Geophys. J. R. astr. Soc. (1980) **63**, 427–440

Evidence for Miocene back-arc spreading in the central Scotia Sea

Ian A. Hill★ and Peter F. Barker *Department of Geological Sciences, University of Birmingham, PO Box 363, Birmingham B15 2TT*

Received 1980 February 25; in original form 1979 October 17

Summary. Extensive marine geophysical surveys within the central Scotia Sea have revealed two areas of lineated magnetic anomalies. The limited length of anomaly sequences makes unique correlation with the reversal time-scale difficult, but a model is derived for the longer sequence requiring slow spreading during the period 21–6 Myr about a ridge trending 085°. The north–south lineated anomalies in the other sequence are well formed, but their identification is unavoidably ambiguous.

The longer spreading sequence is interpreted as back-arc spreading behind the 'Discovery Arc', which was active during at least the period 20–12 Myr ago. The spreading was asymmetric, as is spreading at the present South Sandwich back-arc ridge. More than two-thirds of the oceanic crust of the Scotia Sea has now been shown to be less than 30 Myr old, and it is probable that it formed almost entirely within this period, as a complication of the South American–Antarctic plate boundary.

Introduction

The Soctia Sea is bounded by the Scotia Ridge, a discontinuous loop of islands and submarine ridges extending 1500 km eastwards into the South Atlantic Ocean from Tierra del Fuego and the tip of the Antarctic Peninsula (Fig. 1). Most of the islands scattered along the ridge have a continental geology, easily correlated with elements of the Mesozoic, subduction-related terrain exposed on the Antarctic Peninsula and in southern South America. The identification of these ridges as Pacific margin fragments has resulted in many models for the tectonic evolution of the region (e.g. Hawkes 1962; Barker & Griffiths 1972; Dalziel & Elliot 1973; de Wit 1977). With the exception of de Wit, these authors suggest that the major fragmentation and dispersal of this continental material was a Tertiary event.

At the eastern end of the Scotia Sea, behind the active South Sandwich island arc, a well-defined magnetic reversal anomaly sequence indicates rapid back-arc extension over the past 7 Myr (Barker 1972). In the west, magnetic surveys have revealed the history of sea-floor

★Present address: Department of Geology, University of Leicester, University Road, Leicester LE1 7RH.

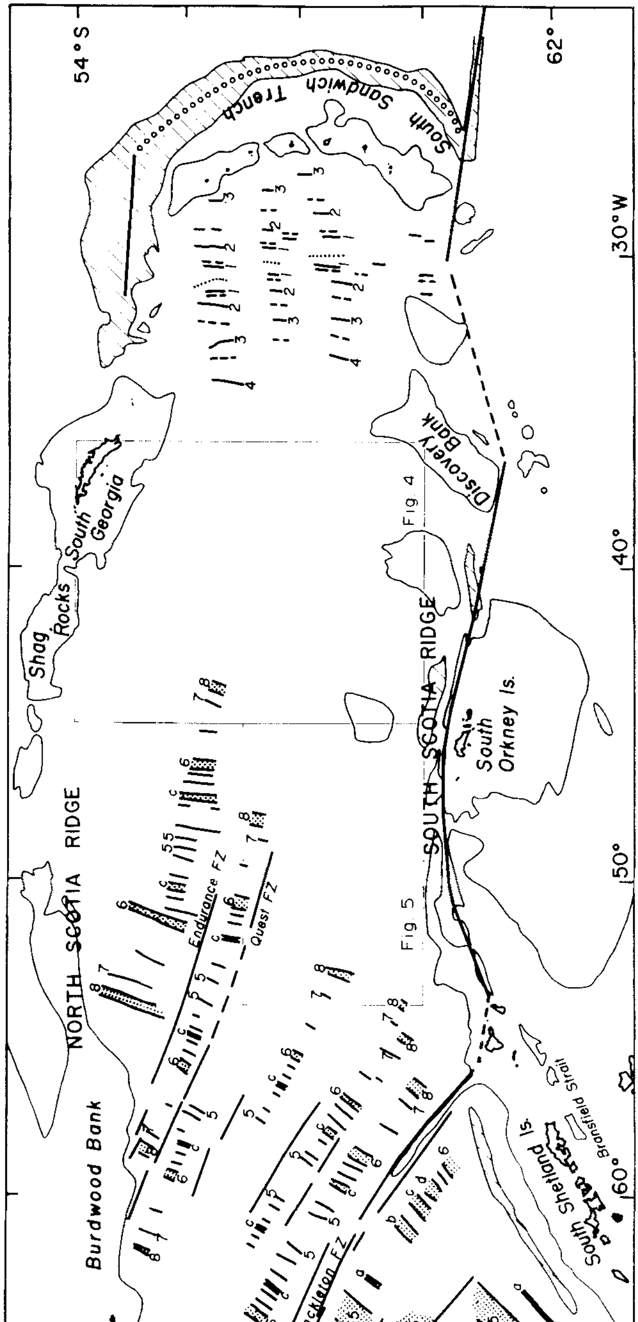

Figure 1. Chart of the Scotia Sea region showing identified magnetic anomalies within the Scotia Sea (Barker 1972; Barker & Burrell 1977) and the location of magnetic anomalies described in this paper in the central Scotia Sea (Fig. 4) and Protector Basin (Fig. 5).

spreading in Drake Passage (Barker & Burrell 1977), which suggests strongly that the Antarctic Peninsula separated from South America mainly during the period 27–6 Myr ago.

