FINAL COPY with minor alterations

MESOZOIC-CAINOZOIC VOLCANISM IN THE SOUTH SHETLAND ISLANDS AND THE ANTARCTIC PENINSULA: GEOCHEMICAL NATURE AND PLATE TECTONIC SIGNIFICANCE.

Stephen Andrew John
~~S~~.D. Weaver, ~~A~~.D. Saunders and ~~J~~. Tarney.

Department of Geological Sciences,
University of Birmingham,
BIRMINGHAM B15 2TT,
U.K.

(Telephone 021-472-1301, Extension 3147)

2 Tables
10 Text Figures

GL03994

(A)

ABSTRACT

The South Shetland Islands form an ensialic island arc with a volcanic history extending back at least 140 Ma. The island block separated from the Antarctic Peninsula during the last 4 Ma or so with the opening of Bransfield Strait, an incipient marginal basin now 65 km wide.

Mesozoic volcanism in the S. Shetland Is. was dominated by the eruption of low-K calc-alkaline basalts and basaltic andesites. In the Antarctic Peninsula calc-alkaline igneous rocks yield ages up to about 180 Ma and were related to subduction of Pacific Ocean lithosphere along the west side of the Peninsula. Mesozoic volcanics vary from dominantly basaltic on the west side of the Peninsula to dominantly rhyolitic on the east. The tectonic setting and the chemistry of the east coast silicic volcanics is similar to that of the extensive Tobifera silicic volcanics of southernmost South America.

In the Tertiary, subduction and related magmatism probably ceased progressively from south to north along the Antarctic Peninsula as sections of spreading ridge arrived at the continental margin, and as the Pacific and Antarctic Plates became coupled. Spreading in west Drake Passage and subduction opposite the S. Shetland Islands continued throughout the Tertiary. Early Tertiary volcanics are intermediate in character between island-arc tholeiite and calc-alkaline types. However, Plio-Pleistocene volcanism on the S. Shetland Islands had an incompatible-element enriched, more distinctly calc-alkaline nature, and may have heralded the opening of Bransfield Strait.

Bransfield Strait appears to have opened as spreading in west Drake Passage and subduction at the S. Shetland trench ceased. The Quaternary volcanoes of Deception and Bridgeman are situated on the axis of back-arc spreading, and their lavas have geochemical characteristics intermediate between calc-alkaline and ocean-floor type, consistent with ensialic marginal basin development.

Ⓐ

INTRODUCTION

The Antarctic Peninsula is a long, narrow sliver of continental crust bordered by oceanic crust of the Pacific to the west and the Weddell Sea to the east. There are many geological similarities between the Antarctic Peninsula and the Andean cordillera of southernmost Chile. Indeed, the abrupt termination of structural and geological features at Cape Horn and at the northern end of the Peninsula suggests that these two areas were in some way continuous during the early Mesozoic (Barker and Griffiths, 1972; Dalziel and Elliot, 1973; Barker and Griffiths, 1977). The details of this relationship are still not well known. In particular, evidence of early plate motions is largely dependent upon interpretation of the sedimentary, igneous and tectonic records.

The aim of this paper is to monitor the geochemical pattern of volcanism in the Peninsula, both in space and time, in relation to the progressively changing plate-tectonic regime following the break-up of Gondwanaland. Comparisons will also be made with southernmost South America. There was widespread calc-alkaline igneous activity in both areas during the Mesozoic; this continued into the late Tertiary in the northern part of the Antarctic Peninsula with the last vestiges occurring on the South Shetland Islands.

The magmatic record of subduction along the west coast of the Antarctic Peninsula extends at least as far back as the Lower Jurassic (Rex, 1976). Magmatism persisted until mid-Tertiary times when subduction ceased along most of the Peninsula as the Pacific and Antarctic plates became coupled (Hayes and Ewing, 1970; Herron and Tucholke, 1976).

The identification of magnetic anomalies in the south-east Pacific, south-west of the Hero Fracture Zone (Figure 1) indicates that ocean crust was being generated in this area from the late Cretaceous (Herron and Tucholke, 1976). Since the Palaeocene there appears to have been a progressive northeastward consumption of the spreading sections (Aluk Ridge) and concomitant cessation of subduction along the western margin of the Antarctic Peninsula.

The formation of the Scotia Sea is considered to be an essentially Tertiary event (Barker and Griffiths, 1972; Barker and Burrell, 1977), accomplished by spreading in east Drake Passage from about 30 Ma. Late Tertiary lineations west of the Shackleton Fracture zone parallel the line of the South Shetland Islands. Only extremely slow spreading has been taking place since about 4 Ma (Barker, 1976) and the South Shetland trench (Figure 1) has become partially buried.

The islands of the South Shetland group (Figure 2) constitute an ensialic crustal block separated from the tip of the Antarctic Peninsula by Bransfield Strait and lying at the western extremity of the south Scotia Ridge. Bransfield Strait is an asymmetric graben-like structure of extensional origin (Ashcroft, 1972; Barker, 1976). The precise age of opening has yet to be established but the formation of the basin appears to be causally related to the geologically recent subduction at the South Shetlands trench and may still be in progress. The Recent volcanoes of Deception and Bridgeman Islands lie astride the axial magnetic anomaly along the line of Bransfield trough (Barker, 1976). Penguin Island lies at the north-western faulted-bounded margin of Bransfield Strait. Recent volcanic activity has also occurred in the vicinity of James Ross Island and Seal Nunataks, off the east coast of the Peninsula (Figure 1).

INSERT FIGURE 1 ABOUT HERE

Volcanic rocks from four main areas have been studied.

1. Mesozoic succession of the Danco Coast on the west coast of the Antarctic Peninsula.
2. Mesozoic succession of the Oscar II, Foyn and Bowman Coasts on the east coast of the Antarctic Peninsula.
3. Mesozoic volcanic rocks of the Tobifera Series of the Islas de los Estados, Tierra del Fuego.
4. Mesozoic-Cainozoic successions of the South Shetland Islands, Bransfield Strait and the James Ross Island Volcanic Group.

MESOZOIC VOLCANIC ROCKS OF THE ANTARCTIC PENINSULA

Calc-alkaline volcanics referred by B.A.S. geologists to the 'Upper Jurassic Volcanic Group' have a widespread occurrence on both the west and east coasts of the Antarctic Peninsula (Adie, 1972). The volcanics comprise a basalt-andesite-rhyolite suite and have usually near-horizontal dispositions, the maximum recorded thickness of about 3000 m being on the east coast of Graham Land.

At Hope Bay, on Trinity Peninsula, a sequence of rhyolites lies conformably above, and is interbedded with, sediments of Middle Jurassic age (Adie, 1964; Bibby, 1966). Andesitic pyroclastic rocks occur in Aptian sediments on Alexander Island (Horne, 1968). Rex (1968) reports K/Ar ages on rocks from the 'Upper Jurassic Volcanic Group' in the range 186-86 Ma but of course young apparent ages may represent thermal resetting by 'Andean' intrusions. Ages in the range 140-90 Ma may be confidently inferred for the volcanic succession of Byers Peninsula, Livingston Island. The term 'Upper Jurassic Volcanic Group' seems therefore to be no longer justified and we prefer the informal description 'Mesozoic volcanics'.

Samples used in this study from the Danco Coast (Figure 1) have been described by West (1974); those from the Oscar II, Foyn and Bowman Coasts (Figure 1) were described by Fleet (1968), Marsh (1968) and Stubbs (1968).

Ⓐ

TOBIFERA SERIES OF ISLAS DE LOS ESTADOS

In the Middle-Upper Jurassic, vast extrusions of dacite-rhyolite lavas and pyroclastic rocks occurred over much of southern South America giving rise to a lithostratigraphic unit of widespread continuity (Ludwig et al 1968) which extends from the Patagonian massif to Tierra del Fuego and from the western Cordillera to the eastern continental shelf. These volcanic rocks are know as the 'Serie Tobifera' and include silicic tuffs, ignimbrites, lavas and associated quartz-feldspar-porphyry flows and intrusives.

At the southern margin of South America the silicic volcanics are abruptly terminated by the north Scotia Ridge. On Islas de los Estados, east of Tierra del Fuego (Fig. 1) a thick sequence of silicic volcanics is interbedded with shallow marine sediments (Dalziel et al, 1974). The structure of Islas de los Estados is representative of a considerable length of the High Cordillera of Tierra del Fuego (Dalziel et al, 1974) but the Pacific side of the Cordillera is absent south of the island, presumably having been translated along the north Scotia Ridge.

Although lithological variations within the Serie Tobifera are not well known, the volcanics appear to become progressively less silicic from east to west (I.W.D. Dalziel, pers.comm.), a situation analagous to that in the Antarctic Peninsula.

Ⓐ

SOUTH SHETLAND ISLANDS

The islands are composed largely of Mesozoic-Cainozoic igneous rocks but have had an earlier geological history similar to that of the Antarctic Peninsula (Adie, 1964). The detailed stratigraphy of the volcanic successions of the South Shetland Islands is to be found in Hawkes 1961a; 1961b; Barton, 1965; Hobbs, 1968 and Baker and others, 1975.

Four groups of volcanic rocks on the South Shetland Islands have been studied (Figure 2).

1. Mesozoic basalt-rhyolite suite of Byers Peninsula, Livingston Island.
2. Lower Tertiary basalts of Fildes Peninsula, King George Island.
3. Plio-Pleistocene basalts and andesites of the south coast of King George Island.
4. Recent volcanic rocks of Deception, Bridgeman and Penguin Islands.

In addition five samples have been obtained from Seal Nunataks as representatives of the James Ross Island Volcanic Group.

INSERT FIGURE 2 ABOUT HERE

Ⓑ Byers Peninsula, Livingston Island

The geology of Byers Peninsula is described by Valenzuela and Hervé (1972) and by Pankhurst and others (in press). Marine shales and sandstones containing a Tithonian-Valanginian fauna (Covacevich, 1976) are conformably overlain by a non-marine sequence of dominantly arenaceous deposits. Basalts, andesites and rhyolites are interbedded with the sediments which are cut by numerous plugs, sills and dykes. K/Ar age determinations indicate that the intrusive and extrusive rocks from the non-marine sequence have ages in the range 125-90 Ma (Pankhurst and others, in press).

Zeolitised flows interbedded with the underlying fossiliferous marine sediments are unsuitable for dating but an age-range of about 140-90 Ma (U. Jurassic - U. Cretaceous) may be inferred for the total succession.

Ⓑ Fildes Peninsula, King George Island

This area is composed of basalt and andesite lavas with subordinate tuffaceous sediments. The volcanic pile is cut by numerous dykes and several large dolerite plugs. Recently obtained K/Ar ages suggest that the whole of the Peninsula is Tertiary in age; most lavas have yielded dates in the range 60-56 Ma and intrusives, 50-46 Ma.

Ⓑ Plio-Pleistocene lavas of southern King George Island

Basaltic and andesitic lavas from four small areas on the southern margin of King George Island are considered here. Those at Lion's Rump (Figure 2) are probably the oldest of the group, immediately underlying the Pecten Conglomerate of Pliocene age (M. Thomson, pers. comm.). Lavas and pyroclastic debris are banked against older, presumably Tertiary, volcanics at Cinder Spur, Martin's Head and Turret Point (Figure 2). The presence of readily recognizable volcanic vents and the unconsolidated nature of the associated tephra suggest that these deposits can be no more than a few million years old. In each case the Plio-Pleistocene volcanics appear to represent remnants of the flanks of volcanoes which lay to the south of the present outcrop and have been downfaulted into what is now Bransfield Strait.

Ⓑ Deception Island

The island is an active, composite stratovolcano about 14 km in diameter and possesses a caldera, 10 km in diameter. Its geology has been described by Hawkes (1961b), Gonzalez-Ferran and Katsui (1970) and by Baker and others (1975). The deposits may be ascribed to pre- and post-caldera events. Pyroclastic rocks predominate, lavas accounting for only 10-20% of the exposed portion of the volcano. Pre-caldera lavas are predominantly basaltic and there has been a general trend towards more evolved dacitic compositions with time although basaltic magma appears to have been available throughout the history of the volcano.

Ⓑ Bridgeman Island

Occupying an area of less than 1 km^2, Bridgeman Island is a remnant of a much larger volcanic edifice. The morphology and state of degradation suggest an age similar to the older post-caldera deposits of Deception Island. Gonzalez-Ferran and Katsui (1970) have described an upper series of basaltic andesites mantling older basalts, basaltic andesites and pyroclastic rocks.

Ⓑ Penguin Island

Penguin Island is situated about 1 km off the south coast of King George Island (Figure 2). It is dominated by the regular uneroded slopes of a basalt scoria cone built-up on a platform of olivine-basalt lavas (Gonzalez-Ferran and Katsui, 1970).

