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A marine geophysical reconnaissance of the Weddell Sea

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Summary. Magnetic, bathymetric and seismic reflection profiler data are described from the accessible central and eastern parts of the Weddell Sea. The shape consistency of the magnetic anomalies is not good, but the profiles show magnetic lineations trending slightly north of east over almost all of the area surveyed. The lineations are undulating, and a small reflection profiler survey has revealed the presence, in the northern Weddell Sea, of several closely spaced, small-offset fracture zones trending north-west to west-north-west. The amplitude of the fracture zone topography increases northward as the fracture zone orientation becomes more oblique to the gross orientation of the magnetic anomalies. Two synthetic magnetic anomaly profiles, each providing a reasonable fit to the observed anomalies, are used to argue that neither the quality of the data set nor the existing level of understanding of the regional tectonic environment is adequate as yet to support either an unambiguous age for the Weddell Sea or a model for its evolution.

1 Introduction

The Weddell Sea is at present part of the Antarctic lithospheric plate, lying between East Antarctica and the Scotia Sea and bounded to the west by the Antarctic Peninsula. Being almost always covered by pack ice, it is very poorly known, especially in the west. In particular, the only reported geophysical data are four widely spaced and poorly navigated Project Magnet aeromagnetic profiles (Bregman & Frakes 1970). Our interest in the tectonic evolution of the Weddell Sea stems partly from our continuing involvement in Scotia Sea studies: it has become increasingly apparent that the Scotia Sea has developed as a complication on the South American–Antarctic (SAM–ANT) plate boundary, largely over the past 30 Myr (Forsyth 1975; Barker & Burrell 1977; Barker *et al.* 1980), but the earlier history of the SAM–ANT boundary is very poorly known and it seemed likely that the Weddell Sea could provide insights about the earliest stages of Scotia Sea evolution. In addition, however, Weddell Sea evolution is of obvious relevance to one of the most important remaining problems of Gondwanaland. This is illustrated by the presence in the otherwise generally accepted reconstruction by Smith & Hallam (1970) of a gross overlap of the Falkland

Plateau and Antarctic Peninsula, both of which are now known to contain a significant component of pre-Jurassic continental crust (Adie 1964; Barker, Dalziel *et al.* 1977; Dalziel 1980). Past relative motion between East Antarctica and the one or more blocks (including the Antarctic Peninsula) which now form West Antarctica would eliminate this overlap, and has been proposed on independent grounds by Schopf (1969), Scharnberger & Scharon (1972) and Molnar *et al.* (1975). It seemed likely (Barker & Griffiths 1977) that the Weddell Sea formed at least partly as a result of such motion, and would thus have preserved a record of it.

This paper describes mainly magnetic data, with some bathymetry and seismic reflection profiles. Following a short reconnaissance aboard *RRS Shackleton* in 1974, a magnetometer was installed for *RRS Bransfield*'s voyages to relieve the British Antarctic Survey base at Halley Bay (H in Fig. 1 inset) during the next three seasons. The distribution of ship tracks over this period (Fig. 1) was governed by the lack of much ship time additional to shortest passage time and the generally unfavourable pack-ice distribution, rather than by any developing understanding of the regional tectonics. For the 1977–78 season, however, the British Antarctic Survey made available a significant amount of additional ship time after Halley Bay relief, and *RRS Bransfield* also carried a seismic reflection profiler.

As is made clear below, we have not solved the problems mentioned by use of the data acquired so far. Extensive oceanic magnetic lineations have been discovered, and some fracture zone topography, but an unambiguous dating of the Weddell Sea floor has not been achieved. We present the incomplete story here because the information required to eliminate the ambiguity may not be available for some years, and is in part beyond our capabilities to acquire.

2 Marine magnetic data

Ship tracks along which magnetic data were acquired during the five southern summer seasons 1974–78 are shown in Fig. 1. Navigation was by satellite, using only a single channel receiver during the first three *Bransfield* seasons (1975–77) but a dual channel receiver in 1974 and 1978. The average distance between satellite fixes was 16 km and the greatest distance 180 km; the ship track is known almost everywhere to better than 2 km. A proton precession magnetometer measured the ambient field with a precision of 1 nT, and the ship's heading effect (Bullard & Mason 1961) was usually restricted to 10 nT. Time variations of the magnetic field have not been removed, but the three-hourly *Kp* indices (NOAA 1975 *et seq.*) were checked for the presence of large magnetic disturbances.

After removal of the International Geomagnetic Reference Field (IAGA 1969, 1976) the magnetic residuals were predominantly positive, so an extra 200 nT was subtracted from profiles along all tracks. In Fig. 1 the direction in which the positive anomalies are shaded is that in which the anomalies are projected onto the ship tracks. It is clear that the zero field level in the eastern part of Fig. 1 is consistently higher than in the west, which must also be attributed to an IGRF defect since such a long-wavelength feature is beyond the generative capacity of crustal sources.