The area of the Scotia Sea floor between these two anomaly sequences has not previously been accurately dated. Seismic refraction data from this area (Allen 1966; Ewing *et al.* 1971) have confirmed that the crustal structure is of oceanic type, at least in the areas of 'normal' oceanic depths, 3000–5000 m. De Wit (1977) drew an interesting comparison between central Scotia Sea crustal structure and that of marginal basins in the western Pacific. The limited quantity and variable quality of Scotia Sea data, however, do not allow great confidence to be placed in this comparison as an indication of a back-arc extensional origin. Various ages for the oceanic crust of this area have been predicted from hypothetical reconstructions of the continental crustal fragments. De Wit (1977) proposed a Cretaceous age, the area being interpreted as a continuation of the now closed marginal basins preserved as ophiolite sequences in the southern Andes and South Georgia. Barker & Griffiths (1972) preferred a Tertiary age, with the crust being formed during the period of separation of the continental blocks to their present positions. The region is still tectonically active, being situated on the South American–Antarctic plate boundary (Forsyth 1975), though the area studied is essentially aseismic, being part of the Scotia Plate.

The purpose of this study was to use geophysical methods to define more closely the mode of evolution and age of the central Scotia Sea.

Bathymetric and magnetic data

The data described in this paper were collected during the period 1972–78 aboard the ships *RRS Shackleton, HMS Endurance* and *RRS Bransfield.* All three ships possessed satellite navigation receivers, although *RRS Bransfield* has only a single channel receiver. The navigational accuracy was generally better than ± 2 km and allows detailed correlation of intersecting data sets. All magnetic measurements were obtained using towed proton-precession sensors with instrumental errors of ± 1 nT and heading errors of less than 10 nT. The data have been reduced by subtraction of the International Geomagnetic Reference Field (IAGA 1969, 1976) but no diurnal correction has been applied. Bathymetry was recorded using precision echo-sounders and all soundings have been corrected for the variation of the velocity of sound in sea-water (Matthews 1939).

BATHYMETRY

Soundings from all available sources have been reviewed but most have poor navigational control. Where they produced no conflict with our accurately fixed data and crossed areas of otherwise poor coverage they were incorporated in our data set. The chart shown in Fig. 2 has been produced by compiling all soundings on 1:1 million plotting sheets and contouring at 500 m intervals.

The elevated blocks of undoubted continental crust, the South Georgia, South Orkneys and Shag Rocks blocks, are immediately apparent, with broad continental shelves falling abruptly to oceanic depths. North of the south Orkney block a row of four elevated blocks is revealed lying on an east–west line. One, the Discovery Bank, has been sampled by rock dredging and shown by petrographic and geochemical analysis and radiometric dating to be a remnant of an intra-oceanic island arc active during at least the period 20–12 Myr ago, (Barker *et al.* in press). The rugged topography of these blocks is due in part to their continued disruption by motions along the Antarctic–Scotia plate boundary, which runs roughly east–west along a line just to the north of the South Orkney block.

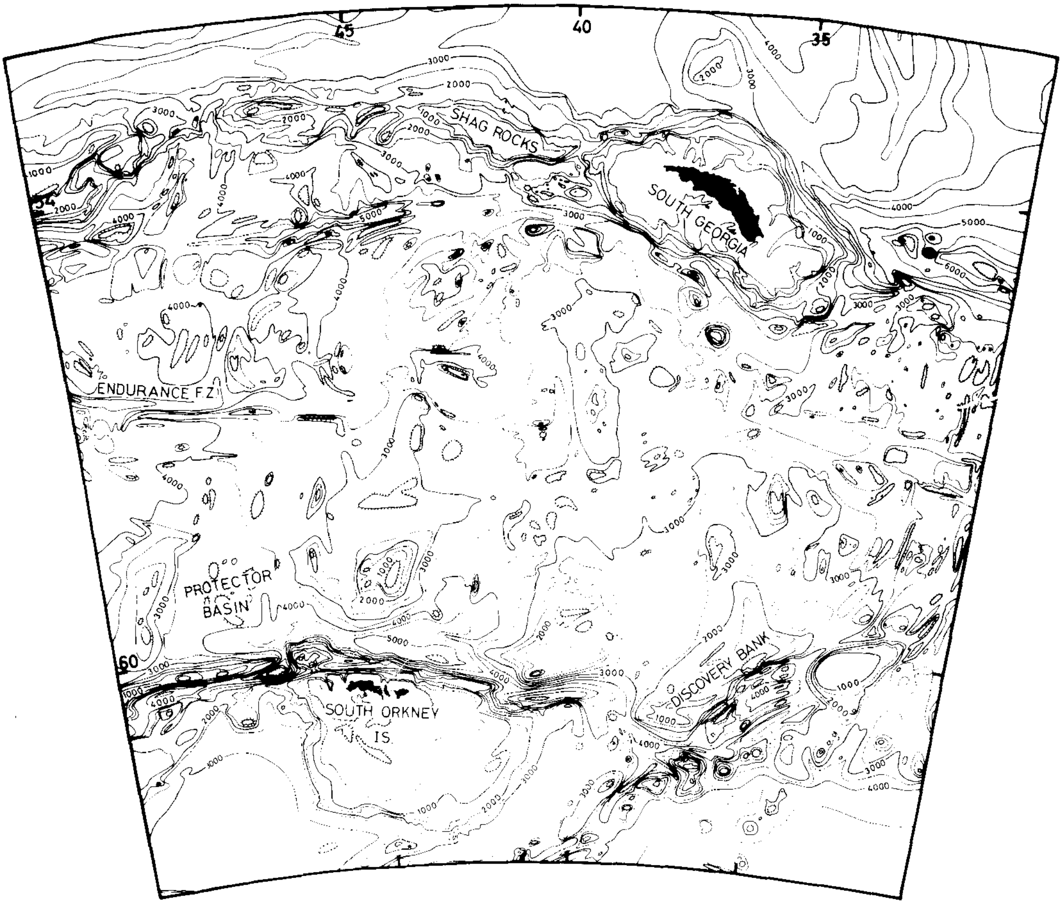

Figure 2. Bathymetric chart of the central Scotia Sea contoured at 500 m intervals (Polar Stereographic Projection).