Ⓐ JAMES ROSS ISLAND VOLCANIC GROUP

Alkali olivine-basalts and hawaiites occur on and around James Ross Island (Nelson, 1975) and at Seal Nunataks in the Larsen Ice Shelf. K/Ar dates reported by Rex(1976) indicate ages for lavas in the vicinity of James Ross Island in the range 6-1 Ma whereas those from Seal Nunataks are < 1 Ma old. Samples from Seal Nunataks used in this study have been described by Fleet (1968).

A

GEOCHEMISTRY

This review of the geochemical characteristics of Antarctic Peninsula volcanism is based on a sample population of about 500 specimens analysed between 1974 and 1977 using standard X-ray fluorescence procedures (summarised in Saunders and others, this volume). Representative analyses of Mesozoic and Cainozoic volcanic rocks are given in Tables 1 and 2. The following classification based on SiO_2 content has been used: < 53%, basalt; 53-56%, basaltic andesite; 56-62%, andesite; 62-68%, dacite; 68-72%, rhyodacite and > 72%, rhyolite.

Insert Table 1 about here

B

Major Element Geochemistry

C

Mesozoic Volcanic Rocks

The observation of Adie (1972) that andesites are volumetrically dominant on the West Coast of the Peninsula and rhyolites on the East Coast is confirmed, and amplified. Figure 3 shows the relative abundance of rock types, based on silica mode, from three different areas arranged in order from west to east. The Mesozoic volcanics of Byers Peninsula on the S. Shetland Islands, lying closest to the trench, are dominated by basalts although more silicic volcanics are also present. The Danco Coast volcanics on the western side of the main Peninsula have a much higher proportion of andesites and dacites, whereas those from the East Coast of the Peninsula are dominated by rhyolites and dacites. Also included in Figure 3 are samples of Tobifera volcanics from Islas de los Estados; these appear to provide a continuation of this trend and are made up almost entirely of dacites and rhyolites.

Insert Figure 3 about here

Analyses of Mesozoic volcanics from the four areas are presented in Table 1. They have definite calc-alkaline characteristics. The more mafic lavas are plagioclase-phyric high-alumina tholeiites and the suite shows only moderate iron enrichment on an AFM diagram ([illegible] 1974).

Significant differences between East Coast and West Coast volcanic suites are also apparent from the Or-Ab-An diagram (Figure 4). To simplify relationships the samples have been divided into East Coast and West Coast groups, irrespective of age, with the South Shetland lavas being included in the latter group. It is clear that compositionally equivalent rock types are distinctly more sodic on the West Coast. Several high-K_2O volcanics occur among the East Coast samples, but appear to have no recorded counterparts in the associated plutonic suites (Saunders and others, this volume).

Insert Figure 4 about here

In many volcanic suites there is a well-marked positive correlation between K_2O and SiO_2. There is also a correlation between the K_2O contents of volcanic rocks of equivalent composition and the depth to the Benioff zone (Dickinson and Hatherton, 1967) although this varies in different island arc and continental margin volcanic suites (Neilson and Stoiber, 1973; Dickinson, 1975). As yet there is no accepted explanation for the K_2O-h relationship (Cawthorn, 1977), although the zone-refining/scavenging hypothesis (Best, 1975) seems to us most plausible. In the Antarctic Peninsula Mesozoic volcanics, rather scattered trends emerge on the K_2O-SiO_2 diagram (Figure 5). Nevertheless mean K_2O values at 57.5% SiO_2 vary across the Peninsula as follows: Byers Peninsula 0.8%, Danco Coast 1.5%, East Coast 1.8%. The equivalent value for the Tobifera volcanics of Islas de los Estados is 2.4% K_2O. These values are consistent with increasing depths to the Benioff zone going from west to east across the Peninsula, and confirm that subduction was from the Pacific side of the Peninsula during the Mesozoic.

Insert Figure 5 about here

C

Cainozoic Volcanic Rocks

Cainozoic volcanism is restricted mainly to the northern end of the Peninsula, particularly the South Shetland Islands. The Tertiary lavas of Fildes Peninsula, mainly plagioclase-phyric olivine-tholeiites, have low K_2O and relatively high Na_2O/K_2O ratios (Table 2) and may be regarded as members of a low-K high-alumina calc-alkaline suite (Tarney and others, 1977). The Plio-Pleistocene basalt-andesite lavas of King George Island however have higher

K_2O levels and lower Na_2O/K_2O ratios (Table 2 and Figure 6) and have more normal calc-alkaline characteristics.

The Recent volcanics in the area show a return to low-K characteristics. Deception Island olivine and quartz-tholeiites and their more siliceous differentiates have low K_2O contents (Fig. 5) and display a marked linear trend of points near the Ab apex in the Or-Ab-An diagram (Fig. 4). The very high Na_2O/K_2O ratios of Deception basalts (Table 2) are matched only by basalts from oceanic spreading centres, and as can be seen from Figure 6, a smooth curve could be drawn from ocean-floor basalts through the whole sequence of Deception differentiates. Although the Deception suite is distinctive in showing marked soda-enrichment (Na_2O reaching 7.5%), peralkalinity is never achieved and in fact Na_2O/K_2O decreases as is consistent with plagioclase fractionation.

Insert Table 2 about here

Bridgeman Island lavas are basaltic andesites having high Ca and Al contents reflecting the abundance (and accumulation) of plagioclase phenocrysts. The olivine-rich magnesian basalts of Penguin Island are slightly silica undersaturated (up to 5% ne) and are distinctly less potassic than the mildly alkaline basalts and hawaiites of the James Ross Island Volcanic Group (Table 2, Figure 6) situated on the East Coast of the Peninsula.

High Na_2O/K_2O ratios characterise the volcanics of the S. Shetland Islands from the Mesozoic to the present day, a feature which appears to correlate with their inferred proximity to the trench and the Benioff zone.

Insert Figure 6 about here

(B)

Trace element variations

The progressive west to east increase in the K_2O content of the Mesozoic volcanic rocks is also mirrored by Rb, Th and to a lesser extent, Ba. K/Rb ratios of most of the Mesozoic volcanics are fairly low (Table 1) except for the mafic lavas of the South Shetland Islands, which together with most of the Tertiary lavas, have high K/Rb ratios and low Rb/Sr and Ba/Sr ratios. These characteristics are typical of island arc tholeiites (Jakes and Gill, 1970). However the abundances of Sr, Ba, Zr, Cr and Ni are much higher than in arc tholeiites. Moreover Ce/Y ratios in these rocks (Tables 1 and 2) suggest that their rare-earth patterns are moderately light-RE-enriched, in contrast to the flat or light-RE-depleted patterns reported for most island arc tholeiites (Jakes and Gill, 1970).

Insert Figure 7 about here

In many volcanic suites the abundance of an incompatible element such as zirconium serves as a useful index of fractionation (Weaver and others 1972; Tarney and others, 1977). Smooth trends are obtained when chemical parameters are plotted against Zr (as in the Deception volcanics, Figure 7), suggesting control by a simple petrogenetic process such as fractional crystallisation. An equivalent Zr-SiO_2 graph is presented in Figure 8 for the Mesozoic lavas. It is clear that, despite the scatter of data points, the nature of the variation is quite different from that in the Deception suite. Zr increases in abundance from the basic rocks up to about 65% SiO_2, beyond which the Zr/SiO_2 ratio falls sharply with increasing silica such that the rhyolites are significantly poorer in Zr than the dacites. One reason for this could be separation of zircon from the magma, but an equally compatible explanation would be that zircon was residual in the source during partial melting or that the siliceous melts are filter-press products from a zircon-bearing crystalline residuum. Of interest here is the most silicic Deception sample, a rhyodacite pumice from the 1967 eruption (Baker and others, 1975), which is impoverished in Zr (Figure 7). With only a 2% increase in SiO_2, Zr has fallen from 650 to 180 ppm. However other incompatible elements (Rb, Ba, Y, Th, REE) are correspondingly low, suggesting that zircon fractionation is not responsible for these discrepancies. It seems unlikely therefore that this rhyodacite is consanguinous with the other Deception lavas, but that it may instead represent partial melting of subjacent crustal material.

Insert Figure 8 about here

The ratio Zr/Nb is a useful discriminant between alkaline and tholeiitic magma types. Zr/Nb is less than 8 in alkali basalts and associated rocks

(Weaver and others, 1972; Weaver, unpublished data) but reaches values in excess of 40 in 'depleted' mid-ocean ridge basalts (Erlank and Kable, 1976) and some calc-alkaline suites (see for example Table 1). Basalts from Seal Nunataks have low Zr/Nb ratios (Table 2) and are truly alkaline on this basis. However the other volcanics, and particularly those from the S. Shetland Islands, have high Zr/Nb ratios.

The rare earth elements have proved to be valuable petrogenetic indicators. So far, complete REE data is available only for the Recent volcanics of Bransfield Strait. However a very good indication of rare-earth characteristics in all the volcanic suites can be obtained from X-ray fluorescence data on La, Ce and Y. Because of its similarity in ionic radius and charge to Yb, the behaviour of Y closely parallels that of the heavy-REE, hence plots of Ce against Y on a chondrite normalised basis are broadly equivalent to using Ce versus Yb. Figure 9 summarises Ce-Y relationships of Antarctic Peninsula and Tobifera volcanic suites.

Chondrite-normalised Ce/Y ratios for the Mesozoic volcanics of Byers Peninsula are rather low, ratios for the basalts lying between 1.5 and 3 with slightly higher ratios for the more silicic rocks. Ratios for the Danco Coast volcanics are within the range 2-4, the East Coast lavas in the range 3-7, whereas the Tobifera volcanics show rather more fractionation with ratios rising from 3 to more than 8 (Figure 9a). Thus there appears to be a significant, though still moderate, transverse variation in Ce/Y ratios across the Peninsula, which correlates with the other geochemical variations noted above. The Ce/Y variations may be depth-related and could indicate the increasing influence of garnet in the source; however much higher Ce/Y ratios would be expected if garnet-rich eclogite were the source because of the strong affinity residual garnet would have for Y. If subducted oceanic crust were the source for the volcanics then the magmas were either generated before convertion to eclogite, or they interacted with the overlying mantle wedge to such an extent that their rare-earth patterns assumed the characteristics of that mantle.

The Tertiary basaltic lavas (Fildes Peninsula) from the S. Shetland Islands also have low Ce/Y ratios (< 2). It would appear that these and the Mesozoic basaltic lavas from Byers Peninsula were generated at relatively shallow depths from a source which contained little or no garnet.

The Quaternary lavas (Deception Is., Bridgeman Is., Penguin Is. and Seal Nunataks) display interesting Ce/Y relationships. Deception lavas produce a remarkably linear trend of rare-earth enrichment, with the Ce/Y ratio remaining constant within the range 1.5 to 2.0 (Fig. 9). This linear trend is characteristic of tholeiitic differentiation at relatively shallow depths (Tarney and others 1977; Saunders and others 1977) where separation of minerals such as olivine, pyroxene and plagioclase is involved. Bridgeman lavas have the same Ce/Y ratios as Deception lavas but all have lower levels of Ce and Y than the most primitive Deception basalts. This implies a much higher degree of partial melting of a similar source to produce the Bridgeman lavas, an explanation that would be consistent with the lower levels of other incompatible elements. Penguin Island basalts however have higher Ce/Y ratios than either Deception and Bridgeman lavas, although their high Cr and Ni contents and high Mg/Fe ratios imply relatively high degrees of partial melting. It is probable that Penguin basalts were generated at greater depth than those of Deception or Bridgeman, in a mantle source where garnet was stable. The alkalic basalts of Seal Nunataks have higher Ce/Y ratios (2.5-4) and also appear to have been generated from a garnet-bearing mantle source.

[illegible]-earth data (Fig. 10) tend to confirm these relationships. The patterns of Bridgeman lavas and Deception lavas are essentially parallel, with normalised Ce/Yb ratios between 1.7 and 2.5, and with Bridgeman lavas having lower REE levels than those of Deception. The more evolved Deception lavas have higher REE levels and show the development of distinct negative Eu anomalies

Insert Figure 10 about here

consistent with plagioclase fractionation. Penguin basalts have steeper REE patterns with normalised Ce/Yb ratios in the range 2.9 - 3.8.