Several features of the residual magnetic anomaly profiles stand out, most notably a large negative anomaly seen between 65° and 66° S on all profiles but the most westerly (AA in Fig. 1). It is grossly oriented slightly north of east but its line undulates, to an extent which cannot be explained by navigational error. Other anomalies, smaller and less obviously correlated but also apparently undulating, lie roughly parallel to the large negative anomaly to north and south. They appear to diverge slightly eastward, but the lower track density in the east makes anomaly correlations there correspondingly less certain. Correlation of

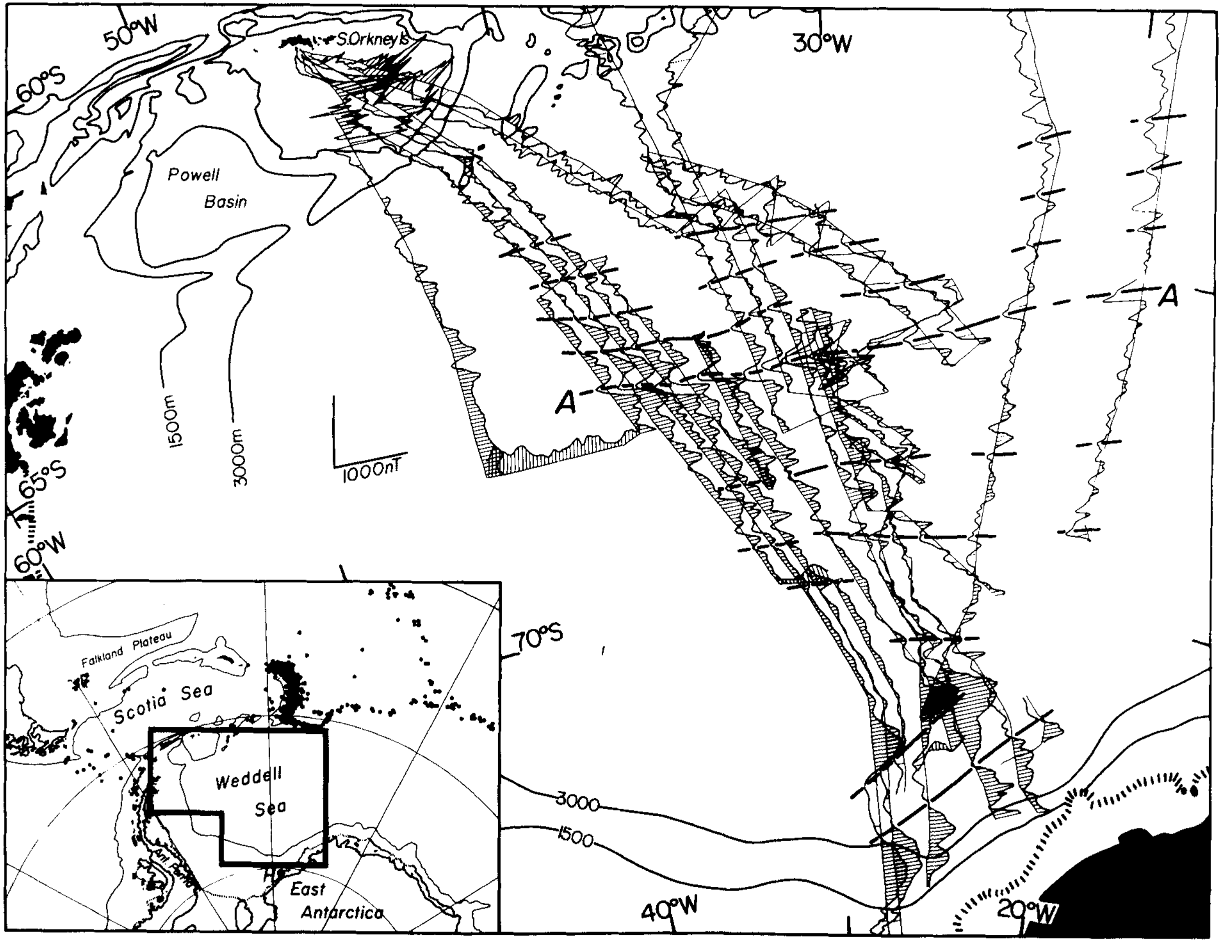

Figure 1. Weddell Sea magnetic lineations, projected on to ship tracks in the direction in which the positive anomaly shading runs. Anomaly correlations are thick dashed lines and a prominent negative anomaly is labelled AA. Inset location chart uses dotted earthquakes to show present plate boundaries.

anomalies on the most westerly track with those farther east is ambiguous. Either the large magnetic anomaly (AA) is offset northward to correlate with the most southerly anomaly on the westernmost track, and those to the north of it are similarly offset, or it disappears and those to the north correlate across almost exactly westward.

