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Back-Arc Extension in the Scotia Sea [and Discussion]

P. F. Barker, I. A. Hill and M. F. Osmaston

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Back-arc extension in the Scotia Sea

By P. F. Barker† and I. A. Hill‡
† *Department of Geological Sciences, University of Birmingham, Birmingham B15 2TT, U.K.*
‡ *Department of Geology, University of Leicester, Leicester LE1 7RH, U.K.*

[Pullouts 1 and 2]

The nature of back-arc extension in the East Scotia Sea is re-examined with the use of an enlarged geophysical data set. Well developed oceanic magnetic lineations confirm that the present spreading episode started about 8 Ma ago, that spreading is asymmetric, and that the total rate increased from 50 to 70 mm/a about 1.5 Ma ago. Most of the currently active South Sandwich volcanic island arc lies upon ocean floor only 6–8 Ma old and generated at the current spreading ridge. Subsequent extension has not modified the curvature of the arc.

East–west magnetic lineations of Miocene age in the Central Scotia Sea and contemporaneous low-K arc tholeiites dredged from the eastern South Scotia Ridge (Discovery Bank) indicate a régime of coupled subduction and back-arc extension preceding that occurring now. A speculative model involving a series of collisions of parts of this earlier Discovery trench with ridge crest sections of the South American–Antarctic plate boundary explains the transformation of this earlier régime into the present, self-contained Sandwich plate régime. The considerable small-scale variability observed in the back-arc region may be seen as an inevitable consequence of the action of the ridge–trench collision mechanism.

The entire Scotia Sea could have formed by a similar kind of back-arc extensional modification of the South American–Antarctic plate boundary.

1. Introduction

The East Scotia Sea provided the first reported example of active back-arc extension generating well developed oceanic (Vine–Matthews) magnetic lineations (Barker 1970, 1972*a*, *b*). Such lineations have now been described from many back-arc basins, but few of them are actively extending and the East Scotia Sea remains in many ways the best known active example. Since the first description, additional marine geophysical data have accumulated, which should permit a better definition of the back-arc basin. Also, considerably more is now known about the age and evolution of other parts of the Scotia Sea to the west, and the Scotia Ridge which surrounds it. It therefore seems timely to re-examine the principal conclusions of earlier studies about the nature of South Sandwich back-arc extension, and to attempt to understand its origin, particularly in relation to any earlier episodes of subduction and back-arc extension and in the context of a developing South American–Antarctic plate boundary.

Our understanding of the present distribution of plate boundaries and motions in the Scotia Sea region is summarized in figure 1 (after Barker & Dalziel 1980). South American–Antarctic (Sam–Ant) motion is slow (*ca.* 20 mm/a), sinistral and approximately east–west throughout the region (Chase 1978*a*; Minster & Jordan 1978). However, the Sam–Ant boundary only exists in simple form east of the South Sandwich Islands, as a spreading centre with long fracture zone offsets (Barker 1970; Forsyth 1975; Sclater *et al.* 1976*a*). Farther west, Sam–Ant motion divides in unknown proportion between the North and South Scotia Ridges, thus defining the

Scotia plate, which includes the greater part of the intervening Scotia Sea. Motion along both of these boundaries is also sinistral and approximately east–west (Barker & Griffiths 1972; Forsyth 1975) and is therefore also slow. At the Pacific margin of southern Chile, south of the Chile Rise, the SAM–ANT boundary reappears as a sediment-filled trench marking a zone of slow east–west convergence.

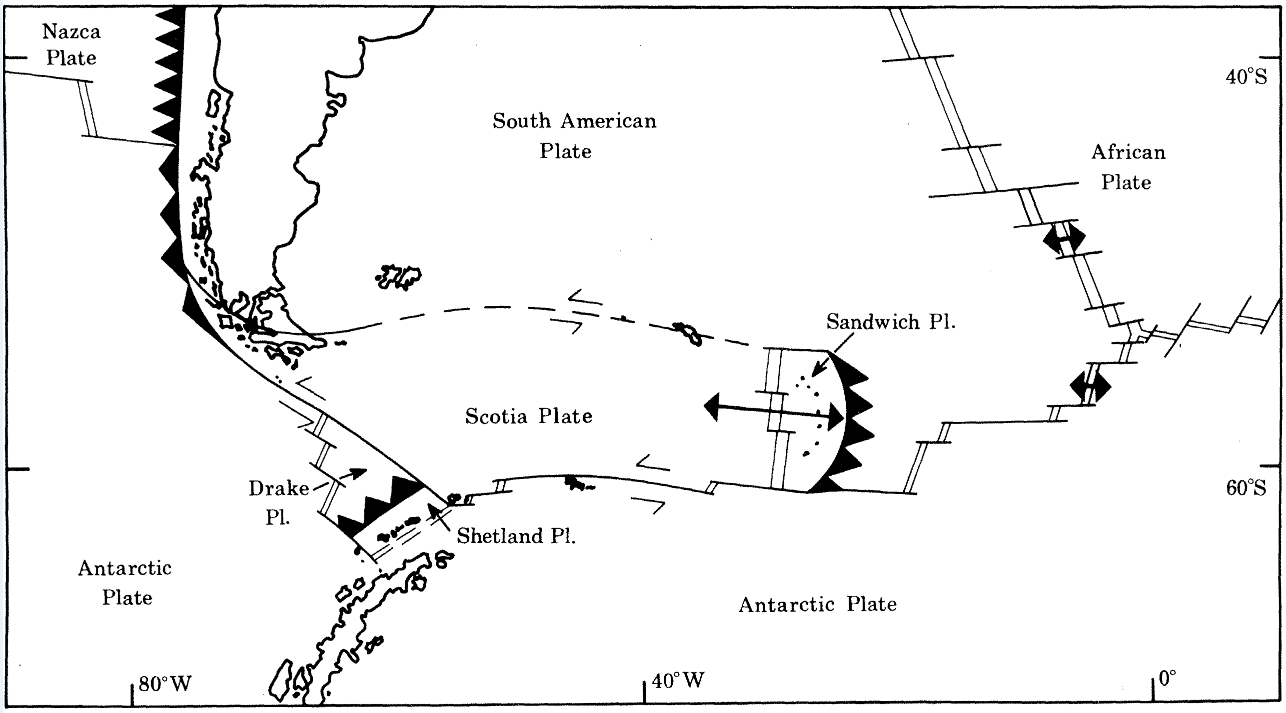

FIGURE 1. Present plate boundaries and motions in the Scotia Sea region. Lengths of the thick arrows indicate relative spreading rates. Redrawn from Barker & Dalziel (1980).

In this regional tectonic setting, the relatively fast back-arc extension of the spreading centre in the East Scotia Sea (Barker 1972*b*) stands out. Apart from such (slow) motion as occurs along the North Scotia Ridge, this rapid extension must exactly compensate for subduction at the South Sandwich trench of oceanic lithosphere belonging to the South American (SAM) plate. The subducted slab may be older at the northern end of the trench than in the south (Forsyth 1975; Brett 1977), if both formed at the SAM–ANT boundary, because of the long ridge–crest offset there. The steeper dip of the slab in the north (Brett 1977) and the change from downdip extensional fault plane solutions for earthquakes in the north to downdip compression in the centre and south (Isacks & Molnar 1971; Forsyth 1975) would be explained if the heavier, older northern part of the slab were pulling down with it the younger, lighter, southern part. At the northern end, earthquake first motions suggest that the subducted slab is being torn at depths of 50–130 km along an eastward propagating line (Forsyth 1975), to accommodate the rapid eastward migration of the small, D-shaped Sandwich plate. The southern boundary of the Sandwich plate is virtually continuous with the SAM–ANT boundary to the east, so that it just fails to override ocean floor belonging to the Antarctic (ANT) plate. This apart, the behaviour of the Sandwich plate appears to be totally independent of the boundaries and motions of the major plates, which raises questions about its origin. Chase (1978*b*) argues for a 'sub-

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duction imperative', that subducting oceanic lithosphere is peeled back to some extent, so that the trench and overriding plate advance (in absolute motion terms), and that back-arc extension is induced when without it this advance would not take place. Absolute motions in the Scotia Sea region at present are compatible with this notion, but the self-contained nature of the present subduction – back-arc extension system is not explained.

Earlier SAM–ANT motion is not precisely known, but indirect evidence (the great length of some South Atlantic fracture zones; see Sclater *et al.* 1978) suggests that it has retained its present character for at least the past 40 Ma. Nothing since found disputes the early suggestion that the Scotia Sea also formed over the past 40 Ma (Barker 1970), essentially as an increasingly intricate modification of the SAM–ANT boundary. The western Scotia Sea (Drake Passage, the most westerly part of the Scotia Plate; figure 1) formed by separation of southern South America from the South Scotia Ridge, in the direction 120°. Well formed magnetic anomalies (Barker & Burrell 1977) show that spreading started 27 Ma ago, or a few megayears earlier, and stopped at about 6 Ma. Within that period, subduction at the Pacific margin of southern South America and the Antarctic Peninsula was more extensive and energetic than today, but events in that region probably did not greatly influence Scotia Sea evolution. The North and South Scotia Ridge are still thought to consist largely of continental fragments, originally part of a continuous South American–Antarctic Peninsula junction and fragmented at the start of Scotia Sea formation. Recent work on the eastern South Scotia Ridge, however (Barker *et al.* 1980), indicates an intraoceanic volcanic arc origin. Also, although fracture zone orientations in Drake Passage are compatible with its having opened as part of a SAM–ANT boundary much simpler than at present, possibly *without* east-directed subduction, recently mapped east–west magnetic lineations in the Central Scotia Sea (Hill & Barker 1980) strongly suggest a more complicated regional tectonic régime, before the onset of the present episode of back-arc spreading in the East Scotia Sea. The nature of that earlier régime, and how and why it was transformed into the present régime, are the principal concerns of this paper.

2. Magnetic and bathymetric data

Figure 2, pullout 1, is a compilation of all magnetic data collected from the East and Central Scotia Sea and surrounding areas during cruises of R.R.S. *Shackleton*, H.M.S. *Endurance* and R.R.S. *Bransfield* between 1968 and 1979. All ship tracks are fixed by satellite navigation to better than 2 km.