Strontium isotope data also indicate time-integrated geochemical differences between the Penguin and Deception-Bridgeman magma sources. (Weaver and others, in preparation). $^{87}Sr/^{86}Sr$ ratios for 3 Bridgeman and 4 Deception samples fall within the range 0.7034-0.7035, whereas the ratios for Penguin basalts are distinctly higher at about 0.7039. The ratios for Penguin basalts are only slightly lower than the initial Sr isotope ratios of the Byers Peninsula Mesozoic volcanics which average about 0.7040. These isotopic relationships indicate a source for the Deception-Bridgeman lavas which is different from that of the Penguin Island and the Mesozoic volcanics. Although Bridgeman and Deception lavas have similar $^{87}Sr/^{86}Sr$ ratios, they do, surprisingly, have very different Rb/Sr ratios. Bridgeman lavas have higher K and especially Rb than the most primitive Deception basalts, but Ba and Sr levels are similar. As a result Bridgeman lavas have equivalent Ba/Sr ratios, but K/Rb and Ba/Rb ratios are lower and Rb/Sr ratios higher (Table 2 and Tarney and others 1977). This could indicate a relatively recent addition of Rb and K to the Bridgeman magma source (? from the subducting plate). Alternatively it is necessary to postulate that a K- and Rb-rich mineral such as phlogopite was residual in the source during the generation of Deception lavas but was consumed during the generation of Bridgeman lavas. Penguin Island volcanics have K/Rb and Ba/Rb ratios higher than, and Rb/Sr ratios as low as the Deception basalts, but this is mainly a result of higher K, Ba and Sr levels rather than lower Rb. Nevertheless this gives rise to a paradox in that there is an apparent inverse relationship between Rb/Sr and $^{87}Sr/^{86}Sr$ ratios in the three recent volcanic suites. It would seem that either phlogopite was residual in the source during generation of Penguin Island basalts, or that any original phlogopite was removed from the mantle source during earlier episodes of calc-alkaline activity in the S. Shetland area.

It is evident that, compared with the relative uniformity of Mesozoic and Tertiary lavas in the South Shetland area, recent volcanism associated with the extensional opening of Bransfield Strait requires more complex petrogenetic schemes. Tarney and others (1977) have argued that the sodic Deception and Bridgeman magmas, with low K, Rb, Rb/Sr, $^{87}Sr/^{86}Sr$, Ce/Yb and high K/Rb, Ba/Rb and Zr/Nb, have close geochemical affinities with mid-ocean ridge basalts. Thus they may be more directly connected with mantle diapirism (back-arc spreading) which has separated the South Shetland Island block from the Antarctic Peninsula. The Mesozoic-Tertiary calc-alkaline lavas on the other hand are related to subduction of Pacific Ocean crust under the South Shetlands, although the lavas themselves may have their origin (in whole or in part) in the mantle wedge above the Benioff zone.

Ⓐ

CONCLUSIONS

The volcanic record of subduction under the Antarctic Peninsula is perhaps not as complete or continuous as the plutonic record (Saunders and others, this volume). Certainly there were vast outpourings of lava throughout the Peninsula during the Mesozoic ('Upper Jurassic Volcanic Group') just as there were in southern S.America ('Serie Tobifera'). Geochemical variations in the lavas across the Peninsula are consistent with subduction from the Pacific side. Similarities in the pattern of Mesozoic volcanism, and in particular the geochemical similarities between the dominantly silicic volcanics from the East Coast of the Peninsula and the Tobifera silicic volcanics, agree with continental reconstructions which place the Antarctic Peninsula in continuity with southern S. America during the Mesozoic. In the Peninsula there is no reason to regard the volcanics as being other than subduction related, although in S.America the Tobifera volcanics extend well back from the active margin. However, the fact that so much of the magmatic activity was expressed as volcanism may demand special tectonic conditions; it may be significant that this period was characterised by extensive rifting connected with the break-up of Gondwanaland

(Barker and Griffiths, 1977).

The strong asymmetry in the present age pattern of the ocean floor in the Pacific suggests that vast amounts of Mesozoic ocean floor (complementary to that in the N.W.Pacific) may have been consumed below S.America, the Antarctic Peninsula and West Antarctica during the Mesozoic and Early Tertiary. From about 65 Ma (Anomaly 26) ocean-crust generated at the Aluk ridge (Herron and Tucholke, 1976) must also have disappeared beneath the Peninsula until this ridge itself was progressively consumed and subduction ceased (except at the northern end of the Peninsula). Apart from that in the South Shetland Islands, very little Tertiary volcanism has been recognised in the Antarctic Peninsula. To what extent this is a function of erosion or lack of exposure, or just that magmatism does not always lead to extrusive activity, is not known.

The most complete record of volcanism in the Peninsula occurs on the South Shetland Islands, and in fact subduction under the South Shetland Islands has ceased only recently. Byers Peninsula lavas (90 - 140 Ma) are near-trench equivalents of the main Mesozoic volcanic group in the Antarctic Peninsula, and may be regarded as members of a low-K calc-alkaline suite derived by relatively shallow-level melting of the mantle wedge above the subduction zone. They are chemically distinct from the arc-tholeiite suites of intra-oceanic island arcs (Jakes and Gill, 1970), but of course at the time they were generated, the South Shetland area was situated at a major continental margin.

The Tertiary Fildes Peninsula volcanics (60 - 40 Ma) are compositionally very similar to the older Byers Peninsula lavas, and indicate steady-state subduction-related magmatism in the area. The former however, represent a pulse of magmatic activity at about 60 Ma. One could speculate that this may be connected with the initiation of spreading at the Aluk ridge at about 65 Ma (Herron and Tucholke, 1976) which might have produced an increase in the rate of subduction beneath the Peninsula.

The Plio-Pleistocene group of lavas of King George Island are generally

richer in incompatible elements (K, Rb,Ba, etc) than the Fildes and Byers suites and are more typically calc-alkaline. However, their age and position, close to the fault-bounded southern margin of King George Island, suggest that they may be connected with the initial stages of the rifting open of Bransfield Strait. The opening of the Strait heralds a major change in the 140 Ma pattern of volcanism in the area. The cause of this incipient back-arc spreading is not fully known, but it may be that with the apparent cessation of spreading in Drake Passage (Barker, 1976) new spreading occurred within the volcanic arc to compensate for continuing but waning subduction under the South Shetland Islands. Recent volcanicity on Deception, Bridgeman and Penguin Islands is more directly related to this mantle diapirism. Deception and Bridgeman lie along the axial magnetic anomaly in Bransfield Strait. Their volcanic products have geochemical and isotopic characteristics which are transitional between ocean-ridge and calc-alkaline magmas (Tarney and others, 1977), as may be expected where back-arc spreading is at an early stage of evolution. Penguin represents an off-axis volcano erupting mildly alkaline basalts which have been derived from greater depth and from a different mantle source than the Bridgeman-Deception group.

The James Ross - Seal Nunataks alkali basalts could represent subduction-related magmatism occurring well behind the arc, as in Japan. However, alkalic magmas are more commonly associated with ensialic rifting and faulting. Such rifting may well be a secondary extensional feature connected with active mantle diapirism beneath Bransfield Strait.

Table 1: Representative chemical analyses of Mesozoic volcanic rocks from the South Shetland Islands (SS), the west coast of the Antarctic Peninsula (WC), the east coast of the Antarctic Peninsula (EC) and the Tobifera Series of Isla de los Estados (TS).

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
Sample No.	P726.5	P664.1	P726.3	P612.1	P648.10	O327.2	O990.2	O934.4	O343.4	O003.1	JP6	TL534.4	TL43.1	TL734.1	TL81.1	TL511.1	ST05.2	ST304	ST238.1	ST218.3
	SS	SS	SS	SS	SS	WC	WC	WC	WC	WC	EC	EC	EC	EC	EC	EC	TS	TS	TS	TS
SiO_2	48.17	50.40	55.00	61.41	78.32	49.63	53.51	57.42	65.50	71.16	48.97	50.05	54.11	66.10	73.87	75.74	60.63	71.80	75.90	79.60
TiO_2	1.07	1.39	1.39	0.58	0.13	0.60	1.31	0.85	1.01	0.38	0.81	1.54	0.07	0.58	0.18	0.12	0.48	0.24	0.13	0.08
Al_2O_3	16.54	15.70	15.60	18.39	12.33	15.48	16.64	16.91	15.86	13.90	17.14	18.50	16.54	15.49	14.47	13.13	10.65	14.64	12.96	10.96
tFe_2O_3	10.89	14.30	11.55	5.97	1.12	8.81	10.06	8.04	4.53	3.17	10.33	10.37	8.49	4.03	2.81	1.48	4.89	3.22	2.26	1.60
MnO	0.20	0.25	0.26	0.25	0.02	0.15	0.17	0.13	0.18	0.11	0.16	0.16	0.13	0.10	0.09	0.03	0.05	0.02	0.01	0.01
MgO	9.58	3.34	4.65	3.55	0.33	10.47	4.13	3.35	1.68	0.53	7.41	8.38	6.37	1.64	0.17	0.25	0.02	0.42	0.19	0.19
CaO	10.49	9.57	7.00	5.71	0.42	11.91	8.32	7.17	3.87	1.19	11.26	6.73	8.00	4.40	1.27	1.50	1.45	0.31	0.21	0.16
Na_2O	2.50	2.50	3.25	4.21	3.19	2.00	3.32	3.28	5.30	4.22	2.36	3.58	3.35	3.30	3.05	1.93	3.31	3.15	3.02	3.00
K_2O	0.24	0.60	1.50	1.03	4.41	0.34	1.15	1.71	1.98	3.71	0.60	1.87	3.11	2.26	5.12	4.80	5.28	5.50	5.44	4.51
P_2O_5	0.23	0.18	0.37	0.23	0.01	0.13	0.28	0.20	0.31	0.07	0.21	0.34	0.24	0.18	0.04	0.03	0.13	0.02	0.02	0.02
Total	100.10	100.38	100.51	99.31	100.35	99.05	98.89	99.08	100.22	99.04	99.31	99.79	99.01	99.11	99.97	99.12	92.45	99.24	100.20	99.47
Cr	236	44	13	10	5	211	10	56	<1	3	127	98	98	14	3	8	30	4	8	6
Ni	84	13	3	4	<1	60	<1	10	<1	<1	29	28	23	<1	<1	<1	16	<1	3	4
Rb	3	10	28	27	110	7	38	49	52	127	14	102	78	73	208	171	189	244	233	162
Ba	71	165	367	237	670	88	460	396	579	834	208	644	615	505	1107	818	1176	2595	942	850
Sr	350	463	329	478	60	446	523	347	426	145	510	570	638	460	200	175	128	94	55	65
Zr	69	77	149	147	108	55	165	220	308	422	77	108	172	225	294	110	324	660	334	198
Nb	3	2	6	6	8	<1	8	9	11	18	5	12	9	13	16	8	16	19	13	10
Y	18	25	32	28	32	12	28	33	44	46	10	26	23	22	38	24	32	61	29	24
La	4	8	21	13	42	4	23	16	25	31	13	38	23	33	30	13	47	72	30	29
Ce	16	20	36	35	64	14	43	42	60	77	10	57	40	48	76	44	79	130	52	59
Pb	3	8	10	3	[illegible]	3	10	11	20	18	5	8	19	11	37	74	14	11	31	14
Th	1	<1	3	4	17	<1	2	6	7	17	<1	<1	6	11	20	18	10	26	23	20
Zn	–	56	93	56	41	66	96	62	93	64	67	91	103	64	156	33	82	124	85	34
Ga	–	21	21	16	5	20	22	20	24	20	21	22	23	21	20	12	29	30	18	8
Na_2O/K_2O	10.42	4.17	2.17	4.09	0.72	5.88	2.89	1.92	2.68	1.33	3.93	1.90	1.11	1.49	0.58	0.40	0.63	0.57	0.56	0.41
K_2O/SiO_2	0.005	0.012	0.027	0.017	0.056	0.007	0.021	0.030	0.030	0.052	0.012	0.037	0.039	0.034	0.070	0.063	0.079	0.077	0.072	0.061
tFe/Mg	1.31	3.11	2.88	1.95	3.94	0.84	3.08	2.74	3.13	6.64	1.63	1.44	1.33	3.49	19.17	6.87	5.91	8.89	13.00	9.77
K/Rb	866	405	445	317	308	403	255	290	316	342	356	152	330	241	204	233	231	180	194	220
Rb/Sr	0.01	0.02	0.08	0.06	1.98	0.02	0.07	0.14	0.12	0.88	0.03	0.18	0.12	0.17	1.04	0.98	1.48	2.62	3.58	2.50
Ba/Sr	0.20	0.22	1.12	0.50	11.17	0.20	0.88	1.11	1.36	5.76	0.34	1.13	0.81	1.29	5.53	4.67	9.19	27.61	14.42	13.02
$(Ce/Y)_N$	1.42	1.64	2.30	4.32	4.39	3.39	[illegible]	2.68	2.38	3.42	3.86	4.16	4.09	4.48	4.43	3.75	5.05	5.31	3.67	5.03
Zr/Nb	23.0	38.5	24.8	24.5	13.50	>55	20.6	25.1	28.1	23.4	15.4	18.5	19.1	17.4	17.8	12.2	20.3	34.7	25.7	19.8