South of about 70° S the magnetic profiles are more subdued, but the tracks here are not so widely spread, so the extent of the 'quiet zone' may not be very great. At its southern margin are seen some rather longer-wavelength anomalies oriented north-east–south-west, parallel to the margin of East Antarctica.

Over most of the area, the shape consistency of anomalies from track to track along their strike is not as good as is usual with oceanic magnetic lineations. In this, and in the undulation but comparative clarity of the large negative anomaly, the magnetic character of the Weddell Sea resembles that of the North Atlantic south of Iceland (Vogt & Avery 1974, Fig. 2B). From Iceland to 56° S, and between the times of anomalies 18 and 6, the direction of spreading became noticeably more oblique to the original north-east–south-west gross trend of the ridge crest, with the creation of numerous small-offset fracture zones. The longer wavelength anomalies survived this disruption better than the shorter, but all developed an undulating strike. A less detailed and systematic survey than that described by Vogt & Avery would have detected an inconvenient degradation in shape consistency of the anomalies between profiles, because of fracture zone crossings and the spreading ridge adjustments. These considerations persuaded us to devote part of the 1977–78 *Bransfield* cruise to a reflection profiling search for fracture zone topography near the large negative anomaly, the results of which are described below.

3 Bathymetry and reflection profiles

Bathymetric data in the Weddell Sea are sparse and unevenly distributed, because of the remoteness of the area and the pack-ice cover. For this reason, the display of bathymetric data in this paper is confined to the definition of the margins of the Weddell Sea by the 1500 and 3000 m contours in Fig. 1, and consideration of one area which is more densely sounded (Fig. 2).

Over much of the central, oceanic area of the Weddell Sea (Fig. 1) the seabed is flat, sloping gently from about 4000 m in the west to 5000 m in the east. This basin extends eastward into the southern Indian Ocean. At the south-eastern margin of the Weddell Sea, the shelf of East Antarctica is flanked by a slightly shoaler region, 100–200 km wide and 3700–4500 m deep, which may be associated with the north-east-trending magnetic anomalies noted above.

The shelf at the head of the Weddell Sea to the west is much broader, but the margin and adjacent ocean floor there and around to the northern end of the Antarctic Peninsula are very poorly known, because of the almost permanent pack ice cover. East of 55° W, the bathymetry of the northern margin of the Weddell Sea is much better known (Harrington, Barker & Griffiths 1972; Watters 1972; Barker *et al.* 1980), although east of 40° W and between 64° and 60° S the seabed topography is extremely rough. In most places the isolated bathymetric profiles (many not satellite-fixed) are inadequate for contouring but the area, which is transitional between the Weddell Sea and the Scotia Sea or south-west Atlantic, is probably associated with the development of the SAM–ANT plate boundary.

The reflection profiles were obtained using a 2.62 l (160 cu. in.) air gun charged to 110 bars (1600 psi) and firing at 16 s intervals into a two-channel, multi-element hydrophone array. Ship's speed varied between 9 and 14 km hr^{-1}. In choosing the survey area we