Data coverage in the Central Scotia Sea is essentially that described by Hill & Barker (1980), so the magnetic profiles will be considered only briefly here. Profiles in the East Scotia Sea are now much more numerous than those described by Barker (1972*b*) although the new data, acquired partly on 'passage' tracks between points chosen for other purposes, are not all of equal value.

No attempt has been made to remove diurnal magnetic variation, but data collected within periods of abnormally high magnetic activity have been omitted. The magnetic residuals (after removal of the International Geomagnetic Reference Field; I.A.G.A. 1969, 1976) are projected generally perpendicular to the ship track, in the directions indicated by the occasional straight line joining track and profile. Positive magnetic anomalies are shaded and identified anomalies numbered. Fracture zones are located mainly on bathymetric evidence, not all of which can be presented here.

Figure 3, pullout 2, is a bathymetric chart of the area shown in figure 2, contoured at 1000 m intervals with areas above 3000 m and below 5000 m shaded. The chart was drawn by using soundings on virtually all of the tracks shown in figure 2, together with some older, celestially navigated data. These latter are in reasonable agreement with satellite-fixed soundings close to land, but elsewhere may be up to 50 or 100 km out of place. Thus, the contours in some little-known areas, such as the eastern South Scotia Ridge, should be used with caution.

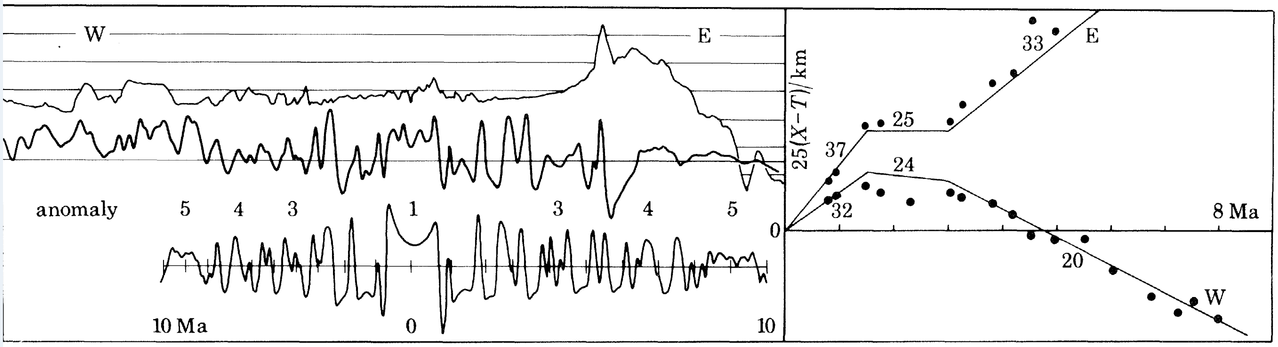

FIGURE 4. West–east magnetic and bathymetric profile crossing the northern part of the East Scotia Sea, compared with a synthetic magnetic profile. Spreading rates used to produce the synthetic profile are the lines (labelled in millimetres per year) drawn through the 'reduced distance plot' (Barker 1979) of identified features taken from the measured profile. The asymmetric nature of the spreading is clearly shown, and the volcanic peak associated with the island arc lies on ocean floor apparently not much more than 5 Ma old. Definite anomaly correlation in the fore-arc region, however, is not implied.

(*a*) *East Scotia Sea*

In general, the new magnetic data in the East Scotia Sea confirm conclusions drawn from the old. There is one change; of two possible anomaly identifications considered by Barker (1972*b*), he preferred one that implied slightly younger ocean floor and faster spreading rates before 3.5 Ma, on the basis that the implied navigational error on the single celestially navigated profile then under consideration would thereby be considerably reduced. The additional data considered here support the alternative interpretation, which is illustrated in figure 4. Spreading on the western flank was consistently slower than on the eastern flank, and before 3 Ma was only 20 mm/a. The reduced distance plot (Barker 1979) in figure 4 shows that spreading was asymmetric, favouring accretion to the eastern, trench flank. Although small ridge jumps probably have occurred in places (one is implied by the discontinuous fracture zones in the densely surveyed northern area, for example), none can be seen on the profile in figure 4, and the asymmetry was essentially smooth. This asymmetry was reported by Barker (1972*b*) and its significance is discussed in detail elsewhere (Barker & Hill 1980). Most of the closely spaced east–west profiles in the northern area were available to Barker (1972*b*) and this remains the best surveyed area. Elsewhere it is not possible to be so confident about the presence or absence of small ridge jumps and fracture zones. One profile across the eastern flank in the central section, where the island arc lies farthest east, suggests a slower spreading rate, which would reduce the degree of asymmetry. A consistent sense of asymmetry, however, which favours accretion to the eastern flank, appears to typify the entire back–arc basin.

As Barker (1972*b*) concluded, the total amount of ocean floor formed between, say, anomaly 4 in the west and 3 in the east, is about the same at 56° and 59° S, showing that back-arc extension has not contributed to the curvature of the arc in general. However, the more recent

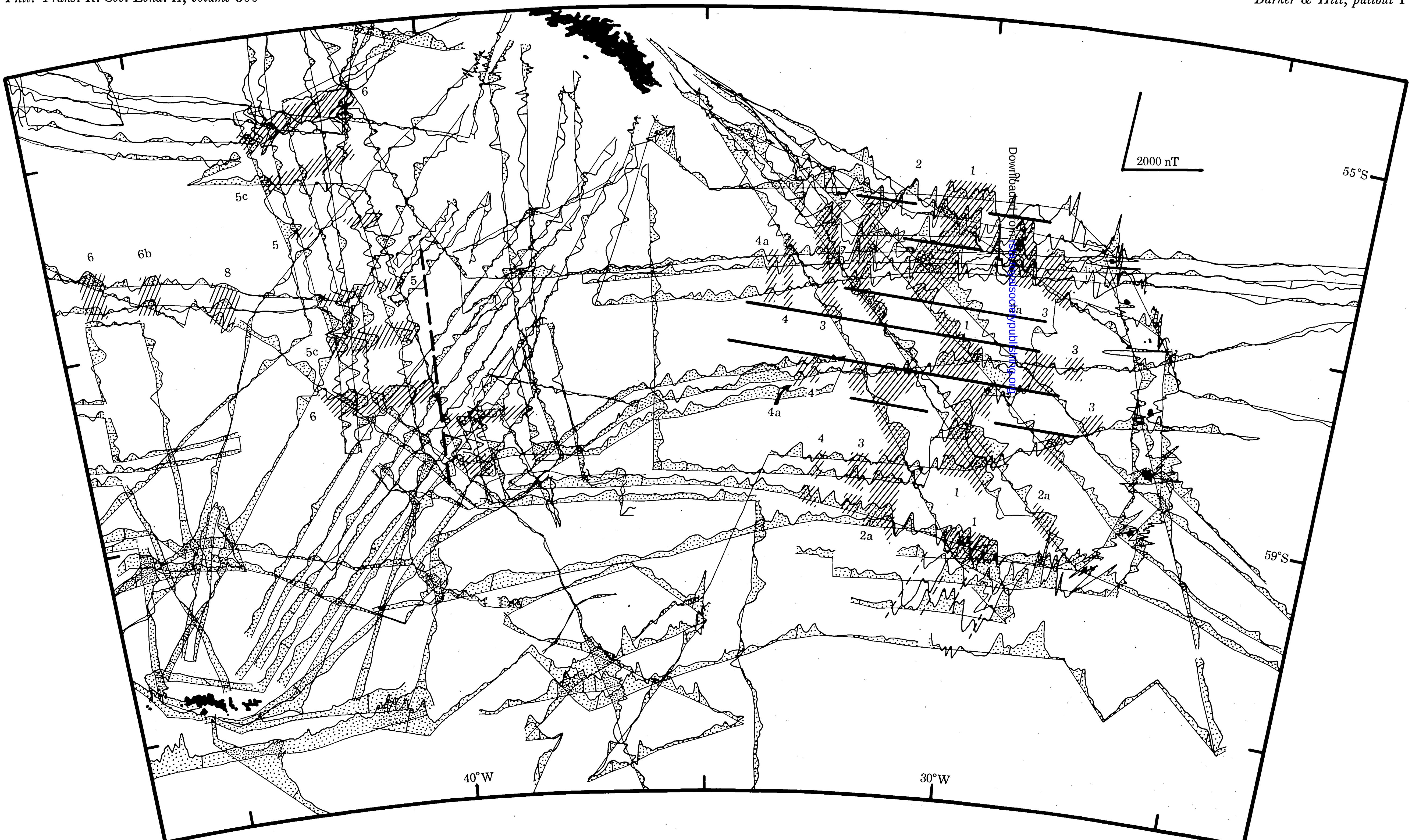

FIGURE 2. Residual magnetic anomalies in the East and Central Scotia Sea, projected generally perpendicular to ship tracks, with positive anomalies stippled. Identified magnetic anomalies are numbered, and marked by diagonal lines.