Analyses: 1-basalt, Byers Peninsula, 2-basalt, Byers Peninsula, 3-basaltic andesite, Byers Peninsula, 4-andesite, Byers Peninsula, 5-rhyolite, Byers Peninsula, 6-basalt, Danco Coast, 7-basaltic andesite, Danco Coast, 8-andesite, Danco Coast, 9-dacite, Danco Coast, 10-rhyodacite, Danco Coast, 11-basalt, Jason Peninsula, 12-basalt, Foyn Coast, 13-basaltic andesite, Oscar II Coast, 14-dacite, Oscar II Coast, 15-rhyolitic tuff, Oscar II Coast, 16-rhyolite, Oscar II Coast, 17-dacitic tuff, Isla de los Estados, 18-rhyodacite, Isla de los Estados, 19-rhyolite, Isla de los Estados, 20-rhyolitic tuff, Isla de los Estados. (Major oxides as wt. %, trace-elements as p.p.m., total iron oxide as Fe_2O_3, chondrite normalised Ce/Y ratio)

Table 2: Representative chemical analyses of Cainozoic volcanic rocks from the South Shetland Islands and Seal Nunataks (James Ross Island Volcanic Group)

	1	2	3	4	5	6	7	8	9	10	11	12	13	14
Sample No.	P600.3	P604.1	P611.1	P438.1	P821.1	P820.3	P815.1	D138.1	D713.2	R184.3	P870.2	P642.2	P770.1	D1609.5
SiO_2	49.44	52.54	62.07	56.18	51.44	51.96	57.60	51.64	52.71	62.57	67.73	54.61	49.05	49.56
TiO_2	0.83	0.87	0.83	0.93	0.87	0.80	0.75	1.37	1.68	1.18	0.30	0.60	1.11	2.01
Al_2O_3	15.81	17.00	16.25	16.31	19.83	18.64	15.86	15.62	16.12	15.59	14.59	18.68	15.04	14.43
tFe_2O_3	10.49	11.03	6.11	7.68	7.97	8.41	6.18	9.63	9.95	7.04	6.16	8.81	9.98	11.48
MnO	0.20	0.22	0.19	0.15	0.14	0.18	0.14	0.18	0.18	0.20	0.16	0.13	0.18	0.14
MgO	7.69	4.58	2.36	5.17	4.05	5.70	7.01	6.43	4.02	1.30	0.40	5.03	9.04	9.19
CaO	10.07	8.39	5.02	6.84	9.90	9.24	7.21	9.03	9.09	3.38	1.81	8.71	10.06	8.44
Na_2O	2.69	3.84	5.49	3.66	3.74	3.71	3.67	4.16	4.00	7.02	7.78	3.55	3.88	4.00
K_2O	0.33	0.58	0.99	1.81	0.81	0.83	1.20	0.31	0.45	1.22	1.39	0.58	0.53	1.02
P_2O_5	0.14	0.15	0.34	0.31	0.20	0.18	0.20	0.21	0.29	0.47	0.10	0.07	0.30	0.21
Total	98.39	99.40	99.74	99.04	98.05	99.01	99.82	98.58	100.29	99.92	99.43	99.87	99.77	100.48
Cr	43	30	8	33	27	26	90	339	52	6	[illegible]	67	408	313
Ni	10	6	2	15	14	16	34	35	15	4	2	21	165	144
Rb	1	8	46	44	12	12	14	3	5	21	30	12	5	14
Ba	151	176	515	437	223	211	252	114	132	270	311	108	189	336
Sr	354	532	440	511	486	476	613	342	383	262	332	318	641	436
Zr	64	68	385	237	115	105	145	156	190	492	651	74	80	159
Nb	2	<1	6	3	<1	<1	3	2	7	12	14	2	1	24
Y	13	14	29	23	23	18	15	28	33	65	71	9	8	30
La	5	6	26	25	11	9	12	8	10	25	27	6	10	20
Ce	17	19	69	51	26	20	26	23	29	56	61	9	22	28
Pb	6	8	11	10	12	6	10	6	2	7	11	2	6	4
Th	3	5	3	8	2	2	4	<1	<1	2	3	3	<1	3
Zn	–	–	–	82	88	72	74	76	80	116	132	52	72	104
Ga	–	–	–	23	28	25	25	21	22	24	27	18	22	24
Na_2O/K_2O	8.15	6.62	5.55	2.02	4.62	4.47	3.06	13.42	10.89	5.75	4.58	6.12	7.32	3.92
K_2O/SiO_2	0.007	0.011	0.016	0.032	0.016	0.016	0.021	0.006	0.008	0.019	0.023	0.011	0.011	0.021
tFe/Mg	1.36	2.79	3.00	1.72	2.28	1.71	1.02	1.74	2.35	7.42	14.96	1.59	1.28	1.45
K/Rb	2740	602	179	341	560	574	712	854	747	482	440	401	880	605
Rb/Sr	0.002	0.015	0.105	0.086	0.025	0.025	0.023	0.009	0.013	0.080	0.227	0.038	0.009	0.034
Ba/Sr	0.37	0.33	1.16	0.86	0.46	0.44	0.41	0.33	0.34	1.03	3.30	0.34	0.35	0.77
$(Ce/Y)_N$	1.89	2.78	2.75	4.53	3.31	3.27	3.54	1.68	1.80	1.76	3.76	2.04	6.00	2.88
Zr/Nb	27.0	>68	30.8	79.0	>115	>105	48.3	78.0	27.1	41.0	46.50	38.0	80.0	6.6

Analyses: 1-basalt, Fildes Peninsula, 2-basalt, Fildes Peninsula, 3-dacite, Fildes Peninsula, 4-andesite, Lion's Rump, 5-basalt, Cinder Spur, 6-basalt, Martin's Head, 7-andesite, Turret Point, 8-basalt, Deception Island, 9-basalt, Deception Island, 10-dacite, Deception Island, 11-dacite, Deception Island, 12-basaltic andesite, Bridgeman Island, 13-basalt, Penguin Island, 14-basalt, Seal Nunataks. (major oxides as wt. %, trace-elements as p.p.m., total iron oxide as Fe_2O_3, chondrite normalised Ce/Y ratio)

Figure 9 : a. Ce v Y graph for Mesozoic volcanic rocks from the South Shetland Islands, the Antarctic Peninsula and Islas de los Estados (symbols as for Figure 5).

b. Ce v Y graph for Cainozoic lavas from the South Shetland Islands and Seal Nunataks (symbols as for Figure 6).

Figure 10 : Rare-earth element patterns for the Quaternary lavas of Bransfield Strait. Open circles – Deception Island (B138.2 – basalt, B202.1 – basaltic andesite, B107.8 – andesite, P870.1 – dacite), crosses – Penguin Island (P807.1, P721.3 – basalts), solid circles – Bridgeman Island (P642.2, P640.1 – basaltic andesites). Analyst – R. J. Pankhurst.

FIGURE CAPTIONS

Figure 1 : Locality map of the Antarctic Peninsula and Tierra del Fuego. Ages of sea-floor are given in Ma (south-west of the Hero F.Z. after Herron and Tucholke (1976), in Drake Passage after Barker and Burrell (1977)). Transform faults – thick dashed line, South Shetlands trench – toothed line.

Figure 2 : Locality and bathymetric map of the South Shetland Islands and Bransfield Strait.

Figure 3 : Histograms of SiO_2 content of all analysed Mesozoic volcanic rocks from the South Shetland Islands, the Antarctic Peninsula and Islas de los Estados.

Figure 4 : Normative Or-Ab-An diagram for Mesozoic-Cainozoic volcanic rocks from the west coast (including the South Shetland Islands) and the east coast of the Antarctic Peninsula. The trend of Deception Island lavas is distinguished.

Figure 5 : K_2O v SiO_2 graph for Mesozoic volcanic rocks of the South Shetland Islands, the Antarctic Peninsula and Islas de los Estados. Filled circles – Byers Peninsula, crosses – Danco Coast, open circles – Oscar II and Foyn Coasts, triangles – Islas de los Estados.

Figure 6 : Na_2O v K_2O graph for Cainozoic lavas of the South Shetland Islands and Seal Nunataks. Filled circles – Fildes Peninsula, crosses – Plio-Pleistocene group, open circles – Deception Island, triangles – Seal Nunataks. Fields for Deception, Penguin and Bridgeman Islands and for 150 ocean-floor basalts are indicated.

Figure 7 : Zr v SiO_2 graph for Cainozoic lavas of the South Shetland Islands and Seal Nunataks (symbols as for Figure 6).

Figure 8 : Zr v SiO_2 graph for Mesozoic volcanic rocks from the South Shetland Islands, the Antarctic Peninsula and Islas de los Estados (symbols as for Figure 5).