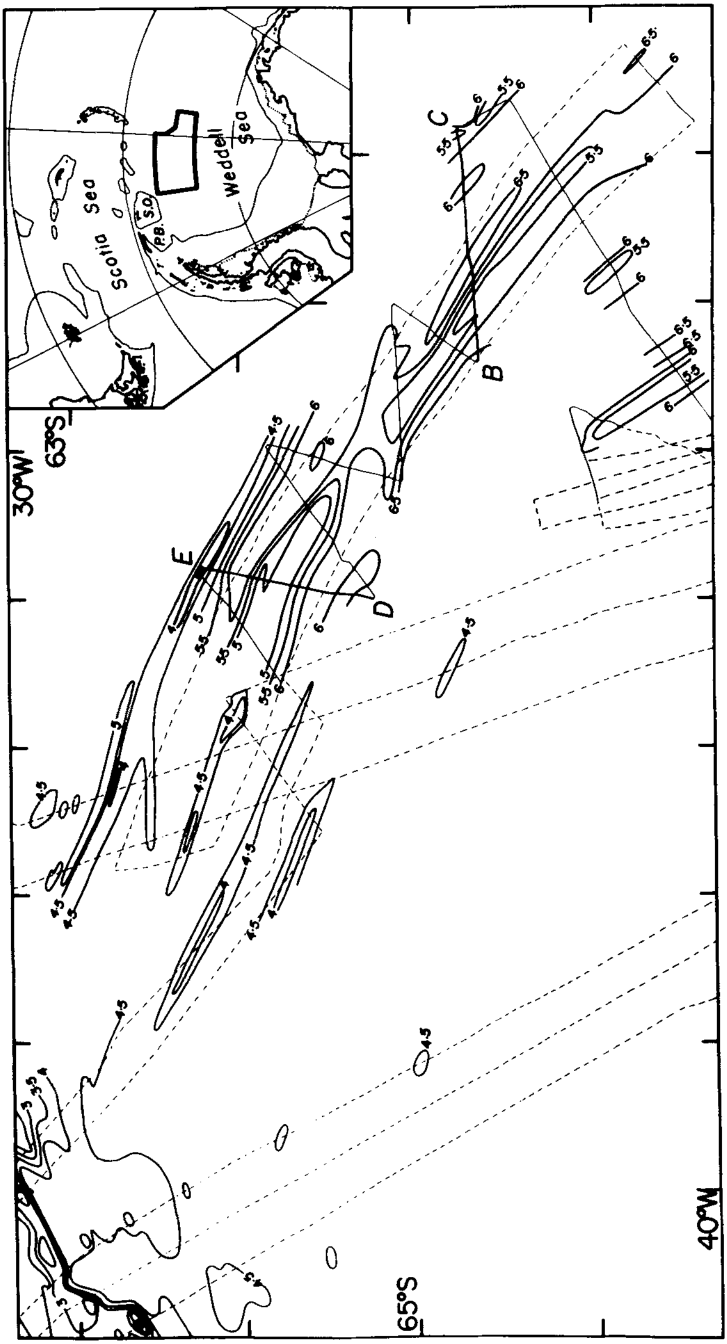

Figure 2. Presumed fracture zone topography in oceanic basement, contoured at 0.5 km intervals from bathymetric (dashed tracks) and seismic reflection profiles (solid tracks). BC and DE are tracks of reflection profiles displayed in Fig. 3.

were greatly helped by a radio report from *M.S. Explora* (Hinz 1978) of a basement high near 66° S, 26° W, close to the large negative magnetic anomaly. The thin, solid zig-zag lines in Fig. 2 are tracks along which reflection profiles were obtained, as the basement high was followed north-westward to where it emerged from the sediment cover as one of a set of WNW-trending bathymetric ridges, within the zone of rough topography already mentioned.

Two contrasting sections of the reflection profile are displayed in Fig. 3. In the more south-easterly section BC, the basement high has a sub-sediment topographic relief of about 1 km (1 s of two-way time) and is strongly asymmetric with a steeper north-eastern side. To the north-west (profile DE), basement relief increases to about 2 km so that, although the depths of the intervening troughs have not changed much, the peaks emerge from the sediment cover. On most, but not all crossings, the subsediment relief is of a similar amplitude and the north-eastern side of the ridge is the steeper. The sediments are well-bedded and show abundant signs of differential subsidence and compaction. Sediment cover on the peaks themselves is thin or absent.

In Fig. 2, data from both bathymetric and seismic reflection profiles (thin dashed and solid lines respectively) are contoured where the density of well-fixed tracks is adequate. The flat sediment cover in the Weddell Sea varies from 4550 m in the south-west corner of Fig. 2 to about 4900 m in the east. Thus, the bathymetric profiles show sub-bottom contours at 4.5 km and above, which are of the rough topography protruding from the ponded sediments. Contours at 5 km and beneath occur only on the reflection profiles, and are obtained using an average value of 2.0 km s^{-1} for the acoustic velocity of the sediments.

Within that part of Fig. 2 where the data are sufficiently dense, the reality of the ridges and their north-west or WNW trend are both obvious. South-west of this area, isolated bathymetric profiles show a small number of peaks protruding above ponded sediments and the most southerly part of the reflection profile suggests that other subsediment ridges exist