The most prominent bathymetric feature to the north of these blocks is a broad ridge running north–south just east of 40° W, rising to just deeper than 2000 m. Its western margin is linear and is shown on several crossings to be a steep scarp. This feature is the eastern limit of recognized magnetic lineations (see below) and may well be related to a fracture zone of the spreading system.

Away from this ridge, the floor of the central Scotia Sea lies at normal oceanic depths, mostly between 3000 and 4000 m, with smooth relief due to a mantle of pelagic sediment. This is illustrated by the seismic profiling record shown in Fig. 3. The sediments in the central Scotia Sea are comparable in character and thickness with those in Drake Passage (Ewing *et al.* 1971; Barker & Burrell 1977) suggesting a broadly similar age and history for both areas. At the northern margin of the basinal area the form of the acoustic basement suggests the presence of normal-faulted blocks (marked F in Fig. 3) implying an extensional origin for the margin.

On the western edge of the study area, water depths exceed 4000 m above oceanic crust of the Drake Passage spreading system with ages of 20–30 Myr (Barker & Burrell 1977). In contrast, the eastern edge of the area has more rugged relief with less sediment cover and was generated at the still active, back-arc South Sandwich spreading centre (Barker 1972).

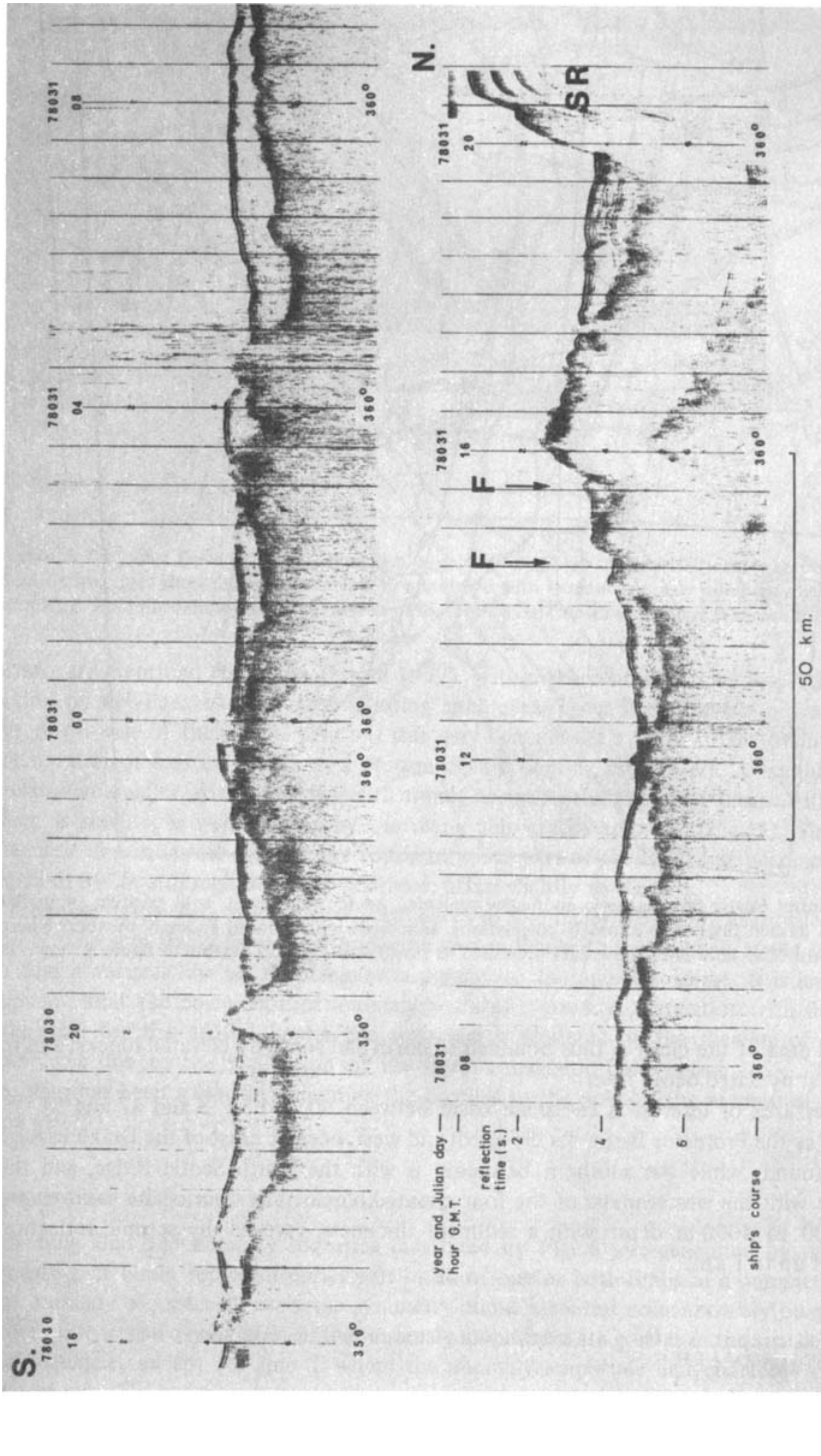

Figure 3. North–south reflection profile crossing the northern part of the central Scotia Sea (northern part of line T of Fig. 4). It shows a typical record of the oceanic crust of this area. Letter F marks positions of normal faulting. SR is the Shag Rocks continental block.

