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The evolution of the Scotia Ridge and Scotia Sea

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Marine geophysical surveys over the Scotia Ridge show it to be composed of blocks mainly of continental origin. Major structures found on the blocks are in many cases truncated at block margins and their existence is also inconsistent with the present isolated situation of the blocks. The evidence suggests post-Upper Cretaceous fragmentation of a continuous continental area. Complementary marine geomagnetic studies over the deep water of the Scotia Sea have dated two areas as younger than 22 million years (Ma) and have indicated the direction of spreading in others. A model of present plate motions, based on the magnetic anomalies, explains the active volcanism of the South Sandwich Islands as being caused by consumption of Atlantic crust at the associated trench at a rate of 5.5 cm/year for the past 7 to 8 Ma at least.

An Upper Tertiary episode of plate consumption at 5 cm/year at the South Shetland trench, suggested by the magnetic lineations, with a secondary slow extensional widening of Bransfield Strait is used to explain similarly the contemporaneous volcanism of the South Shetland Is. Making the reasonable assumption of a Tertiary formation of the undated parts of the Scotia Sea by spreading in the directions indicated by the magnetic lineations, a tentative reconstruction of the component blocks of the Scotia Ridge is made. The attempt is only partly successful in matching structural patterns across adjacent margins of reconstructed blocks, South Georgia being most obviously wrongly situated. It is suggested that the misfits result from minor errors in the initial assumptions and the modification of structures during fragmentation and drift. South Georgia may have formed on the Atlantic rather than the Pacific side of the compact continental region which is thought to have joined South America and west Antarctica for much of the Mesozoic at least. A Gondwanaland reconstruction is presented which is consistent with the Scotia Ridge reconstruction, in which the Antarctic Peninsula lies alongside the Caird Coast of east Antarctica. Upon break-up of Gondwanaland, the Antarctic Peninsula remained rigidly attached to South America, east Antarctica rotating clockwise to open the Weddell Sea, until early Tertiary times when the Peninsula transferred to east Antarctica which continued rotating clockwise to open the Scotia Sea.

Introduction

The deep water of the Scotia Sea is bounded on three sides by the Scotia Ridge, a loop of islands and shallow submarine ridges extending between the southern tip of South America and the Antarctic peninsula. The origin and history of the region has long been disputed on the basis of the geology of the islands (Matthews 1959; Hawkes 1962; Hamilton 1963; Wilson 1966; Moores 1970), it being generally accepted however that the Scotia Ridge was produced by some later distortion of an originally simple and continuous orogenic belt at the margin of Gondwanaland. Interest in the present-day tectonic activity of the area has been stimulated by the recent development of plate tectonics. The boundary between the South American and Antarctic lithospheric plates must lie within the region, although their relative motion is not established and earthquake epicentres are so sparse and diffusely distributed as to leave the exact location open to speculation (Morgan 1968; Le Pichon 1968; Barazangi & Dorman 1969; Vine 1970).

Marine geophysical data are potentially extremely useful as aids to understanding the structure of the region since the islands form such a small part, even of the Scotia Ridge. The Birmingham group have worked in the region since 1959 in cooperation with the British Antarctic Survey and, with others, have accumulated sufficient data to make a more informed, but still rather tentative estimate of the general structure and its evolution. The data divides

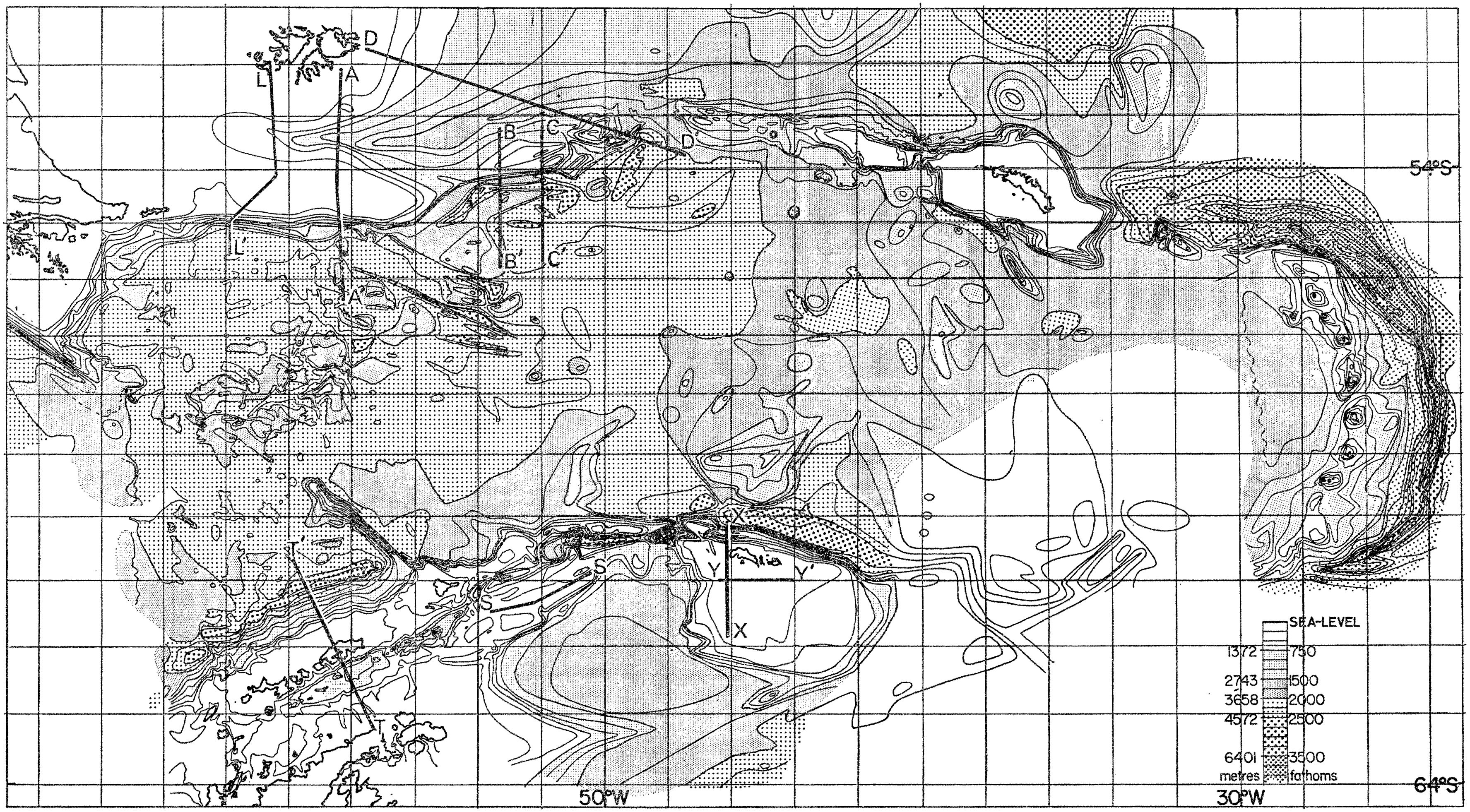

FIGURE 1. Bathymetry of the Scotia Sea. Contour interval 250 fathoms (457 m). (Reproduced with permission from Barker in *Antarctic geology and geophysics*, Oslo, Universitets Forlaget, 1971). Additional lettered lines of section refer to bathymetric or seismic profiles shown in figures 3, 4, 6, 7 and 8.

naturally into a bathymetric and magnetic study of the deep water area of the Scotia Sea, and a study by more varied means, including seismic refraction and marine gravity, of sections of the Scotia Ridge. The former study (Barker 1971) has led already to a postulated model for present plate motions and boundaries (Barker 1970) which is here compared with the distribution of present-day volcanic activity. Also the magnetic data and the derived model both have implications for the earlier structural history of the region which can be assessed mainly by reference to the geology of the Scotia Ridge. It is therefore useful at the outset to summarize what is known of the structure of the north and south Scotia Ridge, including relevant published geological and geophysical data and additional unpublished marine geophysical data. For this the bathymetric chart of figure 1 (from Barker 1971) provides a convenient reference frame.

Structure of the Scotia Ridge

Southern South America

The geology of Patagonia and Tierra del Fuego has been summarized by Harrington (1956, 1965), Munoz Cristi (1956) and Zambrano & Urien (1970). Ludwig, Ewing & Ewing (1965, 1968) have published seismic refraction profiles from the Atlantic continental shelf and Magellan Strait, and Hayes (1966) and Ewing, Houtz & Ewing (1969) have studied the Pacific continental margin.

Harrington (1965) proposes four morpho-structural units on land, south of 47° S. The Coast Cordillera forms the outer islands of the Chilean archipelago and the Patagonian Cordillera lies parallel and to the east, the two becoming difficult to distinguish in the south, where the overall strike bends through southeast to east. The Magellan basin lies eastward again, extending to the Atlantic seaboard except in the northeast where it is contained by the Deseado Massif, lying north of the Rio Chico and thought to extend southeastward to the Falkland Islands.

The Deseado Massif is composed of thin continental sediments of Permian and younger ages, overlying a presumed Precambrian basement. There is no evidence for its submergence below sea level at any time.

The floor of the Magellan basin geosyncline is of Upper Jurassic acid lavas and tuffs, the Serie Tobifera, overlying a basement of granitized schist for which a minimum rubidium–strontium age of 250 Ma has been measured (Halpern 1967). The Tobifera is up to 3 km thick in the west, and absent in places along the Atlantic coast. The overlying Lower Cretaceous sediments, continental at first, there rest directly on the basement, and elsewhere fill depressions in the considerable Tobifera topographic relief. Throughout Cretaceous and Eocene times the Magellan basin region appears to have been similar to a modern continental shelf, dipping gently westward to a shelf break near its present western margin, and receiving its sediments mainly from the east (from the Deseado Massif).

It is thought that after Permian folding and uplift of a Palaeozoic geosyncline on the present site of the Coast Cordillera, this unit subsided in Jurassic times to a shallow offshore ridge acting as the western boundary of a deep sedimentary trough on the site of the Patagonian Cordillera. This situation lasted until the uppermost Cretaceous, when apparently both Cordilleras were intruded by Andean granodiorites, the Coast Cordillera rising to become a source of coarse clastic sediments for the Patagonian Cordillera geosyncline, which was further depressed. In the Oligocene both Cordillera were raised, the Patagonian Cordillera being folded, faulted and thrust to become the major sediment source for the Magellan geosyncline, whose continental Upper Tertiary and Quaternary deposits were thickest in the west and tilted eastward, reversing the earlier pattern.

The western and southern margins of the pre-Oligocene Patagonian–Magellan geosyncline can be defined by the outcrop of the Serie Tobifera, which is seen as far east as Staten Island, or less directly by the termination eastward and northward of a zone of large magnetic anomalies shown in figure 2.

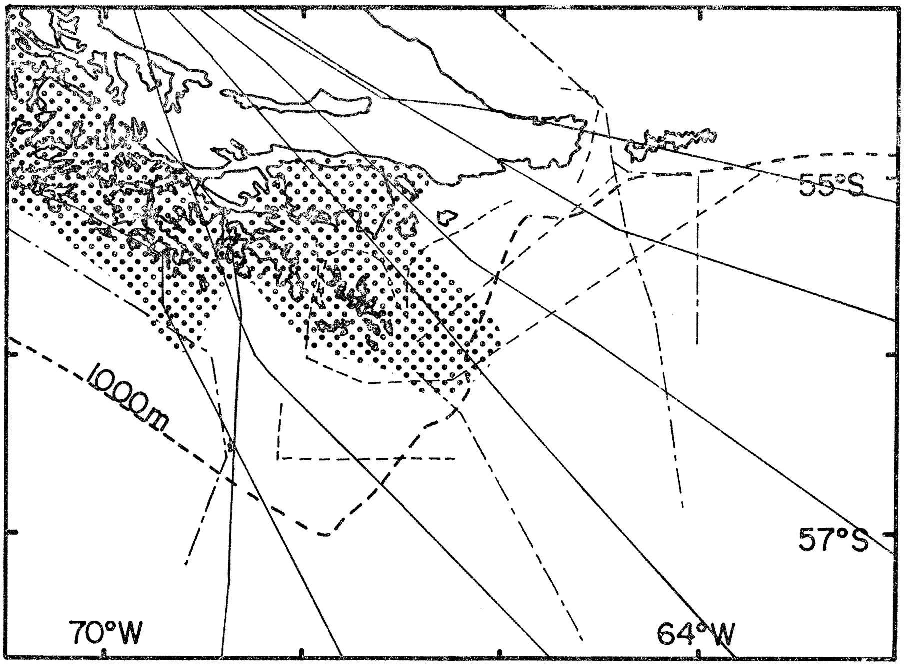

FIGURE 2. Zone of large magnetic anomalies in Tierra del Fuego shown shaded. Solid lines are Project Magnet flight lines, dashed lines are ship tracks.

These originate mainly in the Coast Cordillera and are by now fairly well delineated near Cape Horn (Peter 1962; Project Magnet; C.N.A.I.S.Q. 1968; Kroenke & Woollard 1968). There are many possible sources of the anomalies; the Cordilleras do not have a consistent lithology in detail along the overall strike direction but, for example, Katz & Watters (1966) observe on and around Navarino Island (55° S, 68° W), quartz-dolerite sills in the Lower Cretaceous Yahgan Formation, marginal metamorphosed lavas presumed contemporaneous with the sediments, extensive Upper Cretaceous Andean diorites, post-Andean basic and andesitic lavas and, possibly, modern volcanic cones.