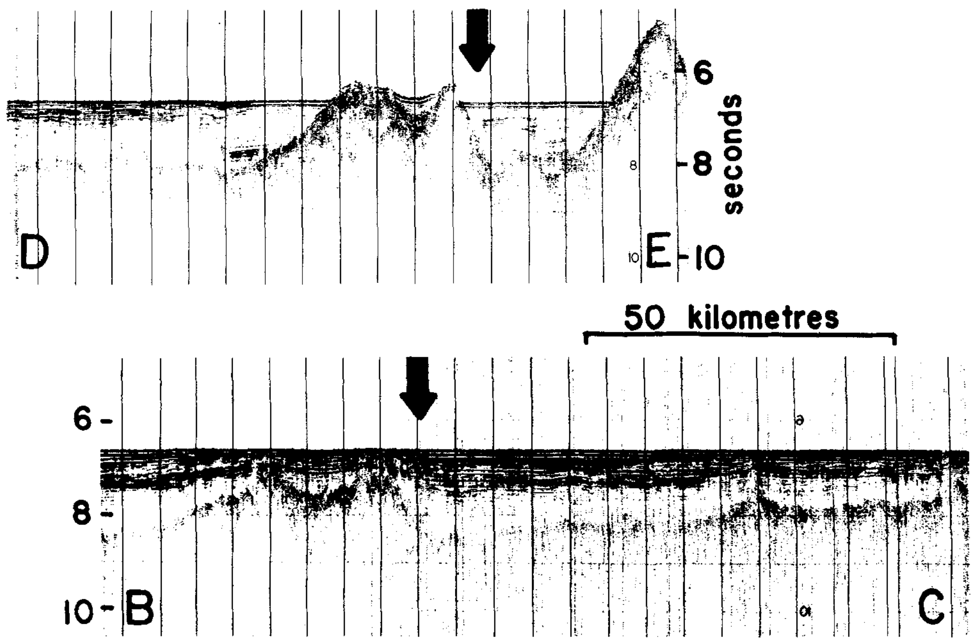

Figure 3. Reflection profiles BC and DE from the northern Weddell Sea. Track locations are given in Fig. 2. Principal scarp of inferred fracture zone is arrowed on each profile.

which may also extend to the north-west. To the north-east of the contoured area, isolated bathymetric profiles, mostly very poorly fixed, show that rough topography emerges northward from a flat sediment pond at about 5000 m, and continues to the eastern South Scotia Ridge (Barker *et al.* 1980), but it is not possible to show whether or not this represents the northward continuation of the set of WNW–ESE ridges described here.

It seems most likely that these parallel, narrow asymmetric ridges represent oceanic fracture zone topography, but of an unusually exaggerated nature. They are very oblique to the overall trend of the magnetic anomalies, and are quite close together, so the magnetic anomaly offset at any one fracture zone should be small. This is borne out to some extent by the two magnetic profiles run approximately parallel to the ridges, at the conclusion of the profiler survey in 1977–78 (Figs 1 and 2). It is not obvious that the ridges show the oblique scarps of small-offset fracture zones in parts of the North Atlantic (Searle 1979), although one discontinuity in the ridge does occur near 64.7° S, 30° W (Fig. 2). Perhaps the topography is kept simple by the great obliquity of the spreading direction; it would be interesting to compare the topography of parts of the south-west Indian Ridge which are similarly oblique.

The north-west corner of Fig. 2 shows a different kind of ridge, oriented roughly along 060° and separating the Weddell Sea from a small sediment pond which skirts the eastern margin of the South Orkney continental block (see also Fig. 1). It is unfortunate that our detailed bathymetric cover does not extend this far west, since this feature appears to be part of the northern margin of the Weddell Sea, the nature of which might be revealed by the behaviour of the fracture zone ridges in its vicinity.

4 Magnetic interpretation and discussion

4.1 REGIONAL TECTONIC CONSIDERATIONS

The dating of the Weddell Sea floor by magnetic anomaly identification has been a central objective of this study. It is perhaps not fully appreciated, however, that the dipolar nature of magnetism and the restricted extent of the source of oceanic magnetic lineations act like a band-pass filter to impose a large measure of ambiguity on magnetic anomaly identifications. This can be eliminated only if the observed anomaly sequence is sufficiently long and well-formed, or if additional information about the expected age range is available. It is our contention that, in the case of the Weddell Sea, neither the quality of the anomalies themselves nor our understanding of the regional tectonics is adequate for this purpose at present.

We will consider first the regional tectonics. Fig. 4 shows the extent of published information about identified magnetic lineations and fracture zone orientations in the southern Atlantic and Indian Oceans, including the Weddell Sea data described above. At present the Weddell Sea lies on the Antarctic plate, with the rather complicated South American–Antarctic (SAM–ANT) plate boundary along its northern edge. It has become increasingly clear, however, that most of the complication of this boundary, including the evolution of the Scotia Sea, occurred during the last 30 Myr (Barker & Burrell 1977; Barker *et al.* 1980). Thus, the simplest and perhaps most likely origin of the Weddell Sea is as a result of earlier SAM–ANT motion. More specifically, Fig. 4 suggests it may have formed by the separation of East Antarctica from the Falkland Plateau (which is continental, and throughout South Atlantic opening remained rigidly attached to South America – Barker, Dalziel *et al.* 1977; Barker 1979; Rabinowitz & LaBrecque 1979). In the absence of direct evidence, this earlier SAM–ANT motion may be obtained by the combination of motions of