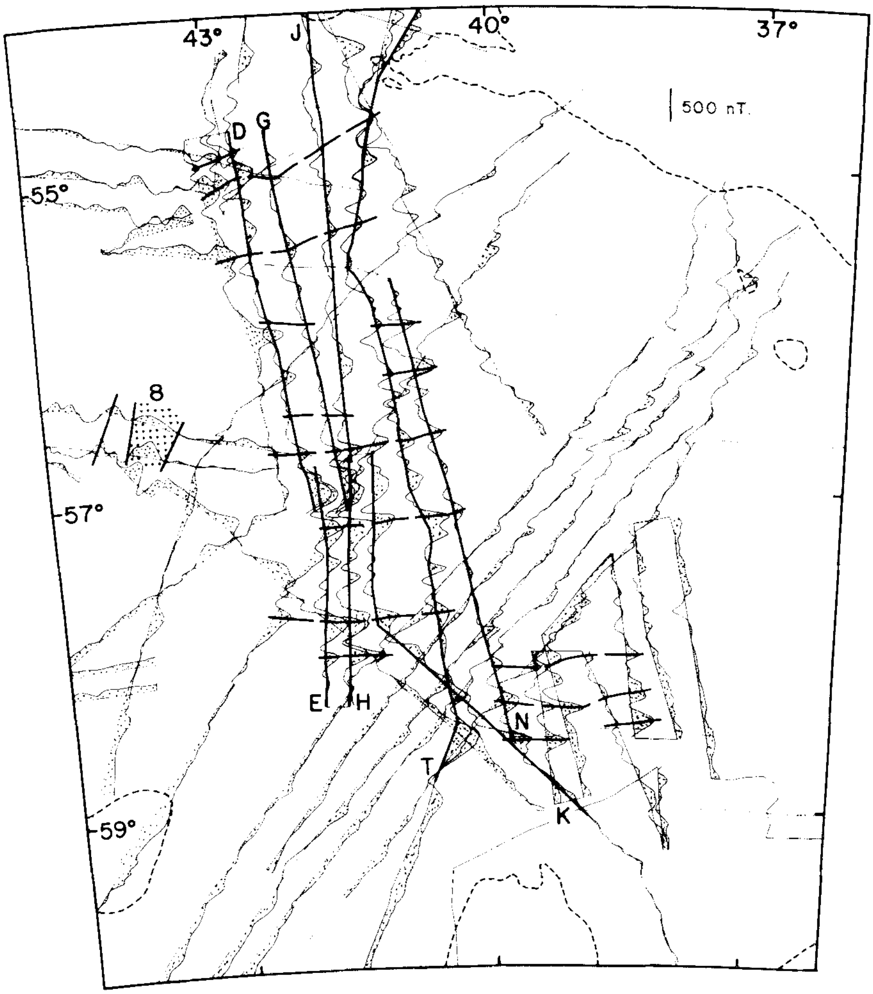

Figure 4. Central Scotia Sea magnetic anomalies projected on to ship tracks, with positive anomalies shaded. Bold dashed lines show anomaly correlations, annotated with Lamont anomaly numbers where previously identified. Bold lines show data presented as profiles in Fig. 6. Location of figure is shown in Fig. 1.

The central area of the chart is thus bounded to north and south by elevated blocks, and to east and west by dated ocean floor.

A further area of interest is the small basin between 60 and 58° S and 47 and 51° W, referred to as the Protector Basin. To the north and west, oceanic crust of the Drake Passage system is found, while the southern boundary is with the South Scotia Ridge, and the eastern one with the westernmost of the four elevated blocks. The floor of the basin is very flat at 3800 to 4000 m depth with a sediment thickness, revealed by seismic reflection profiling, of up to 1 km.

MAGNETIC ANOMALIES

A fence diagram of the magnetic data collected in the central Scotia Sea is shown in Fig. 4. Magnetic lineations are shown as bold lines, annotated with Lamont anomaly numbers where

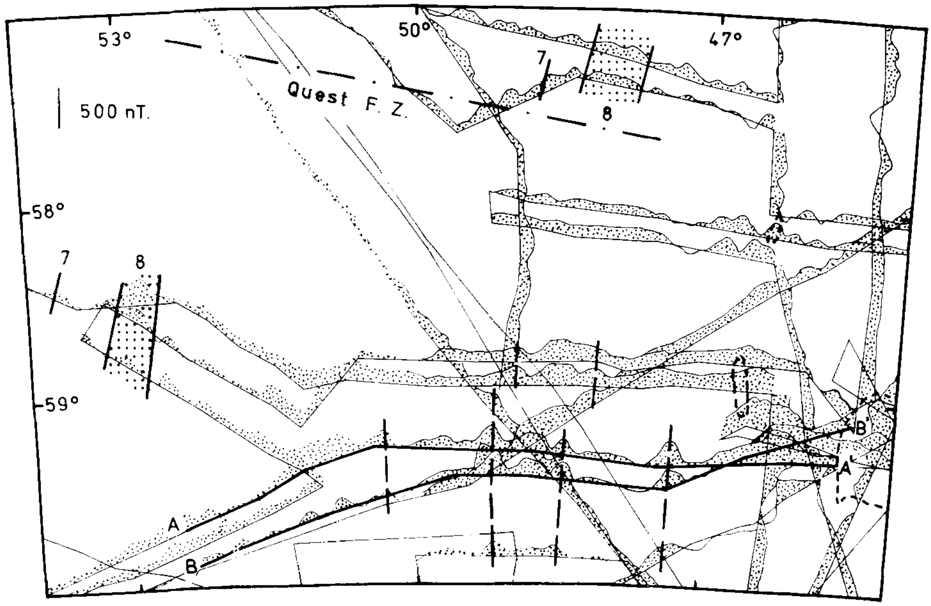

Figure 5. Protector Basin magnetic anomalies projected on to ship tracks with positive anomalies shaded. Bold dashed lines show anomaly correlations annotated with Lamont anomaly numbers where previously identified. Bold lines show data presented as profiles in Fig. 8. Location of figure is shown in Fig. 1.

previously identified (Barker & Burrell 1977). Within the central part of Fig. 4 lies a broad region of well-lineated east–west trending anomalies. These lineations are not apparent in the north-east of the central area but this may be as much a result of the orientation and distribution of existing tracks as a feature of the oceanic crust itself. A second series of lineated anomalies, with a north–south trend, occurs in the Protector Basin. Although this basin is small it is well defined by the many ship tracks across it (Fig. 5). The lineated magnetic anomalies are clear in the southern wider part of the basin but become indistinct north of 59° S, although they may continue, offset slightly to the east.