The Cordilleras end abruptly east of Cape Horn, where the continental shelf edge swings northeastward to Staten Island. The magnetic zone also thins significantly towards the shelf edge and it is interesting that Ludwig *et al.* (1968) report along this discordant margin a 2 km thick wedge of material having a compressional seismic velocity of 4.1 km/s, interpreted as sediment of Jurassic or greater age.

Also of interest is that the narrow negative free air gravity anomaly associated by Hayes with a sediment-filled trench marginal to the Pacific shelf south of 32° S (Ewing *et al.* 1969) is observed only as far round the southern bend as 71° W. It is absent south of Cape Horn, suggesting a different recent structural history inside the Scotia Sea, as also does the truncation of the Cordilleran belt.

The Falkland Islands

Ludwig *et al.* (1968) present seismic data supporting the suggestion that the Falkland Islands lie on a basement platform extending southeast from the Deseado Massif. However, the geological history of the Falkland Islands (Halle 1912) is closer to that of Cape Province, South Africa, since it has a nearly identical Upper Palaeozoic sequence of marine and terrestrial sediments with common fossils, a Permo-Carboniferous glacial sequence, a similar Lower Permian Glossopteris-bearing arkosic sandstone and (?) Rhaetic dolerite dykes (Adie 1952). The seismic sections of Ludwig *et al.* (1968) show the elevated 'basement' of the Falkland platform extending as far north at shallow depth as the Falkland fracture zone which forms the southern rim of the Argentine basin at 49° S, and southward for a limited distance before becoming buried beneath an increasing thickness of younger rocks in the Malvinas basin. Eastward from the Falkland Islands there is no seismic information until 47° W, where refraction profiles show a 'continental' main crustal layer at shallow depth close to the Falkland fracture zone (Ewing & Ewing 1959; Kroenke & Woollard 1968), again plunging southward beneath thickening low velocity sediments. It appears likely therefore that the entire elevated south side of the Falkland fracture zone, as far east as 40° W, has continental affinities.

Burdwood Bank

Burdwood Bank extends eastward from Tierra del Fuego for 450 km and measures 110 km from north to south at the 500 m isobath. It is flat-topped, largely at a depth of 70 to 180 m and drops steeply southward to the Scotia Sea, less steeply northward but with a rugged slope, to the flat-bottomed Falkland trough, which deepens steadily eastward. To the east Burdwood Bank itself appears joined to a sequence of lesser elevated bodies forming the north Scotia Ridge.

One of two published north–south seismic refraction profiles across Burdwood Bank (Ludwig *et al.* 1968) is shown in figure 3. Although there are gaps in the data and only lines 57 and 58 are reversed, there is little doubt about the general interpretation, which is consistent with nearby gravity profiles (F. J. Davey, in preparation). A sedimentary basin, the Malvinas basin, lies beneath the Falkland trough and Burdwood Bank; the underlying basement rocks, rising southward, probably outcrop on the Bank's southern slope. Although strictly their data are inconclusive, the authors point out that probably the Malvinas and Magellan basins are not continuous, but are separated by a basement ridge running northwest from just east of Staten Island.

Griffiths, Riddihough, Cameron & Kennett (1964) note that Burdwood Bank is virtually non-magnetic. A typical magnetic and bathymetric profile across the bank (profile AA′ of figure 4) confirms that there is no anomaly associated with the southern edge of the rising basement, which suggests that lavas of the Serie Tobifera do not occur west of the basement ridge separating the two basins. Few samples have been taken from Burdwood Bank. Ross (1847) reported a sounding of 'coarse black sand and small stones of volcanic origin' from 54° 41′ S, 55° 12′ W in 500 m, which is inconsistent with the seismic and magnetic model. However, Macfadyen (1933) has described dredge hauls of sedimentary rock from three *Discovery II* stations along 54° S which included Upper Cretaceous foraminifera and black phosphatic pebbles, and Goodell (1965) includes a bottom photograph showing small manganese nodules from the eastern end of the Bank. The possibility exists therefore that Ross's specimens were phosphatic or manganese nodules, wrongly identified.

A possible inconsistency between the bathymetry and the seismic model concerns the northern slope of Burdwood Bank. Its rough topography becomes rougher eastward, as the Falkland trough deepens. The roughness is probably inconsistent with the low velocities (1.7 and 2.1 km/s) of the top 2 km of masked layers, incorporated in the model to account for delay times to the lower layers.

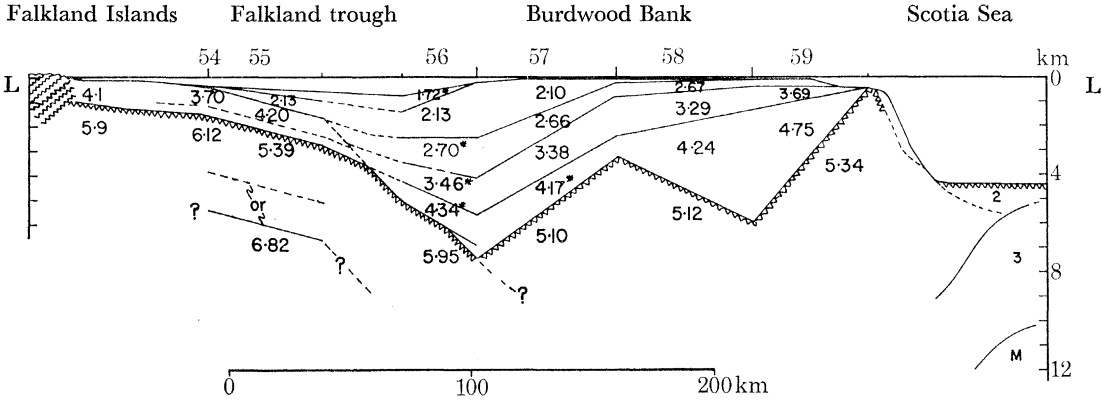

Figure 3. Crustal section from the Falkland Islands to the Scotia Sea through Burdwood Bank, reproduced with permission from Ludwig *et al.* (1968) and located in figure 1 as LL′.

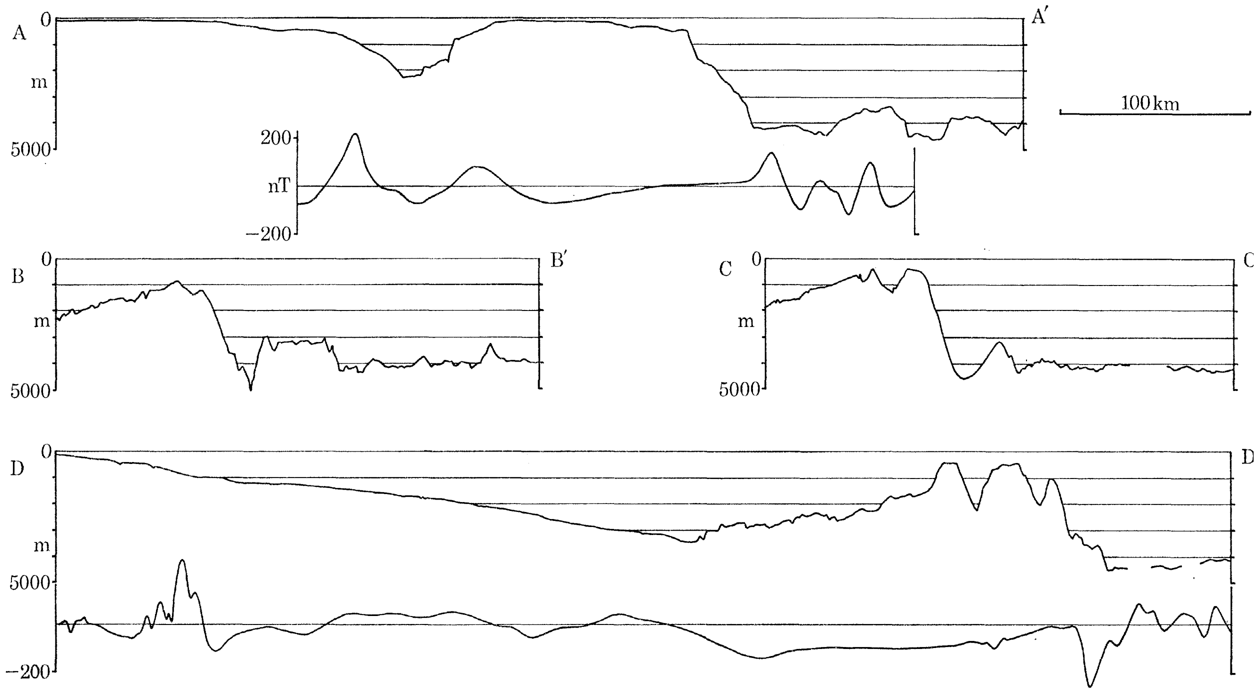

Figure 4. Bathymetric and magnetic profiles AA′, BB′, CC′ and DD′ across Burdwood Bank and north Scotia Ridge, located in figure 1. Vertical exaggeration approx. 14:1.

The layering beneath Burdwood Bank is different from that in the northwest Malvinas basin, which is nearer to the probable northerly sediment sources of the Falkland Islands and Deseado Massif (Ludwig *et al.* 1968, Sections GO and TN). A southerly sediment source is likely for the northward-dipping 3.3 and 4.2 km/s layers, representing perhaps Lower Cretaceous and Jurassic deposition. In contrast, the Coast and Patagonian Cordilleras did not provide sediment to the Magellan geosyncline until the Oligocene (Harrington, in Ludwig *et al.* 1965). Taken with the non-magnetic nature of the truncated basement, this evidence suggests that where the Scotia Sea now lies there was for much of the Mesozoic a sediment source with possibly a different tectonic history from that of the Coast or Patagonian Cordilleras.

Burdwood Bank to South Georgia

The north Scotia Ridge between Burdwood Bank and South Georgia is made up of four main elevated blocks. The lowest block rises to 1300 m below sea-level and the depths of the saddles between the blocks range between 1650 and 3100 m, nowhere reaching the depth of the Scotia Sea to the south or of the Falkland trough to the north. Bathymetric profiles across the Ridge (profiles BB′, CC′ and DD′ of figure 4) show the tops of the blocks to be horizontal or to dip northward. The tops are dissected to a varying extent and at least one edge is steep, indicating that consolidated rock is present at the surface. Between 48 and 58° W the sea-bed south of the blocks is in most profiles deeper than the general level of that part of the Scotia Sea, although the profiles (BB′ and CC′) are not typical of those across marginal trenches and it is suggested that the deeps indicate strike-slip decoupling. Between South Georgia and 48° W the southern marginal deep is absent.

To the north of the north Scotia Ridge lies the Falkland trough, which starts as a slight depression in the continental shelf north of Staten Island, has deepened to 3000 m by 56° W, and then deepens more slowly to just over 3600 m at 48° W. It then shoals slightly to 42° W where it opens out into a basin with a depth of 3800 m. The trough has a narrow bottom of ponded sediments, wider towards the east, and its sides are consistently asymmetric, the steeper more rugged side being that of the north Scotia Ridge to the south. Indeed its northern slope, although possessing a very small-scale roughness, is without major discontinuities and runs in places at a constant gradient from sea-level at the Falkland Islands to 3600 m as shown in profile DD′ of figure 4. The gentle northern slope of the trough extends northwards to the abrupt north-facing scarp of the Falkland fracture zone at about 49° S, as far eastward as 40° W. Further to the east the fracture zone appears only as an east–west band of rough topography separating smooth areas at similar oceanic depths to north and south. Sounding data to the northeast of South Georgia are sparse, but the smooth area of deep ocean is interrupted in places by domed elevations lying along a line at approximately 060° from South Georgia almost to the Mid-Atlantic Ridge and called the South Georgia rise.

Almost all of the area north of the north Scotia Ridge appears to be covered with a layer of soft sediment, even the topographic highs which are in general smooth domes. Few scarp faces remain. In the basin to the northwest of South Georgia up to 4 km of sediments are seen (Ewing & Ewing 1959; Kroenke & Woollard 1968) and, as mentioned above, to the north the main crustal layer is more continental than oceanic in character. The sparse magnetic data bear out this conclusion; the north Scotia Ridge and Falkland Platform are generally non-magnetic. An anomaly appears to be associated with the deeper, eastern part of the Falkland trough but our profiles are few and the angles of crossing highly oblique. Typical oceanic anomalies occur to the north of South Georgia, but their strike cannot be determined; the thick sediment cover in that area would suggest that the crust is old, however, and it is conceivable that the anomalies are associated with the early stages of spreading away from the Mid-Atlantic Ridge.

Shag Rocks

Shag Rocks form the only exposed land upon an irregularly shaped continental block measuring 50 km by 200 km and elongated east–west. The block has a steep southern continental slope and a more gradual northern slope; there is a minimum depth of 1700 m between it and the South Georgia block to the east.

The Rocks have not been visited, but Tyrrell (1945) reports two dredge stations 2 and 45 km to the west, in 200 and 750 m of water respectively, yielding greenstones which resemble greenstone schists from the north end of Clarence Island, and a quartzitic arkose which resembles the Sandebugten type quartzose greywackes exposed on South Georgia.

Two magnetic profiles crossing the continental block show only one small length of anomalous magnetic field, having anomalies of shallow origin but only 40 nT amplitude, about 40 km east of Shag Rocks. The available evidence thus suggests that much or all of the Shag Rocks continental block is composed of the essentially non-magnetic metamorphic 'basement complex' seen elsewhere along the Scotia Ridge, with the possibility of overlying younger sediments in parts not entirely ruled out.