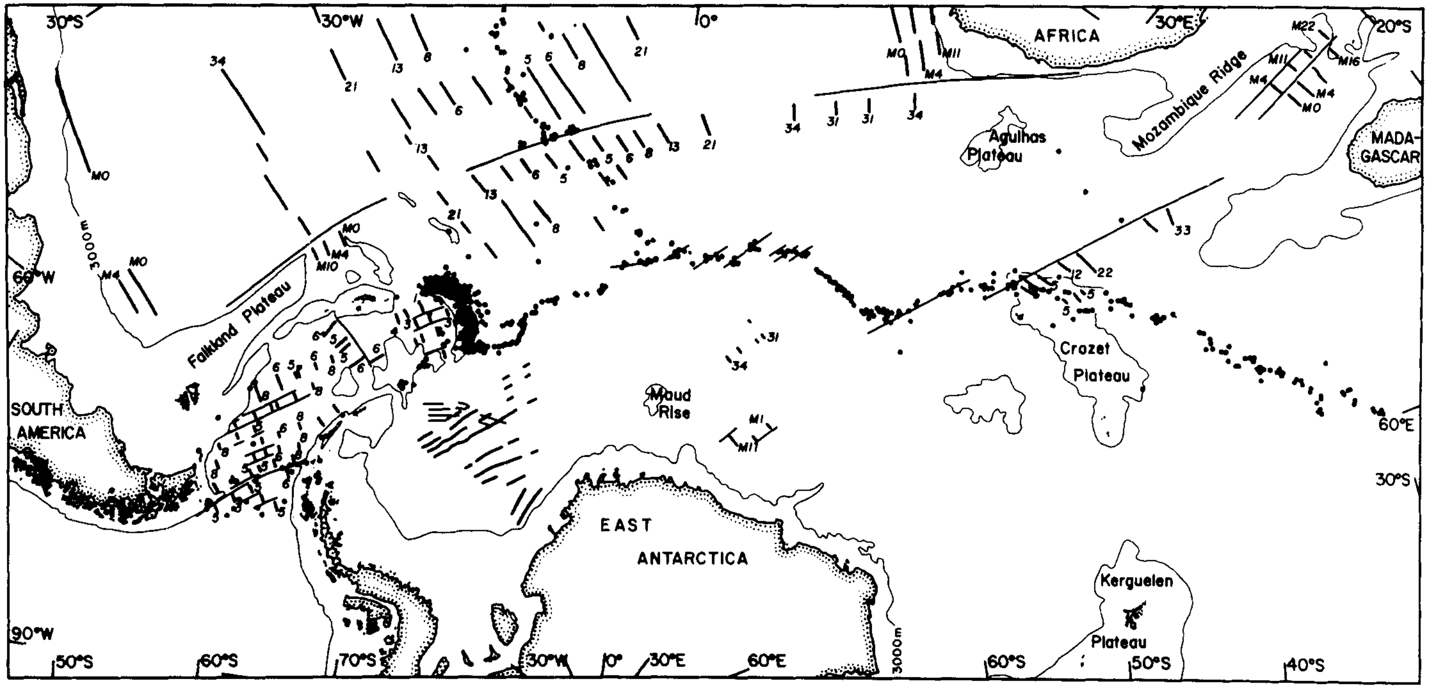

Figure 4. Summary of published magnetic anomaly and fracture zone identifications in the southern Atlantic and Indian oceans, including Weddell Sea data described here. South Atlantic data from Dickson *et al.* (1968), Ladd *et al.* (1973), Barker (1979), Rabinowitz & LaBrecque (1979). Indian Ocean data from Bergh (1971, 1977), Bergh & Norton (1976), Norton (1976), Norton & Sclater (1979), Sclater *et al.* (1976a, 1978), Segoufin (1978), Simpson *et al.* (1979). Scotia Sea data from Barker (1972), Barker & Burrell (1977), Hill & Barker (1980).

other plates, provided these are sufficiently well known. The most direct link is via South American–African (SAM–AFR) and African–Antarctic (AFR–ANT) motions.

The history of South Atlantic opening is relatively well known (Dickson, Pitman & Heirtzler 1968; Ladd, Dickson & Pitman 1973; Larson & Ladd 1973; Ladd 1976; Barker 1979; Rabinowitz & LaBrecque 1979). Opening started about 128 Myr ago and there were major changes in rates and poles of opening at about 107 Myr (M0 time), 68 Myr (A31 time) and 47 Myr (A20 time). South of the Falkland–Agulhas fracture zone a westward ridge jump of 800 km took place within the period 64–58 Myr, and a similar westward jump of 400 km probably occurred at about 98 Myr.