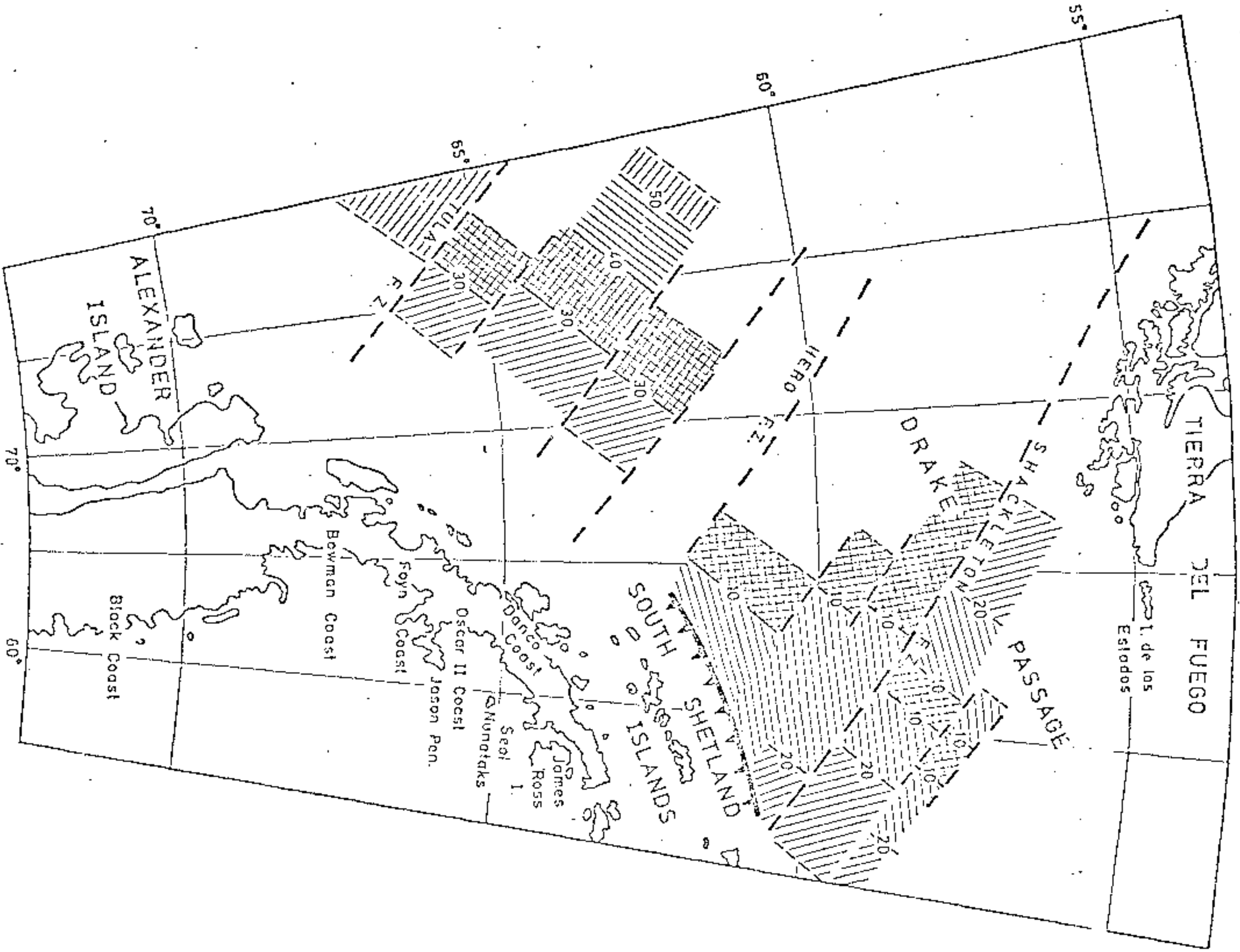


Figure 1

WEAVER

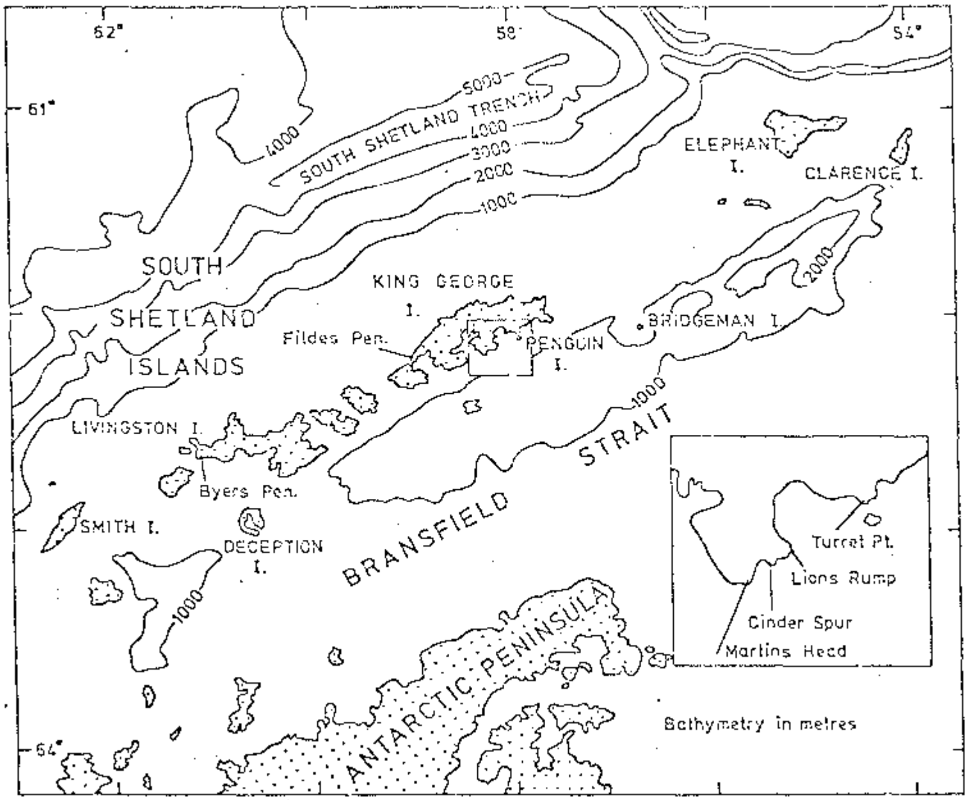


Figure 2

WEAVER

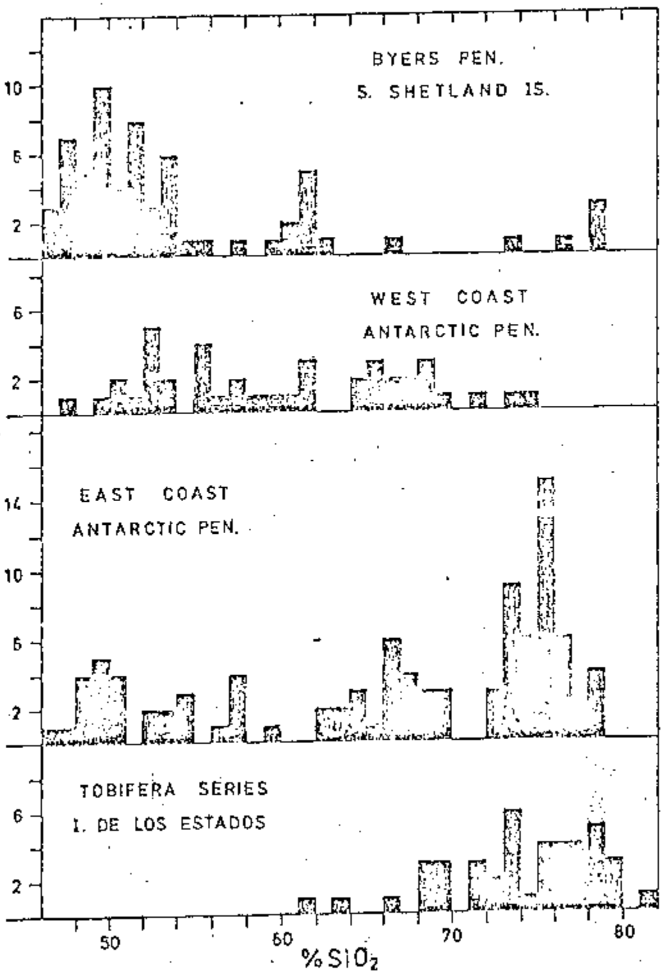


Figure 3

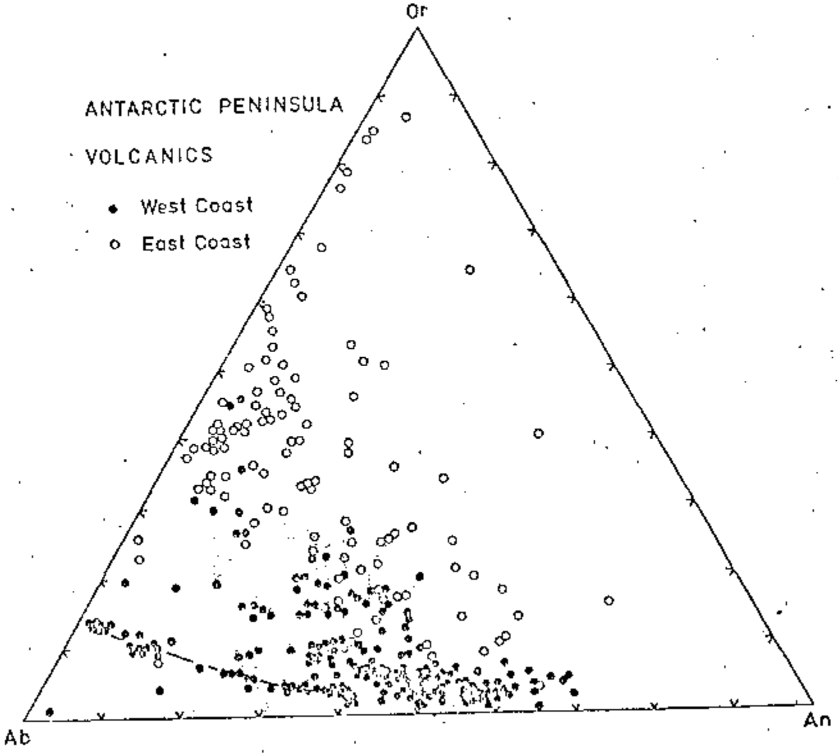
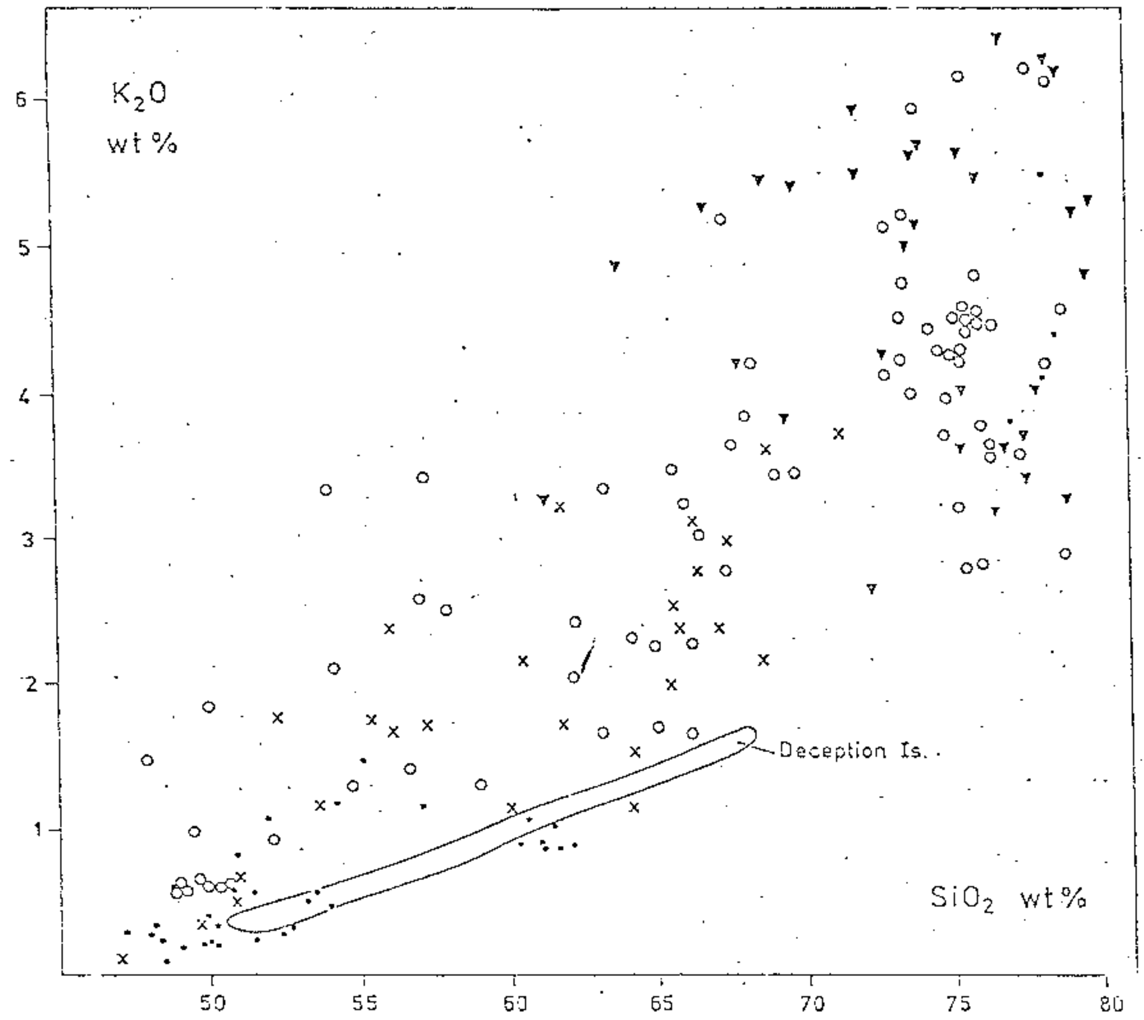


