of the latter, even if the source rock were significantly older. It suggests that the slightly younger age of 74 Ma for P.225.1a is downdated by an unknown subsequent event. Comparable ages of 84 ± 2 Ma and 80 ± 2 Ma were obtained from hypabyssal intrusions on Express Island and Greenwich Island, respectively. These are fairly typical of the complex multiple sills, which are found throughout the outcrops around Macfarlane and English straits. However, two factors complicate the apparently simple conclusion that the volcanism in this area is predominantly Late Cretaceous. Firstly, the lavas of Half Moon Island are cut by a tonalite dated at 102 Ma by Grikurov and others, (1970) and not redated in the present study. Secondly, two younger ages were obtained from this area: 60 ± 1 Ma for a multiple sill at Fort William, Coppermine Peninsula, and 53 ± 1 Ma for a pyroxene andesite lava from Kitchen Point, south-eastern Robert Island. These could be inferred to have lost significant radiogenic Ar, an ever-present problem in K-Ar whole-rock dating, especially since the latter sample is rather altered. However, at this stage and in view of the results from King George Island, it would probably be safer to assume that igneous activity occurred over a considerable time range in most parts of the South Shetland Islands, and that there is overlap in time with adjacent areas where the major activity may be older or younger.

Table XVIII. K-Ar data for Upper Cretaceous–Lower Tertiary volcanic rocks.

Sample Number	*Description*	*Locality*	*% K*	*^{40}Ar rad. (nl/g)*	*% Atmos.*	*Age (Ma)*	
1. COPPERMINE FORMATION							
P.840.4	Basalt lava	Coppermine Peninsula	0.453	1.492 (1)	49	83 ± 3	} 82 ± 2
				1.462 (2)	19	81 ± 2	
P.840.5	Basalt lava	Coppermine Peninsula	0.453	1.497 (1)	52	83 ± 3	
P.840.6	Basalt lava	Coppermine Peninsula	0.428	1.329 (1)	54	78 ± 3	} 80 ± 2
				1.391 (2)	35	82 ± 2	
P.842.4	Basalt lava	Coppermine Peninsula	0.533	1.799 (1)	42	85 ± 2	} 84 ± 2
				1.752 (2)	17	83 ± 2	
P.842.9	Basalt lava	Coppermine Peninsula	0.313	1.014 (1)	58	82 ± 3	
P.225.1a	Basalt sill	West of Sayer Nunatak, Livingston Island	0.428	1.247 (2)	34	74 ± 2	
P.225.1b	Basalt sill	West of Sayer Nunatak, Livingston Island	0.402	1.252 (2)	29	79 ± 2	
P.428.3	Clast in vent	Sayer Nunatak	0.441	1.422 (2)	45	81 ± 2	
P.926.1	Basalt sill	Express Island	0.248	0.829 (2)	51	84 ± 2	
P.485.1	Basalt sill	Greenwich Island	0.429	1.354 (2)	59	80 ± 2	
P.1613.1	Basalt sill	Fort William, Coppermine Peninsula	0.573	1.363 (2)	28	60 ± 1	
P.477.1	Andesite lava	Kitchen Point, Robert Island	0.267	0.552 (2)	55	53 ± 1	
2. FILDES FORMATION							
P.615.1	Andesite lava	Southern Fildes Peninsula	0.474	0.948 (1)	46	51 ± 2	} 51 ± 1
				0.941 (2)	61	50 ± 1	
P.604.1	Andesite lava	Southern Fildes Peninsula	0.554	1.299 (1)	69	59 ± 2	} 59 ± 2
				1.272 (2)	78	58 ± 2	
P.608.5a	Andesite lava	Southern Fildes Peninsula	0.408	0.918 (1)	48	57 ± 1	} 58 ± 1
				0.971 (2)	49	60 ± 2	
P.609.3	Andesite lava	Southern Fildes Peninsula	0.604	1.421 (1)	63	60 ± 3	} 58 ± 2
				1.349 (2)	71	57 ± 2	
P.627.1	"Jurassic lava"	Southern Fildes Peninsula	0.551	1.284 (1)	60	59 ± 2	} 58 ± 1
				1.245 (2)	60	57 ± 2	
P.629.1	"Jurassic lava"	Southern Fildes Peninsula	0.203	0.247 (2)	89	31 ± 3	
P.619.1	Basalt plug	Horatio Stump, Fildes Peninsula	0.348	0.673 (1)	42	49 ± 1	} 51 ± 1
				0.723 (2)	58	53 ± 1	
P.611.1	Andesite plug	Suffield Point, Fildes Peninsula	0.945	1.604 (1)	67	43 ± 1	} 44 ± 1
				1.646 (2)	70	44 ± 1	
P.1149.1	Andesite plug	Northern Fildes Peninsula	0.409	0.914 (1)	89	57 ± 5	} 58 ± 4
				0.947 (2)	92	59 ± 7	
P.1166.7	Basalt lava	Northern Fildes Peninsula	0.452	0.941 (1)	65	53 ± 2	} 52 ± 1
				0.928 (2)	58	52 ± 1	
P.1147.3	Basalt lava	Northern Fildes Peninsula	0.242	0.444 (1)	78	47 ± 2	} 48 ± 1
				0.453 (2)	74	48 ± 2	
P.1147.4	Basalt lava	Northern Fildes Peninsula	0.346	0.664 (1)	76	49 ± 2	} 48 ± 1
				0.645 (2)	72	47 ± 2	
P.1162.5	Basalt lava	Northern Fildes Peninsula	0.244	0.536 (1)	72	56 ± 3	} 57 ± 3
				0.552 (2)	88	57 ± 5	
P.1125.1	Basaltic andesite lava	Northern Fildes Peninsula	0.620	1.056 (1)	65	43 ± 2	} 43 ± 1
				1.059 (2)	66	43 ± 2	
P.1182.1/2	Dacite lava	Northern Fildes Peninsula	1.720	2.826 (2)	25	42 ± 1	
P.1183.2/7	Dacite lava	Northern Fildes Peninsula	1.755	3.141 (2)	24	46 ± 1	
P.1473.5	Andesite lava	Marian Cove	0.456	0.847 (1)	57	47 ± 2	} 46 ± 1
				0.806 (2)	51	45 ± 1	
P.232.1	Basalt lava	Potter Peninsula	0.435	0.754 (2)	49	44 ± 1	
P.696.1	Basaltic andesite dyke	Potter Peninsula	0.286	0.510 (2)	70	45 ± 1	
P.760.1	Basalt lava	Potter Peninsula	0.240	0.397 (2)	69	42 ± 1	
P.758.1	Basaltic andesite lava	Potter Peninsula	0.519	0.952 (1)	36	47 ± 1	} 47 ± 1
				0.949 (2)	53	47 ± 1	
P.757.2	Andesite	Potter Peninsula	1.040	2.001 (1)	47	49 ± 1	} 48 ± 1
				1.934 (2)	31	47 ± 1	
P.685.4	Andesite plug	Three Brothers Hill	1.350	2.422 (1)	22	46 ± 1	} 47 ± 1
				2.585 (2)	22	49 ± 1	
3. HENNEQUIN FORMATION							
P.831.2	Andesite	Point Hennequin	1.770	3.081 (1)	26	44 ± 1	} 45 ± 1
				3.149 (2)	22	45 ± 1	
P.831.3	Andesite	Point Hennequin	0.623	0.641 (1)	85	26 ± 2	} 27 ± 1
				0.680 (2)	87	28 ± 2	
P.831.4	Andesite	Point Hennequin	0.668	0.826 (1)	82	32 ± 2	} 32 ± 1
				0.849 (2)	82	33 ± 2	
P.831.5	Andesite	Point Hennequin	1.015	1.821 (2)	27	46 ± 1	
P.831.8	Andesite	Point Hennequin	0.878	1.606 (1)	21	47 ± 1	} 47 ± 1
				1.610 (2)	28	47 ± 1	
P.560.	Andesite dyke	Keller Peninsula	1.213	1.968 (2)	30	41 ± 1	
P.145	Andesite dyke	Keller Peninsula	1.347	2.339 (2)	44	44 ± 1	
P.1454.1	Andesite dyke	Keller Peninsula	0.867	1.439 (2)	34	42 ± 1	
P.438.1	Andesite lava	Lions Rump	1.265	2.067 (1)	21	42 ± 1	} 42 ± 1
				2.079 (2)	11	42 ± 1	
G.28.1	Andesite plug	Esther Nunatak	1.341	1.682 (2)	22	32 ± 1	

(1) MS 10
(2) MM 1200

The ages obtained from King George Island in the present study are mostly in the range 60–40 Ma. This is in accord with palaeobotanical evidence for a post-mid-Cretaceous age (p. 36). However, Barton (1965) inferred the existence of an older group of volcanic rocks, largely on the basis of a greater degree of deformation and alteration than in the rocks for which there is stratigraphical control. By analogy with the Antarctic Peninsula these older rocks were thought to be of Late Jurassic age. In particular the highly metasomatized volcanic rocks adjacent to Fildes Strait and in a linear zone through Barton Peninsula and the inner part of Admiralty Bay (Fig. 22) have frequently been assigned to this group, although altered rocks also occur south-east of Potter Cove and at Point Hennequin where they are generally accepted as being of Tertiary age. Because of the alteration (pyritization, saussuritization of plagioclase, and complete replacement of ferro-magnesian minerals by epidote–sericite–clay–calcite assemblages) these rocks are usually unsuitable for radiometric dating.

Some of the K-Ar dates so far obtained from this region (Table XIV) might be argued as showing support for Mesozoic volcanism. Grikurov and others (1970) reported an age of 84 Ma for an olivine basalt from Fildes Peninsula and Valencio and others (1979) quoted andesite ages of 27, 61 and 88 Ma from Fildes Peninsula and one of 109 Ma from Fildes Strait. In an attempt to remove altered material, Watts (1982) leached samples of basalt from southern Fildes Peninsula with hydrochloric acid before analysing them. A dyke sample treated in this way yielded an age of 81 Ma whereas two samples from a single lava flow give similar K contents but widely differing ^{40}Ar contents, resulting in discordant apparent ages of 66 and 109 Ma.