AFR–ANT motion is much less well documented. Anomalies in the Mozambique Basin (Segoufin 1978; Simpson *et al.* 1979) show that spreading started about 20 Myr earlier than South Atlantic opening (about M22 time), and younger anomalies mapped by Bergh & Norton (1976) suggest either intermittent spreading or repeated ridge jumps within the Tertiary. These data alone are too sparse to permit an estimate of rates and poles of AFR–ANT motion, but attempts have been made recently to do so indirectly, by way of AFR–Indian and Indian–ANT motions (Johnson, Powell & Veevers 1980; Norton & Sclater 1979). Unfortunately, the results of these attempts disagree, and when combined with SAM–AFR motion produce quite large differences in estimated SAM–ANT motion.

Additional data from the southern Indian Ocean should eventually permit a reasonable estimate of SAM–ANT motion, but it is of course possible that this was *not* the origin of all or even part of the Weddell Sea. For instance, before the South Atlantic started to open, there was a period of 20 Myr when AFR–ANT and SAM–ANT motion were identical; it is virtually impossible to see how this simple motion could have produced both the Mozambique Basin anomalies and any of those mapped in the Weddell Sea. One alternative is that during this period East and West Antarctica were decoupled, along a line of which the north-east-trending anomalies in the south-eastern Weddell Sea were a part. This line could have followed the eastern margin of the Mozambique Ridge, which many Gondwanaland reconstructions suggest, or at least imply, originated in the eastern Weddell Sea (for example, Smith & Hallam 1970; Dietz & Sproll 1970; Norton & Sclater 1979). If East Antarctica and the Antarctic Peninsula *did* form separate plates in the earliest stages of Gondwanaland break-up, this situation could have persisted after the start of South Atlantic opening, providing additional freedom for models of Weddell Sea evolution. Molnar *et al.* (1975), for example, suggest relative motion of East and West Antarctica as recently as the period 80–40 Myr ago. Also, as Fig. 4 makes clear, Weddell Sea anomalies as mapped do not quite extend sufficiently far westward to provide any firm constraint on the motion of the Antarctic Peninsula. It is conceivable that the western, ice-covered part of the Weddell Sea floor was produced by an entirely different tectonic regime.

Thus, at our present level of understanding, the broad regional tectonic environment provides no clear prediction of the age and rate of opening of the Weddell Sea. More locally, the widely applicable relationship between age and depth to oceanic basement (Sclater, Anderson & Bell 1971; Parsons & Sclater 1977) may be of use. In the northernmost Weddell Sea the extreme topographic relief and the proximity of the very complex present-day SAM–ANT boundary make the estimate of an average basement depth both difficult and of dubious value. At about 66° S, however, where subsediment relief is reduced, the average depth, corrected for the isostatic response to sediment loading, is about 5900 m. This corresponds to a basement age of about 115 ± 20 Myr (Parsons & Sclater 1977), which is within the younger part of the M-sequence magnetic anomalies of the early Cretaceous. However, recently reported heat flow values from the Weddell Sea (Zlotnicki *et al.* 1978) are high, and more appropriate to an early Tertiary age, and there is a precedent for anomalously deep ocean floor in the back-arc basins of the Philippine Sea (Sclater *et al.* 1976b).

4.2 MAGNETIC MODELLING AND ITS CONSEQUENCES

In the absence of firm regional tectonic guidance as to a likely age range and spreading rate for the Weddell Sea floor, a broad approach to the magnetic modelling had to be employed. A selection of the profiles was transformed (Blakely & Cox 1972) to poles appropriate to both the present day and the mid-Jurassic, and searched for a centre of symmetry. Synthetic anomaly profiles were computed for a wide range of ages and spreading rates. It quickly became apparent that many sections of the reversal time scale could be used to fit the data to some extent, although none perfectly. This ambiguity was to be expected in view of the poor shape consistency of the observed anomalies along their apparent strike, and the lack of constraint upon the model. The poor shape consistency has been mentioned before, and is quite plausibly explained in terms of the disruptive effects of spreading oblique to the plate boundary. In this situation, nothing was to be gained by replacing the conventional layer 2 block model of the magnetic source body by more complicated (two-layer, diffuse or sloping boundary) bodies whose main effect would be to smooth the synthetic profile and thus increase the potential ambiguity. Fig. 5 shows two of the more useful-looking magnetic profiles, resolved on to the direction 170° T. Their tracks lie quite close together near the western edge of the data set shown in Fig. 1, and are those which extend the farthest south. They are not as oblique to the known fracture zone directions as are the