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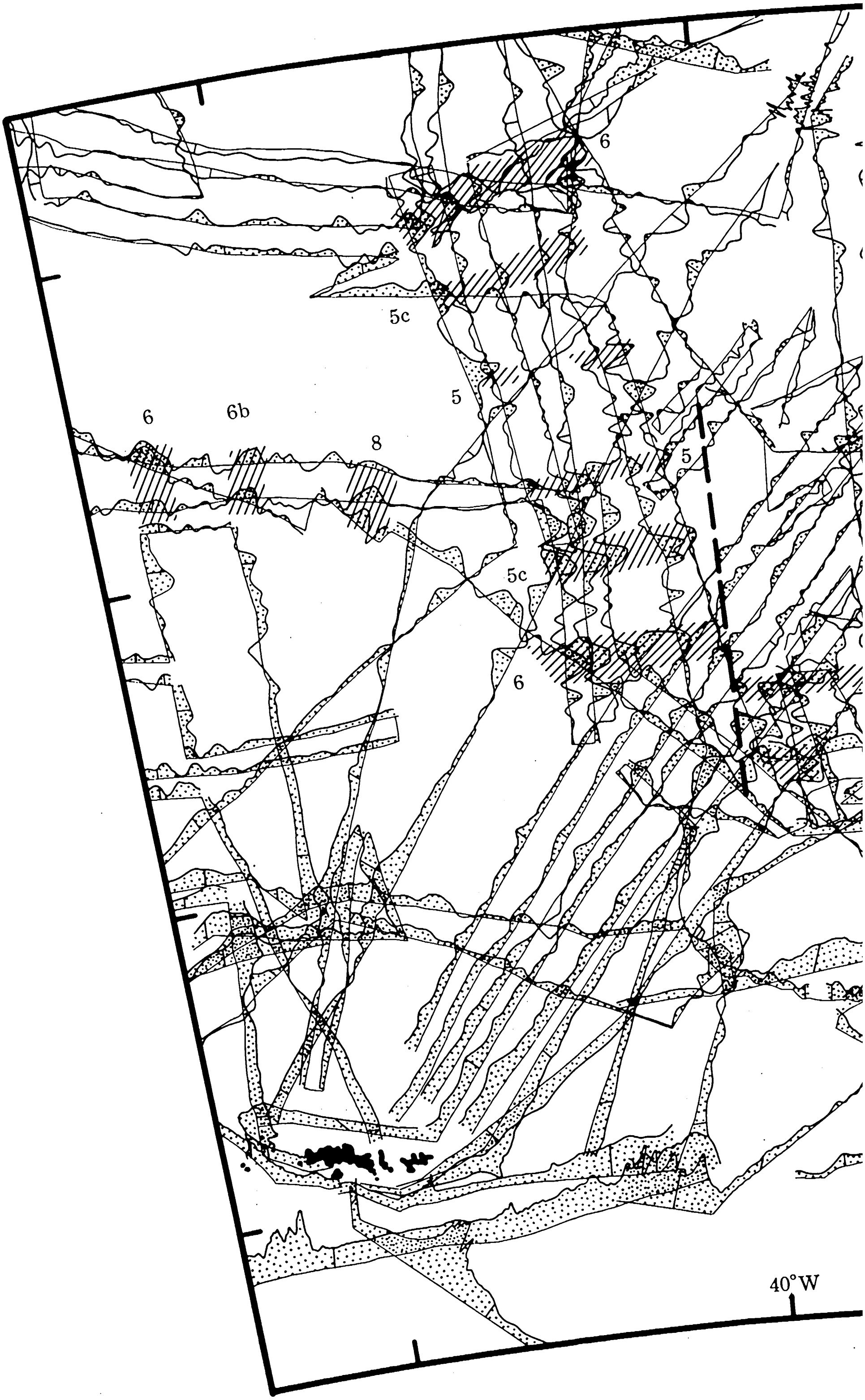

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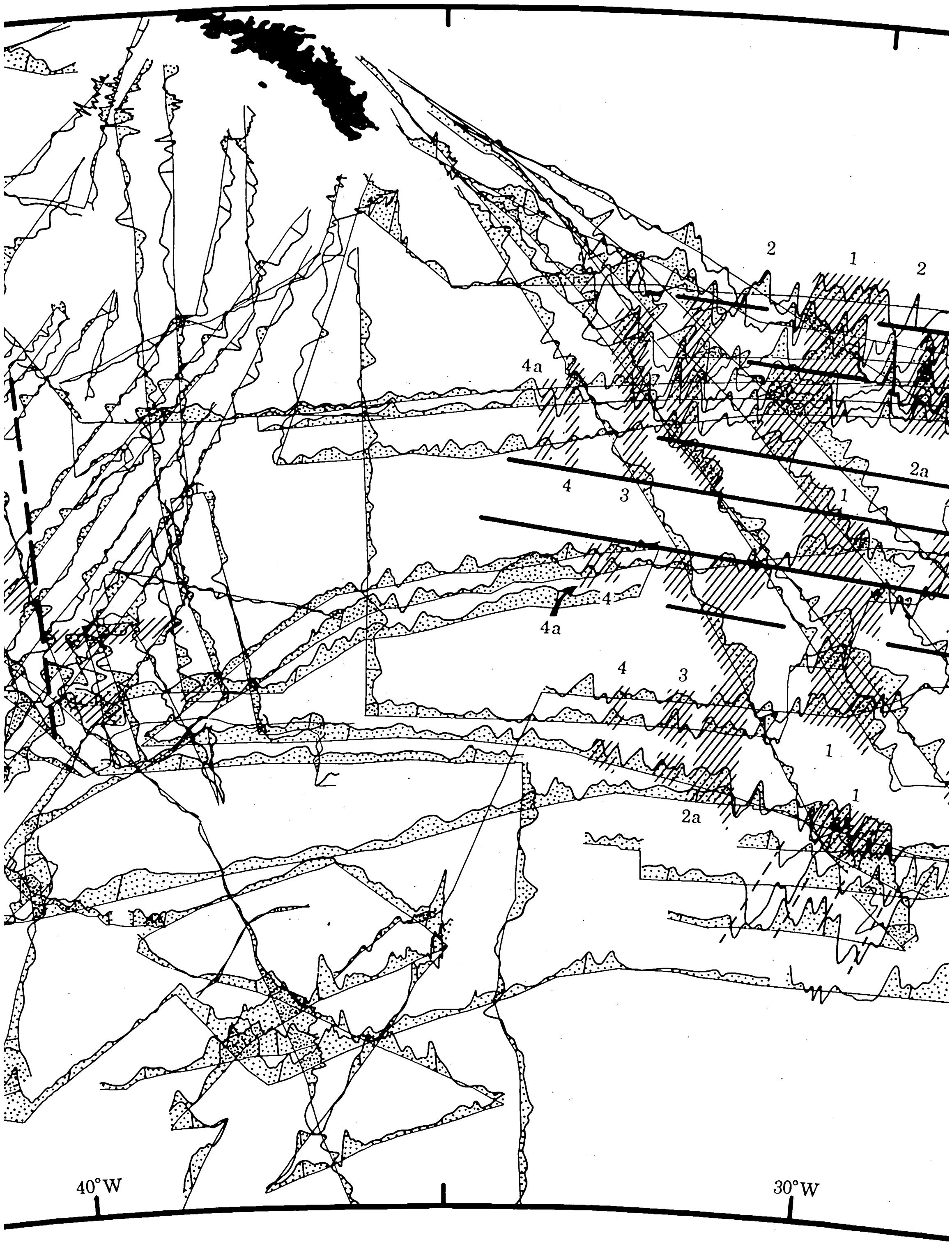

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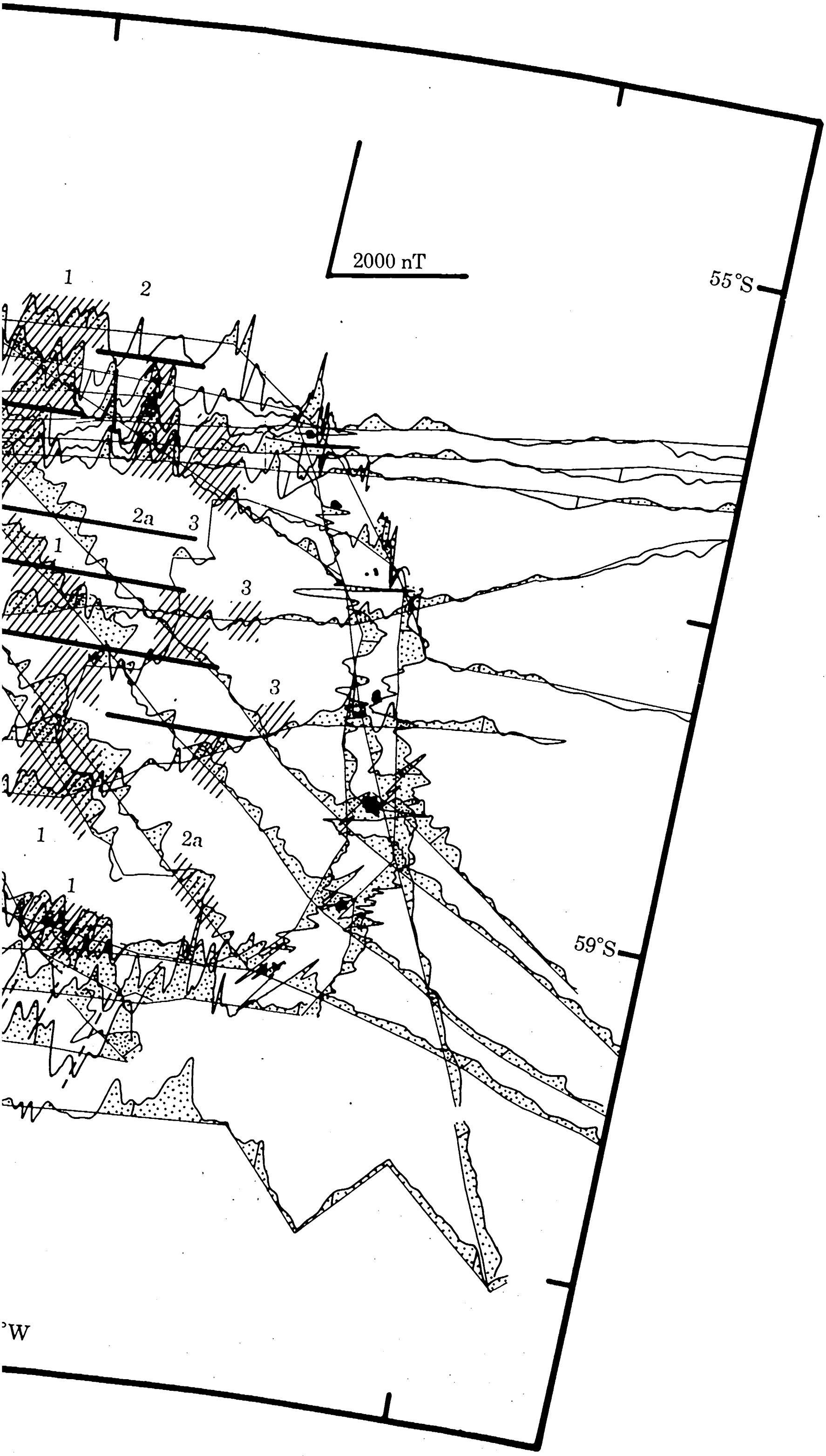