In our view, none of these dates can be regarded as good evidence for Late Jurassic (or Early Cretaceous) volcanism on southern King George Island, for the following reasons:

i. None of these dates is older than mid-Cretaceous. All authors report Early Tertiary ages in addition, comparable to those obtained by us. Thus if any of the volcanic rocks were genuinely of Jurassic age it is necessary to assume considerable loss of Ar during a Tertiary event, such as the emplacement of the granodiorite intrusion on Barton Peninsula.

ii. The scatter in the data does not clearly reflect any single pre-Tertiary event, although the coincidence of three of the ages referred to above at 81–88 Ma could be taken to indicate a Late Cretaceous event in addition to an earlier one (to explain the ages over 100 Ma). This would compare with ages reported here for the islands immediately south-west of King George Island and would not affect our conclusion concerning the overall north-easterly migration of activity (see below).

iii. The ages of 27–88 Ma obtained by Valencio and others (1979) all come from the lava succession between Ardley Island and Flat Top Peninsula, well away from the metasomatized rocks near Fildes Strait. We report (Table XVIII) K-Ar results for four lavas from the same succession. Three of these give concordant ages of 59 Ma within analytical error and one gives a slightly younger age of 51 Ma. The last result is for the most southerly sample, which is slightly altered and has probably lost radiogenic Ar during post-Palaeocene alteration. Watts (1982) also considered this succession to be of Tertiary age since the Horatio Stump plug (Table XVIII) is regarded as a possible feeder for the lavas.

iv. The lack of reproducibility in ^{40}Ar content found by Watts (1982) for samples from a single flow shows severe disturbance, which could represent either partial loss *or* take-up of excess ^{40}Ar during metasomatism. Clearly, no confidence can be placed in the older ages under such circumstances.

v. Field evidence is in part against the existence of older volcanic rocks. No sudden break is found between altered and unaltered rock groups on Fildes Peninsula. On Barton Peninsula, although the Tertiary granodiorite of Noel Hill intrudes the lavas, it could nevertheless be genetically related and hence of *similar* age (Grikurov and Polyakov, 1968*b*; Davies, 1982*a*).

vi. Finally, two new attempts at dating samples from the 'Upper Jurassic Volcanic Group' are reported in Table XVIII. One of these gives a clearly Tertiary age of 58 Ma, whereas the other shows evidence for a later loss of Ar which again suggests that the alteration is post-Palaeocene.

Lavas in the northern part of Fildes Peninsula belong to the upper part of the lower member and the upper member (Table XI). Those of the former gave ages of 58 ± 5 at the base to 47 ± 2 Ma near the top. The plant fossils that occur in the lower member have generally been considered to be Miocene in age (Orlando, 1964), but the radiometric data of Watts (1982) and those published here point unambiguously to a Palaeocene–Oligocene age for the associated volcanism. Three samples from the predominantly andesitic upper member of the Fildes Formation gave significantly younger ages of 42–46 Ma, in keeping with the proposed overall stratigraphy. However, the oldest of these ages is from a lava (P.1183), which is thought to occur near the top of the upper member, again suggesting slight Ar loss from some of the samples. Plugs at Horatio Stump (microgabbro) and Suffield Point (andesite) gave ages of 51 ± 1 and 44 ± 1 Ma, respectively suggesting that they were probably feeders for the lavas. Watts (1982) obtained an age of 56 Ma for Horatio Stump (Table XIV).

Samples from the lavas of Potter Peninsula gave another reasonably compact group of K-Ar ages (42–48 Ma), and the youngest age here is for a dyke. Three ages of lavas from Potter Cove reported by Watts (1982) range from 50 to 59 Ma. Most of these lavas would appear to be stratigraphically equivalent to the upper member of the Fildes Formation. Sample P.232.1 is a lava from below the unconformity described on p. 44, and its rather young age of 44 ± 1 Ma is therefore suspect. This is also suggested by the age of 48 ± 1 Ma for the andesite plug at Three Brothers Hill, which intrudes the upper sequence, and for which Watts (1982) obtained an age of 52 Ma.

Lavas of the Hennequin Formation, sampled at Point Hennequin, mostly gave ages of 45–47 Ma, again in close agreement with those from northern Fildes Peninsula and Potter Peninsula. Their essential contemporaneity is inferred, so that the unconformity at Point Thomas, in which the Hennequin Formation is overstepped by the Fildes Formation (p. 46) cannot be considered of major chronological significance. It seems most likely that the volcanic rocks of the two formations were erupted separately from fairly long-lived centres (e.g. *c.* 10 Ma) whose products may have interfingered. The two younger ages for samples P.831.3 and P.831.4 are not easily interpreted at this stage.

The samples from Keller Peninsula are predominantly from minor andesitic intrusions and these yielded ages of 41–44 Ma. The highly altered volcanic country rocks may be time-equivalents of the upper member of the Fildes Formation, although they were included by Barton (1965) in his Jurassic group. The age of 42 ± 1 Ma for the lava at Lions Rump is consistent with the gradual pattern of decreasing age eastwards so far observed, and this is apparently continued by the age of 32 ± 1 Ma for the andesite plug at Esther Nunatak in the extreme north-east of King George Island. The latter sample is petrographically comparable with others from False Round Point and Bolinder Bluff, but it is considerably fresher. It suggests that much of the volcanic activity of eastern King George Island may have been as young as Oligocene in age. Some of the otherwise inexplicable 30 Ma K-Ar ages further west (e.g. the two from Point Hennequin) may result from sill intrusion at that time; in some cases the dated samples may be intrusions although they were not so recognized in the field, or their K-Ar ages may have been reset by associated thermal effects.

A relatively young age is also confirmed for the tonalite of Barnard Point, Livingston Island, the largest exposure of intrusive rock in the South Shetland Islands. Dalziel and others (1973) reported Rb-Sr and K-Ar ages of 40 Ma for separated biotite, a figure confirmed precisely by new analyses (Tables XVI, XIX). However, the hornblende separate gave an older K-Ar age of 46 ± 1 Ma. There is no clear reason to suspect K-loss in this case, the K-content of the hornblende (0.669%) being quite reasonable for this rock type. This apparent age is indistinguishable from the K-Ar whole-rock and biotite age of 47 ± 1 for the Noel Hill granodiorite of King George Island. The two intrusions are, moreover, very similar in petrological and geochemical features (that of Barnard Point being slightly less evolved) and they could well be petrogenetically related and of the same age. It is suggested that 46 ± 1 Ma is more likely to be the true age of the intrusion, and that the Rb-Sr and K-Ar systems of the biotite are recording a younger event: either re-heating or first uplift and cooling of the pluton to around 200°C. This is a fairly normal pattern of age discordance in metamorphic terrains, but could equally apply in island arcs with high geothermal gradients. Stratigraphically the difference is of no great significance: both 40 Ma and 46 Ma would signify a Late Eocene age.

4. Later Tertiary–Quaternary volcanic rocks

Volcanism in the South Shetland Islands arc undoubtedly reached a climax in latest Cretaceous–Tertiary time. However, there is some evidence that igneous activity in the area has continued, perhaps sporadically to Recent times, even after the supposed cessation of subduction at the South Shetland Islands trench (*c.*4 Ma ago according to Barker (1976)). Rex and Baker (1973) reported a K-Ar biotite age of 9.8 Ma for the granodiorite of Cornwallis Island, near Elephant Island, and the recent activity of Deception Island (and by inference Bridgeman and Penguin islands) has already been noted. Additions to our knowledge of Recent ages are included in Table XX.

Three samples from a plug at Mount Plymouth, Green-

Table XIX. K-Ar data for plutonic rocks.

Sample Number	*Description*	*Locality*	*% K*	*^{40}Ar rad. (nl/g)*	*% Atmos.*	*Age (Ma)*	
P.407.4	Granodiorite	Cape Wallace, Low Island	1.384	6.697 (2)	23	121 ± 3	
P.215.1	Hornblende from micro-adamellite	Near Cape Hooker, Low Island	0.266	1.285 (2)	78	120 ± 5	
P.533.1	Granodiorite	Noel Hill, King George Island	2.010	3.603 (2)	28	46 ± 1	} 47 ± 1
P.535.2/3	Biotite	From above	6.35	12.00 (2)	33	48 ± 1	
P.1259.2	Hornblende from tonalite	Barnard Point, Livingston Island	0.669	1.211 (1)	52	46 ± 2	} 46 ± 1
				1.218 (2)	53	46 ± 1	
P.1259.2	Biotite from tonalite	Barnard Point, Livingston Island	7.40	11.72 (1)	17	40 ± 1	} 40 ± 1
				11.63 (2)	7	40 ± 1	

(1) MS 10
(2) MM 1200

Table XX. K-Ar data for Upper Tertiary–Quaternary volcanic rocks.

Sample Number	*Description*	*Locality*	*% K*	*^{40}Ar rad. (nl/g)*	*% Atmos.*	*Age (Ma)*
P.54.1	Basalt plug	Mount Plymouth, Greenwich Island	0.305	0.002 (2)	99.6	0.2 ± 0.3
P.55.1	Basalt plug	Mount Plymouth, Greenwich Island	0.300	0.002 (2)	99.5	0.2 ± 0.4
P.51.1	Basalt lava	Gleaner Heights, Livingston Island	0.433	0.001 (2)	99.8	0.1 ± 0.4

(2) MM 1200

wich Island (samples P.54.1 and P.55.1) and a lava from Gleaner Heights on nearby Livingston Island (P.51.1) gave no measurable radiogenic Ar content and must be less than 0.5 Ma old. All are fresh olivine–pyroxene basalts with *ne*-normative compositions. Their location certainly does not conform to the south-west to north-east migration of activity noted overall, nor can they obviously be related to back-arc spreading in Bransfield Strait. They appear to have formed in a rather different tectonic environment to the calk-alkaline island arc, as has been suggested for the alkaline–olivine basalts off the east coast of Graham Land and in Marie Byrd Land (Baker and others, 1977).

XII. SUMMARY

The South Shetland Islands, south-west of the Elephant and Clarence islands group, comprise a Mesozoic to Quaternary magmatic island arc, thought to have been founded on a continental basement of schists and sedimentary rocks.