South Georgia

As shown in figure 1, the island of South Georgia occupies the middle of a 'continental' block, 120 km by 350 km in size, elongated slightly south of east. Aspects of the geology of the island have been described by Tyrrell (1930), Trendall (1953, 1959) and Frakes (1966). The majority of rocks exposed are slightly metamorphosed greywackes of the Cumberland Bay Series, comprising the quartzose Sandebugten type greywackes exposed in the northeast and the probably younger, more extensive Cumberland Bay type tuffaceous greywackes. The upper part of the latter contains interbedded basalts and spilites and the youngest exposed beds have yielded Upper Aptian fossils. The exact nature of the junction between the rock types is not clear. In the southeast a suite of acid and basic igneous rocks is intruded into the metamorphic rocks, and granite is exposed on Clerke Rocks farther east. Trendall proposed that the Cumberland Bay type sediments, which Wilckens (1932), Matthews (1959) and Katz & Watters (1966) have compared in age and lithology with the Yahgan formation of southern Tierra del Fuego, were derived from a volcanic island arc to the south of South Georgia and deposited from turbidity currents in a trough oriented approximately along 060°. The Sandebugten type greywackes, which have been compared with the Greywacke Shale Series of the South Orkney Islands and the Trinity Peninsula Series of Graham Land (Adie 1957), had already been deposited and possibly partly folded. In the major folding, post-Aptian in age, the northeast beds were thrust over the southwest beds, with the paratectonic intrusion of the southeast igneous complex. Post-tectonic dykes in the southeastern part of the island have a composition similar to that of the pretectonic lavas.

Several magnetic tracks crossing the South Georgia shelf are shown in figure 5 with those areas shaded which show shallow origin magnetic anomalies. The anomaly locations correspond well with a simple seaward extension of the zone of lavas interbedded with Cumberland Bay type greywackes and indicate that this zone continues to the shelf edge. The magnetic profiles in the southeast corner show even larger amplitude magnetic anomalies of both deep and shallow origin, probably indicating an extension to the shelf edge of the southeast igneous complex. Apart from two small anomalies right at the shelf edge the magnetic profiles in the shelf area north of the island are undisturbed.

The shelf edge is abrupt all round the South Georgia block and seems to truncate the geologic features inferred above, suggesting that the block was part of a larger elevated landmass which was fragmented after the most recent of these features was formed.

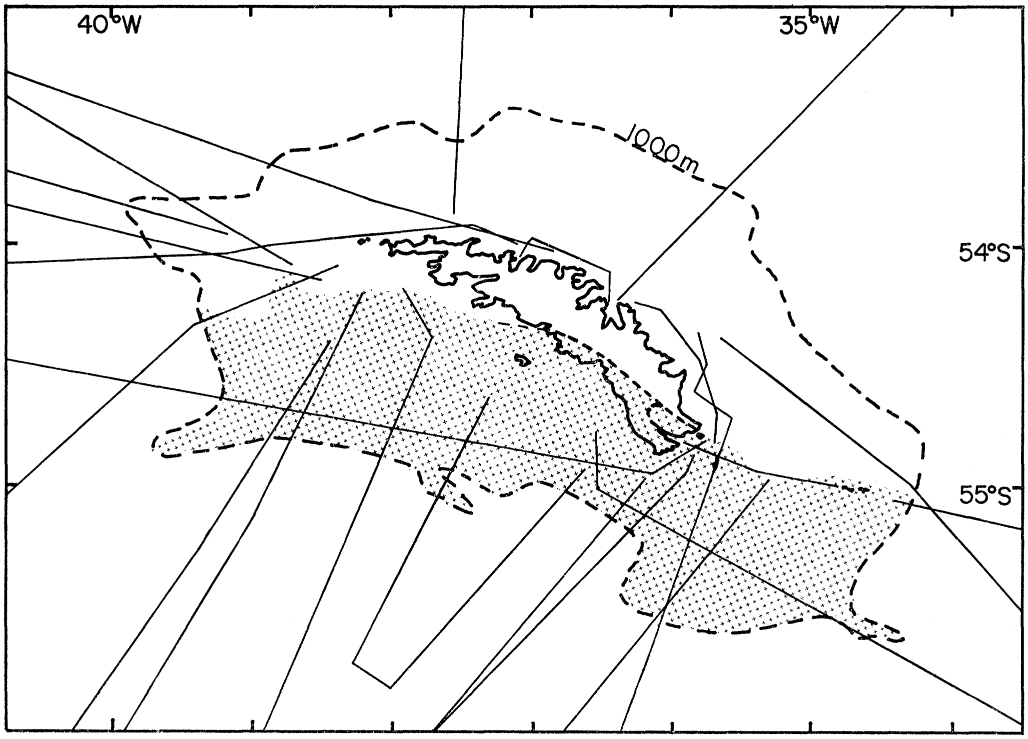

Figure 5. Zone of magnetic anomalies of shallow origin on South Georgia shelf. Ship tracks show extent of magnetic data. Magnetic zone apparently forms simple seaward extension of exposures of igneous intrusives and basic volcanics shown dashed from Trendall (1959).

The South Sandwich Islands

The South Sandwich Is form an active volcanic island arc at the far eastern end of the Scotia Sea, bounded by a trench to the east. The rocks are mainly tholeiitic basalts (Baker 1968) with few occurrences of andesite and only one known rhyolitic rock, the pumice from the 1962 submarine eruption at the extreme northern end of the arc (Gass, Harris & Holdgate 1963). Potassium–argon ages of 0.7 and 4.0 Ma have been found for lavas thought from their field relations to be relatively old (Baker 1968) and earlier suggestions that sediments and a metamorphic basement were exposed on Freezeland Rock (Kemp & Nelson 1931) are now discounted.

Little is known about lateral variation along the arc; the largest island is in the middle, the only island not showing some signs of recent activity lies at the southern end and the most recent eruption occurred at the northern end, as did the deepest recent earthquake (170 km—Gutenberg & Richter 1954). The South Sandwich trench is deepest in its northern part.

Baker (1968) concludes that the arc is in an early stage of evolution, which is consistent with the model derived from the Scotia Sea magnetic data (Barker 1970) and further discussed below.

Southeast Scotia Ridge

The bathymetry of the southeast Scotia Ridge between the South Sandwich Is and the South Orkney Is is shown unshaded in figure 1 to emphasize the comparatively speculative nature of the contouring. Very few sounding lines cross the area, which is ice-covered for almost all of each year. Some of the observations below are based on these isolated lines rather than on figure 1. Both the tilted block on which the South Sandwich Is lie and the trench are truncated at 61° S by a west–east fracture zone which Heezen & Johnson (1965) suggested extended westward to the South Orkney Is and east of the trench towards the Mid-Atlantic Ridge. The floor of the Weddell Sea to the south rises and becomes rougher northwards towards the south Scotia Ridge and Barth Bank at 63° S, 41° W appears to lie on one of a number of elongated bathymetric features trending at 070°. The north–south elevated zone of rough topography which is seen on all crossings of the east Scotia Sea appears to break through the south Scotia Ridge in a 100 km wide zone centred on 30° W. Between there and the South Orkney Is lie a number of steep-sided elevated areas, having tops at between 350 and 1500 m with up to 350 m relief, which is rougher than the tops of other elevated blocks bordering the Scotia Sea. At least one of the blocks includes magnetic material at shallow depth. The blocks are bounded to the south by elongated troughs reaching depths exceeding 5500 m in places, but not forming a simple connexion between the fracture zone observed south of the South Sandwich Is and the deep trough bisecting the south Scotia Ridge farther west. Earthquake epicentres close to these troughs (figure 9 below) suggest that motion along them, which may be dissecting the blocks, is still proceeding, but further examination of this complex and interesting area is obviously necessary.

South Orkney Islands

The South Orkney Is lie on the north side of a rectangular continental block measuring 300 km along 100°, by 200 km. Adie (1964) has summarized earlier geological work on the islands; more recently Matthews & Maling (1967) and Thomson (1968) have described in detail respectively the general geology and the petrology of Signy Island, with additional new data from other islands, and West (1968) has described a rock collection from Inaccessible Islands. Harrington, Barker & Griffiths (1971) describe marine seismic refraction and magnetic measurements made on the continental block, mainly south of the islands.

A parametamorphic Basement Complex of quartz-mica schists, amphibolites and marbles forms much of the western islands, whereas the oldest exposed rocks on the eastern islands are quartz-greywackes of the Greywacke–Shale Series, lithologically similar to the Sandebugten Series of South Georgia. Basement Complex and Greywacke–Shale Series are both intensely folded about approximately similar axes trending slightly west of north. A potassium–argon date of 187 ± 5 Ma for Basement Complex rocks (Miller 1960; Thomson 1968) is considered by Adie to be the age of this folding but younger than the date of the major metamorphism of the Basement Complex. Although the contact between them is nowhere seen, both units are overlain unconformably by flat-lying coarse-bedded conglomerates tentatively assigned a Lower Cretaceous age and gently folded along a west–east axis.

Rare altered dolerite dykes striking north of west cut the Basement Complex and in one locality the conglomerate also. The major tectonic influence on topography is faulting, striking just west of north parallel to the fold axes, but later than the folding as it affects the conglomerate.

Two major structures not even hinted at by the land geology occur on the shelf south of the islands, and are shown in sections XX′ and YY′ of figure 6 (Harrington *et al.* 1971). South of the islands the Basement Complex and Greywacke–Shale Series are buried beneath a west–east elongated sedimentary basin which may close eastward or turn to the south, and probably does not close completely westward before being truncated at the shelf edge. South again of the basin axis a zone of large and complex magnetic anomalies coincides with the occurrence of high velocity (6.0 to 6.7 km/s) rock at shallow depth. The sedimentary layers are presumed to be of

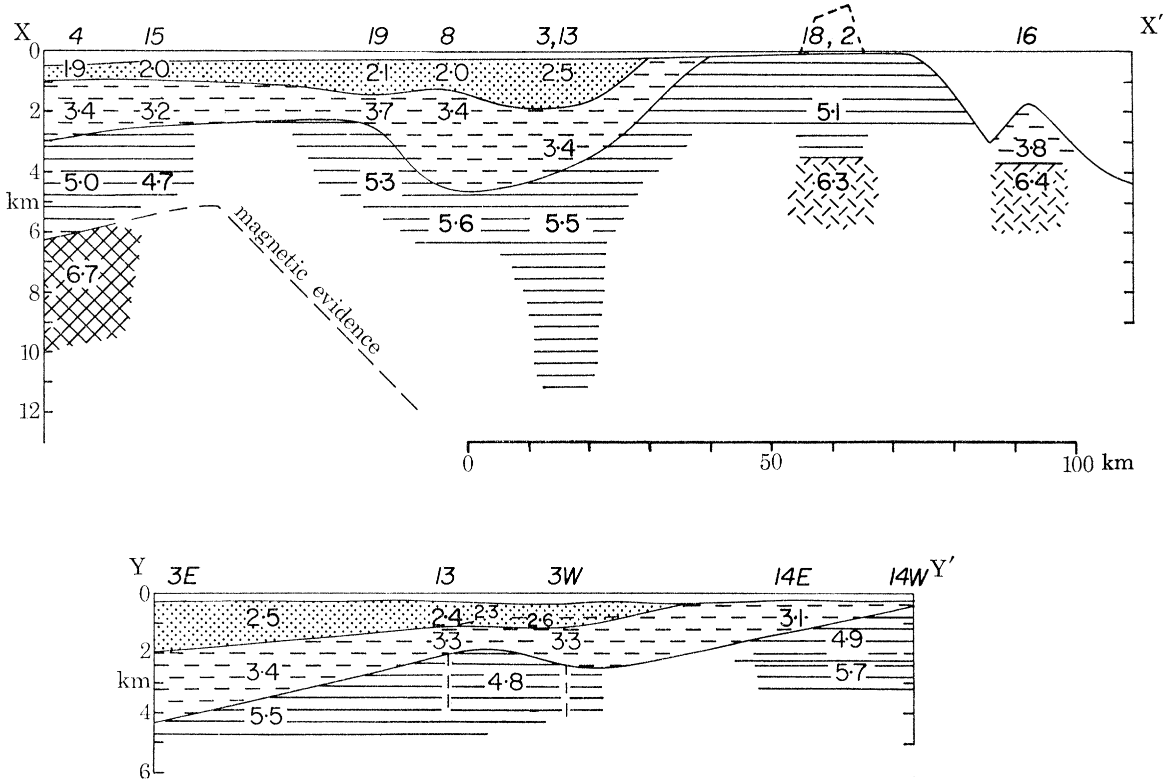

Figure 6. Crustal section XX′ and YY′ across South Orkney Island shelf, reproduced with permission from Harrington *et al.* in *Antarctic geology and geophysics*, Oslo, Universitets Forlaget, 1971, and located in figure 1.

Tertiary and Cretaceous age on the basis of their compressional wave velocities (Ludwig *et al.* 1965, 1968) but above the 6.7 km/s body, the 4.7 to 5 km/s layer may not be the Basement Complex or Greywacke–Shale Series, as it is assumed to be farther north. Probable north–south faulting affects the Cretaceous–Tertiary interface above the high velocity body. The source of the magnetic anomalies is required to be of large dimensions, given reasonable apparent susceptibility values, and is considered to be a granite–gabbro intrusive complex, coincident with the 6.0 to 6.7 km/s body.