Representative data from the two sequences of anomalies are shown as profiles in Figs 6 and 8. The ship tracks have been projected perpendicular to the anomaly strike and aligned so that a vertical line on the diagram is parallel to the anomaly strike. It is immediately apparent that the correlation of anomaly features is good. A correlation with the reversal time-scale for the central Scotia Sea sequence is hindered by the skewing of individual anomalies due to the inclination of the Earth's magnetic field, about $-55°$. This latter problem has been solved by migrating the profiles to the pole by the method of Blakely & Cox (1972).

DATING OF THE MAGNETIC ANOMALIES

Assuming that the anomaly sequence illustrated by Fig. 6 was generated by ocean-floor spreading, it could represent either part or all of one or both limbs of a complete system. The anomaly sequence shows some symmetry about a central point, notably on profiles D and E, but is also asymmetric in that anomaly amplitudes are greater in the southern half of the sequence, except for line T where the anomaly amplitude and character are similar throughout. These features could perhaps be explained by slightly asymmetric spreading from a central ridge, but the evidence for a two-limbed sequence is not overwhelming.

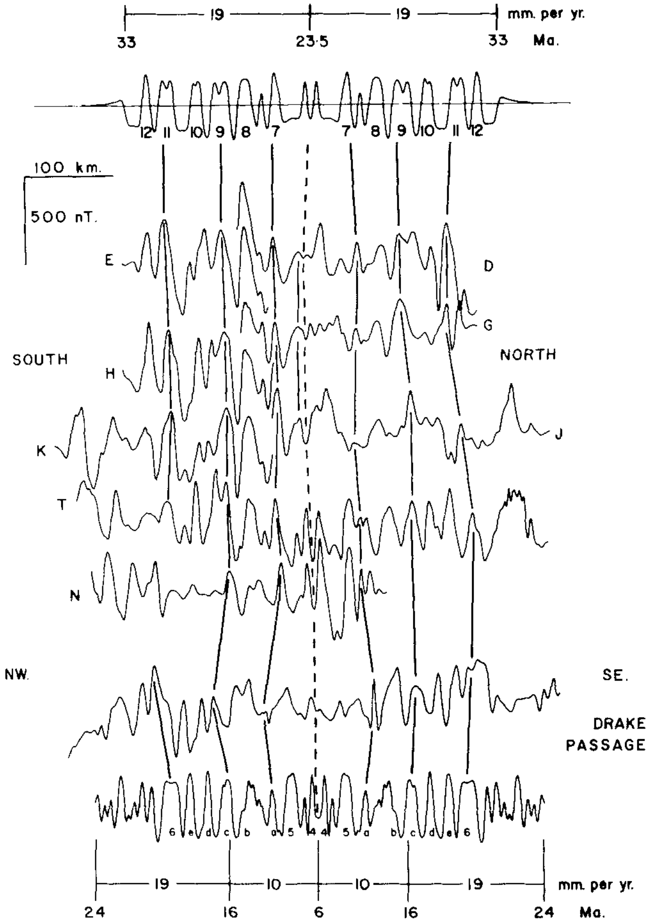

Figure 6. Central Scotia Sea magnetic profiles migrated to the pole, compared with the two synthetic profiles described in the text (top and bottom), and an observed profile from Drake Passage (line 'Z' of Barker & Burrell 1977). Profile locations are shown in Fig. 4.

The tectonic environment provides some guidance to the interpretation of the magnetic data. If the anomaly sequence represents one limb, then a length of oceanic crust greater than that remaining (about 300 km) must have been removed by subduction or strike-slip motion since its formation. Clearly if the crust were as old as early Cretaceous, as de Wit (1977) suggested, it could easily be a fragment, like the continental fragments within the Scotia Ridge, and there would have been many subsequent opportunities for the subduction of the missing portion. If, however, it is only as old as the remainder of the Scotia Sea (i.e. late Tertiary) it is much more likely to be complete since there is no obvious subduction zone, or site on the surface for the missing part, within the Scotia Sea. The general depth of the central Scotia Sea and the similarity of the sediment cover to that of Drake Passage argue that it is young, and thus likely to comprise a complete two-limbed system.

The character of the magnetic anomalies themselves is consistent with this. The sequence is short, but consists of a series of high amplitude near-sinusoidal anomalies. The absence of broad anomalies suggests a slow spreading rate, which would be compatible with the variability of anomaly shape along strike. A reasonable fit to the observed anomalies can be obtained using those sections of the magnetic reversal time-scale which extend from anomaly

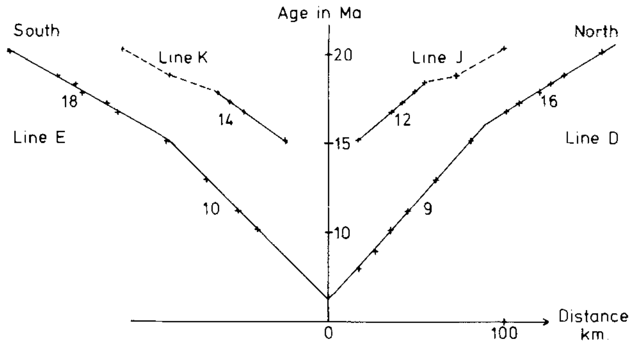

Figure 7. Spreading rates for the central Scotia Sea sequence determined by plotting distance of prominent features of the anomaly profiles against age of corresponding points on a synthetic anomaly profile. Figures by lines are spreading rates in mm yr^{-1}. Line identification letters are as shown in Fig. 4. Note that data for lines K and J are plotted against the same time axis, but displaced along the distance axis to avoid superposition upon lines E and D.