The (?) basement schists occur in isolation on the islands at each end of the group: Elephant and Clarence islands in the north-east and Smith Island in the south-west. Most are low-grade blueschists or phyllites with Na-amphibole and epidote, associated with metacherts and metabasites but, on south-eastern Elephant Island, there are coarser grained quartz-mica-garnet schists, similar to the amphibolite facies rocks of the South Orkney Islands. The idea that these 'basement' rocks constitute a paired metamorphic belt, formed from a pre-Mesozoic arc-trench gap sequence deformed during the Gondwanian orogeny, was developed by Smellie (1981). Direct evidence consistent with this comes from a crude Rb-Sr whole-rock isochron age of 280 ± 55 Ma for the South Orkney Islands' schists (Rex, 1976), and a similar result for shales in the Trinity Peninsula group at Hope Bay (Pankhurst, 1983), but Tanner and others (1982) presented evidence that at least part of the blueschist facies terrain is essentially coeval with the Mesozoic magmatism.

The False Bay schists, which occur as enclaves within an Eocene tonalite intrusion on Livingston Island, are not thought to be true basement rocks (Smellie, 1983). The other pre-arc rock formations are both sedimentary. The Miers Bluff Formation is a highly deformed clastic sequence in which inversion and much of the folding are also ascribed to the Gondwanian event. It is thought to represent part of the proto-arc subduction complex, along with the Greywacke–Shale Formation of the South Orkney Islands (Dalziel, 1982; Smellie, 1981; Hyden and Tanner, 1981). The volcaniclastic Williams Point Beds must also be related to the pre-arc geology since they contain a fossil flora now confirmed as Middle to Late Triassic in age (Lucas and Lacey, 1981). However, they are almost flat-lying and essentially undeformed.

Construction of the South Shetland Islands arc proper began in Jurassic or earliest Cretaceous times in the south-western part of the island chain (Byers Peninsula, Snow Island, Low Island). Marine sediments with Late Jurassic–Early Cretaceous marine faunas are laterally continuous with and succeeded by terrestrial volcaniclastic sandstones and conglomerates with interbedded basalt and basaltic andesite lava flows. An evolved andesite–rhyolite–ignimbrite sequence occurs at Chester Cone, Byers Peninsula and may be of secondary magmatic origin. The volcanic rocks have mostly yielded K-Ar ages concordant with an Rb-Sr isochron age of 111 Ma (Aptian), and plant remains in the terrestrial sediments near Negro Hill have been interpreted as Barremian in age. However, other lavas and sills in the same area have given ages of 74–90 Ma, which could represent either resetting of the K-Ar whole-rock systems during Cenomanian or younger intrusive events, or a continuation of volcanism and sedimentation into the Late Cretaceous. Volcanic rocks of Cretaceous age are thought to extend through north-eastern Livingston Island into Greenwich and Robert islands. Less altered basalts from Coppermine Peninsula, Robert Island, gave K-Ar ages close to 80 Ma and represent the next identifiable major phase of arc building. Some of the extensive multiple sills, which occur from Williams Point north-eastwards across the islands of MacFarlane and English straits, have yielded similar K-Ar ages and may also belong to this phase.

The volcanic rocks of western King George Island appear to be entirely Early Tertiary in age (generally 45–60 Ma). Two distinct stratigraphical sequences, the Fildes and Hennequin formations, are recognized and occupy separate geographical areas with overlap at Point Thomas, Admiralty Bay (Fig. 18).

The Fildes Formation consists of basaltic to andesitic volcanic rocks and a few interbedded terrestrial sediments, including conglomerates and shales, and is divisible into three units. The lowest unit in southern Fildes Peninsula is mostly basalt and basaltic andesite flows, which have yielded K-Ar whole-rock ages of *c.* 58 Ma (late Palaeocene). This is also true (in the present study) of the metasomatized rocks near Fildes Strait, for which previous workers have obtained older but inconsistent ages of 80–110 Ma. Basaltic andesite flows in the lower member of northern Fildes Peninsula have slightly younger K-Ar ages (48–58 Ma; Early Eocene–Late Palaeocene). The predominantly andesitic upper member has yielded K-Ar ages in the range 42–46 Ma (Eocene). Plant fossils in sediments interbedded with the lower member were previously thought to be Miocene in age (Orlando, 1964). However, this stratigraphical age is no longer tenable. At Point Thomas volcanic rocks petrographically comparable to those of the Fildes Formation unconformably overlie lavas and conglomerates of the Hennequin Formation, which is mostly andesitic in character. Nevertheless, ages for some of the latter also fall in the same range as those of the upper part of the Fildes Formation. Andesitic dykes and sills, cutting lavas of the Hennequin Formation on Keller Peninsula were dated at 41–44 Ma. There is no clear evidence for the Jurassic or Cretaceous volcanic rocks previously reported from the island. It seems more likely that the rocks thought to be of these ages are Tertiary rocks metasomatically altered by the emplacement of later plutonic rocks.

Intrusive rocks in the South Shetland Islands include

small bodies ranging from gabbro to microadamellite in composition, and emplaced mostly during the Early Tertiary stages of volcanism. Large bodies are restricted to tonalite and granodiorite of Eocene age. These occur in the False Bay–Renier Point area of Livingston Island and, by inference from discrete surface outcrops, in King George Island.

Thus the radiometric chronology together with the palaeontological evidence suggests a progressive north-easterly migration of intense volcanism from Low Island (Late Jurassic) through Livingston and Greenwich islands (?) Late Jurassic to mid-Cretaceous), Robert Island (mid-Cretaceous) to south-western King George Island (Early Tertiary) (Fig. 49). Ages of 42 ± 1 for andesite from Lions Rump and 32 ± 1 Ma for andesite from Esther Nunatak suggest that this trend continues through to Oligocene activity in north-eastern King George Island. Volcanism and ensuing hypabyssal intrusion continued in most areas for periods of 10–20 Ma. Moreover, in south-western King George Island at least, volcanic rocks of the Fildes and Hennequin formations were erupted partly penecontemporaneously from different centres so that locally the products of the former overlap with those of the latter. Thus, although the commencement of volcanism appears to migrate north-eastwards very regularly, this may not always appear so from the local stratigraphy, at least during the Early Tertiary climax of activity.

During this major phase of arc-building, there are progressive but small changes in the character of the volcanism. The early volcanic rocks are mostly fairly basic in composition with low K, Rb, Ti, Ba and La. The affinity of the basalts is generally intermediate between island-arc tholeiites with low concentrations of lithophile elements and low Rb/Sr and Ba/Sr ratios on the one hand and calc-alkaline basalts with moderately high Sr, Cr, Ca, K/Rb and slight enrichment of light REE compared with heavy REE on the other.

The Upper Cretaceous lavas of the Coppermine Formation are uniformly basaltic with higher Ni and Cr than the earlier basalts, indicating less-fractionated liquids. Never-

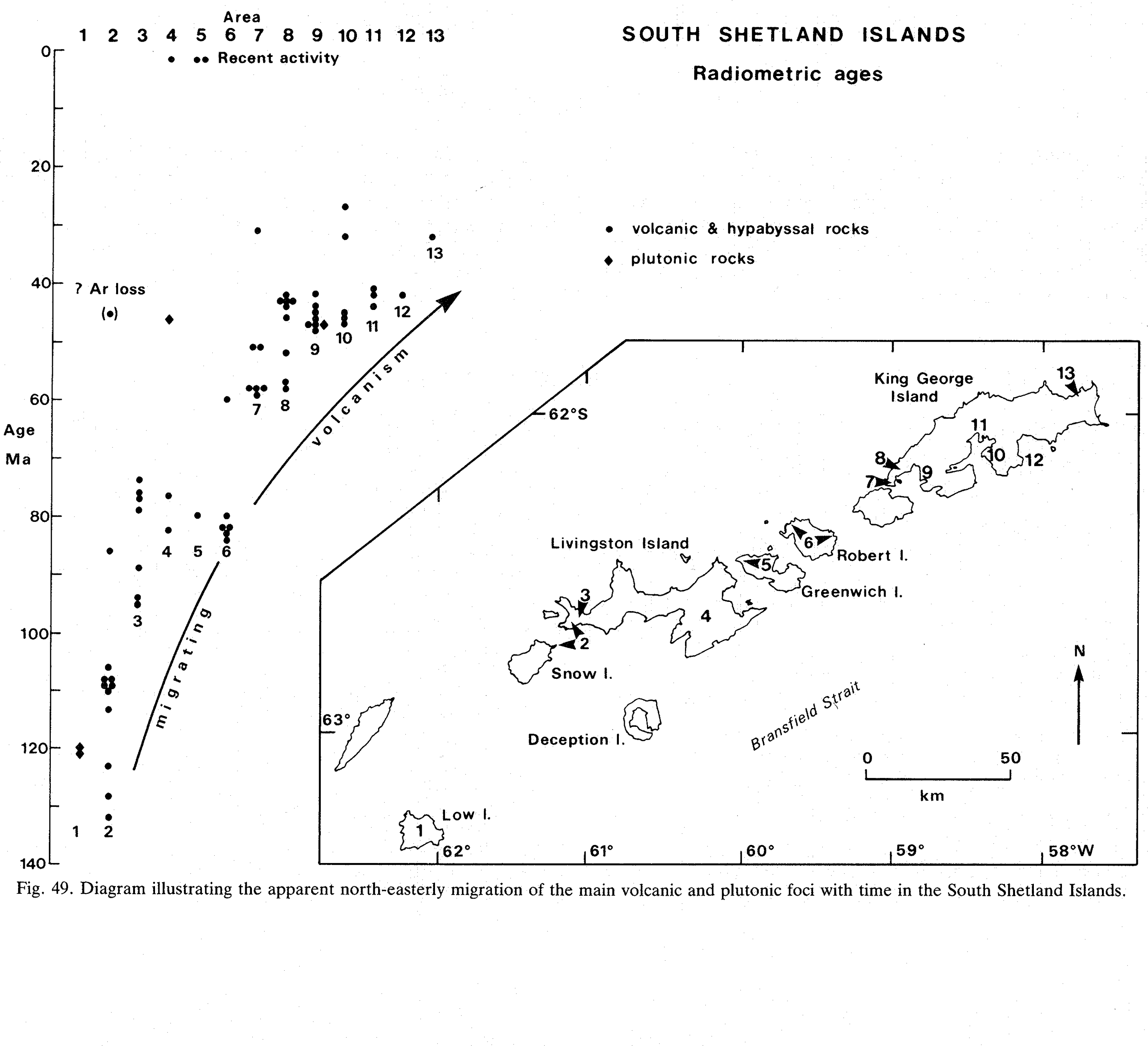

Fig. 49. Diagram illustrating the apparent north-easterly migration of the main volcanic and plutonic foci with time in the South Shetland Islands.

theless, they have high Sr contents and $\mathrm{Ce_N/Y_N}$ ratios, indicating more calc-alkaline affinities. The Fildes Formation shows a return, in Early Tertiary times, to more wide-ranging compositions (basalt to dacite, but with more basic types predominating). These tend to show considerable increase in Fe/Mg and incompatible elements such as Rb and Ba, but high Sr and $\mathrm{Ce_N/Y_N}$ are maintained, some basalts having slight 'alkaline' tendencies with respect to these last two parameters. The broadly contemporaneous Hennequin Formation and the (?) Oligocene volcanic rocks of north-eastern King George Island are composed mainly of andesites with minor dacites. Ca and Sr are relatively depleted in these rocks, whereas K and Rb are relatively enriched. They have low K/Rb and Ca/Sr ratios, but $\mathrm{Ce_N/Y_N}$ ratios which are similar to or slightly higher than the other Upper Jurassic–Tertiary volcanic rocks.