Magnetic anomalies of very shallow origin occur in certain well-defined areas of the shelf. Southeast of Laurie Island in the east, and around the Inaccessible Is in the northwest corner, rock of velocity 4.7 km/s or higher occurs at sufficiently shallow depth to include the source of the anomalies, which might thus be caused by the dolerite dykes occurring in greater concentration than they are seen in the Basement Complex ashore. Other shallow origin anomalies in the region covered by the large and complex anomaly over the southern part of the shelf were examined quantitatively (Smellie 1956) and it was found that sufficient magnetic material to cause 50 nT anomalies had to occur within the presumed Cretaceous sediments. If shallow and deeper anomalies are causally related here, this gives a likely age range for the large magnetic body which is consistent with that of the Andean Intrusive Suite of Graham Land or the South Georgia southeast igneous complex. Also the presence of this body, the sedimentary basin and the rocks exposed ashore are all inconsistent with the present isolated position of the South Orkney Is block.

The post-Cretaceous north–south faulting seen also on the islands, may thus be associated with the later fragmentation of a larger continental area and the truncation of these major structures.

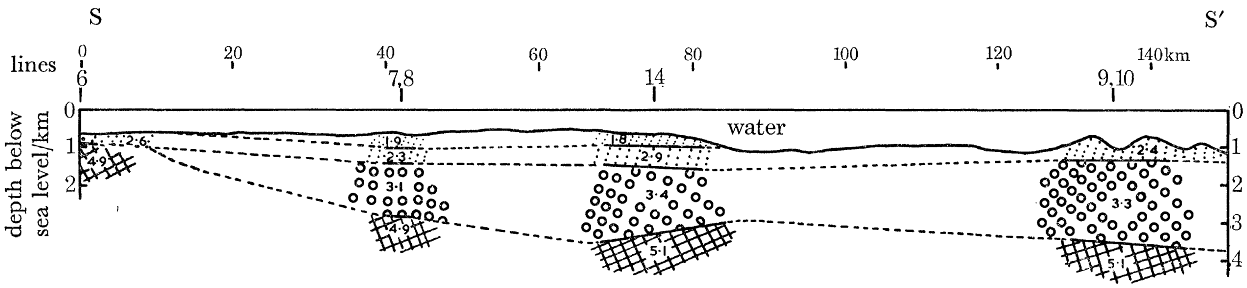

Figure 7. Crustal section SS′ along the southern limb of the south Scotia Ridge, reproduced with permission from Watters, in *Antarctic geology and geophysics*, Oslo, Universitets Forlaget, 1971, and located in figure 1.

The South Orkney Is and Graham Land continental blocks are separated by a quite complex section of the south Scotia Ridge. Their southern margins are joined by a gentle rise separating the deep smooth Weddell Sea bed to the south and an equidimensional basin, at 3300 m depth and also smooth, to the north. Magnetometer profiles show only low amplitude anomalies over both basin and rise.

The section of the Scotia Ridge bounding the basin to the north is double, lies mostly above 1000 m, and has a deep, steep-sided central trough. Herdman (1948) noted that the southern limb of the ridge joined the South Orkney Is block to the Graham Land block, while the northern limb ran eastward from Elephant I to die out north of the South Orkney Is northern shelf edge, the intervening trough continuing eastward to about 40° W. Between there and Bransfield Strait, into which it runs, the trough changes direction discontinuously from 270 to 300°, widening where it turns southward in a manner suggestive of left-lateral strike-slip motion across it. Its depth varies between 900 and 5800 m and the bottom appears to contain little sediment.

Watters (1971) has interpreted a reconnaissance geophysical survey of the two component ridges, which are structurally quite different.

On the northern ridge a veneer of 1.8 to 2.4 km/s velocity sediment overlies irregular thicknesses of between 0 and 2.0 km of material with a compressional wave velocity of between 3.2 and 4.4 km/s. These overlie a basement of velocity 5.2 to 5.6 km/s which, because of the essentially non-magnetic character of the ridge, the measurement of similar velocities close to the South Orkney Is, and the proximity of Elephant and Clarence Is, is considered to be composed of similar parametamorphic rocks to those exposed on both island groups. While faulting has been observed on only one seismic line, the variability of layering suggests that it is more widespread on the northern ridge.

In contrast the southern ridge exhibits a much more regular layering and contains magnetic material at depth. Profile SS′ of figure 7 (Watters 1971) shows a very similar layering to that found on the southern South Orkney Is continental block. Magnetic anomalies of shallow origin are restricted to the southwestern part, south of 61° 30′ S, but the entire south ridge has a magnetic basement layer. Watters also draws attention to similarities between the rocks exposed in northeast Graham Land (q.v.) and the layering of this southern limb, and points out that the widespread truncation of features observed on both limbs, and their incompatibility with their present position, suggest a more recent fragmentation of a more compact continental area. The central dividing trough is regarded as a young feature which may be actively continuing the fragmentation process.

Elephant and Clarence Islands

The Elephant and Clarence Is group lie on the northern limb of the south Scotia Ridge and are geologically distinct from the other South Shetland Is to the southwest. Few rock collections have been made (Tyrrell 1945), mainly from coastal sites as the interiors are largely inaccessible.

All the islands are composed of metamorphic rock; on Elephant I, the largest, the metamorphic grade decreases from south to north, the assemblage as a whole being very similar to the Basement Complex of the South Orkney Is, and possibly representing metamorphosed eugeosynclinal sediments, here folded along a west–east axis. Similar rocks on Clarence I have a northeast–southwest fold axis, and of the smaller islands, Aspland I is similar but with a north–west strike; Gibbs I has high-grade schists in the west, dipping west–northwest and overlying a dunite-serpentinite mass.

The surrounding area of shallow water is magnetically quiet, apart from an anomaly associated with the ultrabasics and one or two others lying on some of the other bathymetric lineations. Ashcroft (in press) finds an abrupt increase in delay time to a 5.8 km/s layer to the southwest of one of these lineations north of Gibbs I and, following Lappin (1966), suggests that the dunite-serpentinite may have been squeezed upwards between faults north and south of the island. An extension of this argument suggests that the other lineations are faults, and even that the other magnetic anomalies may arise from further small associated ultrabasic bodies, or basic dykes. It is thought that the discordant strikes on the islands result from their relative rotation along these faults.

Graham Land

Graham Land, lying on the southern limb of the south Scotia Ridge, is best described next, as its pre-Tertiary geology and that of the remainder of the South Shetland Is bear a close resemblance. Graham Land extends from West Antarctica to 63° S as a central plateau, decreasing in height northwards, lying on a strip perhaps three times as wide at the continental shelf edge. The plateau is dissected to a variable extent, and is flanked by many islands, particularly on the west side.

The western continental slope is steep but the eastern slope, as far as is known, descends gradually towards the Weddell Sea. Many of the islands of the western shelf are bounded by deep channels lying along faults parallel to the length of Graham Land. To the north, the dominant example turns northward to form the western margin of Bransfield Strait.

Adie (1964) has summarized geological exploration to that date. The Basement Complex of Graham Land, in which many metamorphic episodes have been recognized, is different from that of the South Orkney Is and the Elephant and Clarence Is group, and is not seen north of 68° S. The Trinity Peninsula Series of eugeosynclinal sediments is exposed intermittently on both coasts throughout Graham Land, reaching 13 km apparent thickness in its type area at the northern tip. Rare pollens, poorly preserved plant remains and its field relations where seen are all consistent with a Carboniferous age. Its sediments derive largely from a continental environment of acid igneous rocks and metasediments, of high relief. Penecontemporaneous uplift, erosion and acid volcanism probably occurred. Correlation on lithologic grounds has been made with the Greywacke-Shale Series of the South Orkney Is, the Sandebugten Series of South Georgia and less confidently the Miers Bluff Series of Livingston I, South Shetland Is. However, a Cretaceous age has been attributed to a similar eugeosynclinal assemblage from northwest Graham Land by Halpern (1964) on the basis of its field relations with radioactively dated plutonic igneous rocks.

Characteristically in Graham Land the Trinity Peninsula Series is overfolded from the west or northwest, and regionally metamorphosed up to greenschist facies in places. In the north it is possible to assign a pre-Middle Jurassic age to the folding, from the unconformably overlying Mount Flora Plant Beds of that age at Hope Bay. Adie (1964) suggests the folding may be of Lower Jurassic age by analogy with the 187 Ma date (Miller 1960) for the metamorphism of the Basement Complex on the South Orkney Is.

An intermediate to acid volcanic episode, widespread throughout Graham Land and the South Shetland Is and resulting in a 3 km thickness in places, has been given an Upper Jurassic age because associated tuffs and rhyolites conformably overlie the Mount Flora Plant Beds at Hope Bay.

Post-Jurassic sediments and volcanics are of more restricted occurrence than the older rocks; 5 km of eastward dipping Cretaceous sediments, derived largely from the older rocks of Graham Land are found mainly in the James Ross Is group and are overlain by thin Miocene sediments and more than 1 km of horizontal, mildly alkaline basic volcanic rocks of Plio–Pleistocene age (Rex 1971). Similar basalts occur at Seal Nunataks, also on the east coast. The Cape Legoupil Formation (Halpern 1964) is thought also to be of Cretaceous age and Mesozoic conglomerates are thought to form much of eastern Joinville I (Elliot 1965).

The northeast coast sequence mentioned above has helped to date as Upper Cretaceous to Lower Tertiary, members of the Andean Intrusive Suite exposed in the area. This granite-to-gabbro suite occurs extensively in Graham Land and the South Shetland Is, forming the high land in the south and thermally metamorphosing much of the exposed Trinity Peninsula Series and Upper Jurassic volcanic group rocks. The concept of a single Andean intrusive episode, however, seems likely to be modified by radioactive dates; Halpern (1962, 1964) reports ages of 75 ± 8, 86 ± 7, 100 ± 20 and 116 ± 4 Ma for intrusive rocks in the Cape Legoupil area, and Scott (1965) finds dates of 52 ± 2 and 94 ± 8 Ma for bodies previously called Andean near Anvers I on the west coast. Many more computed dates, unpublished as yet in detail, promise to demonstrate several intrusive episodes between the Eocene and Lower Jurassic, two or more of which had previously been called Andean (Anon 1969).

The present high relief of Graham Land results from block faulting and uplift thought to be associated with the late stages of emplacement of the Andean Intrusive Suite. The set of prominent longitudinal faults on the west coast may have this origin, but occasional exposures of very fresh dykes, tuffs and lavas in their vicinity (Goldring 1962; Hooper 1962; Elliot 1964) suggest additional later movement, possibly associated with Tertiary and Recent volcanic activity on the South Shetland Is. Scott (1965) suggests a right-lateral movement across the Peltier shear zone on the west coast about 50 Ma ago.

South Shetland Islands

The South Shetland Is, excluding the Elephant and Clarence Is group, and Smith and Low Is to the southwest, are composed almost entirely of extrusive and intrusive igneous rocks and have an early history very similar to that of Graham Land (Adie 1964; Barton 1965; Hobbs 1968). On Livingston I an extensive exposure represents 3 km thickness of the eugeosynclinal Miers Bluff Series, containing interbedded andesites, inverted (Dalziel 1971), and dipping at 45° to the northwest. Except for the andesites the Series is lithologically similar to the Trinity Peninsula Series, with which it has therefore been correlated by Hobbs; it does predate the presumed Andean intrusives in the area.

Apart from the rocks described above, and occasional blocks of gneiss within Recent agglomerates, the oldest exposed rocks on the South Shetland Is are altered andesite–rhyolite lavas correlated with the Upper Jurassic Volcanic Group of Graham Land. Here they predate the Andean Intrusive Suite, which has caused their alteration and veining, and with which they form the bulk of the elevated central region of the islands. Eocene to Miocene andesitic and basaltic lavas also occur to north and south of this central uplifted zone, but the youngest of these and the more alkaline, basic, Pliocene to Recent volcanics occur only to the south. The final stages of the Andean intrusions are thought to have initiated differential uplift of the central section along faults parallel to the present southeast coasts, with the younger volcanics being associated with the outer fault zones. The volcanoes of Deception I, which is active, and Bridgman I lie on a parallel line farther to the southeast.

Bransfield Strait

The similarities between the geology of the South Shetland Is and Graham Land, and between Elephant and Clarence Is and the South Orkney Is, and the differences between one of these pairs and the other, suggest that the crustal structure of Bransfield Strait and the ridge to the north of it is likely to be of extreme interest. Much work has been done (Cox 1964; Griffiths *et al.* 1964; Ashcroft, in press; Davey 1971). Ashcroft described seismic refraction measurements in the area and summarized other available bathymetric and geophysical data. His conclusions have been substantiated but slightly modified firstly by the results of marine gravity data (Davey 1971) and secondly by a preliminary study of the location of magnetic boundaries extracted from a detailed survey of part of Bransfield Strait which has not yet been fully reduced.