12 to 7 or from 6 to 5. The similarity of these two sections has been well illustrated by published interpretations of the Shikoku Basin anomalies (Tomoda *et al.* 1975; Watts & Weissel 1975; Klein, Kobayashi *et al.* 1978). These papers also serve as good illustrations of the difficulties of correlating short anomaly sequences with the reversal time-scale, and of deciding whether such short sequences are one-sided.

Synthetic anomaly profiles have been computed using the magnetic reversal time-scale of La Brecque *et al.* (1978) and a body thickness of 0.4 km beneath a sea-bed depth varying as the square root of age (Trehu 1975). The intensity of remanent magnetization is taken to vary smoothly from 1.6 Am^{-1} at 100 Myr ago to 2.2 Am^{-1} at 10 Myr ago and 3.8 Am^{-1} at 0.7 Myr ago.

Using the older reversal sequence (anomalies 12 to 7) a spreading rate of 19 mm yr^{-1} per side between 33 and 23.5 Myr produced a synthetic profile correlating well with some profiles of the southern limb, but less well with the northern limb. Using the younger sequence a good fit was obtained to all the observed profiles of the southern limb and to some of the northern limb from anomaly 6 to 5c (21 to 16 Myr) with a rate of 19 mm yr^{-1} per side, but to complete a symmetric sequence it was found necessary to continue at a rate of 10 mm yr^{-1}, with anomaly 5a correlated with the prominent narrow positive anomaly seen on all profiles. The resulting model spans the period from 21 to 6 Myr with the change in spreading rate at 16 Myr and is shown in Fig. 6. The correlation of this model with the observed anomalies is considered to be slightly better than that of the earlier model.

It is not easy to discriminate between these two models purely on the correlation with the observed data. Both require a spreading ridge to be active at least partly within the time-span of the Drake Passage system, so consideration of the relationship to this system might supply further constraints. The longest continuous magnetic profile across Drake Passage (Barker & Burrell 1977, line 'Z') has been migrated to the pole and is shown at the foot of Fig. 6. The resemblance between the observed anomaly sequences in Drake Passage and the central Scotia Sea is clear, and supports the younger of the previous models. The similarity of the two sets of observed anomalies from 6 to 5b is very striking. The possibility that Drake Passage spreading may also fit the older model is discounted since the greater length of anomaly sequence and larger number of observed profiles in Drake Passage do allow the identification of Barker & Burrell to be considered essentially correct. It is interesting that Barker & Burrell see in Drake Passage a slowing of the spreading rate at 16 Myr (using the

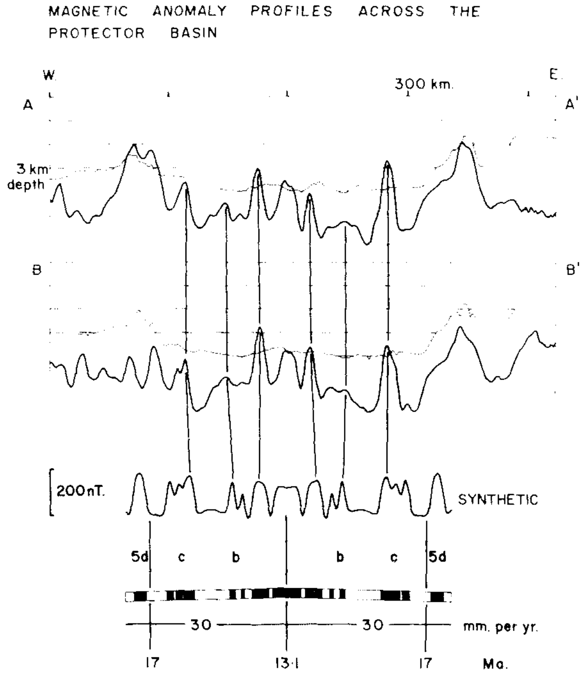

Figure 8. Protector Basin magnetic and bathymetric profiles, compared with one possible synthetic magnetic profile. Location of profiles shown in Fig. 5.

La Brecque *et al.* (1978) time-scale). Thus the histories of the two spreading systems are very similar, implying a close tectonic relationship.

From the correlations shown in plan and in profile in Figs 4 and 6 it is apparent that the spreading rate is not uniform across the area, being faster to the east, which indicates that the pole of opening for the relative motion is at no great distance to the west. The small areal extent of the data prevents location of this pole with any accuracy. Fig. 7 shows a plot of anomaly distance against age for lines D, E, J and K. This shows the faster rates to the east of the sequence, but also reveals an asymmetry in spreading rates, with greater crustal accretion to the south. The asymmetry is about 5 per cent of the total rate irrespective of the mean spreading rate. This effect may partly explain the poorer definition of anomaly shapes on the northern limb of the system.

In Fig. 3, a short sequence of magnetic anomalies also lineated east–west occurs to the south-east of those previously discussed. The most reasonable assumption is that they also belong to the central Scotia Sea sequence, but are offset. A correlation with anomalies 6 to 5d is reasonable since the anomalies are known to be at the southern end of the sequence present at that longitude. If this is correct the fracture zone offset must be about 75 km. The fracture zone is detected where it is crossed by line N, but cannot be followed farther north on the magnetic chart. Fig. 2 shows a west-facing scarp bounding the anomalously higher bathymetry east of 40° W. This scarp could be related to the fracture zone, which suggests that the elevated area to the east also originated at the central Scotia Sea spreading centre.

The Protector Basin is the second area in which lineated magnetic anomalies have been discovered. The data from two tracks across the well-developed anomalies are shown as profiles in Fig. 8. The magnetic anomaly pattern has an obvious symmetry about the centre of the basin. Because of the very limited length of the sequence an unambiguous correlation with the reversal time-scale is not considered possible. Within the period 0 to 40 Myr, however, perhaps the simplest acceptable correlation is that shown in Fig. 8. All the anomalies are well matched, even the minor ones corresponding to Lamont number 5b, and the fit could be improved by slight modifications to the spreading rate.