Thus the period between Late Jurassic and Tertiary times was characterized by primitive magmas, intermediate between island-arc tholeiites and calc-alkaline types. During mid-Tertiary times, the predominant type changed to calc-alkaline. There is also a trend of north-easterly decreasing initial $^{87}\mathrm{Sr}/^{86}\mathrm{Sr}$ ratios from >0.7040, as in many calc-alkaline island arcs, towards values of 0.7030–0.7035, more usually associated with simple mantle source regions.

Quaternary volcanic rocks are patchily distributed between eastern Livingston and King George islands but they are more typical of the south-eastern side of the islands, close to and within Bransfield Strait. The rocks are again dominantly basalts but in this instance they have strong alkaline affinities, about 50% of the rocks analysed being nepheline-normative. Na, Cr and Ni are all higher than in the tholeiitic and calc-alkaline types. The change in chemistry and the break in geographical migration suggests a change in the mechanism of magma production at about the time that active subduction along the South Shetland trench ceased. Baker and others (1977) proposed a switch to tensional tectonics to explain the Recent undersaturated basalts of the James Ross Island and Seal Nunataks areas, east of the Antarctic Peninsula, and this idea is also applicable to explain the observed changes in South Shetland Islands' volcanism. As shown by Pankhurst (1982) the alkalinity and $\mathrm{Ce_N/Yb_N}$ ratios of Recent basalts increase from the peninsula to maximum values in the Ross Island petrological province of Greater Antarctica, corresponding to increasing depth of melting in the mantle and a thicker lithosphere. The chemistry of the South Shetland Islands' volcanic rocks of this age would represent a still less fractionated (shallow-melting) end member for this model.

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XIV. REFERENCES

Adie, R. J. 1954. The petrology of Graham Land: I. The Basement Complex; early Palaeozoic plutonic and volcanic rocks. *Falkland Islands Dependencies Survey Scientific Reports,* No. 11, 22 pp.

Adie, R. J. 1957. The petrology of Graham Land: III. Metamorphic rocks of the Trinity Peninsula Series. *Falkland Islands Dependencies Survey Scientific Reports,* No. 20, 26 pp.

Adie, R. J. 1964. Geological history. (*In* Priestley, R. E., Adie, R. J. *and* Robin, G. de Q. *eds. Antarctic research.* London, Butterworth, 118–62.)

Adie, R. J. 1972. Evolution of volcanism in the Antarctic Peninsula. (*In* Adie, R. J., *ed. Antarctic geology and geophysics.* Oslo, Universitetsforlaget, 137–42.)

Aitkenhead, N. 1975. The geology of the Duse Bay–Larsen Inlet area, north-eastern Graham Land (with particular reference to the Trinity Peninsula Series). *British Antarctic Survey Scientific Reports.* No. 51, 62 pp.

Alarcón, B., Ambrus, J., Olcay, L. *and* Viera, C. 1976. Geología del Estrecho de Gerlache entre los parallelos 64° y 65° lat. sur, Antártica chilena. *Serie científica Instituto Antártico Chileno,* **4,** No. 1, 7–51.

Anderson, J. E. 1969. Development of snowflake texture in welded tuff, Davis Mountains, Texas. *Geological Society of America Bulletin,* **80,** No. 10, 2075–9.

Anderson, J. E. 1970*a*. Recognition and time distribution of texturally altered welded tuff. *Geological Society of America Bulletin,* **81,** No. 1, 287–91.

Anderson, J. E. 1970*b*. Snowflake texture not diagnostic of devitrified ash-flow tuffs: reply. *Geological Society of America Bulletin,* **81,** No. 8, 2529–30.

Andersson, J. G. 1906. On the geology of Graham Land. *Bulletin of the Geological Institution, University of Upsala,* **7,** 19–71.

Anon. 1821. Notizen über das neue südliche Land. *Neue allgemeine geographische Ephemeriden, Weimar,* **9,** Pt. 4, 514–5.

Araya, R. *and* Hervé, F. 1965. Serie sedimentaria volcánica con plantas en las islas Snow y Livingston. *Sociedad Geológica de Chile, Resumenes,* No. 10, 1–3.

Araya, R. *and* Hervé, F. 1966. Estudio geomorfológico y geológico en las Islas Shetland del Sur, Antártica. *Publicaciones del Instituto Antártico Chileno,* No. 8, 76 pp.

Ashcroft, W. A. 1972. Crustal structure of the South Shetland Islands and Bransfield Strait. *British Antarctic Survey Scientific Reports,* No. 66, 43 pp.

Askin, R. A. 1983. Tithonian (Uppermost Jurassic)–Barremian (Lower Cretaceous) spores, pollen and microplankton from the South Shetland Islands, Antarctica. (*In* Oliver, R. L., James, P. R. *and* Jago, J. B. *eds. Antarctic Earth science.* Cambridge, Cambridge University Press and Canberra, Australian Academy of Sciences, 295–7.)

Baker, P. E. 1972. Recent volcanism and magmatic variation in the Scotia arc. (*In* Adie, R. J., *ed. Antarctic geology and geophysics.* Oslo, Universitetsforlaget, 57–60.)

Baker, P. E., McReath, M. A., Harvey, M. R., Roobol, M. J. *and* Davies, T. G. 1975. The geology of the South Shetland Islands: V. Volcanic evolution of Deception Island. *British Antarctic Survey Scientific Reports,* No. 78, 81 pp.

Baker, P. E., Buckley, F. *and* Rex, D. C. 1977. Cenozoic volcanism in the Antarctic. (*In* Fuchs, V. E. *and* Laws, R. M., organizers. Scientific research in Antarctica. *Proceedings of the Royal Society of London, Series B,* **279,** 131–42.)

Barker, P. F. 1971. Plate tectonics of the Scotia Sea region. *Nature, London,* **228,** No. 5278, 1293–6.

Barker, P. F. 1972. Magnetic lineations in the Scotia Sea. (*In* Adie, R. J., *ed. Antarctic geology and geophysics,* Oslo, Universitetsforlaget, 17–26.)

Barker, P. F. 1976. The tectonic framework of Cenozoic volcanism in the Scotia Sea region – A review. (*In* González-Ferrán, O., *ed. Symposium on Andean and Antarctic volcanological problems.* Rome, International Association of Volcanology and Chemistry of the Earth's Interior, 330–46.)

Barker, P. F. *and* Griffiths, D. H. 1972. The evolution of the Scotia Ridge and Scotia Sea. *Philosophical Transactions of the Royal Society of London, Series A,* **271,** 151–83.

Barth, T. F. W. *and* Holmsen, P. 1939. Rocks from the Antarctandes and the Southern Antilles. Being a description of rock samples collected by Olaf Holtedahl 1927–1928, and a discussion of their mode of origin. *Scientific results of the Norwegian Antarctic Expedition,* No. 18, 64 pp.

Barton, C. M. 1964. Significance of the Tertiary fossil floras of King George Island, South Shetland Islands. (*In* Adie, R. J., *ed. Antarctic geology.* Amsterdam, North-Holland Publishing Company, 603–8.)

Barton, C. M. 1965. The geology of the South Shetland Islands: III. The stratigraphy of King George Island. *British Antarctic Survey Scientific Reports,* No. 44, 33 pp.

Bell, C. M. 1973*a.* The geology of Beethoven Peninsula, south-western Alexander Island. *British Antarctic Survey Bulletin,* No. 32, 75–83.

Bell, C. M. 1973*b.* The geology of southern Alexander Island. *British Antarctic Survey Bulletin,* Nos. 33 and 34, 1–16.

Best, M. G. 1969. Differentiation of calc-alkaline magmas. (*In* McBirney, A. R., *ed.* Proceedings of the andesite conference. *Bulletin. Oregon State Department of Geology and Mineral Industries,* No. 65, 65–75.) [International Upper Mantle Project, Scientific Report, No. 16].

Bibby, J. S. 1961. The geology of Ezcurra Inlet and Point Thomas, Admiralty Bay, King George Island, South Shetland Islands. *Falkland Islands Dependencies Survey Preliminary Geological Report,* No. 8, 10 pp. [Unpublished.]

Birkenmajer, K. 1979. A revised lithostratigraphic standard for the Tertiary of King George Island, South Shetland Islands (West Antarctica). *Bulletin de l'Academie Polonaise des Sciences, Ser. Sciences de la Terre,* **27,** Nos. 1 and 2, 49–57.

Birkenmajer, K. 1980. Geology of Admiralty Bay, King George Island (South Shetland Islands) – an outline. *Polish Polar Research,* **1,** No. 1, 29–54.

Birkenmajer, K. 1982*a.* Pliocene tillite-bearing succession of King George Island (South Shetland Islands, Antarctica). *Studia Geologica Polonica,* **74,** Pt. 3, 7–72.