Figure 4

Figure 5



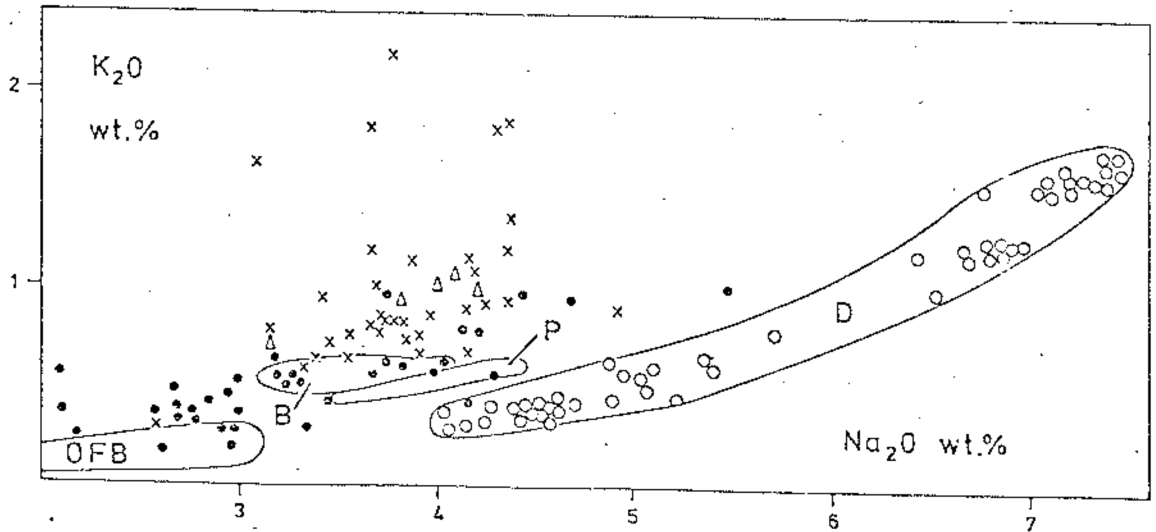


Figure 6

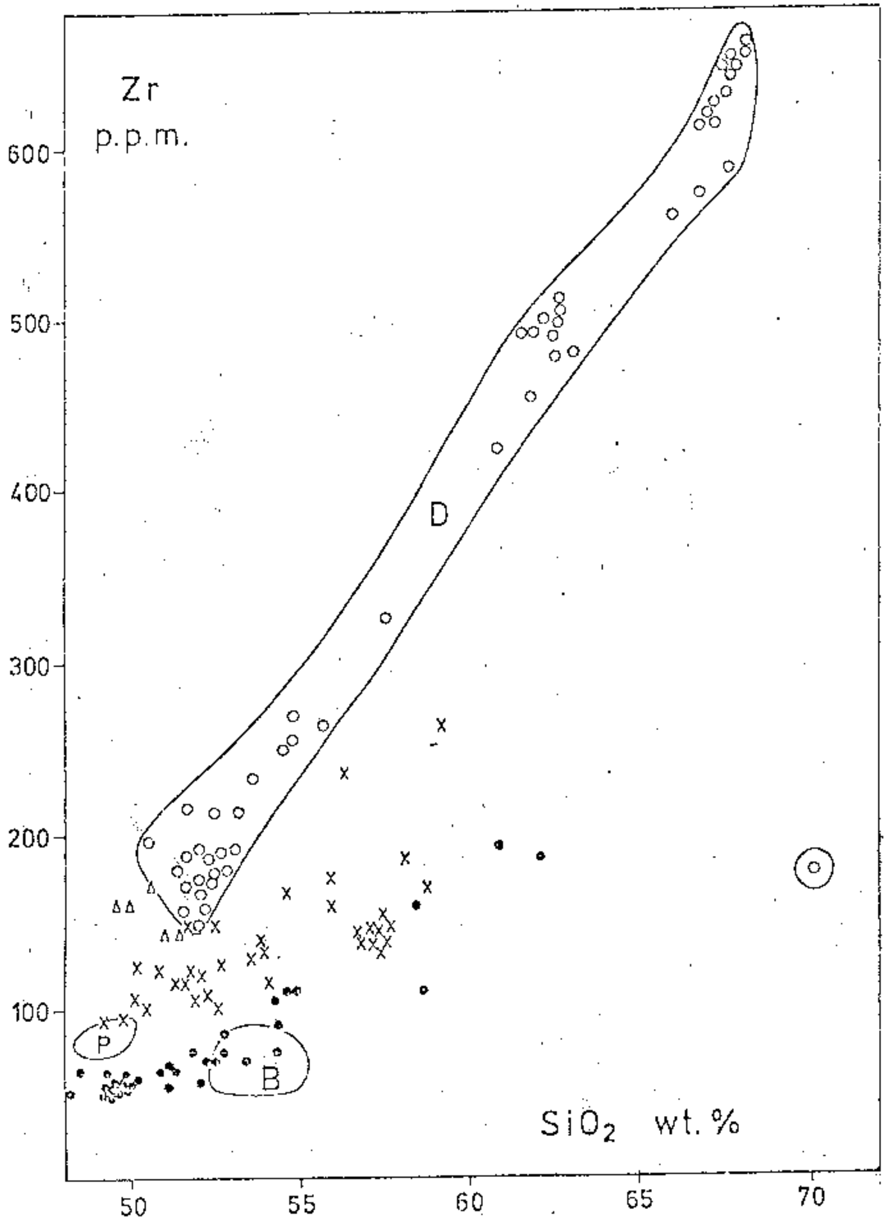


Figure 7

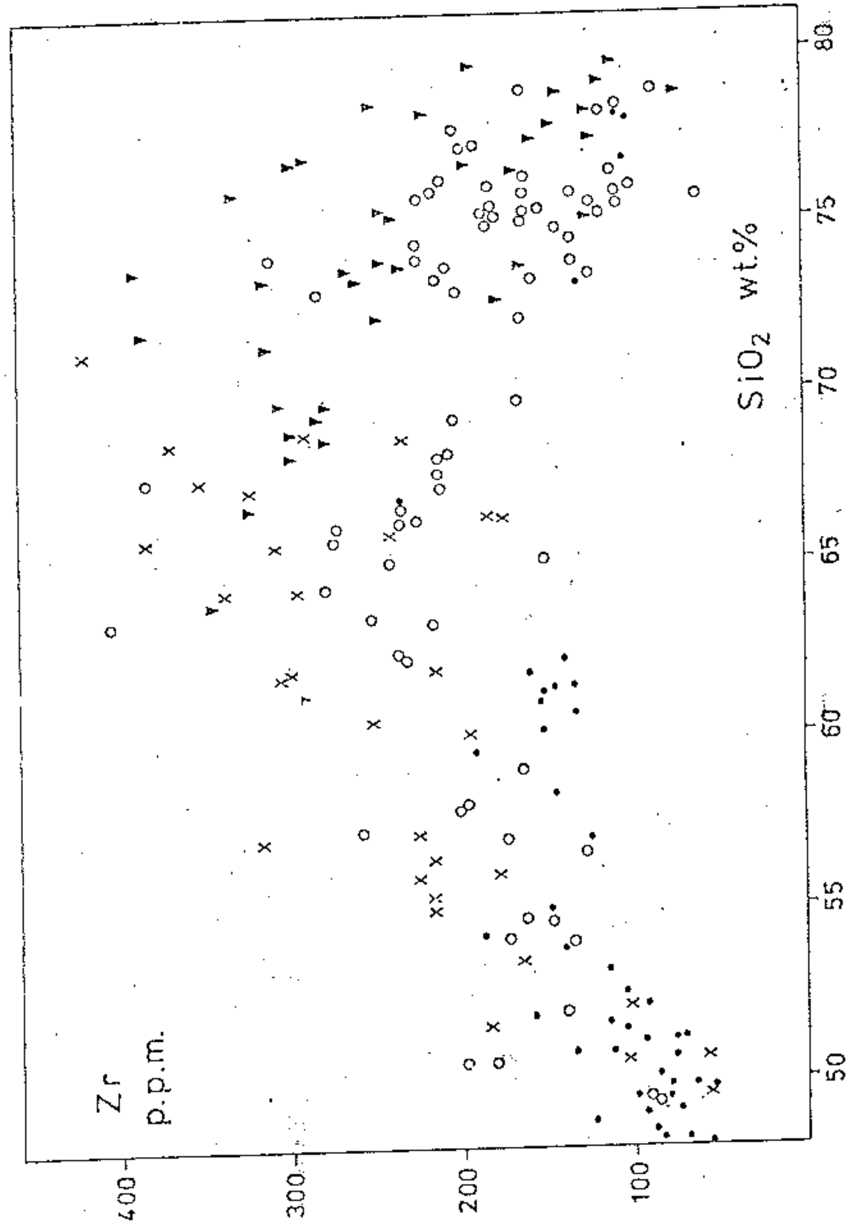


Figure 8

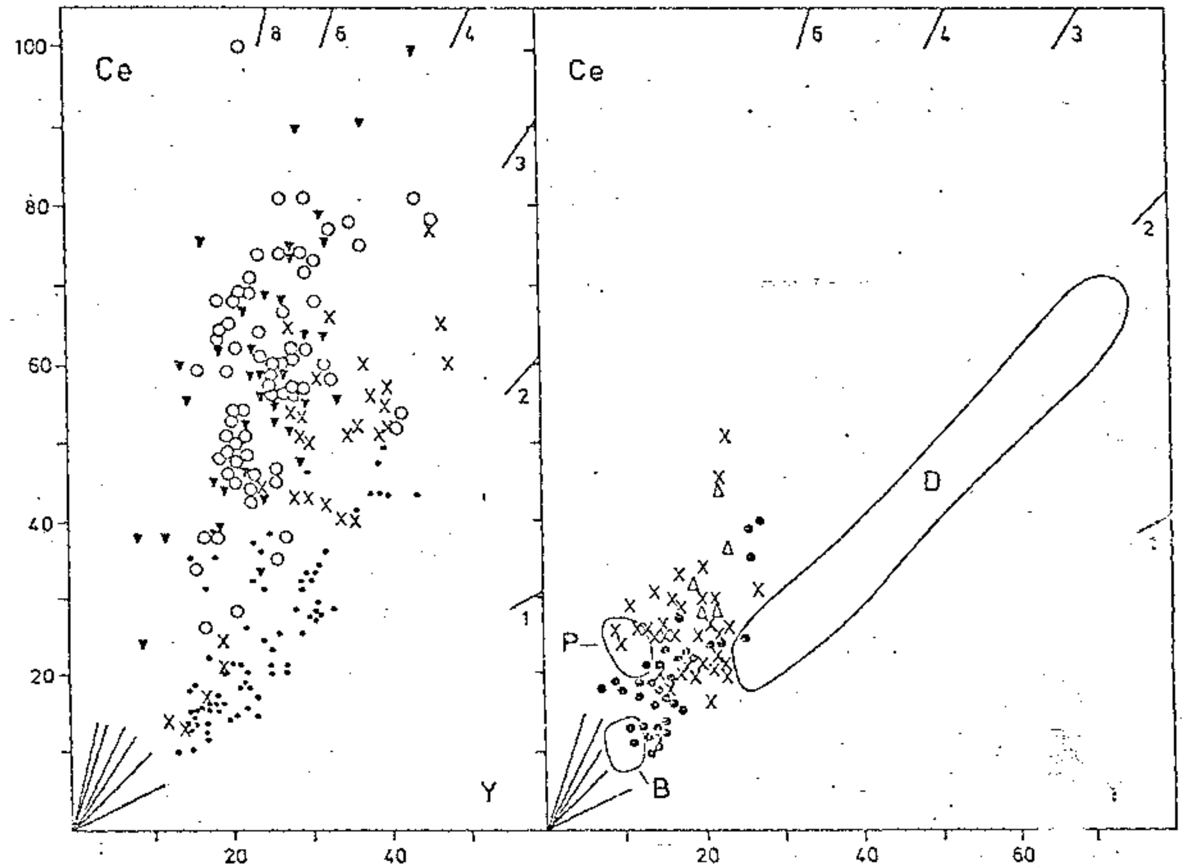


Figure 9 a

b

WEAVER

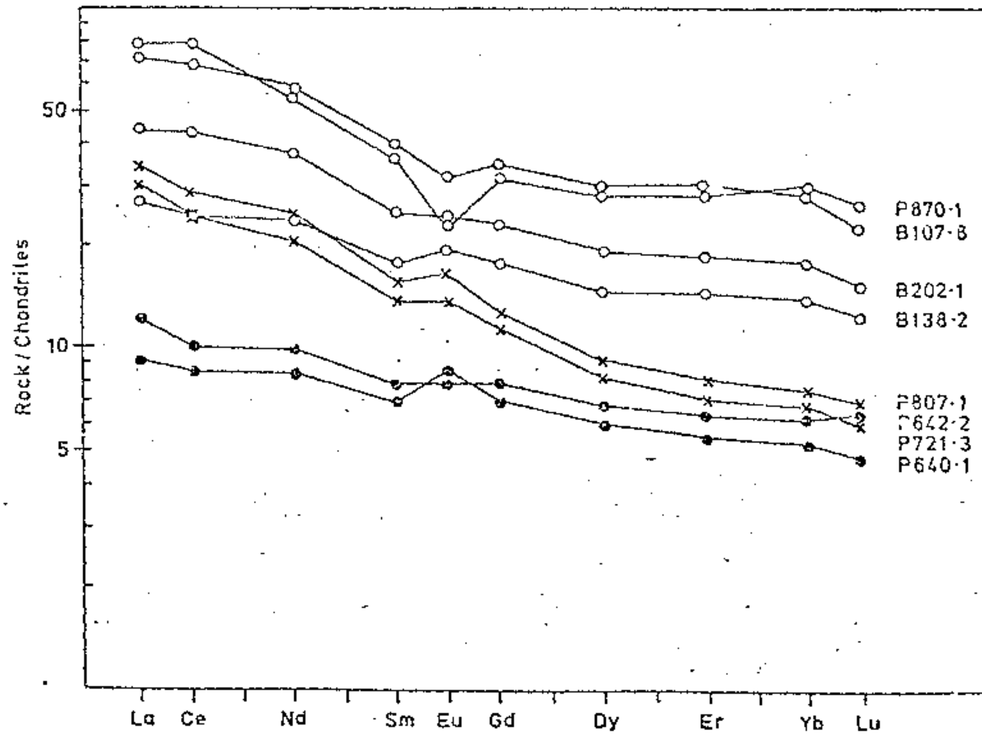
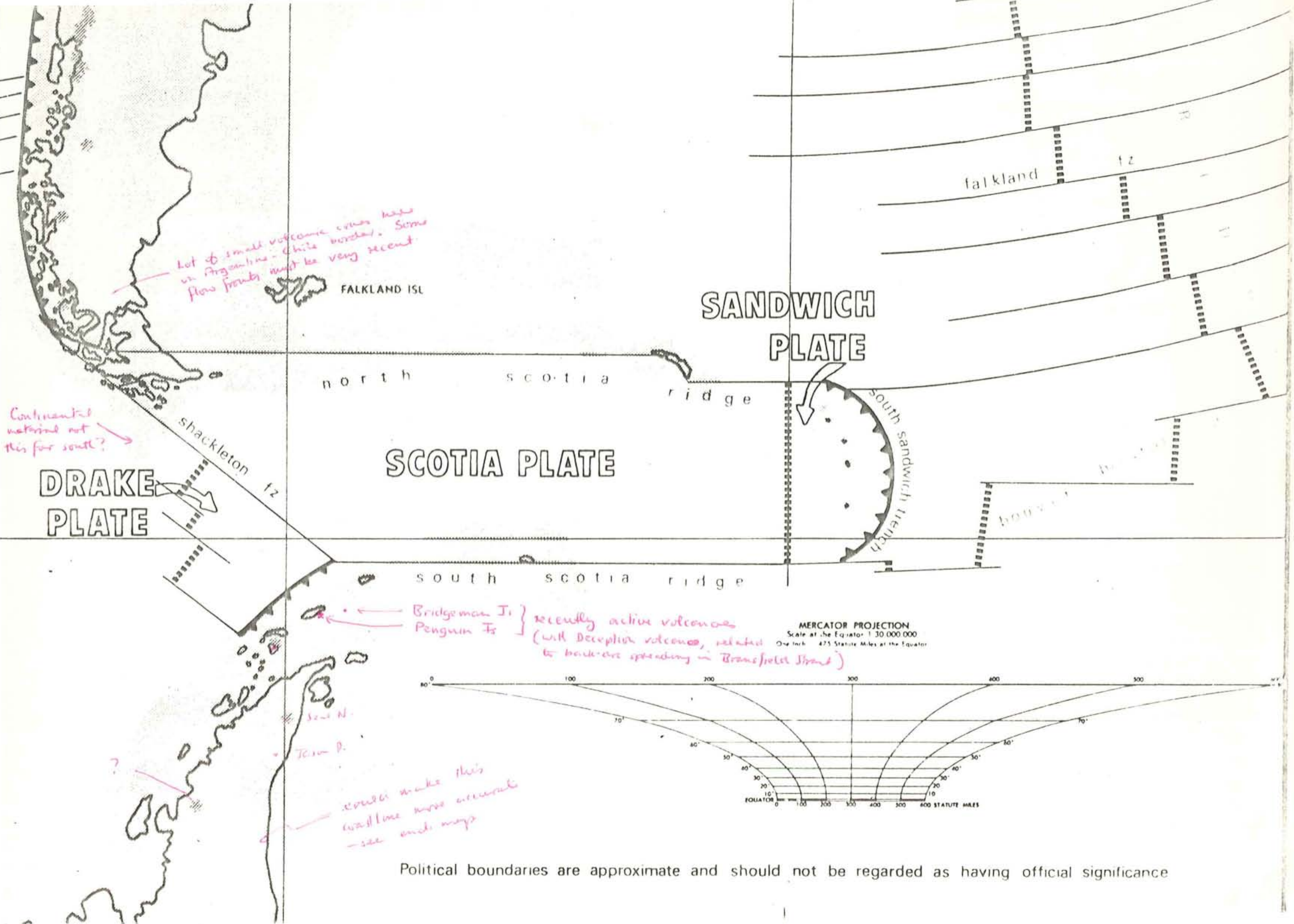