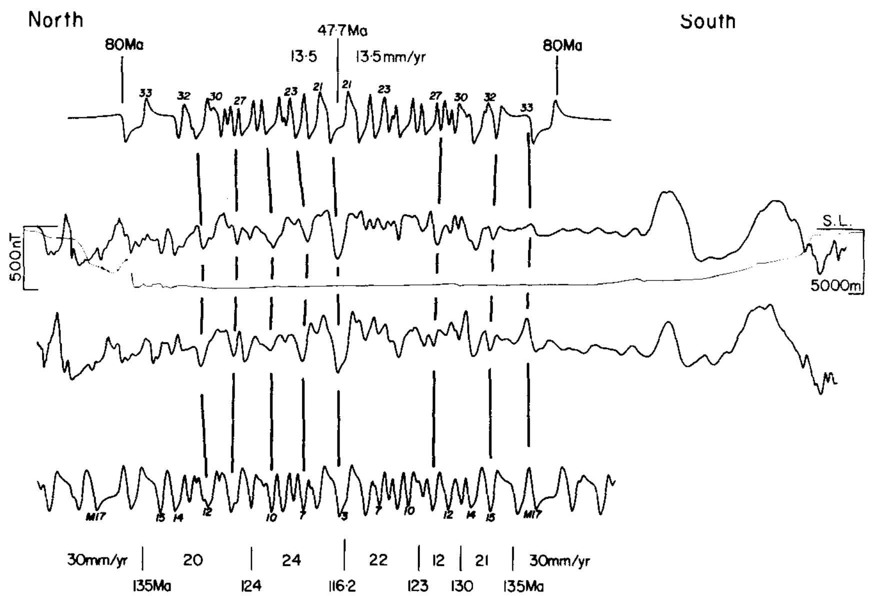

Figure 5. Observed magnetic and bathymetric profiles crossing the Weddell Sea, compared with two synthetic magnetic profiles. The ambiguity which this comparison demonstrates cannot at present be resolved. Synthetic profiles were generated using the time scales of LaBrecque *et al.* (1977) for the last 80 Myr and Larson & Hilde (1975) for the earlier period, together with (respectively) the present axial magnetic dipole and that for the mid-Jurassic of East Antarctica (Barker & Griffiths 1977). Source bodies were vertical-sided, 0.4 km thick, and had a depth to top given by the empirical age–depth relationship derived by Tréhu (1975). The anomaly correlations drawn are those also drawn in Fig. 1.

more easterly tracks, which may explain the unusually good shape consistency of the anomalies. Two synthetic profiles have been fitted to them in Fig. 5, one spanning most of the early Cretaceous and the other the late Cretaceous and early Tertiary. The anomaly correlations drawn between them are those which are also drawn in Fig. 1. Both models are symmetric, and centred on the large negative anomaly AA.

We wish to emphasize the following aspects of this model-fitting exercise and its consequences.

(a) Each model is a reasonably good match to the observed anomaly profiles. Some sections of each fit very well. We suggest that, were either model supported by firm regional tectonic information, it could become generally accepted.

(b) Either model could be made reasonably compatible with the *existing* regional tectonic information, which is uncertain and sparse, and with the available heatflow data and basement depths.

(c) Both models employ relatively simple sets of spreading rates. The histories of SAM–AFR and AFR–ANT motion as known at present contain sufficient discontinuities to make a model with a more complicated set of spreading rates equally acceptable. Also, the other observed magnetic profiles show a lesser consistency of anomaly shape than those displayed in Fig. 5. Thus the two models are clearly not the only reasonable ones which can be constructed.

(d) In particular, it is not necessary for a model to be symmetric about anomaly AA. Fig. 4 shows how the Weddell Sea magnetic anomalies could represent only, or mostly, the southern limb of a spreading system, with part or all of the northern limb having disappeared beneath the Scotia Sea. The Scotia Sea has formed largely over the past 30 Myr, and east-directed subduction has been part of that evolution for at least the past 20 Myr, if not for longer (Barker *et al.* 1980).

(e) Thus, neither of these models is put forward as a preferred solution to the problem of dating the Weddell Sea. Rather, we use them to argue that Weddell Sea magnetic data as presently available are incapable of sustaining by themselves an unambiguous model of the regional tectonic evolution.

The negative nature of these conclusions makes it necessary to consider what might be achieved eventually. Although beyond our own capabilities, an improved understanding of AFR–ANT motion seems feasible within a very few years. This will permit a model for SAM–ANT motion to be constructed against which Weddell Sea anomalies can be tested. Whether they are found to represent SAM–ANT motion or to involve the motion of an additional plate, perhaps the Antarctic Peninsula, the Weddell Sea anomalies should then provide tight constraints on the reconstruction of the south-western part of Gondwanaland.

It is possible also to define the principal objectives of future work within the Weddell Sea itself. The symmetry of Weddell Sea spreading may be assessed by seeking the equivalent of the exaggerated fracture zone topography on the hypothetical southern limb of the spreading centre. Also, the relevance of the magnetic anomalies to the early evolution of the Antarctic Peninsula may only be judged when the magnetic and seismic reflection data set extends farther west than at present.

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