Birkenmajer, K. 1982*b.* Report on geological investigations on King George Island and Nelson Island (South Shetland Islands, West Antarctica) in 1980–81. *Studia Geologica Polonica,* **74,** Pt. 3, 175–97.

Blatt, H., Middleton, G. *and* Murray, R. 1972. *Origin of sedimentary rocks.* New Jersey, Prentice-Hall Incorporated.

Buma, G., Frey, F. A. *and* Wones, D. R. 1971. New England granites: trace element evidence regarding their origin and differentiation. *Contributions to Mineralogy and Petrology,* **31,** 300–20.

Burn, R. 1981. Early Tertiary calc-alkaline volcanism on Alexander Island. *British Antarctic Survey Bulletin,* No. 53, 175–194.

Burn, R. W. *and* Thomson, M. R. A. 1981. Late Cenozoic tillites associated with intraglacial volcanic rocks, Lesser Antarctica. (*In* Hambrey, M. J. *and* Harland, W. B., *eds. Pre-Pleistocene tillites: A record of Earth's glacial history.* Cambridge, Cambridge University Press, 199–203.)

Caballero, M. A. *and* Fourcade, N. H. 1959. Observaciones geológicas en Caleta Mina de Cobre, Islas Shetland del Sur. *Contribuciones del Instituto Antártico Argentino,* No. 23, 39 pp.

Camacho, H. H. *and* Villar Fabre, J. 1959. Observaciones geológicas y petrográficas en Bahía Esperanza, Puerto Paraíso e islas Shetland del Sur y Melchior. (*In* Camacho, H. H., Villar Fabre, J., Corte, A. E. *and* Somoza, A. L. Algunas observaciones geológicas y criopedológicas en la Antártida. *Publicaciones del Instituto Antártica Argentino,* No. 4, 19–61.)

Caminos, R., Marchese, H. G., Massabie, A. C., Morelli, J. R., Rinaldi, C. A. *and* Spikermann, J. P. 1973. Geología del sector noroccidental de la Península Hurd, Isla Livingston, Shetland del Sur, Antártida argentina. *Contribuciones del Instituto Antártico Argentino,* No. 162, 32 pp.

Care, B. C. 1980. The geology of Rothschild Island, north-west Alexander Island. *British Antarctic Survey Bulletin,* No. 50, 87–112.

Carmichael, I. S. E., Turner, F. J. *and* Verhoogen, J. 1974. *Igneous petrology.* New York, McGraw-Hill.

Christie, E. W. H. 1951. *The Antarctic problem: an historical and political study.* London, George Allen and Unwin.

Codignoto, J. O., Llorente, R. A., Mendia, J. E., Olivero, E. *and* Spikermann, J. P. 1978. Geología del Cabo Spring y de las islas Leopardo, Pingüino y Cesar. *Contribuciones del Instituto Antártico Argentino,* No. 216. 41 pp.

Condie, K. C. *and* Lo, H. H. 1971. Trace element geochemistry of the Louis Lake batholith of early Precambrian age, Wyoming. *Geochimica et Cosmochimica Acta,* **35,** No. 11, 1099–119.

Covacevich, V. 1976. Fauna valanginiana de Peninsula Byers, Isla Livingston Antarctica. *Revista geológica de Chile,* No. 3, 25–56.

Covacevich, V. *and* Hernandez, P. 1971. Investigaciones paleontológicas en las Islas Shetland del Sur, Antártica 1970–1971. *Boletin. Instituto Antártico Chileno,* No. 6, 3–7.

Covacevich, V. *and* Lamperein, C. 1969. Nota sobre el hallazgo de icnitas fósiles de aves en Peninsula Fildes, Isla Rey Jorge, Shetland del Sur, Antártica. *Boletin. Instituto Antártico Chileno,* No. 4, 26–8.

Covacevich, V. *and* Lamperein, C. 1970. Hallazgo de icnitas en Peninsula Fildes, Isla Rey Jorge, Archipelago Shetland del Sur, Antártica. *Serie Cientifica, Instituto Antártico Chileno,* **1,** No. 1, 55–74.

Covacevich, V. *and* Lamperein, C. 1972. Ichnites from Fildes Peninsula, King George Island, South Shetland Islands. (*In* Adie, R. J., *ed. Antarctic geology and geophysics,* Oslo, Universitetsforlaget, 71–4.)

Covacevich, V. *and* Rich, P. V. 1982. New bird ichnites from Fildes Peninsula, King George Island, West Antarctica. (*In* Craddock, C., *ed. Antarctic geoscience,* Madison, University of Wisconsin Press, 245–54.)

Culbert, R. R. 1972. Abnormalities in the distribution of K, Rb and Sr in the Coast Mountains Batholith, British Columbia. *Geochimica et Cosmochimica Acta,* **36,** No. 10, 1091–1100.

Dalziel, I. W. D. 1969. Structural studies in the Scotia arc: Livingston Island. *Antarctic Journal of the United States,* **4,** No. 4, 137.

Dalziel, I. W. D. 1972*a.* Large-scale folding in the Scotia arc. (*In* Adie, R. J., *ed. Antarctic geology and geophysics.* Oslo, Universitetsforlaget, 47–55.)

Dalziel, I. W. D. 1972*b.* K–Ar dating of rocks from Elephant Island, south Scotia Ridge. *Geological Society of America Bulletin,* **83,** No. 6, 1887–94.

Dalziel, I. W. D. 1974. Evolution of the margins of the Scotia Sea. (*In* Burk, C. A. *and* Drake, C. L., *eds. The geology of continental margins.* Berlin, Springer-Verlag, 567–80.)

Dalziel, I. W. D. 1976. Structural studies in the Scotia arc: "basement" rocks of the South Shetland Islands (R/V *Hero* Cruise 76–1). *Antarctic Journal of the United States,* **11,** No. 2, 75–77.

Dalziel, I. W. D. 1982. The early (pre-Middle Jurassic) history of the Scotia arc region: A review and progress report. (*In* Craddock, C., *ed. Antarctic geoscience.* Madison, University of Wisconsin Press, 111–26.)

Dalziel, I. W. D., Klingfield, R., Lowrie, W. *and* Opdyke, N. D. 1973. Paleomagnetic data from the southernmost Andes and the Antarctandes. (*In* Tarling, D. H. *and* Runkorn, S. K. *ed. Implications of continental drift to the earth sciences.* New York, Academic Press, 87–101.)

Davey, F. J. 1972. Marine gravity measurements in Bransfield Strait and adjacent areas. (*In* Adie, R. J., *ed. Antarctic geology and geophysics.* Oslo, Universitetsforlaget, 39–46.)

Davies, R. E. S. 1982*a.* The geology of the Marian Cove area, King George Island, and a Tertiary age for its supposed Jurassic volcanic rocks. *British Antarctic Survey Bulletin,* No. 51, 151–65.

Davies, R. E. S. 1982*b.* New geological interpretation of Admiralen Peak, King George Island, South Shetland Islands. *British Antarctic Survey Bulletin,* No. 51, 294–6.

Davies, T. G. 1976. *The geology of part of northern Palmer Land, Antarctica.* Ph.D. Thesis, University of Birmingham, 152 pp. [Unpublished.]

Del Valle, R., Morelli, J. *and* Rinaldi, C. A. 1974. Manifestación cupro-plumbífera "Don Bernabé" Isla Livingston, Islas Shetland del Sur, Antártida Argentina. *Contribuciones del Instituto Antártico Argentino,* No. 175, 35 pp.

Diaz, H. *and* Teruggi, M. E. 1956. Descripción geológica y petrográfica de algunas localidades de la Antártida occidental. (*In* Olsacher, J., Diaz, H. *and* Teruggi, M. E. Contribución a la geológia de la Antártida occidental. *Publicaciones del Instituto Antártico Argentino,* No. 2, 79–152.)

Dickinson, W. R. 1970. Interpreting detrital modes of graywacke and arkose. *Journal of Sedimentary Petrology,* **40,** No. 2, 695–707.

Drake, M. J. *and* Weill, D. F. 1975. Partition of Sr, Ba, Ca, Y, Eu^{2+}, Eu^{3+}, and other REE between plagioclase feldspar and magmatic liquid: an experimental study. *Geochimica et Cosmochimica Acta,* **39,** No. 5, 689–712.

Edwards, C. W. 1982. New paleontologic evidence of Triassic sedimentation in West Antarctica. (*In* Craddock, C., *ed. Antarctic geoscience.* Madison, University of Wisconsin Press, 325–30.)

Eights, J. 1833. Description of a new crustaceous animal found on the shores of the South Shetland Islands, with remarks on their natural history. *Transactions of the Albany Institute,* **2,** No. 1, 53–69.

Elliot, D. H. 1965. Geology of north-west Trinity Peninsula, Graham Land. *British Antarctic Survey Bulletin,* No. 7, 1–24.

Elliot, D. H. 1966. Geology of the Nordenskjöld Coast and a comparison with north-west Trinity Peninsula. *British Antarctic Survey Bulletin,* No. 10, 1–43.

Ernst, W. G. 1961. Stability relations of glaucophane. *American Journal of Science,* **259,** No. 10, 735–65.

Ernst, W. G. 1972. Occurrence and mineralogic evolution of blueschist belts with time. *American Journal of Science,* **272,** No. 7, 657–68.

Ferguson, D. 1921. Geological observations in the South Shetland Islands, the Palmer Archipelago and Graham Land, Antarctica. *Transactions of the Royal Society of Edinburgh,* **53,** Pt. 1, No. 3, 29–55.

Fisher, R. V. 1961. Proposed classification of volcaniclastic sediments and rocks. *Geological Society of America Bulletin,* **72,** No. 9, 1409–11.

Floyd, P. A. *and* Winchester, J. A. 1975. Magma type and tectonic setting discrimination using immobile elements. *Earth and Planetary Science Letters,* **27,** 211–18.

Fourcade, N. H. 1960. Estudio geológico-petrográfico de Caleta Potter, Isla 25 de Mayo, Islas Shetland del Sur. *Publicaciones del Instituto Antártico Argentino,* No. 8, 121 pp.

Francis, P. W., Moorbath, S. *and* Thorpe, R. S. 1977. Strontium isotope data for recent andesites in Ecuador and north Chile. *Earth and Planetary Science Letters,* **37,** 197–202.