Bransfield Strait is occupied by the asymmetric Bransfield trough, whose axial depth varies from 1100 m in the southwest to 2800 m in the northeast, south of Elephant I. A shelf of hard rock above 200 m depth extends for 50 km northwestwards from Graham Land, from which rise several islands whose geology is unknown, but which are probably igneous in composition as magnetic anomalies of shallow origin are seen on all profiles approaching the coast. A gradual slope leads from the shelf to a lip at 800 m whence the sea-bed falls more steeply to the level floor of the Bransfield trough. Ashcroft's seismic data, discussed here with respect to section KK′ of figure 8 are consistent with a wedge of sediment beneath the southeastern slope of the trough, but Davey invokes a faulted southeastern margin to this layer (at 90 km on KK′) to explain the gravity anomalies. The horizontal sediment fill of the trough is disturbed along the line of Deception and Bridgman Is by a series of sharp peaks with associated magnetic anomalies, presumed also volcanic and suggested to lie along a fault. The northwest slope of Bransfield trough is steep; Ashcroft (1971) and Davey (1971) have confirmed that it too is probably the site of normal faulting parallel to that seen ashore (Barton 1965; Hobbs 1968) and downthrown to the southeast, as suggested by Griffiths *et al.* (1964) on the basis of the magnetic anomaly and steep seaward slope of the land gravity data. Ashcroft could see no seismic velocity contrast across this slope at a point on its extension northeast of Bridgman I, but Davey suggests the continued presence of the faults.

The anomalous mantle velocity and thick 6.6 km/s crustal layer beneath Bransfield Strait persists along the strike, at least between Deception and Bridgman Is, but the 6.7 km/s layer beneath the main islands is less consistent, dropping in velocity to 6.2 km/s beneath Livingston I in the southwest, and being lost beneath downfaulted 5.8 km/s material to the northeast at successive faults thought to be those lying north and south of Gibbs I. Thus the geophysical data suggest that Bransfield Strait is a graben, with present-day volcanic activity confined within its bounding faults and extending along its axis from about 62° W to 55° W. This length just exceeds the extent of Tertiary volcanism on the South Shetland Is shelf and matches the extent of the trench to the northwest (Davey 1971; Barker 1970). The amount of extension of Bransfield Strait perpendicular to its strike is probably less than the 65 km between its bounding faults; the 20 km width of the central magnetic anomaly provides an alternative estimate.

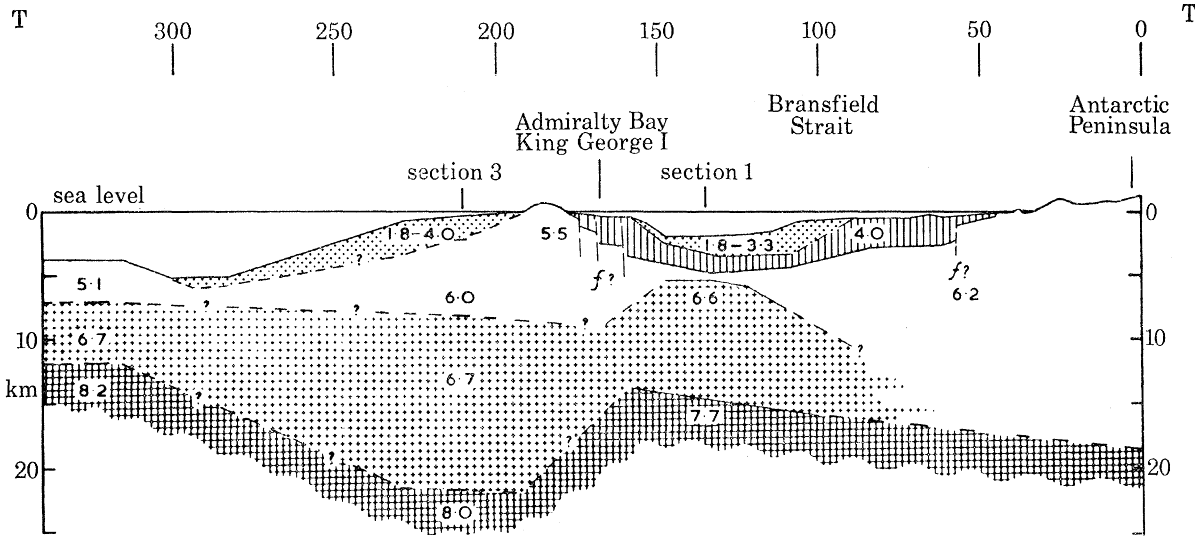

FIGURE 8. Crustal Section TT′ from Graham Land across Bransfield Strait and the South Shetland Islands to the Scotia Sea, reproduced with permission from Ashcroft, *Br. Antarct. Surv. Scient. Rep.* no. 66, figure 32.

In summary the Scotia Ridge, with the exception of the young oceanic island arc of the South Sandwich Is, is composed in large part of crustal blocks of continental origin. Instances abound of internal structures which are incompatible with the present isolated situations of the blocks, and which are truncated at present block margins. In the next section we shall discuss briefly the character and origin of the Scotia Sea, whose formation is thought to be associated with that of the fragmented blocks.

Formation of the Scotia Sea

Present plate motions and South Sandwich Is volcanicity

Barker (1971) has described a recent attempt at correlation of anomalies between magnetic profiles on isolated tracks crossing the Scotia Sea. As shown in figure 9, anomalies in the west and far east Scotia Sea have been identified with sequences from the magnetic reversal time scale of Heirtzler *et al.* (1968). Although it has not so far proved possible in the central areas of the Scotia Sea to date the anomalies unambiguously, and some of the correlations are themselves doubtful, other correlations are sufficiently good to establish the general trend of the lineations. By comparison with the ages of the dated areas of sea-floor to either side, a Tertiary to Recent age was assumed for the floor of the central Scotia Sea.

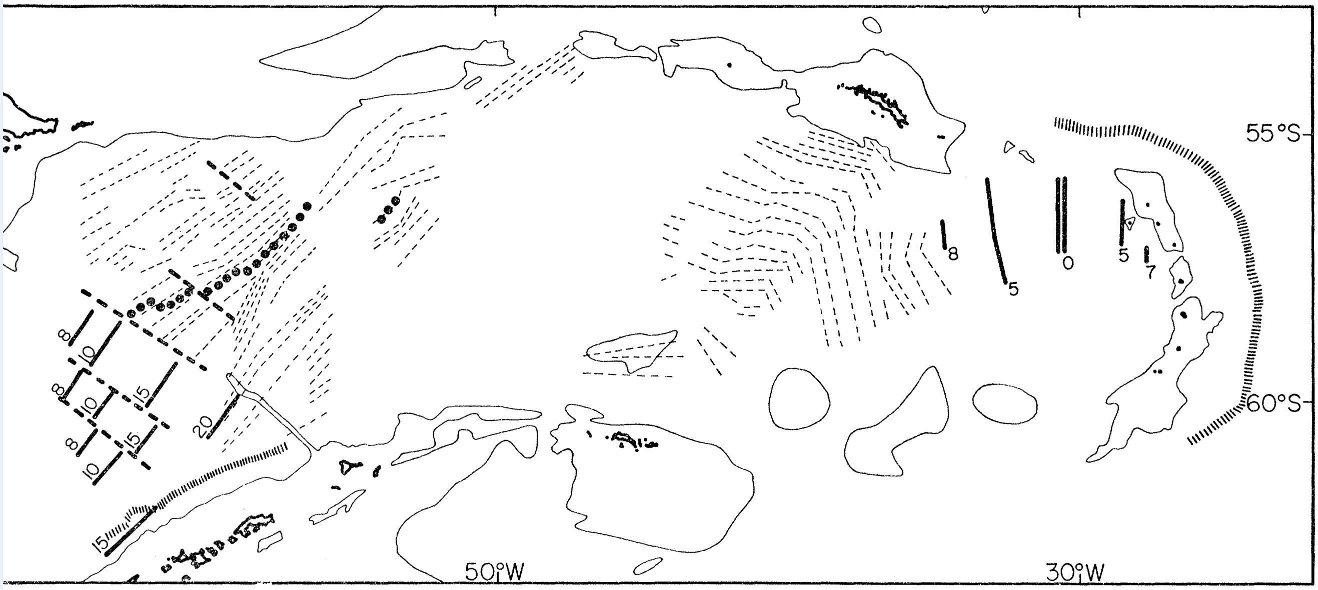

FIGURE 9. Magnetic lineations in the Scotia Sea. Undated anomaly lineations are shown dashed, and numbers in dated regions are millions of years. 2000 m isobath drawn. Reproduced with permission from Barker, in *Antarctic geology and geophysics*, Oslo, Universitets Forlaget, 1971.

A model has been constructed (Barker 1970) of present plate boundaries and motions, based on the magnetic lineations and to some extent on the distribution of epicentres of shallow earthquakes (Barazangi & Dorman 1969), shown superimposed on the model boundaries in figure 10. The elements of figures 9 and 10 are best described together.

The relative rotation of the Antarctic and South American plates, according to the model, is approximately 1.8×10^{-7} degrees/year about a pole close to 72° S, 150° W. This is an approximate result, consistent with:

(1) A separation of 0.8 cm/year along 290° at the South Atlantic triple junction computed from best available estimates of motion on the other two spreading centres.

(2) Pure strike-slip motion along the Shackleton fracture zone, a prominent magnetic boundary, linear bathymetric feature and earthquake epicentre locus extending northwestward from near Elephant I to the southern tip of the South American shelf. The relative motion is therefore subject to large uncertainties and should be regarded as provisional.

The model implies a slow (1.2 to 1.4 cm/year) oblique convergence at the west coast of

Chile, where only three shallow epicentres are seen on figure 10, and extension at 1.2 cm/year in the western Scotia Sea. The latter is assumed to be taken up mainly by slightly oblique spreading at a central double bathymetric ridge in Drake Passage which is also the centre of a dubious and degraded magnetic anomaly symmetry, coupled with a small secondary strike-slip motion along the central trough of the south Scotia Ridge. The model considers the Tertiary spreading centre responsible for the dated anomalies lying to the west of the Shackleton Fracture Zone to be inactive. Similarly, the source of the anomalies lying between South Georgia and the South Orkney Islands is not considered active at present, partly because the topography here is more subdued than further west. In summary, the general scheme of the model is attractive in that a better explanation is afforded of the sparse and diffuse earthquake epicentre distribution than has been achieved hitherto. In a sense, however, although the Scotia Sea details of the model of present-day plate motions are the most likely, they will remain little more than geometrically plausible until data of better quality are available.

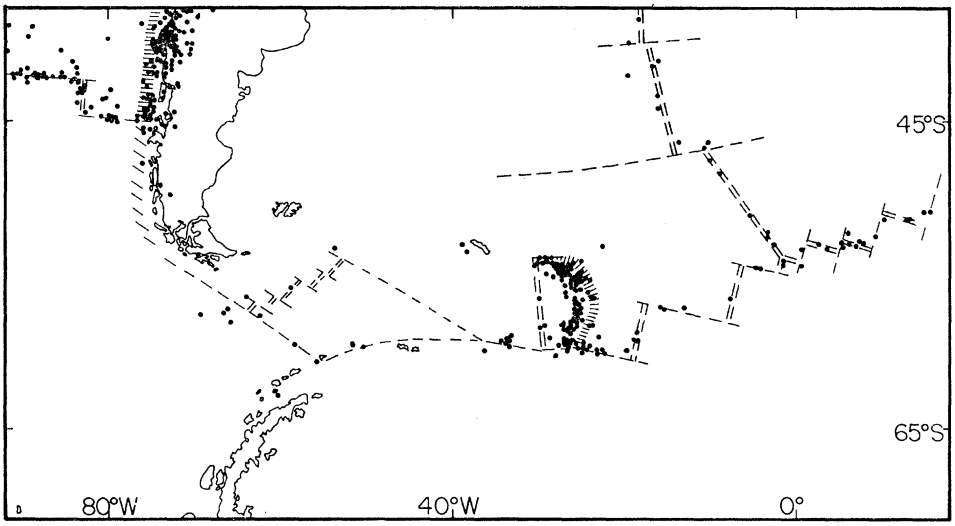

FIGURE 10. Distribution of epicentres of shallow earthquakes, taken from Barazangi & Dorman (1969), super imposed on model of present day plate boundaries in the Scotia Sea region.

In contrast to the remainder of the region, the South Sandwich island arc and trench is the site of intense, shallow and intermediate depth earthquake activity, down to 170 km toward the northern end. To the west, an active spreading centre has been recognized, coinciding where seen with the centre of a north–south zone of rough, elevated topography along 30° W. The spreading centre is assumed to extend between transform faults at the northern and southern ends of the trench and with them to define the small Sandwich lithospheric plate. Magnetic anomalies have been dated out to the 7 to 8 Ma isochron, which eastward lies at the islands, and the spreading rate is 2.7 cm/year/side along 080°. As the model shows no plate boundary at present along the north Scotia Ridge, the rate of consumption of South American plate at the trench is 5.4 cm/year; if this rate had continued for 7 to 8 Ma the deepest earthquake might have been expected to exceed 170 km in depth (Isacks *et al.* 1968; McKenzie 1969) but qualitatively the intense earthquake and volcanic activity is explained. The youth of the spreading centre-trench system is consistent with Baker's (1968) conclusions on petrologic grounds that the island arc is in an early stage of development.

Because, at present, trench and spreading centre are coupled so directly, it is difficult to see how the system originated. As secondary extensional features are now being found behind many oceanic island arcs (Karig 1970) it seems more likely that the trench came first, but its time and mode of origin are as yet unknown.