There are two interesting features about the age of this basin as deduced from this model. The first is that despite the small size of the basin the general level of the bathymetry agrees well with the depth–age relationships for ocean basins (Sclater, Anderson & Bell 1971). The second is that the oldest observed anomaly has an age of about 16 Myr. The coincidence of this date with the spreading rate changes for the two adjacent larger spreading systems is remarkable, and lends some support to the choice of this particular model. The spreading rate is higher than either, however, and the model may prove difficult to reconcile with the regional tectonics.

Discussion

The Scotia Sea is now seen to contain at least four different sequences of magnetic reversal anomalies. The dating of the Drake Passage and South Sandwich sequences is considered to be reliable. Whichever of the two models illustrated in Fig. 6 is considered, the central Scotia Sea spreading episode must have been in part contemporaneous with Drake Passage opening. This being so, their histories would be expected to show related features. For the younger, preferred model the similarities of their spreading histories are remarkable, both showing a decrease in spreading rate with time, having a major change in spreading rate at 16 Myr, and stopping at about the time that South Sandwich back-arc spreading started. The possibility of the Protector Basin anomalies also being related to the date of 16 Myr may provide additional support. Given all the circumstantial evidence, the dating of the central Scotia Sea sequence can be regarded as reasonably certain. It then becomes necessary to relate this spreading to any synchronous tectonic activity.

The evidence for the identification of some of the elevated blocks of the eastern South Scotia Ridge as fragments of an intra-oceanic island arc, active at least within the period 12–20 Myr ago has been given elsewhere (Barker *et al.* in press). Basalts dredged from Discovery Bank (Fig. 1) were found to be geochemically almost identical with those from the South Sandwich Arc. It was inferred that the trench for this 'Discovery Arc' lay to the south-east of the present position of the blocks and, like the South Sandwich trench, was the side of subduction of oceanic crust of the South American plate.

South American–Antarctic (SAM–ANT) plate motion at present is slow and approximately east–west (Minster & Jordan 1978) and sparse information on its history, gleaned indirectly from SAM–AFR and AFR–ANT motion (Ladd, Dickson & Pitman 1973; Bergh & Norton 1976; Sclater *et al.* 1978), suggests that this has been the case generally for the past 40 Myr. Whilst it is conceivable that the Drake Passage spreading centre was part of a simple SAM–ANT boundary for much of that time (Fig. 1 and Barker & Burrell 1977), it is clear that the much faster South Sandwich back-arc extension over the past 7 Myr has not been (Barker 1972). Similarly, it is difficult to see how the north–south extension of the central Scotia Sea could have represented the simple east–west SAM–ANT motion. It is concluded that instead it took the form of back-arc extension behind the Discovery Arc, akin to the present day South Sandwich spreading centre. In this context, it is interesting to note that, like South Sandwich back-arc extension, spreading in the central Scotia Sea was asymmetric, favouring accretion to the arc side.

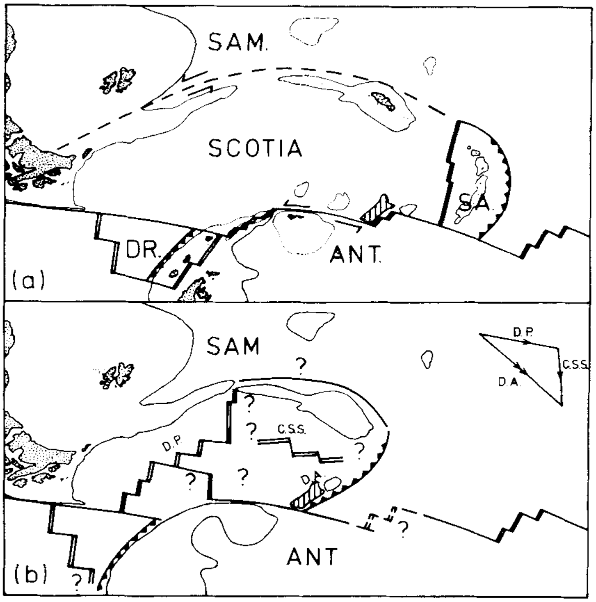

Figure 9. Schematic diagrams of the tectonics of the Scotia Sea region (a) at the present day (b) about 16 Myr ago. All motion is shown relative to the South American plate (SAM). In (a) the Sandwich Plate carrying the South Sandwich Arc (S.A.) moves eastwards by the spreading of the east Scotia Sea back-arc ridge. In (b) the Discovery Arc (D.A.) moves south-eastwards by the vector sum of Drake Passage (D.P.) and Central Scotia Sea (C.S.S.) spreading. ANT is Antarctic plate; DR is the Drake plate. (Bold lines are transform faults; double lines are ridges; toothed lines are trenches.)

Since there were two, or for a short period perhaps three, spreading ridges simultaneously active within the Scotia Sea while subduction was taking place at the Discovery Arc, the tectonic pattern was necessarily more complex than that of the present Sandwich Arc system. A speculative comparison of the plate boundaries at 16 Myr, and at the present day is shown in Fig. 9. It has been suggested (Barker *et al.* in press) that the change in plate geometry was caused by collision of the Discovery Arc with sections of the SAM–ANT spreading ridge which existed to the south-west of those seen today. The collision is inferred to have effectively stopped subduction at the Discovery Trench. This event would have had to occur about 7 Myr ago, when a change in plate motions is revealed by the cessation of Drake Passage and central Scotia Sea spreading, and the start of east Scotia Sea extension.