Fuenzalida, H. 1964. Coastal phenomena in the South Shetland Islands. (*In* Adie, R. J., *ed. Antarctic geology.* Amsterdam, North-Holland Publishing Company, 48–52.)

Fuenzalida, H. 1965. Serie sedimentaria volcánica con plantas en las islas Snow y Livingston. B. Informacion paleobotánica preliminar. *Sociedad geológica de Chile, Resumenes,* No. 10, 3–4.

Fuenzalida, H., Araya, R. *and* Hervé, F. 1972. Middle Jurassic flora from north-eastern Snow Island, South Shetland Islands. (*In* Adie, R. J., *ed. Antarctic geology and geophysics.* Oslo, Universitetsforlaget, 93–8.)

Gledhill, A., Rex, D. C. *and* Tanner, P. W. G. 1982. Rb–Sr and K–Ar geochronology of rocks from the Antarctic Peninsula between Anvers Island and Marguerite Bay. (*In* Craddock, C., *ed. Antarctic geoscience.* Madison, University of Wisconsin Press, 315–23.)

González-Ferrán, O. 1972. Distribution, migration and tectonic control of Upper Cenozoic volcanism in West Antarctica and South America. (*In* Adie, R. J., *ed. Antarctic geology and geophysics.* Oslo, Universitetsforlaget, 173–80.)

González-Ferrán, O. *and* Katsui, Y. 1970. Estudio integral del volcanismo cenozoico superior de las Islas Shetland del Sur, Antártica. *Serie Cientifica. Instituto Antártico Chileno,* **1,** No. 2, 123–74.

González-Ferrán, O., Katsui, Y. *and* Tavera, J. 1970. Contribución al conocimiento geológico de la Peninsula Byers de la Isla Livingston: Islas Shetland del Sur, Antártica. *Serie Científica. Instituto Antártico Chileno,* **1,** No. 1, 41–54.

Gould, R. T. 1941. The charting of the South Shetland Islands, 1819–28. *Mariner's Mirror,* **27,** No. 23, 206–42.

Griffiths, D. H., Riddihough, R. P., Cameron, H. A. D. *and* Kennett, P. 1964. Geological investigation of the Scotia arc. *British Antarctic Survey Scientific Reports,* No. 46, 43 pp.

Grikurov, G. E. *and* Dibner, A. F. 1968. Novye dannye o Serii Triniti (C_{1-2}) v zapadnoy Antarktide. *Doklady Akademii Nauk SSSR,* **179,** No. 2, 410–12. [English translation: More information on the Trinity Series (C_{1-3}) [*sic*] of western Antarctica. *Doklady (Proceedings) of the Academy of Sciences of the U.S.S.R.,* Geological sciences section, **179,** 39–41.]

Grikurov, G. E. *and* Polyakov, M. M. 1968*a*. Geologicheskoye stroenie p-ova Failds, yugo-zapadnaya okonechnost, o King Dzhordzh (Vaterloo). *Informatsionnyy Byulleten' Sovetskoy Antarkticheskoy Ekspeditsii.* No. 71, 17–24. [English translation: Geological structure of Fildes Peninsula, southeastern tip of King George Island (Waterloo). *Information Bulletin. Soviet Antarctic Expedition,* No. 71, 189–93.]

Grikurov, G. E. *and* Polyakov, M. M. 1968*b*. Novye dannye po geologii Yuzhnykh Shetlandskikh ostrovov (po polevym rabotam Trinadtsatoy sovetskoy antarkticheskoy ekspeditsii v yanvare-fevrale 1968g). *Informatsionnyy Byulleten' Sovetskoy Antarkticheskoy Ekspeditsii.* No. 71, 25–31. [English translation: New data on the geology of the South Shetland Islands (from field work by the Thirteenth Soviet Antarctic Expedition in January–February 1968). *Information Bulletin. Soviet Antarctic Expedition,* No. 71, 193–6.]

Grikurov, G. E., Krylov, A. Ya. *and* Silin, Yu. I. 1967. Absolutnyy vozrast nekotorykh porod dugi Skottia i Zemli Aleksandra I (Zapadnaya Antarktika). *Doklady Akademii Nauk SSSR,* Geology, **172,** No. 1, 168–71. [English translation: Absolute age of some rocks from the Scotia arc and Alexander I Land (western Antarctica). *Doklady (Proceedings) of the Academy of Sciences of the U.S.S.R.,* Geological sciences section, **172,** 19–22.]

Grikurov, G. E., Krylov, A. Ya., Polyakov, M. M. *and* Tsovbun, Ya. N. 1970. Vozrast porod v Severnoi chasti Antarkticheskogo poluostrova i na Yuzhnykh Shetlandskikh ostrovakh (po dannym kaliy-argonovogo metoda). *Informatsionnyy Byulleten' Sovetskoy Antarkticheskoy Ekspeditsii.* No. 80, 30–33. [English translation: Age of rocks in the northern part of the Antarctic Peninsula and on the South Shetland Islands (according to potassium-argon data). *Information Bulletin. Soviet Antarctic Expedition,* No. 80, 61–3.]

Gusev, B. V., Grikurov, G. E. *and* Polyakov, M. M. 1972. Paleomagnetizm izverzhennich porod ostrova King Dzhordzh (Antarktika). [Palaeomagnetism of igneous rocks of King George Island (Antarctica).] *Geofizicheskiye Metody Razvedki v Arktike,* **7,** 105–9.

Halle, T. G. 1913. The Mesozoic flora of Graham Land. *Wissenschäftliche Ergebnisse der schwedischen Südpolar-Expedition 1901–1903,* **3,** Lief. 14, 123 pp.

Halpern, M. 1964. Cretaceous sedimentation in the "General Bernardo O'Higgins" area of north-west Antarctic Peninsula (*In* Adie, R. J., *ed. Antarctic geology.* Amsterdam, North-Holland Publishing Company, 334–47.)

Halpern, M. 1972. Rb–Sr total rock and mineral ages from the Marguerite Bay area, Kohler Range and Fosdick Mountains (*In* Adie, R. J., *ed. Antarctic geology and geophysics.* Oslo, Universitetsforlaget, 197–204.)

Hawkes, D. D. 1961. The geology of the South Shetland Islands: I. The petrology of King George Island. *Falkland Islands Dependencies Survey Scientific Reports,* No. 26, 28 pp.

Hawkesworth, C. J., Norry, M. J., Roddick, J. C., Baker, P. E., Francis, P. W. *and* Thorpe, R. S. 1979. $^{143}Nd/^{144}Nd$, $^{87}Sr/^{86}Sr$ and incompatible element variations in calc-alkaline andesites and plateau lavas from South America. *Earth and Planetary Science Letters,* **42,** 45–57.

Hemming, R. F. *and* Rankin, P. C. 1979. Ce-anomalous lava from Rabual Caldera, Papua-New Guinea. *Geochimica et Cosmochimica Acta,* **43,** 1351–55.

Hennig, A. 1911. Le conglomérat pleistocène à Pecten de l'île Cockburn. *Wissenschäftliche Ergebnisse der schwedischen Südpolar-Expedition 1901–1903,* **3,** Lief. 10, 72 pp.

Hernández, P. J. *and* Azcárate, V. 1971. Estudio paleobotánico preliminar sobre restos de una tafoflora de la Península Byers (Cerro Negro), Isla Livingston, Islas Shetland del Sur, Antártica. *Serie Científica. Instituto Antártico Chileno,* **2,** No. 1, 15–50.

Hobbs, G. J. 1968. The geology of the South Shetland Islands: IV. The geology of Livingston Island. *British Antarctic Survey Scientific Reports,* No. 47, 34 pp.

Holtedahl, O. 1929. On the geology and physiography of some Antarctic and sub-Antarctic islands. *Scientific Results of the Norwegian Antarctic Expedition,* No. 3, 172 pp.

Hooper, P. R. 1962. The petrology of Anvers Island and adjacent islands. *Falkland Islands Dependencies Survey Scientific Reports,* No. 34, 69 pp.

Hoskins, A. K. 1963. The basement complex of Neny Fjord, Graham Land. *British Antarctic Survey Scientific Reports,* No. 43, 49 pp.

Hyden, G. *and* Tanner, P. W. G. 1981. Late Palaeozoic–early Mesozoic fore-arc basin sedimentary rocks at the Pacific margin in western Antarctica. *Geologische Rundschau,* **70,** No. 2, 529–41.

Iltchenko, L. N. 1972. Late Precambrian acritarchs of Antarctica. (*In* Adie, R. J., *ed. Antarctic geology and geophysics.* Oslo, Universitetsforlaget, 599–602.)

Jakes, P. *and* Gill, J. 1970. Rare earth elements and the island arc tholeiitic series. *Earth and Planetary Science Letters,* **9,** 17–28.

Jakes, P. *and* White, A. J. R. 1970. K/Rb ratios of rocks from island arcs. *Geochimica et Cosmochimica Acta,* **34,** No. 8, 849–56.

Jakes, P. *and* White, A. J. R. 1972. Major trace element abundances in volcanic rocks of orogenic areas. *Geological Society of America Bulletin,* **83,** No. 1, 29–40.

Jefferson, T. H. 1980. Angiosperm fossils in supposed Jurassic volcanogenic shales, Antarctica. *Nature, London,* **285,** No. 5761, 157–8.

John, B. S. *and* Sugden, D. E. 1971. Raised marine features and phases of glaciation in the South Shetland Islands. *British Antarctic Survey Bulletin,* No. 24, 45–111.

Kuryvial, R. J. 1976. Element partitioning in alkali feldspars from three intrusive bodies of the central Wasatch range, Utah. *Geological Society of America Bulletin,* **87,** No. 5, 657–60.

Lacey, W. S. *and* Lucas, R. C. 1981. The Triassic flora of Livingston Island, South Shetland Islands. *British Antarctic Survey Bulletin,* No. 53, 157–73.

Lambert, R. S. J. *and* Holland, J. G. 1974. Yttrium geochemistry applied to petrogenesis utilizing calcium-yttrium relationships in minerals and rocks. *Geochimica et Cosmochimica Acta,* **38,** No. 9, 1393–1414.