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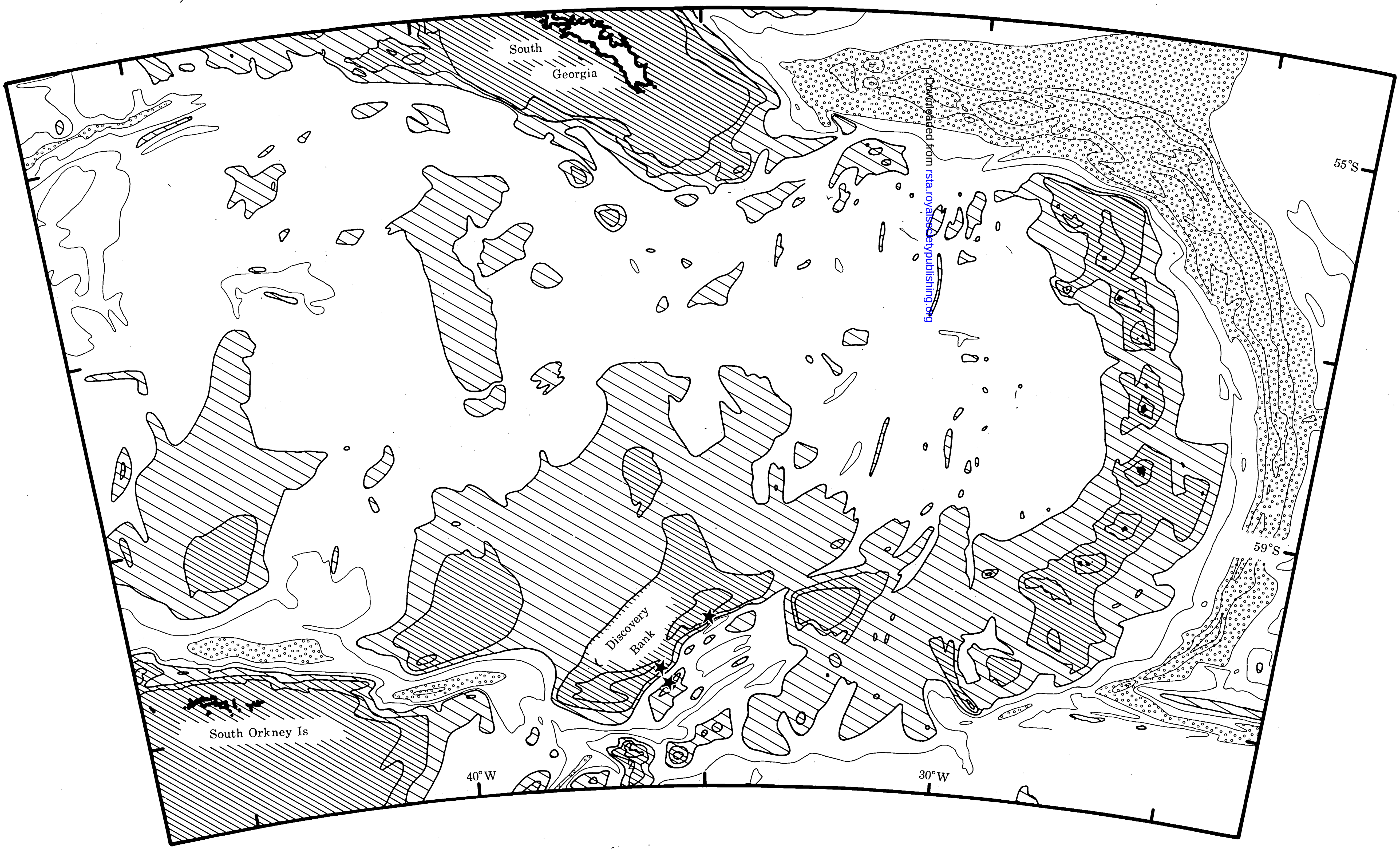

Figure 3. Bathymetric chart of the East and Central Scotia Sea. Corrected soundings (Matthews 1939) are contoured at 1000 m intervals; areas above 3000 m are thinly lined and above 2000 m densely lined, and below 5000 m are stippled. Dredge stations on the eastern South Scotia Ridge near 61° S 35° W (Barker *et al.* 1980) are starred.

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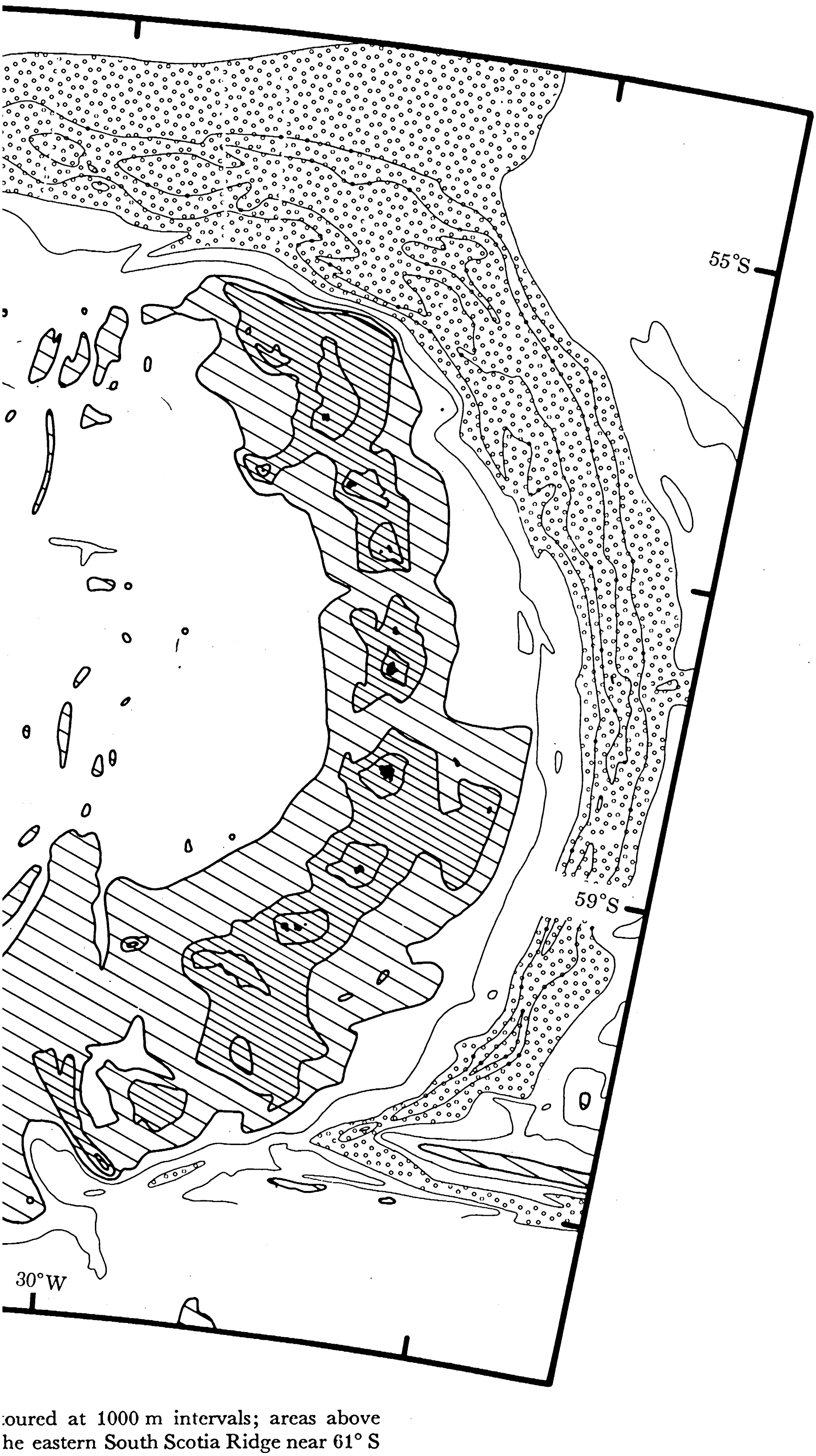

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spreading (1.5 Ma to the present) appears slightly faster in the south, and the older spreading, where it can be seen, faster in the north.