Miocene plate motions and South Shetland Is volcanism

In figure 10 no active plate boundaries are shown west of the Shackleton fracture zone or in Bransfield Strait, although Deception I. erupted in 1967, 1969 (Baker, Davies & Roobol 1969) and 1970. In order to explain this apparent discrepancy between model and observation, let us consider the Upper Miocene (10 Ma) plate régime for the western Scotia Sea, shown schematically in figure 11. Making the reasonable assumption that relative motion between the major plates were largely as at present, the Scotia Sea east of the Shackleton fracture zone would have been opening at 0.6 cm/year per side or a similar, slow rate. West of the facture zone, we have identified one limb of a centre then spreading, presumably symmetrically, at 2.4 cm/year per side. Given the much slower relative motion of the two major plates, it is clear that spreading at this high rate could not have taken place without a complementary consumption of crust. This could have taken place indirectly, by strike slip decoupling across 2500 km to the Pacific–Antarctic Ridge, or at some hypothetical island arc lying to the northwest; a much

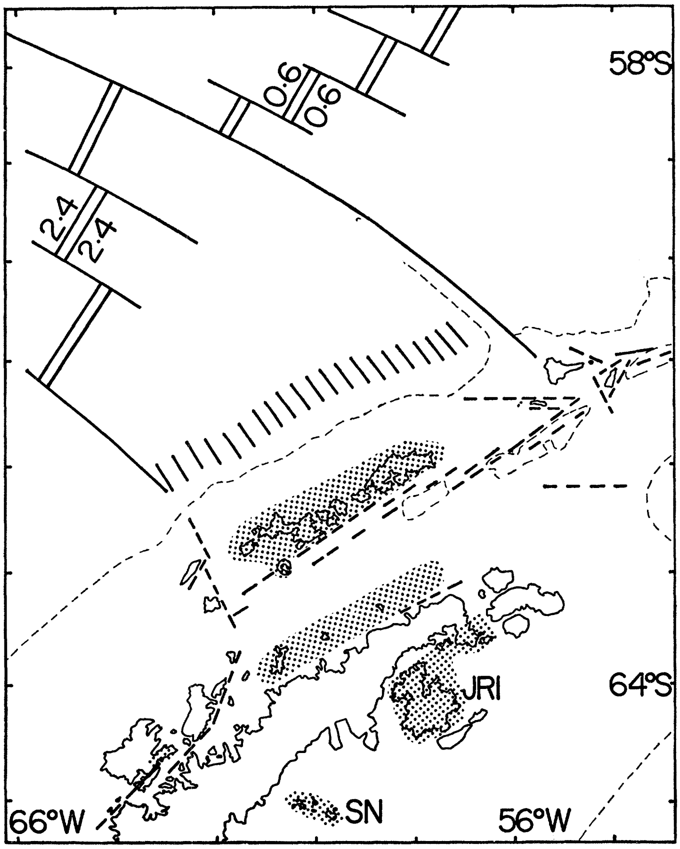

FIGURE 11. Upper Miocene (10 Ma) plate boundaries and motions in the western Scotia Sea. Faults in continental regions are shown dashed and areas of probable Upper Tertiary volcanic rocks, including Seal Nunataks (SN) and James Ross Island (JRI) are shaded. Plate consumption at the South Shetlands trench would have been at about 5 cm/year.

more likely site, however, is the partly filled trench lying at the foot of the continental slope off the South Shetland Is between 57 and 64° W (Barker 1971).

The magnetic data extend only over sea-floor dated at between 8 and 15 Ma (extending less certainly to 21 Ma); as the trench is now seismically inactive we deduce that the coupled crustal spreading and consumption have both ceased, at some time between 8 Ma and the present. The times of initiation and cessation of spreading, and therefore, if the coupling is simple, of consumption, should be detected by further magnetic measurements to the northwest of our present data coverage. Both of these times are of extreme importance to any attempt to relate South Shetland Is Tertiary and Recent volcanism to this episode of plate consumption.

A further complicating factor is the Bransfield Strait graben, which is thought to be a late extensional modification of the older series of faults extending southwestward down the west coast of Graham Land and eastward along the bisecting trough of the south Scotia Ridge. The extension is considered to be a further secondary effect of plate consumption (Karig 1970) at the South Shetlands trench, but may not have started or stopped opening exactly when consumption at the trench started and stopped.

If we assume that the northwestern limb of the spreading centre west of the Shackleton fracture zone was part of the Antarctic plate, and that Bransfield Strait was opening at 0.1 cm/year per side ($\approx$ 20 km in 10 Ma), the resultant rate of plate consumption at the South Shetland trench, 10 Ma ago was 5 cm/year.

As outlined in an earlier section, andesitic and basaltic–andesitic activity between Eocene and Miocene to north and south of the central axis of the South Shetland Is was replaced by mildly alkaline basaltic activity restricted to the southern area near the start of the Pliocene (Adie 1964; Baker 1971). This may have signalled the end of fast plate consumption or the start of secondary extension. Also, it is not known whether the extension, which was probably at a very slow rate, still proceeds or whether the activity at Deception I. is relict. Baker (1971) has pointed out the similarities in petrology and age between the mildly alkaline lavas of Deception I. and Penguin I. in Bransfield Strait, and those of James Ross I. and Seal Nunataks (located in figure 10) on the east coast of Graham Land. No other plate boundaries are known which are closer than those under discussion to these latter two volcanic occurrences, and their isolation is worth further investigation. Other small isolated occurrences of presumed Upper Tertiary volcanic rocks are reported from the west coast of Graham Land.

Thus, the Tertiary and Recent volcanic activity of the South Shetland Is may be related to an episode of crustal consumption at the South Shetland trench, and a consequent slow opening of Bransfield Strait. Specification of the timing of this episode may be expected to improve as more marine magnetic data are acquired; this will allow an examination of the extent to which volcanic activity associated with motion at a plate boundary may occur remote in space and time from that boundary. This question becomes important when estimates are made of previous plate motions and boundaries from study of the remnants of their associated volcanic rocks.

West coast of South America

At this point let us consider the west coast of South America, south of 45° S, where at present the Chile rise intersects the margin. To the north the Nasca plate is moving beneath the South American plate at the Peru–Chile trench, and the accompanying rhyolitic and andesitic volcanism, and deep and shallow earthquakes, are well known. To the south our model of present plate motions predicts a slow convergence at 1.2 to 1.4 cm/year, and indeed there is a little evidence of some kind of motion. Three epicentres are shown in figure 9 between 45° S and 55° S, there is a sediment-filled trench along the margin (Hayes 1966; Ewing *et al.* 1969) and potassium–argon dates of 1.7 and 3.2 Ma (Mercer 1969) have been measured for lavas from the southern end of the Patagonian basalt plateau, which extends between 45 and 53° S. However, despite recent support for the idea of slow convergence at plate margins without underthrusting (Menard 1969), we regard this prediction of the model as its least successful and, without prejudicing the model by doing so, prefer an alternative explanation for the second and third of these features.

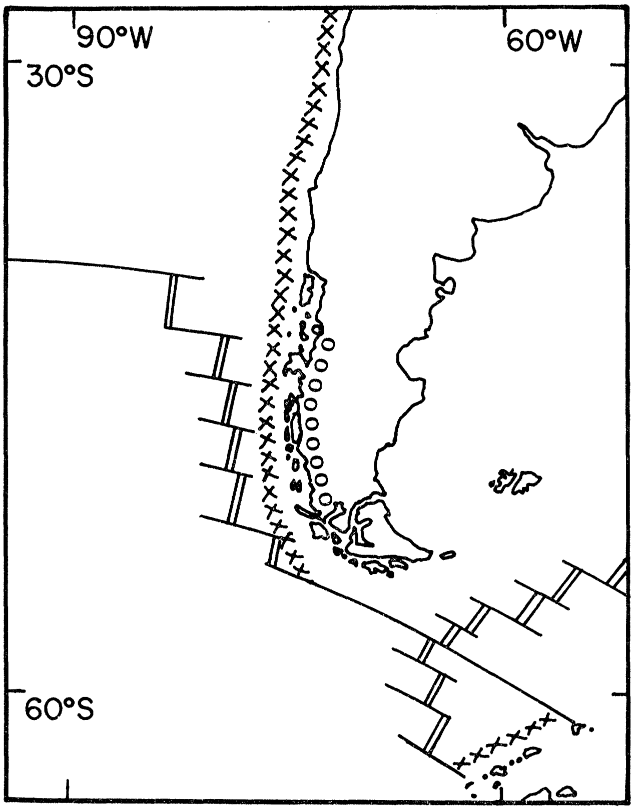

Figure 12. A possible Miocene plate régime for South America, showing plate consumption down the entire length of the Pacific coast, caused by a southward extension of the Chile rise into the Scotia Sea. Extent of Patagonian plateau basalts is shown by circles. More acid volcanism occurring further north is not shown.

Interpretations of magnetic profiles across the Chile rise conflict as to the orientation of the sections of active spreading centre (Morgan, Vogt & Falls 1969; Herron & Hayes 1969). If the direction 010°, which is perpendicular to the fracture zones as defined by shallow seismicity, is preferred then a scheme for the Miocene which is like that shown in figure 12 can be derived. At present the spreading centre sections of the Chile rise are all migrating eastward toward the Peru–Chile trench and, the most southerly first, will eventually meet the trench, whereupon the Antarctic plate will lie at the margin of South America as is now the case farther south. Conversely, in the past, other more southerly sections of the Chile rise may have existed and since been consumed. This would explain the sediment-filled trench off southern Chile and the Patagonian basaltic volcanism and would suggest that the Upper Tertiary Drake Passage spreading centre was then part of the Chile rise.

Tertiary plate motions and formation of the Scotia Sea

In order to make a detailed reconstruction of the postulated continental region whose fragmented components now make up the Scotia Ridge it would be necessary to date most of the Scotia Sea floor. However, correlated magnetic anomalies lying between the Shackleton fracture zone and the spreading centre associated with the Sandwich plate cannot be dated unambiguously at present, some correlations are doubtful and no data are available for large areas (figure 9 and Barker 1971). Nevertheless, a generalized reconstruction may still be attempted. Orientations of magnetic lineations are probably mainly correct and show the directions in which continental fragments on either side have moved, unless there was contemporaneous or later decoupling between the block and the adjacent ocean floor. Such decoupling, of course, may well be revealed by the bathymetry.

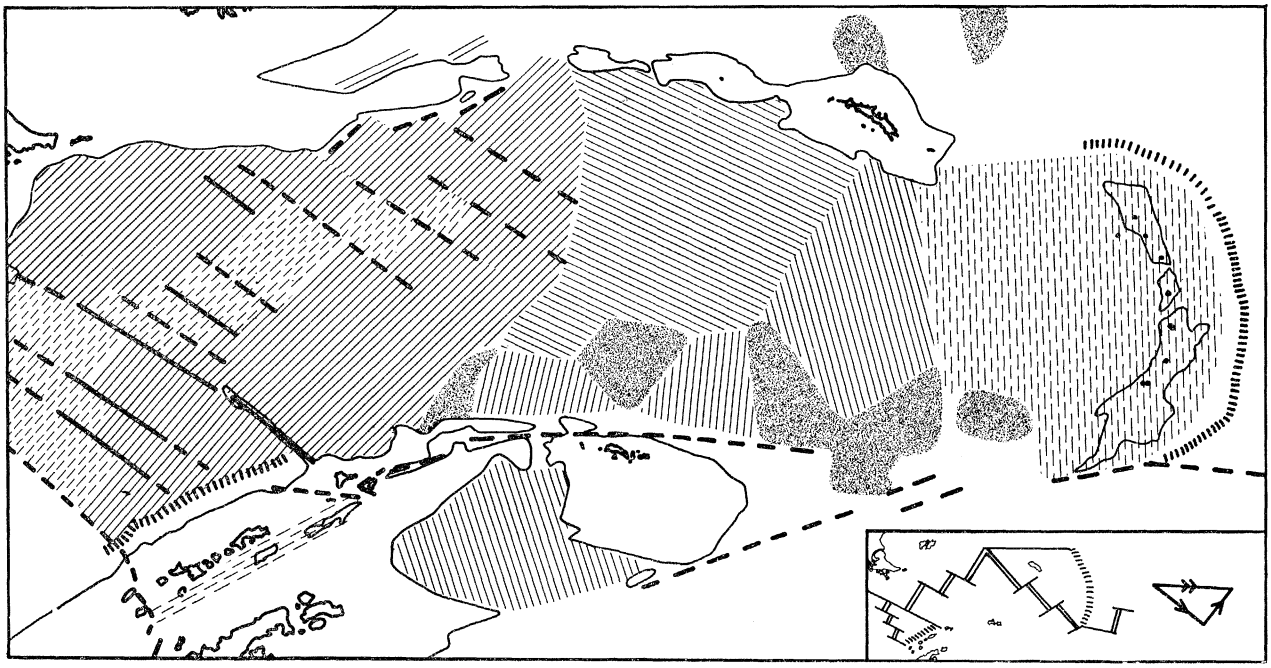

FIGURE 13. Schematic diagram of likely ages and spreading directions of Scotia Sea floor, described in text. 2000 m isobath drawn.

Many internal structures, the youngest of about Upper Cretaceous age, on the component blocks of the Scotia Ridge, are truncated at the block margins. Thus, although Barker (1971) suggested that most of the Scotia Sea had formed in the past 40 Ma, it is only necessary for the purposes of reconstruction to assume a post-Cretaceous commencement of the fragmentation process. In figure 13, areas of ocean floor thought to be of post-Cretaceous age are shaded, the direction of shading representing roughly the direction of anomaly lineations in that area. Ocean floor thought to be younger than 10 Ma is shaded with broken lines. Zones of decoupling, such as fracture zones, are marked by heavy solid lines where more certain, by heavy dashed lines where less certain. Trenches are hachured and the heavy shading shows areas which are of intermediate depth and are either known or believed to have intermediate crustal structure.