Lemasurier, W. E. 1972. Volcanic record of Cenozoic glacial history of Marie Byrd Land. (*In* Adie, R. J., *ed. Antarctic geology and geophysics.* Oslo, Universitetsforlaget, 251–60.)

Lemasurier, W. E. *and* Rex, D. C. 1982. Volcanic record of Cenozoic glacial history in Marie Byrd Land and western Ellsworth Land: Revised chronology and evaluation of tectonic factors. (*In* Craddock, C., *ed. Antarctic geoscience.* Madison, University of Wisconsin Press, 725–34.)

Lofgren, G. 1971. Experimentally produced devitrification textures in natural rhyolite glass. *Geological Society of America Bulletin,* **82,** No. 1, 111–24.

Lucas, R. C. *and* Lacey, W. S. 1981. A permineralized wood flora of probable early Tertiary age from King George Island, South Shetland Islands. *British Antarctic Survey Bulletin,* No. 53, 147–51.

Miers, J. 1820. Account of the discovery of New South Shetland, with observations on its importance in a geographical, commercial and political point of view. *Edinburgh Philosophical Journal,* **9,** Pt. 4, No. 6, 367–80.

Miller, J. A. 1960. Potassium–argon ages of some rocks from the South Atlantic. *Nature, London,* **187,** No. 4742, 1019–20.

Miyashiro, A. 1973. *Metamorphism and metamorphic belts.* London, George Allen and Unwin.

Nathorst, A. G. 1907. On the Upper Jurassic flora of Hope Bay, Graham Land. *Comptes rendus. 10th International geological Congress, Mexico, 1906,* **10,** Pt. 2, 1269–70.

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

Nockolds, S. R. *and* Allen, R. 1953. The geochemistry of some igneous rock series. *Geochimica et Cosmochimica Acta,* **4,** No. 3, 105–42.

Olsacher, J. 1958. Observaciones geológicas en Caleta Armonía, Isla Nelson, *Contribuciones del Instituto Antártico Argentino,* No. 20, 25 pp.

Orlando, H. A. 1963. La flora fósil en las inmediaciones de la Península Ardley, Isla 25 de Mayo, Islas Shetland del Sur. *Contribuciones del Instituto Antártico Argentino,* No. 79, 14 pp.

Orlando, H. A. 1964. The fossil flora of the surroundings of Ardley Peninsula [Ardley Island], 25 de Mayo Island [King George Island], South Shetland Islands (*In* Adie, R. J., *ed. Antarctic geology.* Amsterdam, North-Holland Publishing Company, 629–36.)

Orlando, H. A. 1967. Primera florula Triasica de la Antártida occidental. *Contribuciones del Instituto Antártico Argentino,* No. 118, 16 pp.

Orlando, H. A. 1968. A new Triassic flora from Livingston Island, South Shetland Islands. *British Antarctic Survey Bulletin,* No. 16, 1–13.

Orlando, H. A. 1971. Las floras fósiles de Antártida occidental y sus relaciones estratigráficas. *Contribuciones del Instituto Antártico Argentino,* No. 140, 12 pp.

Pankhurst, R. J. 1982. Sr-isotope and trace element geochemistry of Cenozoic volcanic rocks from the Scotia arc and northern Antarctic Peninsula. (*In* Craddock, C., *ed. Antarctic geoscience,* Madison, University of Wisconsin Press, 229–34.)

Pankhurst, R. J. 1983. Rb–Sr age constraints of basement rocks of the Antarctic Peninsula. (*In* Oliver, R. L., James, P. R. *and* Jago, J. B., *eds. Antarctic Earth science,* Cambridge, Cambridge University Press and Canberra, Australian Academy of Sciences, 367–71.)

Pankhurst, R. J., Weaver, S. D., Brook, M. *and* Saunders, A. D. 1980. K–Ar chronology of Byers Peninsula, Livingston Island, South Shetland Islands. *British Antarctic Survey Bulletin,* No. 49, 277–82.

Pearce, J. A. *and* Cann, J. R. 1973. Tectonic setting of basic volcanic rocks determined using trace element analyses. *Earth and Planetary Science Letters,* **19,** 290–300.

Pettijohn, F. H., Potter, P. E. *and* Siever, R. 1972. *Sand and sandstone.* New York, Springer-Verlag.

Philippi, R. A. 1887. *Fósiles terciarios y cuatarios de Chile.* Santiago.

Philpotts, J. A. *and* Schnetzler, C. C. 1970. Phenocryst-matrix partition coefficients for K, Rb, Sr and Ba, with applications to anorthosite and basalt genesis. *Geochimica et Cosmochimica Acta,* **34,** No. 3, 307–22.

Plumstead, E. P. 1964. Palaeobotany of Antarctica. (*In* Adie, R. J., *ed. Antarctic geology,* Amsterdam, North-Holland Publishing Company, 637–54.)

Quartino, B. J. 1959. Rocas eruptivas de Caleta Armonía, Isla Nelson, Shetland del Sur. *Contribuciones del Instituto Antártico Argentino,* No. 25, 26 pp.

Rao, A. R. 1953. Some observations on the Rajmahal flora. *Palaeobotanist,* **2,** 25–28.

Rex, D. C. 1972. K–Ar age determinations on volcanic and associated rocks from the Antarctic Peninsula and Dronning Maud Land. (*In* Adie, R. J., *ed. Antarctic geology and geophysics.* Oslo, Universitetsforlaget, 133–6.)

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

Rex, D. C. *and* Baker, P. E. 1973. Age and petrology of the Cornwallis Island granodiorite. *British Antarctic Survey Bulletin,* No. 32, 55–61.

Richards, T. A. *and* McTaggart, K. C. 1976. Granitic rocks of the southern Coast Plutonic Complex and northern Cascades of British Columbia. *Geological Society of America Bulletin,* **87,** No. 6, 935–53.

Rivano, S. *and* Cortés, R. 1976. Note on the presence of the lawsonite-sodic amphibole association on Smith Island, South Shetland Islands, Antarctica. *Earth and Planetary Science Letters,* **29,** 34–6.

Ross, C. S. *and* Smith, R. L. 1961. Ash-flow tuffs: Their origin, geologic relations and identification. *U.S. Geological Survey Professional Paper,* No. 366, 81 pp.

Rutford, R. H., Craddock, C., White, C. M. *and* Armstrong, R. L. 1972. Tertiary glaciation in the Jones Mountains. (*In* Adie, R. J., *ed. Antarctic geology and geophysics.* Oslo, Universitetsforlaget, 239–43.)

Saunders, A. D., Weaver, S. D. *and* Tarney, J. 1982. The pattern of Antarctic Peninsula plutonism. (*In* Craddock, C., *ed. Antarctic geoscience,* Madison, University of Wisconsin Press, 305–14.)

Schauer, O. C. *and* Fourcade, N. H. 1963. Estudio geológico–petrográfico del extremo occidental de la Isla 25 de Mayo, Islas Shetland del Sur. *Contribuciones del Instituto Antártico Argentino,* No. 78, 14 pp.

Schauer, O. C. *and* Fourcade, N. H. 1964. Geological–petrological study of the western end of 25 de Mayo Island (King George Island), South Shetland Islands. (*In* Adie, R. J., *ed. Antarctic geology,* Amsterdam, North-Holland Publishing Company, 487–91.)

Schauer, O. C., Fourcade, N. H. *and* Dallinger, R. E. 1961. Contribución al conocimiento geológico del extremo occidental de Isla 25 de Mayo y Península Ardley, Islas Shetland del Sur. *Contribuciones del Instituto Antártico Argentino,* No. 60, 16 pp.

Schopf, J. M. 1973. Plant material from the Miers Bluff Formation of the South Shetland Islands. *Report. Institute of Polar Studies. Ohio State University,* No. 45, 45 pp.

Sherrat, R. 1821. Observations on South Shetland. *Imperial Magazine, London,* columns 1214–18.

Singleton, D. G. 1980. The geology of the central Black Coast, Palmer Land. *British Antarctic Survey Scientific Reports,* No. 102, 47 pp.

Smellie, J. L. 1980. The geology of Low Island, South Shetland Islands, and Austin Rocks. *British Antarctic Survey Bulletin*, No. 49, 239–57.

Smellie, J. L. 1981. A complete arc-trench system recognized in Gondwana sequences of the Antarctic Peninsula region. *Geological Magazine*, **118**, No. 2, 139–59.

Smellie, J. L. 1983. Syn-plutonic origin and Tertiary age for the (?) Precambrian False Bay schists of Livingston Island, South Shetland Islands. *British Antarctic Survey Bulletin*, No. 52, 21–32.

Smellie, J. L. *and* Clarkson, P. D. 1975. Evidence for pre-Jurassic subduction in western Antarctica. *Nature, London*, **258**, No. 5537, 701–2.

Smellie, J. L., Davies, R. E. S. *and* Thomson, M. R. A. 1980. Geology of a Mesozoic intra-arc sequence on Byers Peninsula, Livingston Island, South Shetland Islands. *British Antarctic Survey Bulletin*, No. 50, 55–76.

Smith, C. G. 1977. *The geology of parts of the west coast of Palmer Land, Antarctica*. Ph.D. thesis, University of Birmingham, 193 pp. [Unpublished].

Steiger, R. H. *and* Jäger, E. 1977. Subcommission on geochronology: convention on the use of decay constants in geo- and cosmochronology. *Earth and Planetary Science Letters*, **36**, 359–62.

Stipanicic, P. N. *and* Bonetti, M. I. R. 1970. Posiciones estratigráficas y edades de las principales floras jurásicas argentinas. II. Floras doggerianas y málmicas. *Ameghiniana*, **7**, No. 2, 101–18.

Suárez, M. 1976. Plate-tectonic model for southern Antarctic Peninsula and its relation to southern Andes. *Geology*, **4**, No. 4, 211–14.

Tanner, P. W. G., Pankhurst, R. J. *and* Hyden, G. 1982. Radiometric evidence for the age of the subduction complex in the South Orkney and South Shetland islands, West Antarctica. *Journal of the Geological Society of London*, **139**, Pt. 6, 683–90.