It is still necessary to conclude that at least some of the South Sandwich Islands themselves lie on ocean floor formed *during* the present spreading episode. This is quite reasonable, since the island arc volcanism is a secondary rather than a primary feature of subduction, but, like the present independence of the Sandwich plate system, it draws attention to the problem of the

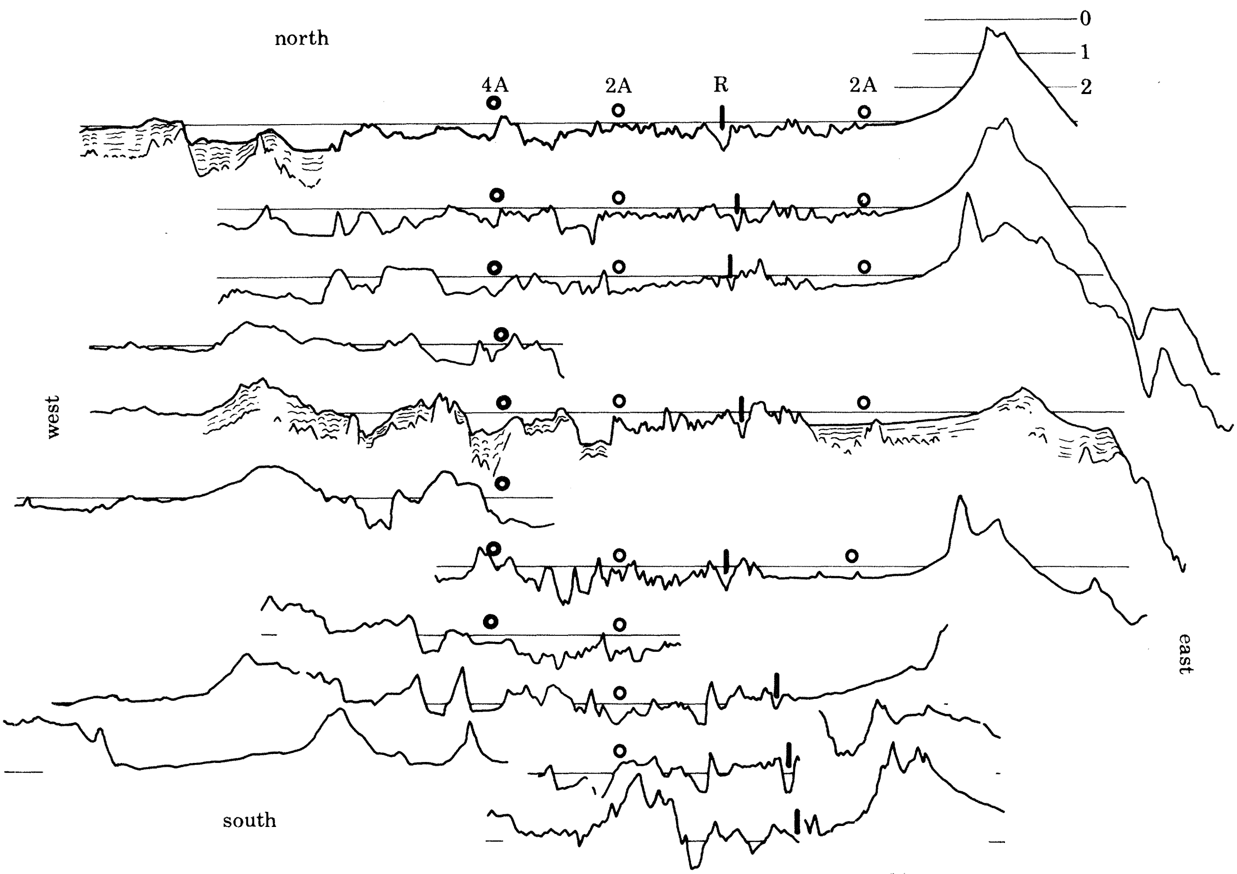

FIGURE 5. Bathymetric profiles crossing the East Scotia Sea, resolved along the direction 090°, with seismic reflexion information added where available. Positions of magnetic anomalies 2A and 4A, and the ridge crest (R) are marked where known, and the profiles are aligned on the western anomaly 2A. The 3000 m depth level is marked on all profiles.

origin of subduction here. The oldest anomaly certainly seen on the majority of crossings of the western flank is 4A (*ca.* 7.5 Ma). A broad anomaly often seen directly west of it *could* be correlated with anomaly 5, but may easily have other origins. In other small areas farther to the west, north–south magnetic lineations may be inferred, but certain identification and correlation between areas are impossible on the basis of existing data, and could remain so because of the essential ambiguity of dating short isolated magnetic anomaly sequences.

A sharp topographic boundary might reasonably be expected between a remnant arc and ocean floor formed at the start of the present spreading episode. Figure 5, a collection of long bathymetric profiles across the East Scotia Sea aligned on the western anomaly 2A, shows that this is not so. The ocean floor at the ridge crest itself has a mean elevation about 500 m below the oceanic average (Tréhu 1975), not uncommon in back-arc basins (see, for example, Sclater *et al.* 1976*b*), and on most crossings is not particularly rough. The eastern flank away from the ridge crest is covered by a thick apron of volcanigenic sediment derived from the present arc, but the western flank becomes rougher westward, perhaps reflecting the slower early spreading rate. Assuming the persistence of the ridge crest topographic anomaly, and normal cooling, ocean floor 8 Ma old without sediment cover should lie at about 4 km depth.

Seismic reflexion data exist for only two of the profiles in figure 5, and even those are not continuous. Sediments in the west are uneven, having been deposited under the influence of strong bottom currents of the Antarctic Circumpolar Current (Goodell 1973; Barker & Burrell 1977, 1980). The sediments do thicken westward, as expected, but in the vicinity of anomaly 4A do not exceed a few hundred metres thickness on topographic highs. Thus, it is clear that, not very far west of anomaly 4A, extensive topographic highs occur, which are very unlikely to be oceanic crust formed at the present South Sandwich spreading centre and unmodified by subsequent events. The highs may well be parts of a remnant arc, but that arc is not a well defined feature (figure 3) and its eastern margin is not obviously an isochron. The elevation of the topographic high appears to increase southward and its likely age to decrease. Thus, the early phase of South Sandwich back-arc extension may have been somewhat chaotic. We return to this topic in §§ 2*c* and 3.

The character of the most southerly part of the back-arc basin in the East Scotia Sea is different from that of the remainder. The gross strike of the magnetic anomalies (figure 2) changes to south-southwest, more nearly parallel to that of the island arc, although it is impossible to tell from existing data whether this is effected by repeated fracture zone offsets, or results from the involvement of a third plate. Nor is it possible to make an unambiguous magnetic anomaly identification. The rough and elevated topography suggests that an active ridge crest does pass through the area, but has a much smaller east–west extent between the island arc and the smoother but more elevated topography of the eastern South Scotia Ridge (compare figures 2 and 3). It seems most likely that spreading here started more recently than farther north, perhaps as recently as 1.5 or 3 Ma ago. Farther south still, the magnetic field is much more subdued, and there are no bathymetric signs of active back-arc spreading. The southern boundary of the back-arc basin is probably the westward extrapolation of the long east–west fracture zone which forms the SAM–ANT boundary to the east.

(*b*) *Central Scotia Sea*

Apart from the East Scotia Sea, magnetic lineations are found in only two small areas of figure 2. Those in the far west are the oldest, most easterly of those produced during Drake Passage opening (Barker & Burrell 1977). Between 40° and 43° W lies a second set of anomalies, lineated east–west and described recently by Hill & Barker (1980). The limited extent of these anomalies makes a degree of ambiguity in their identification unavoidable; figure 6 (from Hill & Barker) provides two alternative models. The younger sequence, from 21 to 6 Ma with spreading slowing at 16 Ma, is preferred, on the basis of its strong similarity, in both anomaly shape and inferred spreading history, to the adjacent Drake Passage sequence (figure 6, and Barker & Burrell 1977). This is supported by the results of work on the eastern South Scotia Ridge (see below, and Barker *et al.* 1980). The anomalies suggest a pole of opening to the west, and show a 5–10% asymmetry favouring accretion to the southern flank. The short anomaly sequence to the southeast is considered to have formed on the older part of the southern flank

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of the same spreading centre, offset about 100 km to the south, but this is by no means certain. The area to the north of this short south-eastern sequence is abnormally elevated, and the expected younger anomalies are not found. It is possible that subsequent tectonic events producing the elevation also degraded the anomalies, that the older anomalies to the south are misidentified, or that the tectonic régime was altogether more complex.

Thus, identified magnetic lineations are confined to two areas, covering half at most of the central and eastern Scotia Sea. Some other parts have not been surveyed in detail, but it seems

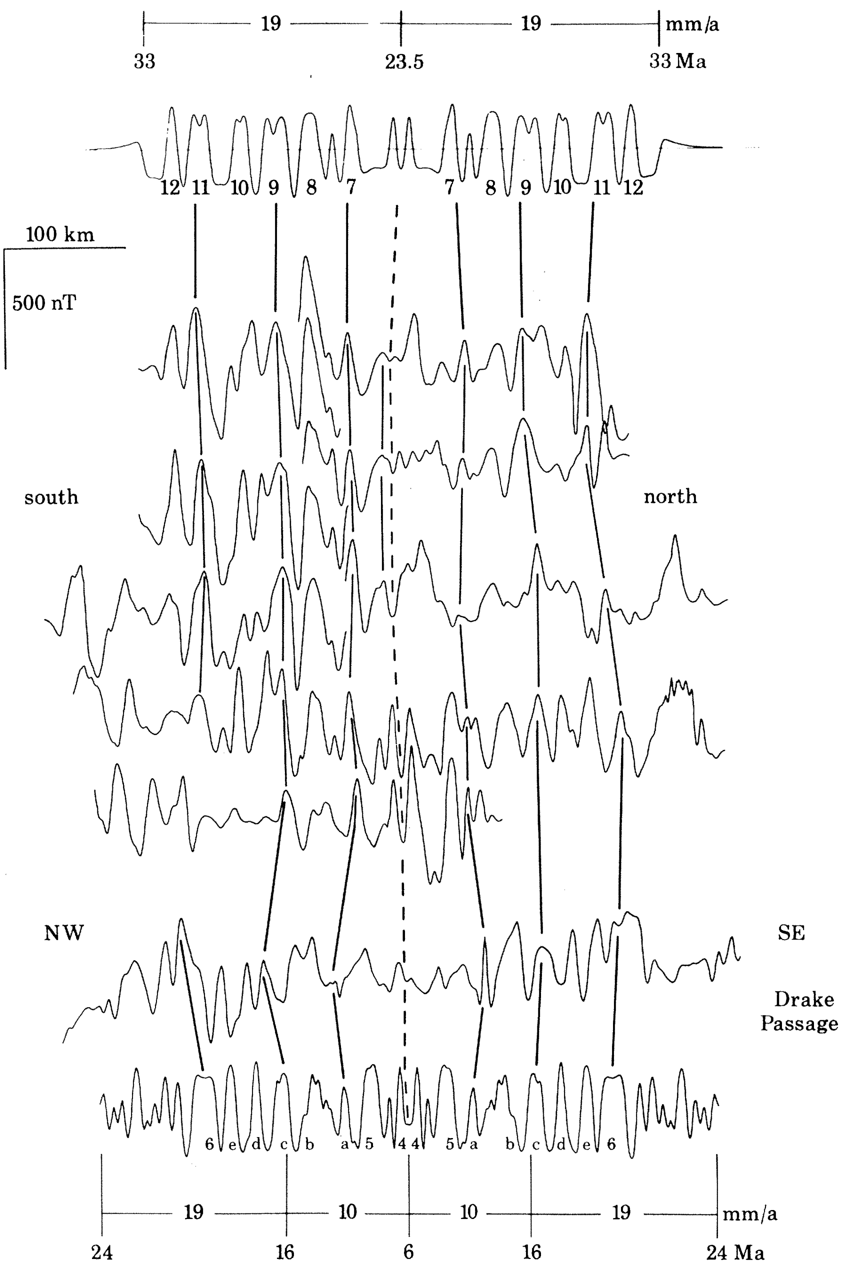

FIGURE 6. Magnetic anomaly profiles from the Central Scotia Sea, migrated to the pole and compared with two synthetic magnetic profiles (produced by using different sections of the magnetic reversal timescale) and with a profile from Drake Passage. Reproduced with permission from Hill & Barker (1980).