The sea-floor west of the Shackleton fracture zone is dated as shown in figure 9 and, outside the area of known data, by extrapolation at 2.4 cm/year, but without assuming a time of cessation of spreading. Bransfield Strait has been given dashed shading, but it has not been assumed that it was formed entirely within the past 10 Ma. East of the Shackleton fracture zone the central, dashed shading is appropriate to spreading at 0.6 cm/year per side for 10 Ma. Note that even at this slow rate of spreading, the entire west Scotia Sea could have been formed since the start of Tertiary. In accord with our present-day model the active centre does not extend to the eastern end of this area, whose boundary with the next area to the east is indeterminate for lack of data. In addition to marked oceanic fracture zones, sections of anomalously deep water at the northeastern margin, perhaps resulting from strike-slip decoupling, are marked with thick dashed lines. The double bathymetric ridge, about which a degraded magnetic symmetry can be seen on two profiles, can only be thought to lie centrally in this area if reconstruction is made to the intermediate depth ridge which extends north-eastwards from the south Scotia Ridge near 51° W, rather than to the south Scotia Ridge itself.

Farther east the sea floor is smoother, perhaps because of a greater age (but see Goodell & Watkins (1968) for variations in sedimentation rate) and more of the blocks of intermediate depth, mentioned above, occur south of 58° S. Generally these have steep southern sides and a gentle north-dipping top which, at the southeast Scotia Ridge rises to 400 m in places. The block lying north of the South Orkney Is has a more continental than oceanic crustal structure (Barker 1971), similar to that of the Falkland platform. The blocks appear to have been fragmented and surrounded by younger oceanic crust. By analogy with the blocks of the Scotia Ridge, these intermediate blocks may represent a fragmented epicontinental sea province. The magnetic character of the intervening oceanic areas is unknown, but the spreading direction will not necessarily be the same as that of the area to the north. The far east Scotia Sea is younger than 10 Ma as discussed above.

The area of Tertiary shading lying between the South Orkney Is block and Graham Land has been added as we think this deep water area may have been created by the separation of these blocks during the early stages of formation of the Scotia Sea. Other small areas of deep water northeast of Burdwood Bank may also have this origin. The remainder of the oceanic areas shown in figure 13 probably were formed by spreading from the Mid-Atlantic Ridge and are therefore of pre-Tertiary age.

From figure 13 it can be seen that the south Scotia Ridge moved southwestward away from South America, Elephant Island originally having lain close to Cape Horn. Similarly, South Georgia and the south Scotia Ridge have separated along a northeast–southwest line. Secondary strike-slip motion along the dividing trough of the south Scotia Ridge is now more likely to be sinistral, but may not have been so in the Tertiary. Thus, relative motion in the past, as indicated by the magnetic lineations, was complex and different from that believed to be occurring at present, and we do not know how its component motions were related in time. A plate boundary solution for the case where the east and west Scotia Sea are opening simultaneously and strike-slip motion along the south Scotia Ridge is negligibly small is shown inset in figure 13. South Georgia is seen to have a resultant eastward motion relative to the South American plate, made possible by strike-slip decoupling along the Falkland trough, and having to be accommodated by some such device as a trench to the east, forerunner perhaps of the South Sandwich trench. Other solutions are possible.

Scotia Ridge reconstruction

In attempting to reproduce the relative positions of the continental fragments before their dispersal by the Tertiary opening of the Scotia Sea we have followed the procedures listed below, essentially reversing the drift process.

(1) The south Scotia Ridge was moved northwestward *en bloc* along the line of the Shackleton fracture zone until close to South America, without any appreciable rotation of Graham Land.

(2) At the same time South Georgia and the two blocks lying to its west were moved southwestward toward the south Scotia Ridge.

(3) Bransfield Strait was closed by 20 km.

(4) We consider that several small, apparently random relative motions of component blocks are likely to have occurred, but in the very early stages of fragmentation and drift, before the addition of much new oceanic crust gave rigidity and moment to the continental fragments. The separation of the South Orkney Is block from Graham Land and the separation of the blocks of intermediate crustal structure now found mainly in the southeast Scotia Sea may have been the largest of these small, early stage motions. Others include the effective elongation of the eastern north Scotia Ridge and of the northern south Scotia Ridge. At present we have no guide as to the nature of these small relative movements, but the better quality data we hope to acquire in future may well define them quite precisely.

An example of the kind of reconstruction to which this procedure can give rise is shown in figure 14*a*, a Mercator projection in which the size of the component blocks has been adjusted according to the amount of northward movement to which they have been subjected. The south Scotia Ridge, the eastern and western north Scotia Ridge and the intermediate depth areas are shaded differently to aid in their identification and the arrows show the present direction of true north for each block.

Present structural units, such as the south Scotia Ridge are reasonably coherent in the reconstruction, and block rotation is generally small. Dextral strike-slip elongation of the northern part of the south Scotia Ridge is assumed, and a similar sinistral elongation of the eastern north Scotia Ridge.

Figures 14*b* and *c* are shaded to show the extent to which major structural features occurring on the fragmented blocks are alined by this particular reconstruction. Before the figures are discussed in more detail we must define the shading more closely and examine the inherent difficulties of such a comparison.

Zones of magnetic disturbance are shaded in figure 14*b*. Source bodies where known include Andean intrusives in the Coast and Patagonian Cordilleras, Lower Cretaceous basic lavas and later intrusives in South Georgia, Upper Jurassic to Cretaceous–Tertiary intrusives and later lavas in Graham Land and the South Shetland Is. This list illustrates a difficulty of using this characteristic to find pre-drift alinements, in that some of the magnetic source bodies are younger than the time of fragmentation. The unknown sources of anomalies in areas entirely submerged, such as the northwest corner of the South Orkney Is block, may also have been emplaced during or after fragmentation.

Given the uncertainty of the method, a degree of order has nevertheless been established, notably in the magnetic zone now forming a northwestern and northeastern border to Graham Land, including the South Shetland Is and South Orkney Is blocks and part of the south Scotia Ridge. On the other hand, no eastward continuation of the Cordilleran magnetic belt is seen, and South Georgia's magnetic southern margin is isolated, although parts of the intermediate depth blocks are magnetic (though not shaded in figure 14*b*) and may solve the latter difficulty. A reconstruction in which South Georgia is placed immediately adjacent to Tierra del Fuego so that their magnetic zones are continuous appears less likely at present.

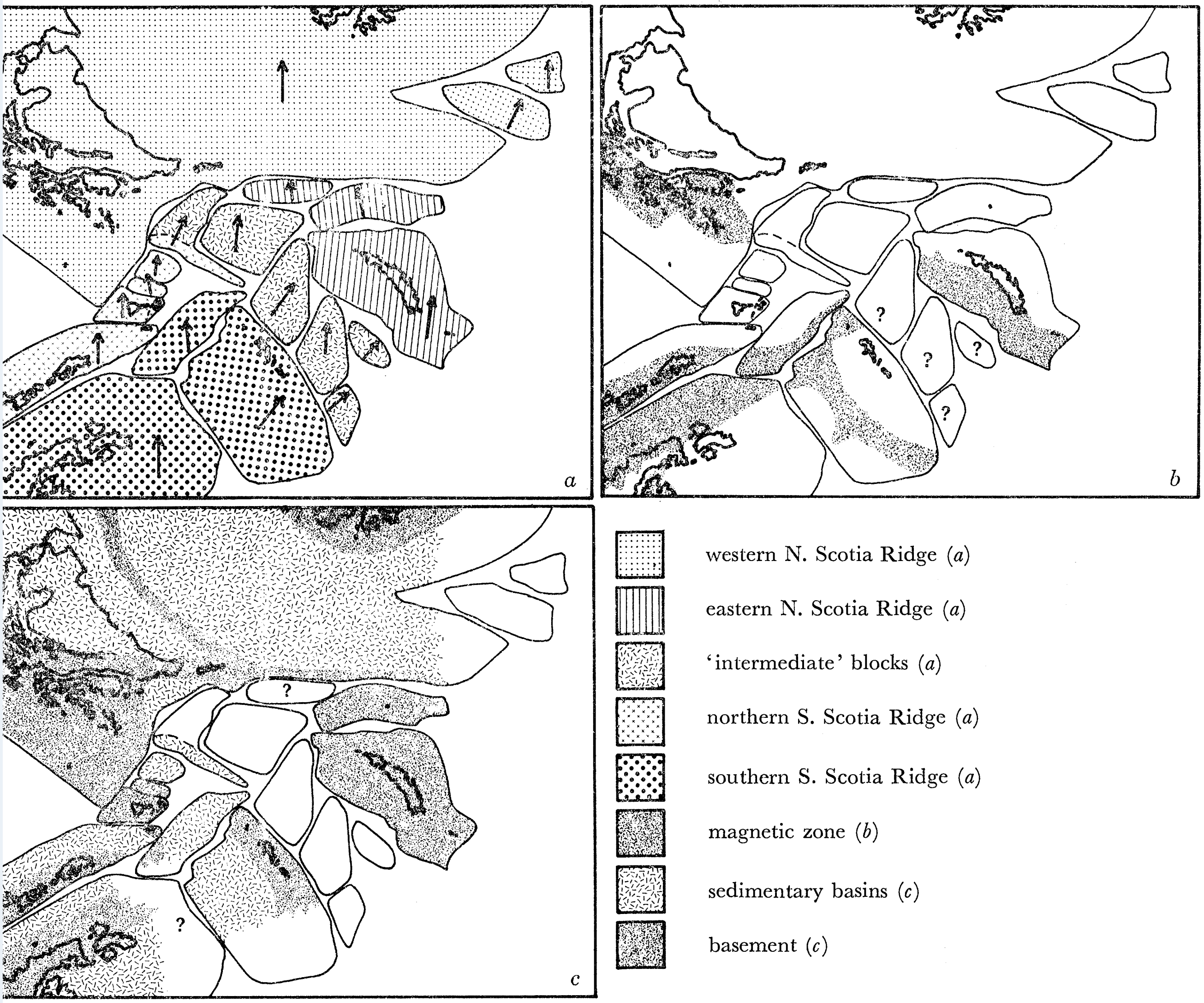

FIGURE 14. Reconstruction of Scotia Ridge before lower Tertiary fragmentation and opening of Scotia Sea, based on assumptions of figure 13. Blocks defined roughly by 2000 m isobath. (*a*) Provenance by shading and arrowed direction of present north for each block. (*b*) Zones of intense magnetic disturbance. (*c*) Shallow basement and sedimentary basins. Shading described more fully in text.

Figure 14*c* shows the distribution of sedimentary basins and of shallow or exposed basement rocks. Contorted or metamorphosed rocks, of compressional wave velocity 4.5 km/s and above, at depths of 1 km or less below the surface, are heavily shaded. In Graham Land and on the south Scotia Ridge this means pre-Lower Jurassic rocks, pre-Permian rocks in the Coast Cordillera (with a rider that an Oligocene orogenic episode is reported as having occurred in the Patagonian Cordillera), and pre-Upper Cretaceous rocks on South Georgia, which includes all exposed sediments. The lighter shading represents areas having more than 2 km of sediments only gently folded or of velocity less than 4.5 km/s. A similar problem to that of the magnetic zones arises in that the process of fragmentation and dispersal may have caused differential uplift and erosion sufficient to change a basin area into one where basement rocks are exposed at the surface. This process is probably undetectable, unlike the reverse process of sinking and deposition, which would produce Tertiary basins. However, thick sediments having a velocity appropriate to a Tertiary age are rare in the areas surveyed, most of the basin fill being of probable Cretaceous age. As in figure 14*b* the 'intermediate depth' area is not shaded, although on one block 2 km of sediments are seen.

As in the magnetic case, the degree of order of major geological structures resulting from the reconstruction is not high. However, the South Orkney Is shelf continues the area of Jurassic and Cretaceous sedimentation of eastern Graham Land, although some magnetic material must occur above 2 km in places. A probable area of exposed basement occurs south of Burdwood Bank to continue the southward basement rise of the bank, and the basement high dividing the Magellan and Malvinas basins. Similarly, the basement of the Coast Cordillera presumed to occur along the southwestern margin of Tierra del Fuego may continue into the Elephant I. block and the south Scotia Ridge.

Other reconstructions are possible, the one shown here depending upon our assumptions about the age of the magnetic lineations, their directions in the unsurveyed areas and the extent of strike-slip and convergent motion. Further survey and where possible palaeomagnetic estimates of the amount of rotation undergone by individual blocks should eliminate many of these uncertainties and lead to a solution which is more plausible geologically. However, the family of reconstructions which can be obtained at present by varying the unknown parameters appear to have certain common characteristics. Basically these amount to the existence of a compact continental or epicontinental area joining the Antarctic Peninsula to southern South America before the formation of the Scotia Sea. The joined continental regions had a continuous, cuspate Pacific margin limited to South America northwestward from Cape Horn and the Antarctic Peninsula southwestward from Elephant I. There is some support for this pattern in the land geology in that such indicators of the presence of an active continental margin as acid and intermediate calc-alkaline volcanism and extensive igneous intrusion with associated uplift all appear to die out eastward. In particular it is possible that the Cretaceous–Tertiary intrusives of the Coast and Patagonian Cordilleras do not continue at all, eastward from Cape Horn, and that because of this and of the Lower Tertiary drift, the region which lay to the east along the strike never underwent the Oligocene episode of folding and uplift which affected this formation in southern Chile. Thus one would not necessarily expect an eastward continuation of the zone of shallow magnetic anomalies and contorted sediments, and the location there in the reconstruction of the intermediate depth blocks may be perfectly acceptable.