Tarney, J., Weaver, S. D. *and* Saunders, A. D. 1977. Geochemistry of volcanic rocks from the island arcs and marginal basins of the Scotia arc region. (*In* Talwani, M. *and* Pitman, W. C., *ed. Island arcs, deep sea trenches and back-arc basins*. Washington, American Geophysical Union, 367–78.)

Tarney, J., Weaver, S. D., Saunders, A. D., Pankhurst, R. J. *and* Barker, P. F. 1982. Volcanic evolution of the northern Antarctic Peninsula and the Scotia arc. (*In* Thorpe, R. S., *ed. Andesites: Orogenic andesites and related rocks*. Chichester, John Wiley & Sons, 371–400.)

Tavera, J. J. 1970. Fauna Titoniana-Neocomiana de Isla Livingston, Islas Shetland del Sur, Antártica. *Serie Científica. Instituto Antártico Chileno*, **1**, No. 2, 175–86.

Taylor, B. J., Thomson, M. R. A. *and* Willey, L. E. 1979. The geology of the Ablation Point–Keystone Cliffs area, Alexander Island. *British Antarctic Survey Scientific Reports*, No. 82, 65 pp.

Thomas, H. H. 1921. On the Innes Wilson collection of rocks and minerals from the South Shetland Islands and Trinity Island. *Transactions of the Royal Society of Edinburgh*, **53**, Pt. 1, No. 5, 81–9.

Thomson, J. W. 1968. The geology of the South Orkney Islands: II. The petrology of Signy Island. *British Antarctic Survey Scientific Reports*, No. 62, 30 pp.

Thomson, J. W. 1973. The geology of Powell, Christoffersen and Michelsen islands, South Orkney Islands. *British Antarctic Survey Bulletin*, Nos. 33 and 34, 137–68.

Thomson, J. W. 1974. The geology of the South Orkney Islands: III. Coronation Island. *British Antarctic Survey Scientific Reports*, No. 86, 39 pp.

Thomson, M. R. A. 1975. New palaeontological and lithological observations on the Legoupil Formation, north-west Antarctic Peninsula. *British Antarctic Survey Bulletin*, Nos. 41 and 42, 169–85.

Thomson, M. R. A. 1977. An annotated bibliography of the paleontology of Lesser Antarctica and the Scotia Ridge. *New Zealand Journal of Geology and Geophysics*, **20**, No. 5, 865–904.

Thomson, M. R. A. 1982*a*. Mesozoic paleogeography of West Antarctica. (*In* Craddock, C., *ed. Antarctic geoscience*. Madison, University of Wisconsin Press, 331–7.)

Thomson, M. R. A. 1982*b*. Late Jurassic fossils from Low Island, South Shetland Islands. *British Antarctic Survey Bulletin*, No. 56, 25–35.

Thomson, M. R. A. *and* Burn, R. W. 1977. Angiosperm fossils from latitude 70°S. *Nature, London*, **269**, No. 5624, 139–41.

Traill, T. S. 1822. Mineralogische Notiz von und aus Neu-Süd-Shetland. *Neue allgemeine geographische Ephemeriden, Weimar*, **10**, Pt. 1, 99–102.

Turner, F. J. 1968. *Metamorphic petrology. Mineralogical and field aspects*. New York, McGraw-Hill Book Company.

Tyrrell, G. W. 1921. A contribution to the petrography of the South Shetland Islands, the Palmer Archipelago, and the Danco Coast, Graham Land, Antarctica. *Transactions of the Royal Society of Edinburgh*, **53**, Pt. 1, No. 4, 57–79.

Tyrrell, G. W. 1945. Report on rocks from West Antarctica and the Scotia Arc. *Discovery Reports*, **23**, 37–102.

US Oceanographical Office. 1960. *Sailing directions for Antarctica, including islands south of latitude 60°*. Washington, US Government Printing Office.

Valencio, D. A. *and* Fourcade, N. H. 1969. Estudio paleomagnetico y petrográfico de algunas formaciones cenozoicas de las Islas Shetland del Sur. *Contribuciones del Instituto Antártico Argentino*, No. 125, 25 pp.

Valencio, D. A., Mendía, J. E. *and* Vilas, J. F. 1979. Palaeomagnetism and K–Ar age of Mesozoic and Cenozoic igneous rocks from Antarctica. *Earth and planetary Science Letters*, **45**, 61–8.

Valenzuela, E. *and* Hervé, F. 1972. Geology of Byers Peninsula, Livingston Island, South Shetland Islands. (*In* Adie, R. J., *ed. Antarctic geology and geophysics*. Oslo, Universitetsforlaget, 83–90.)

Villaroel, H. S. 1966. Estudio cristalográfico de minerales de la Antártica. I Parte. *Publicaciones del Instituto Antártico Chileno*, No. 12, 25 pp.

Watts, D. R. 1982. Potassium–argon ages and paleomagnetic results from King George Island, South Shetland Islands. (*In* Craddock, C., *ed. Antarctic geoscience*. Madison, University of Wisconsin Press, 255–61.)

Weaver, S. D., Saunders, A. D., Pankhurst, R. J. *and* Tarney, J. 1979. A geochemical study of magmatism associated with the initial stages of back-arc spreading. The Quaternary rocks of Bransfield Strait, South Shetland Islands. *Contributions to Mineralogy and Petrology*, **68**, No. 2, 151–69.

Weaver, S. D., Saunders, A. D. *and* 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, 263–73.)

West, S. M. 1974. Geology of the Danco Coast, Graham Land. *British Antarctic Survey Scientific Reports*, No. 84, 58 pp.

Willey, L. E. 1973. Belemnites from south-eastern Alexander Island: II. The occurrence of the family Belemnopseidae in the Upper Jurassic and Lower Cretaceous. *British Antarctic Survey Bulletin*, No. 36, 35–59.

Williams, P. L., Schmidt, D. L., Plummer, C. C. *and* Brown, L. E. 1972. Geology of the Lassiter Coast area, Antarctic Peninsula: Preliminary report. (*In* Adie, R. J., *ed. Antarctic geology and geophysics*. Oslo, Universitetsforlaget, 143–8.)

Winkler, H. G. F. 1974. *Petrogenesis of metamorphic rocks*. 3rd edition. Berlin, Springer-Verlag.

APPENDIX

ANALYTICAL METHODS

1. K-Ar dating

An extensive programme of K-Ar dating of 75 rocks and a few separated minerals has been carried out in order to delimit the chronology of igneous activity in the South Shetland Islands. The first part of this work, on the Mesozoic rocks of Byers Peninsula, has been published previously (Pankhurst and others, 1980). The new data are presented in Tables XV, XVIII, XIX and XX. All the analyses were carried out at the British Geological Survey, Grays Inn Road, London

Whole-rock samples were selected to be as free as possible of petrographic alteration and were prepared in a number of different ways. After removal of weathered surfaces and jaw-crushing to *c.* 1–3 mm, some samples were analysed for Ar directly, a small aliquot of the material being ground to a fine powder for K analysis. Most samples, however, were ground and sieved, both Ar and K being analysed in the 60–85 mesh size fraction. Where direct comparison with the former method was made this was found to result in a lower proportion of atmospheric Ar (Pankhurst and others, 1980), presumably due to the loss of fine-grained alteration on products in the 85 mesh fractions. Some of the more altered samples were ultrasonically washed in dilute HNO_3 to remove carbonates prior to analysis.

K determinations were performed at least in duplicate by dissolution with $HF/HClO_4$ and flame emission spectrophotometry, with an Instrumentation Laboratory IL543 flame photometer, using Li as an internal standard. Linearity at half-scale reading was checked on each occasion and only replicates which agreed to within 1.5% were accepted. The K contents of standard samples determined in this way were: BCR–1 = 1.440%, JB–1 = 1.192%; JG–1 = 3.341%; GL–0 = 6.596%. Comparison with the results obtained in the Byers Peninsula work suggests that the ages already published (Pankhurst and others, 1980) could be about 2% high relative to the new results, because of systematic differences in K-determination.

Ar was determined by isotope dilution with a ^{38}Ar spike, following fusion under vacuum in a molybdenum crucible. Samples were baked to 150–200°C overnight prior to fusion. Until about half way through the programme, the mixed gasses were cleaned up using liquid N_2 cold traps and Ti sponge heated by the same radio-frequency induction heater used for sample fusion, and analysed statically on an AEI MS10 mass-spectrometer with simple manual peak switching. Subsequently a new extraction system was employed with four separately valved fusion lines and resistance-heated Ti sponge furnaces. Latterly, one of these Ti furnaces was replaced by a Ti-wire sublimation pump. The new system was constructed by VG Isotopes Ltd and the gasses were analysed on a 12 cm radius MM1200 mass-spectrometer with an electromagnet and a source potential of 3 kV. Peak switching was carried out automatically under the control of a Hewlett Packard 9830A calculator, and memory effects were corrected by subtracting initial background peak measurements and extrapolating peak ratios back to the time of sample inlet. C. C. Rundle (British Geological Survey) devised the analysis programme. All samples previously analysed on the MS10 were re-analysed on the MM1200 and generally the agreement overall is acceptable. Many samples were analysed more than once on both systems and the data presented in Tables XV, XVIII, XIX and XX are averages. Reproducibility was sometimes poor for whole-rocks (± 10%), possibly due to the unavoidable presence of zeolite minerals and consequent heterogeneous distribution of Ar.

Ages were calculated using the conventional constants recommended by Steiger and Jäger (1977).

2. *Rb-Sr dating*

Most rocks from the South Shetland Islands are unsuitable for Rb-Sr dating because of their low Rb/Sr ratios and/or young ages. A suite of acid rocks from Chester Cone, Byers Peninsula was analysed as an independent check on the published K-Ar data from this area (Pankhurst and others, 1980). Rb and Sr were determined by X-ray fluorescence, with errors largely controlled by counting statistics. Sr was separated by standard ion exchange and its isotopic composition determined on a fully automated VG Micromass 30 spectrometer. Two biotite and hornblende separates were also analysed by mass-spectrometric isotope dilution, using the same procedure but with the addition of ^{87}Rb- and ^{84}Sr-enriched spikes.

Previously published ages have been recalculated to the decay constants recommended by Steiger and Jäger (1977). Throughout this report, ages are quoted with two-sigma errors wherever these can be ascertained; in some previous publications the confidence limits were not specified.