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an unavoidable conclusion that many areas that might be expected to show magnetic lineations do not do so. To pursue this problem farther, we must look at the bathymetric data.

(*c*) *Regional bathymetry*

In describing the bathymetry of the Scotia Sea region (figure 3) we are seeking to extend the other available data (magnetic anomalies, land geology, earthquake locations and first motions) by attributing a present tectonic function, structure or past history to each apparent morphologic unit. For example, we know that the South Sandwich trench exceeds 8000 m in depth in places, is continuous at the 5500 m level and dies out in the south where the trough of the most southerly active fracture zone of the present Sam–Ant boundary runs into it from the east. To the northeast, east and southeast of the trench lies normal ocean floor of the South Atlantic and Weddell Sea. The blocks on which the South Orkney Islands and South Georgia lie are continental fragments forming part of the South and North Scotia Ridge respectively. The present Scotia–Ant plate boundary runs westward in some fashion from the Sam–Ant boundary mentioned above, along the northern margin of the South Orkney block, making use in some way of the deep troughs shown in figure 3 (Barker & Griffiths 1972; Forsyth 1975). The Sam–Scotia boundary extends westward from the east–west trough that is the trace of the northern end of the South Sandwich trench, probably along the northern margin of the South Georgia block and ultimately to the Pacific margin of South America (figure 1).

Within the Scotia Sea, virtually all of the identified magnetic lineations occur in water depths greater than 3000 m. This in itself is not unusual, but an exceptionally large part of the Central and East Scotia Sea is less than 3000 m deep. These shallow areas could be subsided continental fragments, but a more likely origin is by the modification of normal oceanic crust by subduction-related igneous activity. The present South Sandwich arc, which the magnetic anomalies suggest was mostly erupted within the last 5–6 Ma onto ocean floor formed within the last 8 Ma, provides a model for application to these unknown areas. The islands themselves surmount a volcanic ridge about 500 km long and 100 km wide at the 3000 m contour, and a thick wedge of volcaniclastic sediment extends even farther westward into the back-arc basin (figure 5, and Heezen & Johnson 1965). The southern part of the ridge is broader and, albeit less continuously, extends south of 60° 30′ S where earthquake evidence places the present plate boundary (Forsyth 1975). The arc appears to be leaving more southerly fragments of itself behind as it moves eastward.

Further evidence of an originally more extensive island arc comes from three dredge sites (starred in figure 3), about 90 km apart on two of the elevated blocks of the eastern South Scotia Ridge. The dredged rocks (described in detail by Barker *et al.* 1980) comprise large quantities of fresh basalt of only two lithologic types, and a basaltic agglomerate incorporating fragments of the same material. The basalts were undoubtedly *in situ* and probably had been erupted subaerially. Chemically they are low-K tholeiites, typical of an early stage of intra-oceanic island arc formation and indistinguishable from those found on the South Sandwich Islands. K–Ar dates on representative fresh samples range from 12 to 20 Ma, but true ages may all be closer to 16 Ma. Discovery Bank (figure 3), the largest feature dredged, slopes gently down to the northwest where there is a sedimentary apron resembling that seen west of the South Sandwich Islands. Its southeastern margin is steep and forms the edge of an unsedimented area of steep scarps with up to 3 km of relief, decreasing to the southeast. We interpret Discovery Bank as a remnant of an intraoceanic island arc (the 'Discovery Arc'), ancestral to the South Sandwich arc and active at least within the period 12–20 Ma ago. The Discovery trench lay to the southeast, where no trace of it can now be seen, and later tectonic events, such as motion along the Scotia–Ant plate boundary, have dissected the arc to produce the present high relief. We have argued (Hill & Barker 1980) that the east–west magnetic anomalies in the Central Scotia Sea were produced by back-arc extension associated with this Miocene subduction episode.

Thus, many of the more elevated southern parts of the East and Central Scotia Sea may be fragments of island arc, with thick volcaniclastic sediment aprons raising the sea floor above 3000 m on some flanks. Reflexion profiler data are unfortunately sparse, but support this notion to some extent (Hill & Barker 1980; Barker *et al.* 1980). The more scattered elevations farther to the north may be remnant arcs, isolated between successive back-arc basins. This seems an inherently reasonable interpretation of the regional bathymetry, and may also explain the absence of magnetic lineations over sea floor above 3000 m. Not all back-arc basins possess well formed magnetic lineations, and those anomalies that were produced may have been erased by later episodes of reheating associated with island arc formation, or by faulting within the arc–trench gap.

3. Tectonic evolution

The bathymetric, magnetic and geochemical evidence indicates that the present episode of coupled subduction and back-arc extension involving the Sandwich plate, which started about 8 Ma ago, was preceded by a similar episode, existing with certainty about 16 Ma ago, and probably extending from 21 Ma to about 6 Ma ago. In this earlier episode, back-arc extension in the Central Scotia Sea was in a north–south direction and the island arc lay to the south or southeast. These episodes represent successive and essentially different modes of development of the Scotia Sea as a complication of the Sam–Ant plate boundary. This context should ideally be incorporated in any attempt to understand these episodes of subduction and back-arc extension, and the transition from one to the other. Since the nature of neither Sam–Ant boundary nor motion is known before about 3 Ma, however (Sclater *et al.* 1976*a*), we are forced in this attempt to make assumptions about both. We restrict ourselves to consideration of only the past 10 Ma, and assume that Sam–Ant motion throughout this period has been similar to that of today (i.e. about 20 mm/a, east–west, sinistral; see Minster & Jordan 1978; Chase 1978*a*). More speculatively, we suggest that Sam–Ant *boundary* changes over this same period provide the trigger for developments in Scotia Sea evolution.

It is clear from figure 1 that if present plate motions continue, the Sandwich plate will eventually overtake and override the most southerly ridge crest section of the Sam–Ant boundary to the east. As the magnetic lineations off Baja California (Atwater & Menard 1970; Chase *et al.* 1970) and the Antarctic Peninsula (Herron & Tucholke 1976) suggest, subduction can stop when a ridge crest meets a trench, provided that the newly opposed plate is not being subducted elsewhere along its boundary. We suggest that other, more southerly ridge crest sections of the Sam–Ant boundary have been consumed in the recent past at the South Sandwich trench and its predecessor the Discovery trench, whereupon subduction at that particular section of trench has stopped. This would explain the coincidence of the southern end of the Sandwich plate with the Sam–Ant boundary, which as already noted means that oceanic lithosphere of the Antarctic plate is just not being subducted. More than one such encounter between trench and ridge crest section may have taken place, each resulting in failure to subduct

Antarctic plate and a consequent change in the plate régime in the back-arc area to the north. Incorporated in this mechanism is the assumption that elsewhere along the trench, the excess mass of the descending slab would ensure that subduction of South American oceanic lithosphere would continue.

By analogy with the Antarctic Peninsula and Baja California, neither topographic nor gravity expression of the trench would be expected to survive its collision with the ridge crest. Although the topography is rough to the south of the eastern South Scotia Ridge, suggesting repeated fracture zone offsets (Barker & Jahn 1980), there is no magnetic evidence of the age of the ocean floor to establish a detailed history.

It was suggested initially (Barker *et al.* 1980) that a single ridge crest–trench collision 7 or 8 Ma ago produced a simple, instantaneous change from Discovery to South Sandwich subduction, and thus from Central to East Scotia Sea back-arc extension. The considerable evidence of variability on scales of 1–3 Ma and 100–200 km within the region now suggests that this was an oversimplification. However, as was pointed out earlier, such short times and distances lead to ambiguity, so that a more detailed evolutionary model is much more difficult both to produce and to test.

Figure 7 shows the tectonic elements of the Scotia Sea region (*a*) at present, (*b*) 5 Ma ago and (*c*) 10 Ma ago. Figure 7*a* combines the magnetic data described in § 2 with other published identifications (Barker & Burrell 1977; Hill & Barker 1980). Present plate boundaries and motions, also shown in figure 1, are summarized in the upper right corner. Essentially, plate motion is slow everywhere except for the fast coupled subduction and back-arc extension that define the Sandwich plate. Conditions were very similar 5 Ma ago (figure 7*b*) except in the far west, which for this discussion may be ignored. South Sandwich back-arc extension had recently started and was slightly slower than at present (see figure 4). We suggest, as a means of explaining some of the small-scale complexity of the southernmost part of the back-arc region, that one more short ridge-crest section of the SAM–ANT boundary then existed, south of the present boundary. Before the collision of this section of ridge crest with the trench, and perhaps for a while afterwards until plate boundaries were adjusted, the back-arc spreading centre may have been actively dissecting the Discovery Arc, occupying the position of the present Scotia–ANT boundary rather than its own more easterly present location. Both the disposition of the youngest magnetic anomalies (figure 2) and the strong bathymetric indications (figure 3) of east-northeast movement of the small block now at 60° S 32° W would be explained by this process. The increase in spreading rate at 1.5 Ma (figure 4) suggests a time for the final boundary change, which had the overall effect of detaching island arc and oceanic crust from the southern edge of the Sandwich plate.