The exception of South Georgia continues to mock the reconstruction. We must consider for the moment either that the reconstruction is in large part wrong and South Georgia was part of the active Pacific margin for much of the Cretaceous or, as we would prefer, that the Cretaceous orogenic activity shown on South Georgia was part of some other small consuming plate boundary, perhaps directed eastward as the South Sandwich island arc now is. Without commenting further upon this latter possibility, we will now consider the question which it raises, of the effect upon the region of the fragmentation of Gondwanaland and its place in a Gondwana reconstruction.

The Scotia Ridge and Gondwanaland reconstructions

As yet there is no commonly accepted reconstruction of Gondwanaland, particularly with regard to the position of Antarctica and the time of fragmentation. Generally, the reconstructions based on palaeomagnetism are incompatible with those based on matching geology or a depth contour, or on extrapolation of sea-floor spreading data, and within each group considerable differences occur, owing to the limitations of each method. Of recent attempts at reconstruction, essentially different schemes are described by Briden (1967), Francheteau & Sclater (1969), Van der Linden (1969), Dietz & Holden (1970), Smith & Hallam (1970), Vilas & Valencio (1970), Tarling (1971) and Elliot (1971). We therefore make no excuse for presenting our own version which, of those above, is most like that of Elliot. Figure 15 is a photographic projection of the reconstruction which was performed on a hemispherical overlay to a 40 cm globe, using the 1000 fathom (1830 m) depth contour.

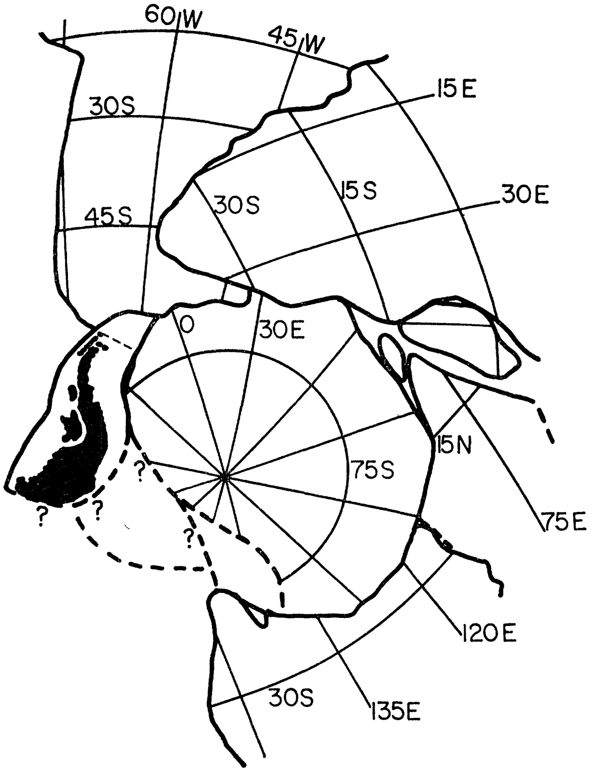

FIGURE 15. Reconstruction of Gondwanaland, consistent with L. Tertiary Scotia Ridge reconstruction of figure 14. Drawn from photograph of fitting by eye on overlay to 40 cm globe using 1000-fathom (1830 m) contour.

We consider firstly the fitting of South America and Africa. In this, the continental crust of the Falkland Platform as far east as 40° W should be included in the South American block. The least squares fit of the 500 fathom (914 m) lines of these two continents by Bullard, Everett & Smith (1965) leaves a 250 km wide channel of deep water between the south coast of Africa and the Falkland platform. We close this channel by a small anticlockwise rotation of southern Tierra del Fuego and the Falkland platform as it seems highly likely that the southern tip of Africa separated from and moved eastward along the Falkland fracture zone and a slight rotation may have been necessary for the separation to proceed. The presence in southern

Argentina of three east–west basins, the Salado, Colorado and San Jorge basins, formed in late Jurassic or early Cretaceous times (Zambrano & Urien 1970) which is within the time range proposed for initial opening of the South Atlantic, supports this contention.

Madagascar is moved northwestward to a position opposite Tanzania, Australia and Antarctica are joined in approximately the usual manner and India and Antarctica joined so that the Ganges delta lies at the western margin of Australia. Africa–South America is then joined to Antarctica–Australia–India as shown in figure 15 so that Bombay lies opposite northern Madagascar and Lourenço Marques lies opposite the Riiser–Larsen Peninsula in eastern Queen Maud Land.

It is obvious that neither this reconstruction, nor any other of those listed above can be reconciled with our reconstruction of the Scotia Ridge shown in figure 14 without some relative motion between east and west Antarctica since the break-up of Gondwanaland. No direct evidence of such motion is at present available, but the extensive Jurassic dolerite intrusions of the elevated scarp bordering east Antarctica between the Caird Coast and Victoria Land, the apparent 90° rotation of the geologically similar Ellsworth Mountains and the considerable subglacial relief of west Antarctica which includes large areas below sea-level all suggest that profound disturbances of some kind have occurred. Palaeomagnetic measurements suggest movement of Marie Byrd Land independently of the remainder of west Antarctica (Scharnberger & Sharon, in press).

We have placed the Antarctic Peninsula block, with the Scotia Ridge components added, in the same place relative to South America in the Gondwana reconstruction of figure 15 as in our Lower Tertiary reconstruction of figure 14. The east coast of the Antarctic Peninsula thus lies against Princess Martha Coast and the Caird Coast of east Antarctica. We have made an arbitrary division between the Antarctic Peninsula and the remainder of west Antarctica ,which is presumed to have formed a separate plate, and do not propose here to consider the latter, or the New Zealand block, further. Our hypothesis is that, as east Antarctica and South America started to separate, before or at the same time as Africa separated from South America, the Antarctic Peninsula remained attached to South America. The consequent relative rotation of the Antarctic Peninsula and east Antarctica (about an axis close to their junction, say at 80° S, 90° W) opened the Weddell Sea until some time in the early Tertiary when the Antarctic Peninsula became fixed to the remainder of the Antarctic plate and separated from South America to form the Scotia Sea, as already discussed.

It is not possible, even with relative movement of east and west Antarctica, to reconcile our pre-Lower Tertiary reconstruction of figure 14 with the position for east Antarctica adopted by Dietz & Sproll (1970) or Smith & Hallam (1970). To the extent that either is valid, however, the Scotia Ridge and Gondwana reconstructions support each other. It is interesting that using our own Gondwana reconstruction, the relative motion of South America and Antarctica before and after the transfer of the Antarctic Peninsula from one to the other would have been very similar. Both had a pole to the southwest of the Scotia Sea and both may have been slow. If we accept Smith & Hallam's age for Gondwana fragmentation as Jurassic or early Cretaceous, and of Scotia Ridge fragmentation as early Tertiary, then the Weddell Sea opening would have proceeded at a rate, opposite the eastern end of Graham Land, of 1 to 2 cm/year per side. The direction of Weddell Sea opening is approximately consistent with the extremely speculative magnetic anomaly correlations made by Bregman & Frakes (1970) across widely separated Project Magnet flight lines there.

SUMMARY AND DISCUSSION

In this paper we have summarized geological and marine geophysical knowledge of the Scotia Sea and proposed a model for the main events in the structural evolution of the region, as follows:

(1) Southern South America and west Antarctica were originally part of a continuous orogenic belt at the Pacific margin of Gondwanaland.

(2) When Gondwanaland broke up the Antarctic Peninsula and an undefined portion of the remainder of west Antarctica remained fixed to South America as east Antarctica rotated clockwise about an axis near the South Pole, thereby opening the Weddell Sea.

(3) In early Tertiary times the Antarctic Peninsula transferred from South America to east Antarctica which continued rotating clockwise, thereby opening the Scotia Sea, fragmenting the continental region close to the opening and moving the fragments to their present locations on the Scotia Ridge.

(4) Since this opening smaller plates have formed, first in Drake Passage and then west of the South Sandwich trench, resulting in intense volcanic activity on parts of the Scotia Ridge.

(5) The opening of the Scotia Sea continues at present, slowly in the west by the separation of the South American and Antarctic plates and more quickly in the east by consumption of Atlantic crust at the South Sandwich trench.

A more specific structural history has not been attempted here as the details of our model are likely to be changed much more by new data than the general framework outlined above. While so much uncertainty remains, however, some speculation on detail may be useful in directing future fieldwork. For this reason we comment further below on certain aspects of the model.

(1) We have assumed that the cuspate shape of the junction between South America and the Antarctic Peninsula existed before the breakup of Gondwanaland and resembled the Kamchatka–Aleutians junction in having resulted from the separate development of two adjacent arcs, rather than from the bending of one. The oroclinal bending of an island arc or active continental margin at a late stage in its development can now be seen to be unlikely if the rigid plate to which it is attached must also be deformed. For example, although now only 7 to 8 Ma old, the South Sandwich plate probably will not bend further. This having been stated as the general case, however, we see that the Antarctic Peninsula, at the time of breakup of Gondwanaland, may have been exceptional. A thin orogenic belt broke away from Antarctica, and may have been bent slightly then, before the addition of Weddell Sea crust made it more rigid. In those circumstances it would be better to think of a slow relative motion between South America and the Antarctic Peninsula through the Upper Mesozoic rather than a rigid connexion, and to look for a different initial Gondwana reconstruction, as our present one is completely consistent with Mesozoic rigidity and an initial cuspate shape. Detailed palaeomagnetic sampling of the range of Mesozoic intrusive bodies exposed in the Antarctic Peninsula may resolve this ambiguity.

(2) The question of why so thin a strip as the Antarctic Peninsula then was broke away from east Antarctica when Gondwanaland was fragmented is worth considering. A likely explanation, provided that Pacific crust was being consumed at that time, involves exactly the same process of secondary extension as is now being found behind many island arcs and active continental margins, and in this paper is considered to have opened Bransfield Strait and formed much of the east Scotia Sea.

(3) It is understood that intermittently, both before and after the breakup of Gondwanaland, the Pacific margins of its component continents have been the sites of consumption of Pacific oceanic crust. We have not attempted to define these episodes of consumption, apart from the Upper Tertiary South Shetlands episode, because the relationship between them and the intrusive bodies which they have generated is as yet unknown. In particular, we do not consider it valid to define the commencement and cessation of Weddell Sea opening using ages of intrusive bodies in the Antarctic Peninsula, for the above reason and because crustal extension in the Weddell Sea could have been compensated for by adjustments at other plate boundaries elsewhere in the world. A much more promising approach to this problem lies in magnetic survey in the Weddell Sea, which may be feasible in very good ice years.

(4) The region of Gondwanaland to the east of its marginal orogenic belts may have been partly epicontinental sea for some time before its breakup. Parts of the Falkland platform and the intermediate depth blocks in the southeast Scotia Sea may have this origin, and South Georgia similarly, before it was modified by orogenesis. In the Scotia Ridge reconstruction, South Georgia is separated from the Pacific margin by the reconstructed intermediate depth blocks. Although other explanations are possible if our reconstruction is rejected, it seems reasonable to us that South Georgia should have formed, not at the Pacific margin but to the east, in response to Atlantic or Weddell Sea opening. Palaeomagnetic examination of its orientation during the Cretaceous should help resolve this problem.

(5) In considering plate motions and boundaries at present and in the recent past we have assumed slow but relatively steady motions of the major plates. There is always the danger when using earthquakes, which are effectively instantaneous, to indicate plate boundaries, and spreading rates averaged over millions of years to estimate plate motions, of misinterpreting completely a change of speed or direction taking place over a million years or so. Although inertial considerations apparently rule out so short a time constant for motions of the major plates, it is conceivable that in a smaller area, such as the Scotia Sea, significant changes over this time interval are entirely possible. Future discoveries of this sort may well reconcile some of the minor inconsistencies and puzzles of the present plate model, such as the computed slow convergence at the Pacific coast of Chile south of 45° S, the mode of origin of the Sandwich plate and the relict activity of Deception I.

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Answer to question by Le Bas

Dr P. F. Barker. The distribution of epicentres of shallow earthquakes (figure 10 and Barazangi & Dorman 1969; Stover 1968) clearly includes a third line in the South Atlantic, less well defined than the mid-Atlantic ridge and the Atlantic–Indian ridge, extending from 55° S, 1° W to the southern end of the South Sandwich island arc.

The marine magnetic data bearing on the nature of the South Atlantic triple junction have been discussed briefly by Barker (1970). The motion of the South American and African plates is relatively well established (Dickson, Pitman & Heirtzler 1968; Morgan 1968; Le Pichon 1968) and the spreading rate at the junction, on this limb, is approximately 1.4 cm per year per side along 070°. Spreading rate data for the Atlantic–Indian ridge are sparse; Le Pichon & Heirtzler (1968), recognizing no anomalies on several east–west profiles, suggested either a very slow spreading or none at all at present. Le Pichon calculated a small north–south separation from consideration of other plate motions. As yet, however, the only observed magnetic data, on a single (and therefore ambiguous) Project Magnet profile (Morgan & Johnson 1970) lying close to the junction, give a separation of about 1 cm per year per side along 030°. The combination of these best estimates on two of the ridges gives a provisional separation rate of 0.8 cm per year per side along 290° for the third limb. Probably, therefore, the line of earthquake epicentres leading to the South Sandwich arc is a slow spreading centre, with long fracture zones and short ridge sections.

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