Figure 10

WEAVER



Lot of small volcanic cones here in Argentine - Chile border. Some flow fronts must be very recent

Continental material not this far south?

Bridgeman I.
Penguin Is } recently active volcanoes (with Deception volcanoes, related to back-arc spreading in Bransfield Strait)

Seal N.

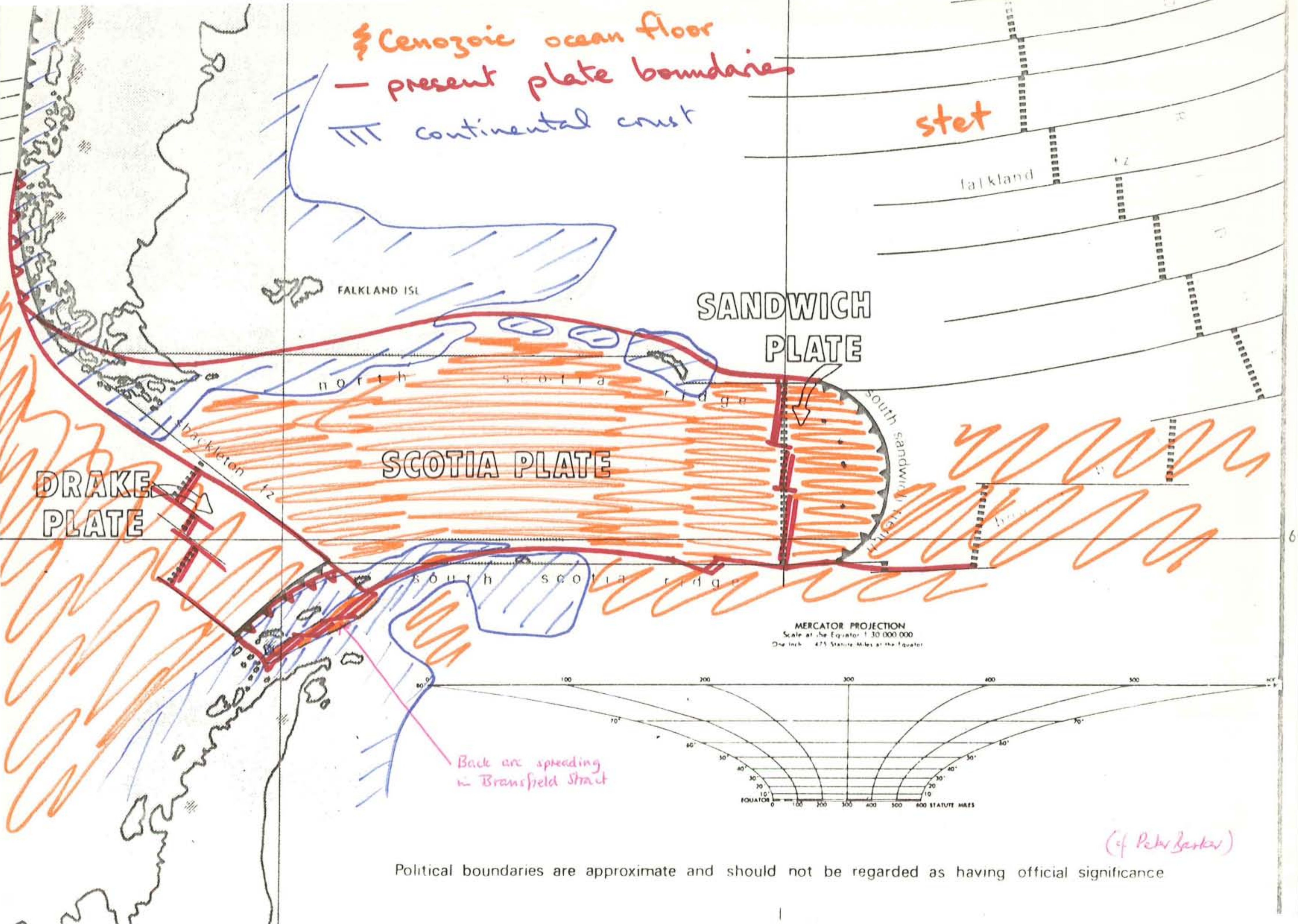
Jason P.

?

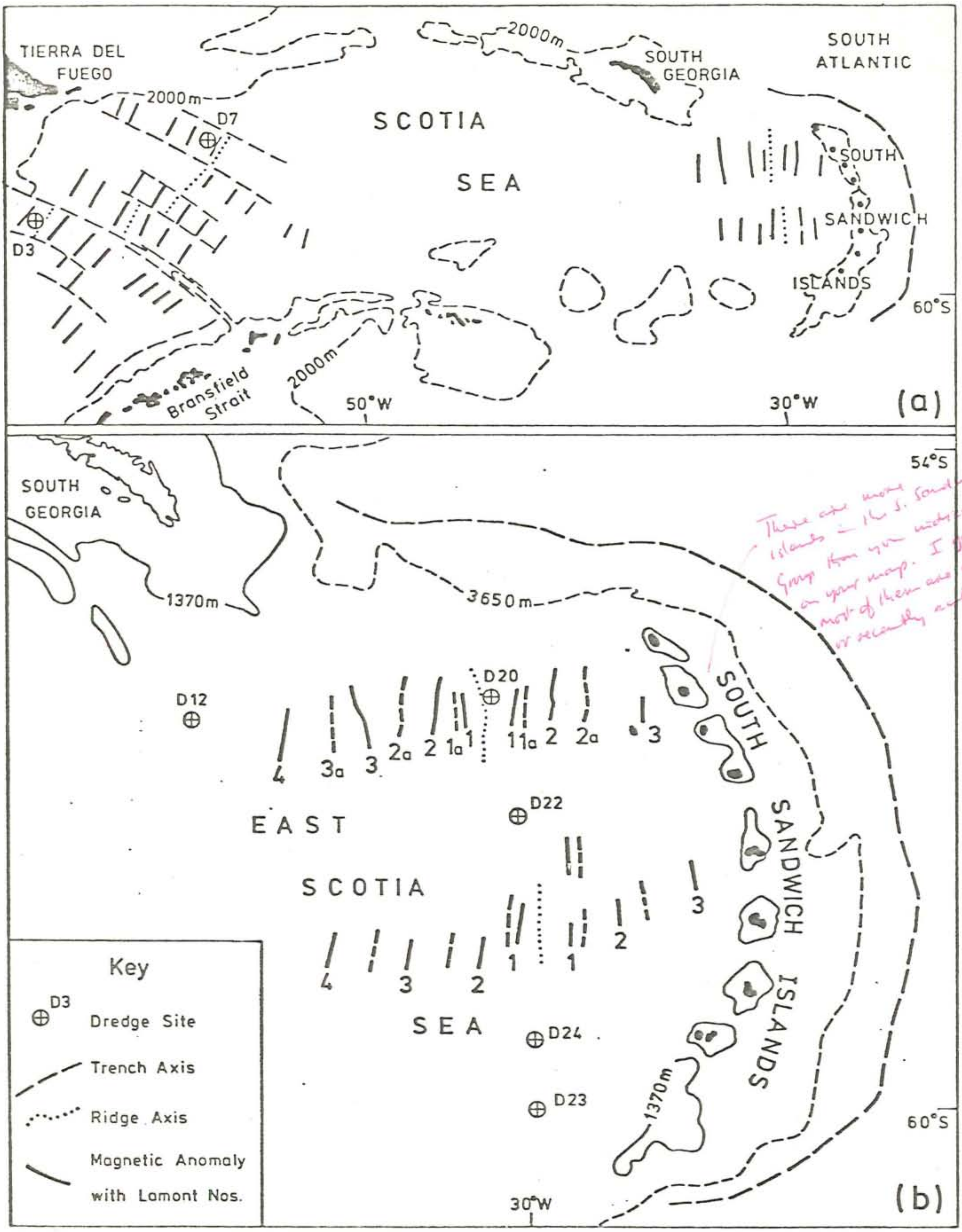
could make this coastline more accurate — see encl. maps

MERCATOR PROJECTION
Scale at the Equator 1:30 000 000
One Inch = 473 Statute Miles at the Equator

Political boundaries are approximate and should not be regarded as having official significance