Plate boundaries and motions 10 Ma ago were more fundamentally different. Both Drake Passage and the Central Scotia Sea were actively extending, each at about 10 mm/a per side. Motion along the South Scotia Ridge had probably not started, but some kind of slow deformation seems likely at the Falkland Trough (Ludwig *et al.* 1979). The nature of the coupling between the Drake Passage and Central Scotia Sea spreading systems is unknown, but is assumed here to be such as to cause the southward migration of the central Scotia Sea spreading centre (i.e. the north–south dashed line is an active fracture zone). Under these circumstances, the more northerly part of the Discovery trench moves east relative to South America at about 20 mm/a, and the more southerly part southeast at about 30 mm/a. Thus, the trench is being lengthened in its middle, and slow subduction takes place continuously beneath the newly

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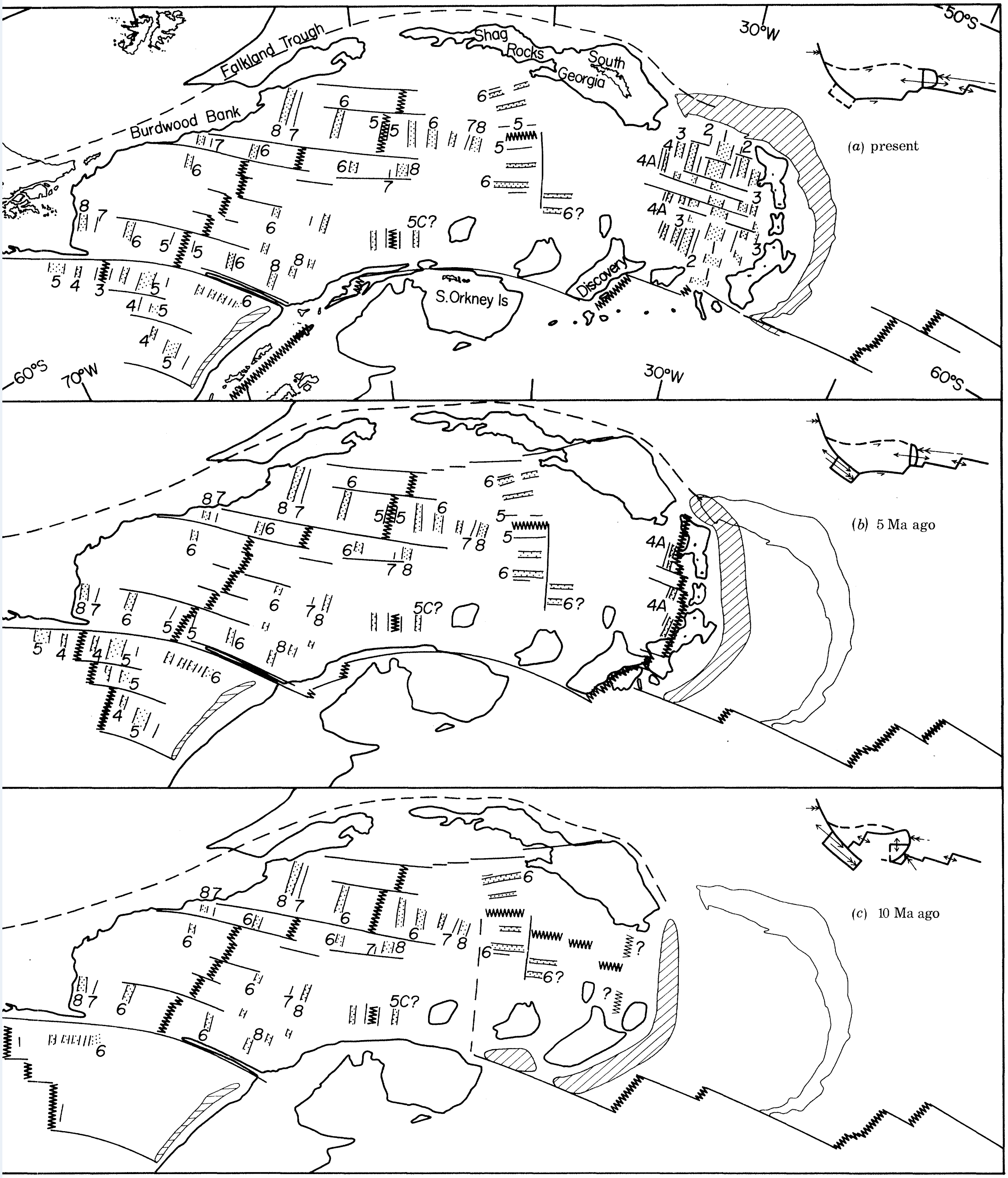

FIGURE 7. A compilation of magnetic anomaly and fracture zone identifications in the Scotia Sea region, from this paper and other sources referred to in the text, (a) for the present day, (b) on a 5 Ma reconstruction and (c) on a 10 Ma reconstruction. In a small sketch in the top right of each section are shown the plate boundaries active at each time together with arrows whose lengths indicate rates of spreading, strike-slip or subduction.

created back-arc basin. The possibility of east-directed back-arc extension of some kind *before* 8 Ma, as the north–south section of the trench lengthened, is included tentatively in figure 7*c*, although the evidence for it in the area of the Scotia Sea between 34° and 38° W is very slight. The suggestion by Chase (1978*b*), that trenches advance, might explain its presence, although absolute plate motions in the region 10 Ma ago are not known. Without it, all of this same area would be expected to show east–west lineations. It is interesting to note that, under this spreading régime, the southern part of the present South Sandwich arc should contain elements older than anything to be found farther north. These might be part of the much better-developed fore-arc region of the southern half (figure 3).

Figure 7*c* suggests that the interaction between the SAM–ANT plate boundary and the Discovery trench would inevitably have been complicated. The trench would probably encounter both ridge crest and fracture zone sections of the boundary, and would do so obliquely and thus progressively rather than normally and instantaneously. The preservation of the single large Discovery Bank suggests that these variations may have been dominated by one main event, perhaps at 6 Ma to explain the cessation of spreading in Drake Passage and the Central Scotia Sea, and the overall geometry indicates a general eastward progression with time. There seems no shortage of potential explanations, however, for short-term variability in the back-arc region.

We have not attempted to extend figure 7 beyond 10 Ma ago, even though spreading in the Central Scotia Sea is known to extend back to 21 Ma, and in Drake Passage to at least 27 Ma. Nothing is known over this period about SAM–ANT motion or the nature of the coupling between the two Scotia Sea spreading systems, and considerable speculation is already incorporated into the 10 Ma reconstruction in figure 7*c*. Nevertheless, this work does have some significance for studies of the earlier history of the region. For example, an east-facing subduction zone apparently has existed for the past 21 Ma, about two-thirds of the lifetime of the Scotia Sea. It seems at least possible that it was also a feature of the earliest third, and that the entire Scotia Sea has formed essentially by some kind of back-arc extension over the past 30 Ma. To understand this thoroughly, it will be necessary to study the SAM–ANT boundary *outside* the Scotia Sea, where it is at present, and presumably has always been, much more simple.

4. Summary and conclusions

In general, the conclusions of earlier work about the nature of back-arc extension in the East Scotia Sea have been confirmed by this study of a more extensive data set. In addition, more recent work in the Central Scotia Sea and eastern South Scotia Ridge has provided an explanation for the origin of the Sandwich plate system, the self-contained, independent nature of which was originally quite puzzling. We may list these conclusions in detail.

1. Magnetic anomalies in the East Scotia Sea are well formed, indistinguishable from those found in the main ocean basins. Spreading started about 8 Ma ago and has accelerated from about 50 mm/a originally to about 70 mm/a over the past 1.5 Ma. Spreading is asymmetric, with accretion favouring the eastern, trench flank, but has not contributed to the curvature of the arc. Most of the islands of the present South Sandwich arc appear to lie on ocean floor formed during the present spreading episode. The water depth at the ridge crest is about 500 m deeper than the oceanic average.

2. East–west magnetic lineations of probable Miocene age in the Central Scotia Sea and subaerial low-K tholeiitic lavas of a similar age from Discovery Bank, part of the eastern South

Scotia Ridge, indicate the existence of a subduction–back-arc extension system older than the present Sandwich plate. In our speculative model the change from the one plate régime to the other is caused by one or more collisions between the Discovery trench and ridge–crest sections of the SAM–ANT boundary; the collision chokes the trench, so that all oceanic lithosphere on the South American plate but none on the Antarctic plate is subducted. The present location of the Sandwich plate *on* the SAM–ANT boundary and its (otherwise) independence of major plate boundaries and motions, thus become natural consequences of the operation of this collision mechanism, as does (while not explained in detail) the considerable small-scale variability observed in the back-arc region.

3. This more detailed study does nothing to invalidate Chase's (1978*b*) use of the Sandwich plate example to support his argument that back-arc extension occurs when trenches cannot otherwise advance (in an absolute motion reference frame). Moreover, the primacy and continuity of subduction of South American oceanic lithosphere elsewhere along the trench, through whatever transitions take place, is an additional implicit assumption of our collision model. The sense of asymmetry of East Scotia Sea spreading (see Barker & Hill 1980) also suggests a sensitivity of back-arc extension to absolute plate motions. In short, we find such concepts much more illuminating, in the Scotia Sea region, than those that explain back-arc extension in terms of forced convection (see, for example, Toksöz & Bird 1977).

4. Reconstructions of stages of Scotia Sea evolution earlier than 10 Ma ago have not been attempted, because of the considerable uncertainties remaining, but the study described here makes clear that the entire Scotia Sea could have formed as a similar subduction–back-arc extension complication of the SAM–ANT boundary over the past 30 Ma.

We wish to thank the ships' companies of H.M.S. *Endurance*, R.R.S. *Shackleton* and R.R.S. *Bransfield*, the staff of Research Vessel Services and others for willing help with data collection at sea, often under trying conditions. P. L. Barber, J. Burrell, R. A. Jahn, E. C. King and P. Simpson assisted with data reduction and, with Professor D. H. Griffiths, provided helpful comments. J. K. Weissel critically reviewed the manuscript. This work was carried out under an N.E.R.C. research grant and contract.