Including the results presented here, more than 70 per cent of the Scotia Sea floor has been dated, all of it as younger than 30 Myr. It seems unlikely that much of the remainder will prove to be significantly older. For at least the last two-thirds of the life of the Scotia Sea, there has been subduction of South American oceanic crust at its eastern end, similar to that taking place today. Also, there is an apparent close coupling between the spreading histories of the Drake Passage, central Scotia Sea and South Sandwich spreading systems. These factors combine to indicate that the Scotia Sea has formed almost completely over the past 30 Myr, essentially as a complication on the SAM–ANT plate boundary.

Recognition of this represents a significant step towards the clearly desirable aim of a reconstruction of the development of the Scotia Sea, to extend back to the original relative positions of the Scotia Ridge continental fragments at the Pacific margin. The solution to this problem, however, is beyond the scope of this paper, not least because of the major uncertainties which remain. These include:

(i) the history of coupling between the limbs of the several spreading centres, which is difficult to deduce but essential to a reconstruction;

(ii) the history of SAM–ANT motion over the past 30–40 Myr, to provide a baseline for Scotia Sea evolution;

(iii) the time and mode of origin of Atlantic directed subduction at the eastern end of the Scotia Sea. Did it exist even before 30 Myr?

Acknowledgments

Invaluable help in data collection was given by the officers and crew of *RRS Shackleton, HMS Endurance* and *RRS Bransfield,* and members of Research Vessel Services, Barry, as well as the other members of the Antarctic Marine Geophysics Group, J. Burrell, R. A. Jahn and P. Simpson. The work was supported by an NERC research contract.

References

Allen, A., 1966. Seismic refraction investigations in the Scotia Sea, *Br. Antarct. Surv. Sci. Repts, No. 55.*

Barker, P. F., 1972. A spreading centre in the east Scotia Sea, *Earth planet. Sci. Lett.*, **15**, 123–132.

Barker, P. F. & Griffiths, D. H., 1972. The evolution of the Scotia Ridge and Scotia Sea, *Phil. Trans. R. Soc. Lond. A*, **271**, 151–183.

Barker, P. F. & Burrell, J., 1977. The opening of Drake Passage, *Mar. Geol.*, **25**, 15–34.

Barker, P. F., Hill, I. A., Weaver, S. D. & Pankhurst, R. J., in press. The origin of the eastern South Scotia Ridge as an intra-oceanic island arc, in *Antarctic Geoscience,* ed. Craddock C., Proceedings Symposium Antarctic Geology and Geophysics, Madison, Wisconsin.

Bergh, H. W. & Norton, I. O., 1976. Prince Edward fracture zone and the evolution of the Mozambique Basin, *J. geophys. Res.*, **81**, 533–530.

Blakeley, R. J. & Cox, A., 1972. Identification of short polarity events by transforming marine magnetic profiles to the pole, *J. geophys. Res.*, 77, 4339–4349.

Dalziel, I. W. D. & Elliot, D. H., 1973. The Scotia Arc and Antarctic margin, in *The Ocean Basins and Margins Vol. 1, the South Atlantic,* eds Nairn, A. E. M. & Stehli, F. G., pp. 171–246, Plenum Press, New York.

de Wit, M. J., 1977. The evolution of the Scotia Arc as the key to the reconstruction of southwestern Gondwanaland, *Tectonophysics,* **37**, 53–81.

Ewing, J. I., Ludwig, W. J., Ewing, M. & Eittreim, S. L., 1971. Structure of the Scotia Sea and Falkland Plateau, *J. geophys. Res.*, **76**, 7118–7137.

Forsyth, D. W., 1975. Fault plane solutions and tectonics of the South Atlantic and Scotia Sea, *J. geophys. Res.*, **80**, 1429–1443.

Hawkes, D. D., 1962. The structure of the Scotia Arc, *Geol. Mag.*, **99**, 85–91.

IAGA, 1969. International geomagnetic reference field, 1965, *J. geophys. Res.*, 74, 4407.

IAGA, 1976. International geomagnetic reference field, 1975, *EOS Trans. Am. geophys. Un.*, **57**, 120–121.

Klein, G. de V., Kobayashi, K., *et al.* 1978. Off-ridge volcanism and sea-floor spreading in the Shikoku Basin, *Nature,* **273**, 746–748.

La Brecque, J. L., Kent, D. V. & Cande, S. C., 1977. Revised magnetic polarity time scale for late Cretaceous and Cenozoic time, *Geology,* **5**, 330–335.

Ladd, J. W., Dickson, G. O. & Pitman, W. C. III, 1973. The age of the south Atlantic, in *The Ocean Basins and Margins: The South Atlantic,* eds Nairn, A. E. M. & Stehli, F. G., pp. 555–573, Plenum, New York.

Matthews, D. J., 1939. *Tables for the velocity of sound in pure water and sea water for use in echo sounding and sound-ranging,* 2nd edn, HMSO, London. (Admiralty Hydrographic Department H.D. 282.)

Minster, J. B. & Jordan, T. H., 1978. Present day plate motions, *J. geophys. Res.*, 83, 5331–5354.

Sclater, J. G., Anderson, C. N. & Bell, M. L., 1971. Elevation of ridges and evolution of the central eastern Pacific, *J. geophys. Res.*, **76**, 7888–7915.

Sclater, J. G., Dick, H., Norton, I. O. & Woodroffe, D., 1978. Tectonic structure and petrology of the Antarctic plate boundary near the Bouvet triple junction, *Earth planet. Sci. Lett.*, 37, 393–400.

Tomoda, Y., Kobayashi, K., Segawa, J., Nomura, M., Kimora, K. & Saki, T., 1975. Linear magnetic anomalies in the Shikoku Basin, northeastern Philippine Sea, *J. Geomagn. Geoelectr.*, **28**, 47–56.

Trehu, A. M., 1975. Depth versus $(age)^{1/2}$: a perspective on mid-ocean ridges, *Earth planet. Sci. Lett.*, **27**, 287–304.

Watts, A. B. & Weissel, J. K., 1975. Tectonic history of the Shikoku marginal basin, *Earth planet. Sci. Lett.*, **25**, 239–250.