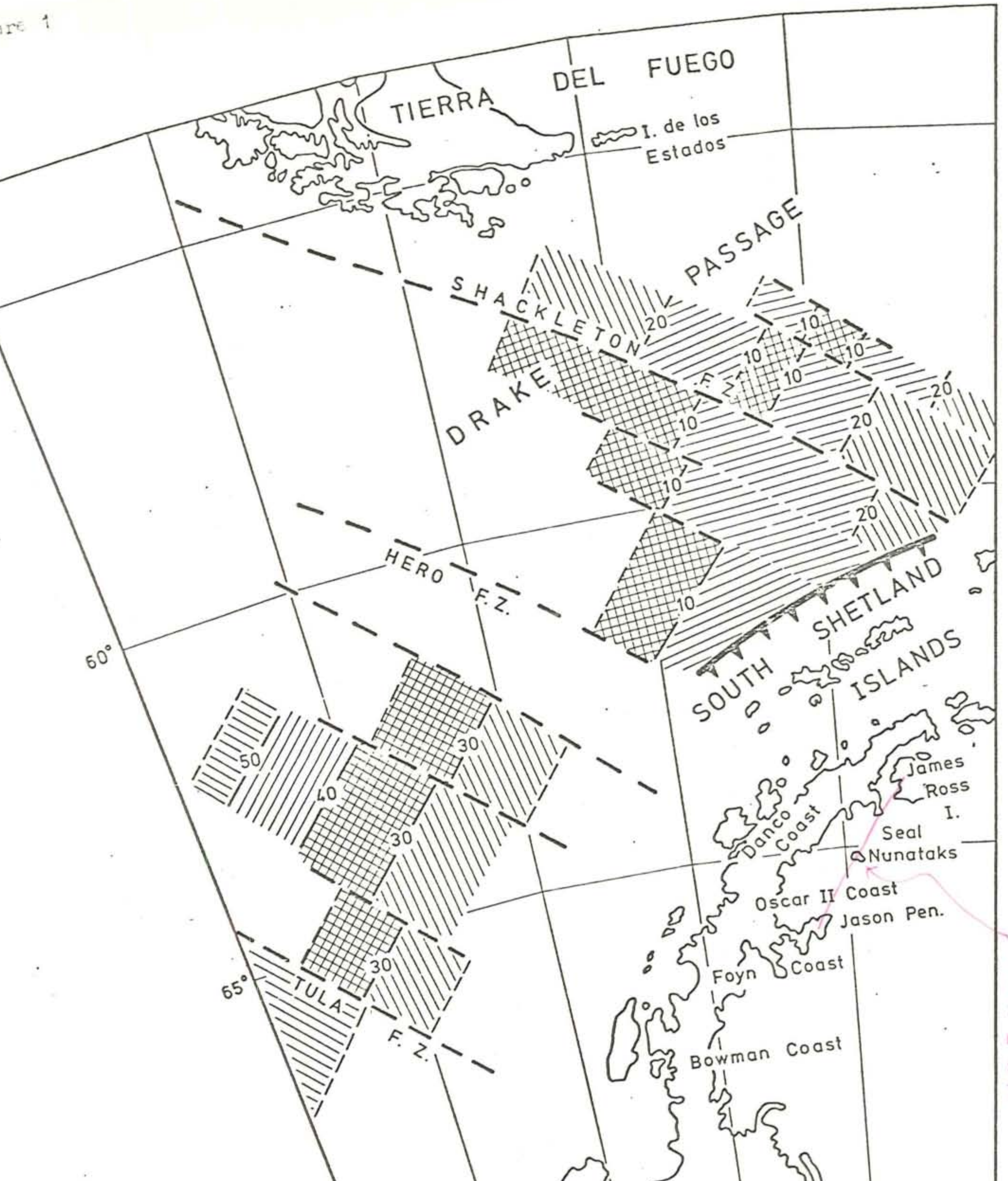
Political boundaries are approximate and should not be regarded as having official significance



There are more islands in the S. Sandwich Group than you indicate on your map. I guess most of them are active or recently active

Figure 1

ure 1



Recent basaltic
(mainly alkali basal
activity known on
James Ross and Se
Nunataks. Also (
small cones forma
Jason Peninsula

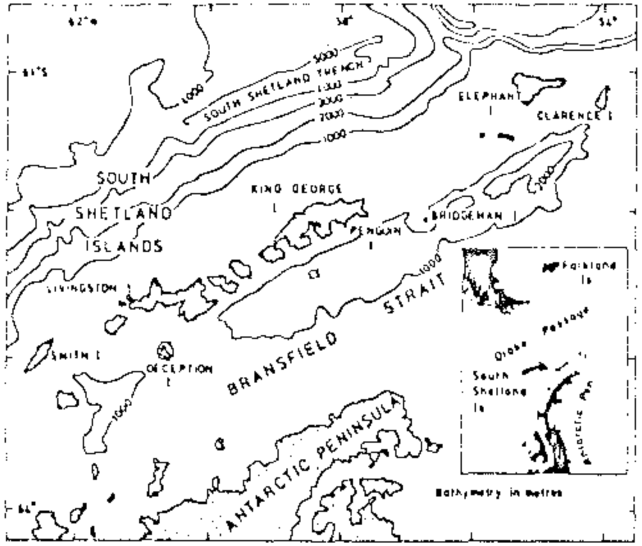


Figure 1

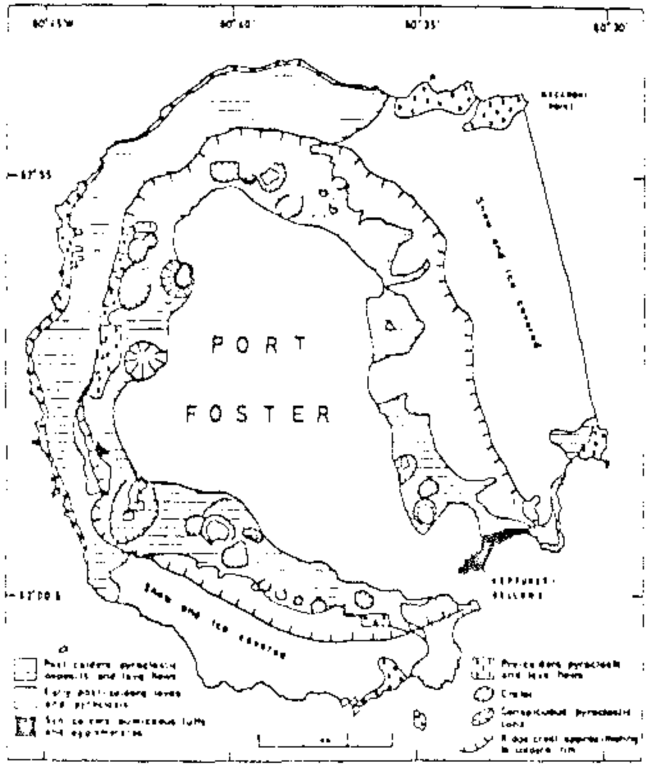


Figure 2

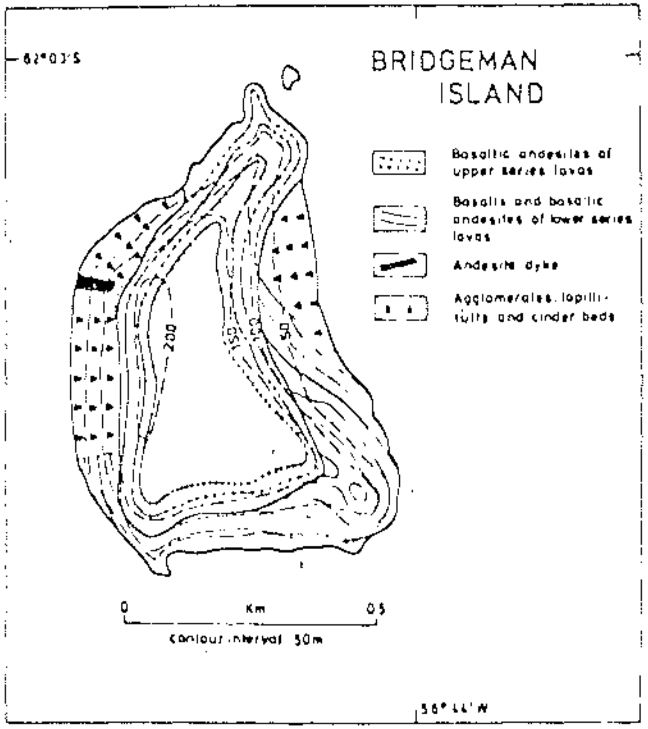


Figure 3

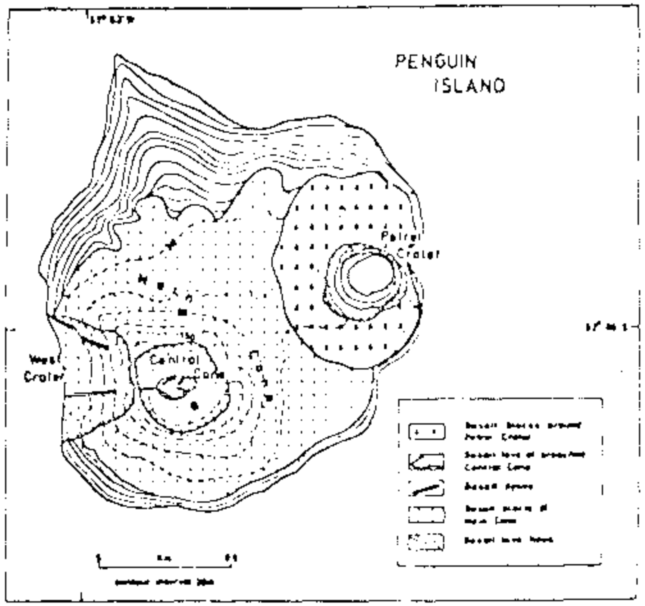


Figure 4

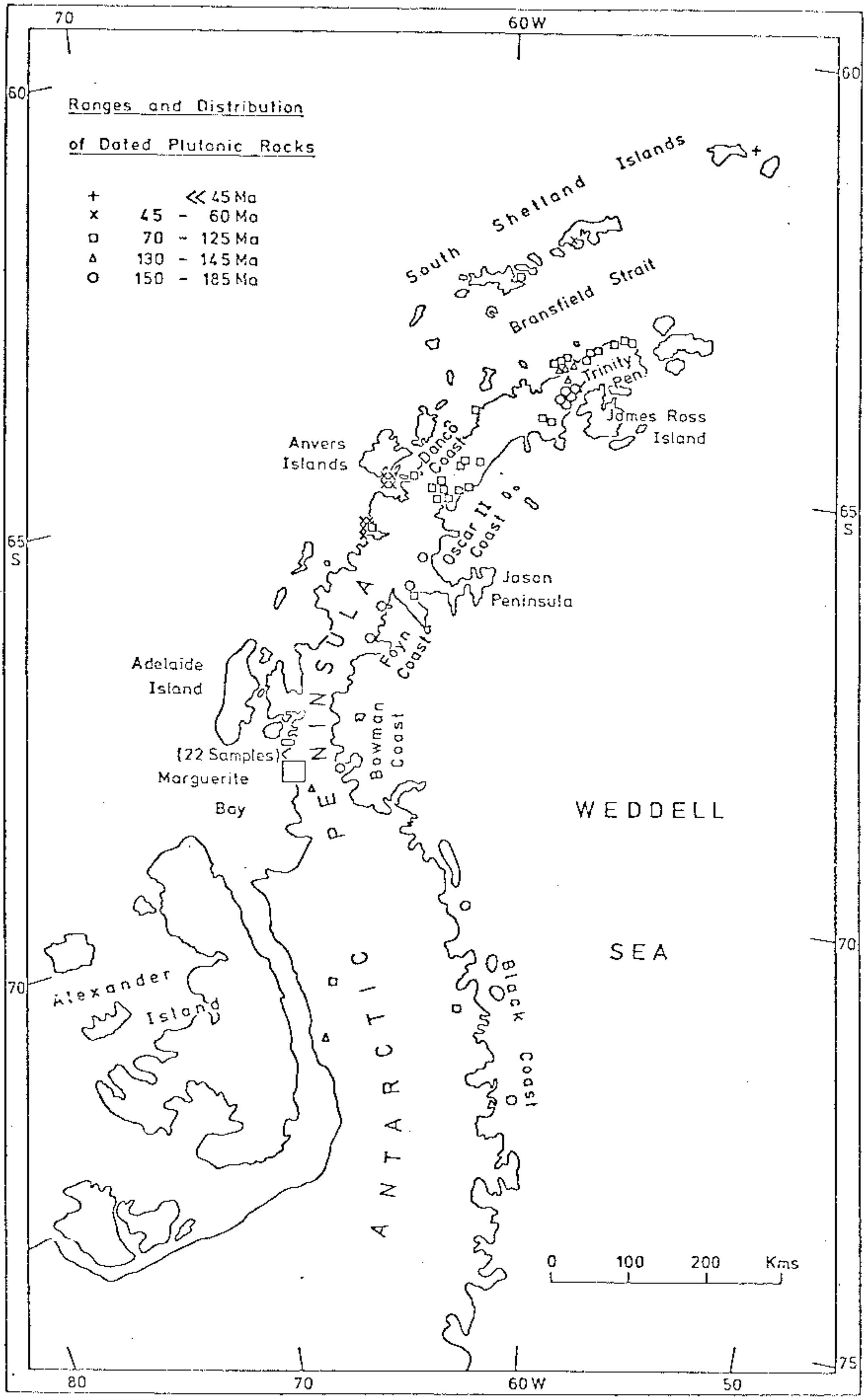

70
60 W
60
60
Ranges and Distribution
of Dated Plutonic Rocks
+ << 45 Ma
x 45 - 60 Ma
□ 70 - 125 Ma
△ 130 - 145 Ma
○ 150 - 185 Ma
South Shetland Islands
Bransfield Strait
Trinity Pen.
James Ross Island
Anvers Islands
Danco Coast
Oscar II Coast
Jason Peninsula
65 S
65 S
Foyn Coast
Adelaide Island
PENINSULA
Bowman Coast
(22 Samples)
Marguerite Bay
WEDDELL
SEA
ANTARCTIC
Alexander Island
Black Coast
70
70
0 100 200 Kms
75
80
70
60 W
50

Figure 1