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Discussion

M. F. Osmaston (*The White Cottage, Sendmarsh, Ripley, Woking, Surrey, U.K.*). The authors have shown that, on the east side of the East Scotia Sea spreading axis the older magnetic anomalies appear to be cut off by the South Sandwich arc itself, whereas the anomalies go back to at least anomaly 4a on the west side. Since dating of the South Sandwich arc goes back only to 3.5 Ma, it would seem possible that the East Scotia axis developed *before* the South Sandwich arc, possibly as a jump from the South Atlantic Ridge. While it is clear that spreading has *continued* while in a back-arc situation, the authors have not, I believe, demonstrated that it was initiated as such. The former is understandable, particularly if the plate is thick so that the source material has high heat content, in terms of the self-maintenance of diapiric upwelling, once it has been initiated; the latter presents a quite different problem.

P. F. Barker and I. A. Hill. There seems little doubt that here, as elsewhere in the world, subduction is the primary process, maintained by the excess weight of the descending slab. Island arc volcanism and back-arc extension are both secondary effects of subduction. The name 'back-arc extension' is firmly established, and in many ways attractive, but unfortunately promotes some confusion about cause and effect. Thus, we *do* think that the East Scotia Sea started to open before the present South Sandwich arc was produced. Indeed, some of the islands apparently lie on ocean floor created by the present spreading system. However, spreading did not start before the onset of *subduction*, as your ridge jump notion appears to require. If there is a mystery about the onset of east-directed subduction in the Scotia Sea region, the recognition of the Miocene Discovery Arc, and of contemporaneous spreading in the Central Scotia Sea oblique to and in excess of what could be associated with a simple Sam–Ant motion, together move that mystery back to at least 21 Ma ago; the development of the Sandwich plate over the past 8 Ma now appears fairly straightforward.

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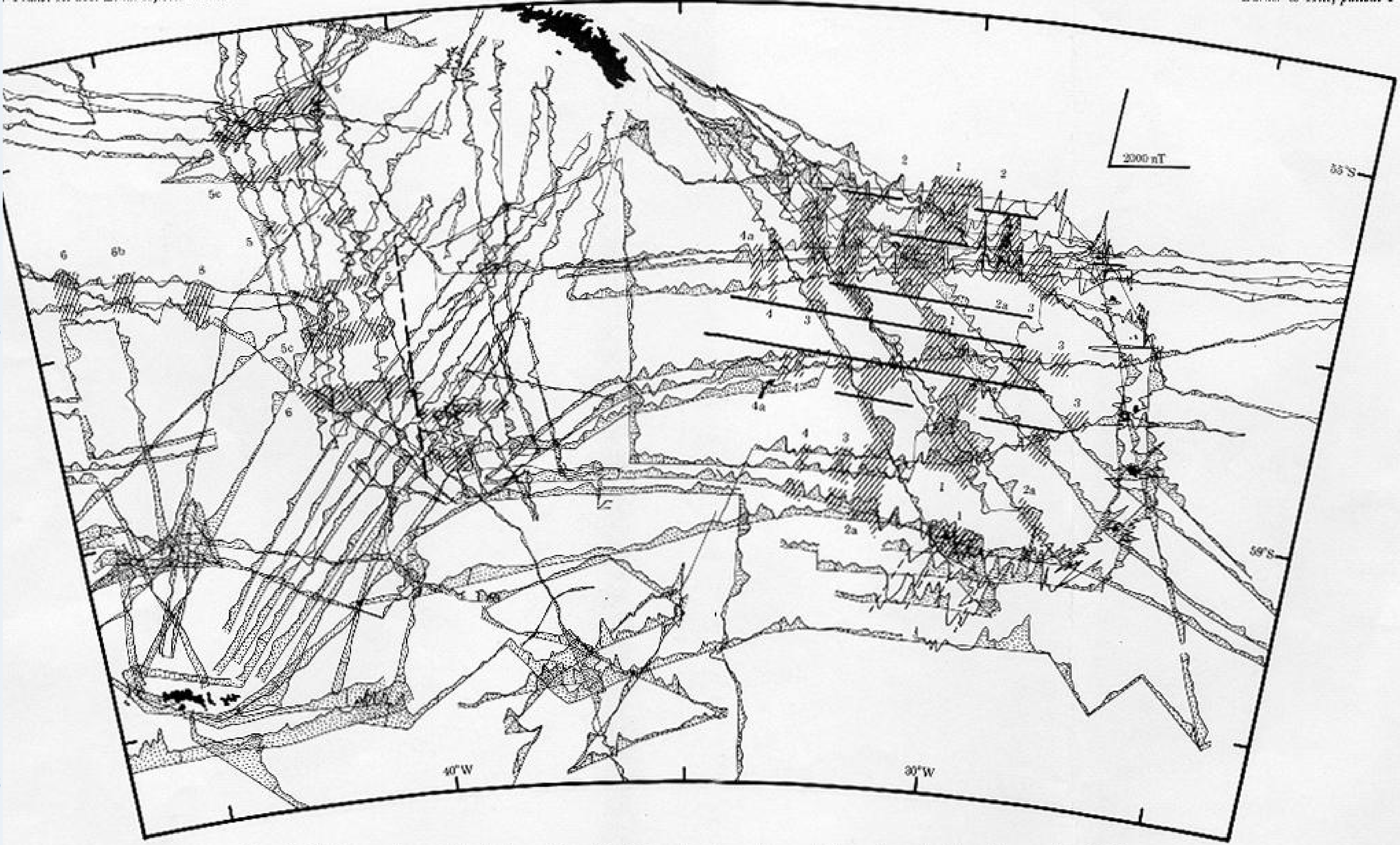

FIGURE 2. Residual magnetic anomalies in the East and Central Scotia Sea, projected generally perpendicular to ship tracks, with positive anomalies stippled. Identified magnetic anomalies are numbered, and marked by diagonal lines.

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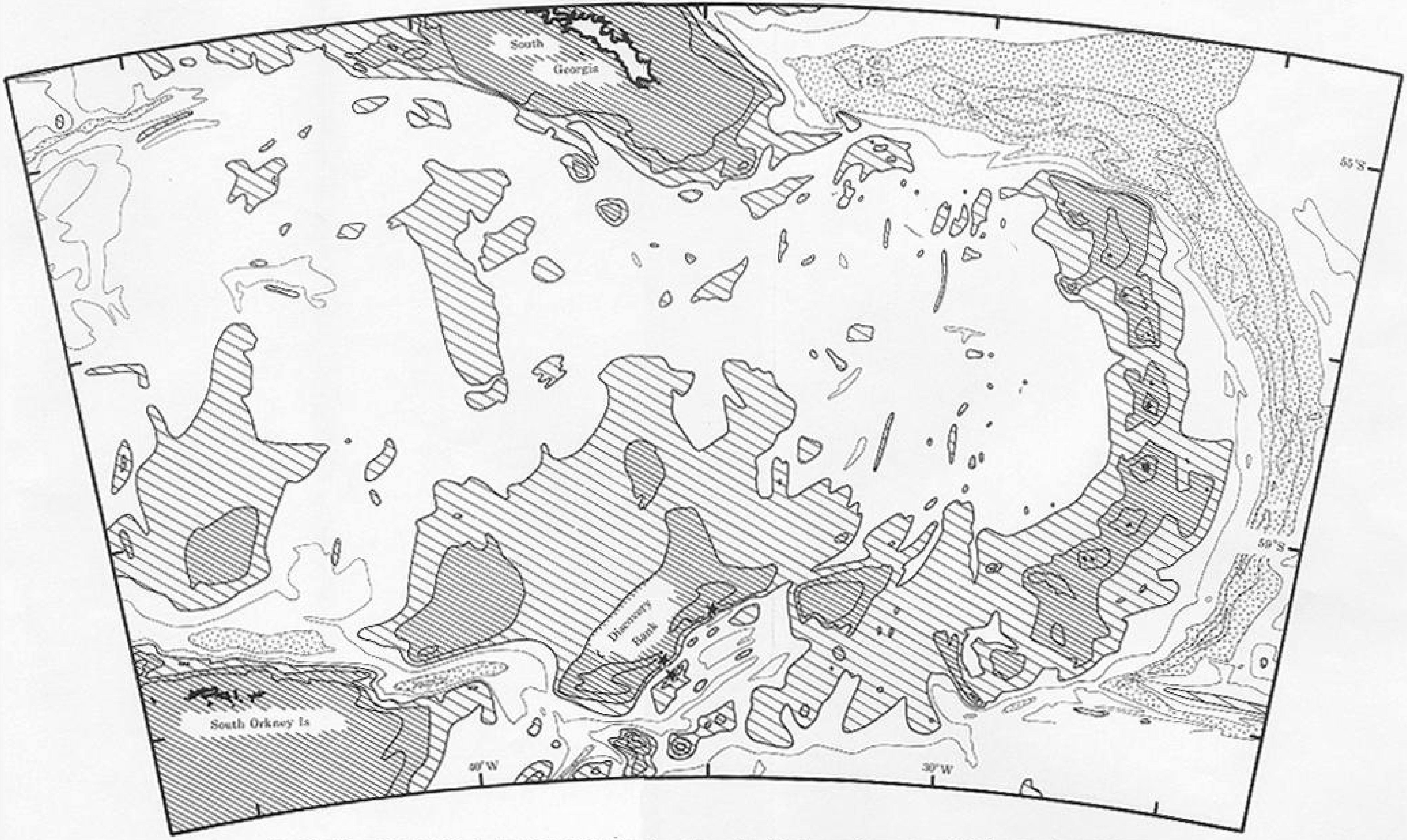

FIGURE 3. Bathymetric chart of the East and Central Scotia Sea. Corrected soundings (Matthews 1939) are contoured at 1000 m intervals; areas above 3000 m are thinly lined and above 2000 m densely lined, and below 5000 m are stippled. Dredge stations on the eastern South Scotia Ridge near 61° S 35° W (Barker *et al.* 1980) are starred.