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Phil. Trans. R. Soc. Lond. B 1977 **279**, 143-159
doi: 10.1098/rstb.1977.0079

Phil. Trans. R. Soc. Lond. B. **279**, 143–159 (1977) [143]
Printed in Great Britain

Towards a more certain reconstruction of Gondwanaland

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In the absence of identified magnetic anomalies in the southernmost Atlantic and Indian Oceans, palaeomagnetic data provide the most precise test of the initial relative positions of East and West Gondwanaland, with an uncertainty of about 10°. Two models are presented which lie within this uncertainty, but which have very different consequences for the initial position of the Antarctic Peninsula and the evolution of the Weddell Sea. Consideration of these models and their evolution shows that, in turn, a combination of mid-Jurassic palaeomagnetic data from the Peninsula and knowledge of Weddell Sea magnetic lineations should indicate the initial relative positions of East and West Gondwanaland.

Introduction

For the past few years we have been attempting to elucidate the structure and history of the Scotia Sea region. In essence the region evolved largely in the Neogene, by fragmentation of an originally continuous continental connection between South America and the Antarctic Peninsula; the fragments were dispersed into the Scotia Ridge and the Scotia Sea formed in their wake. In detail the processes are much more complex and we have started now to look outside the Scotia Sea itself, in the hope of gaining an understanding of the conditions under which Scotia Sea evolution started. This has led in turn to an interest in reconstructions of Gondwanaland, particularly the 'southwestern' region, where southern Africa and South America, East Antarctica and the Antarctic Peninsula were clustered before their early Cretaceous dispersal. For this southwestern region, existing reconstructions are less than satisfactory, although in other respects a reasonable consensus about Gondwanaland is developing. In this paper we firstly review the criteria guiding reconstruction to see how much justifiable uncertainty exists within the consensus. We then set up two models lying within this uncertainty, but having very different consequences in southwestern Gondwanaland, where our main interest lies. The models are simplifications, designed primarily to illustrate extremes, although in most respects they are also among the most likely. Their main value lies in predicting which measurements within our capabilities are sensitive to variations lying within the present uncertainty of Gondwanaland reconstruction.

Criteria for reconstructions

Of all the existing Gondwanaland reconstructions, the two we propose below probably differ least from that of Smith & Hallam (1970). For this reason, and in view of the wide use of this reconstruction by others, we use it here (figure 1) to illustrate the process of re-assembly and the criteria used.

The most powerful aid to reconstruction is the recognition of a complete set of marine magnetic anomalies between two continents, coupled with the certainty that none of the crust formed in their wake was subsequently destroyed. Such is the case for the Australia–East Antarctica separation (Weissel & Hayes 1972) and, with slightly less certainty, for South Atlantic opening (Larson & Ladd 1973, Ladd Dickson, & Pitman 1973). Most, but not all of the northward migration of India away from East Antarctica is similarly documented (McKenzie & Sclater 1971). In the western and southwestern Indian Ocean, however, and southernmost South Atlantic, such information is not yet available, partly because of the paucity of data but also because the slow and oblique spreading suspected to have formed much of these regions renders mapping more difficult.

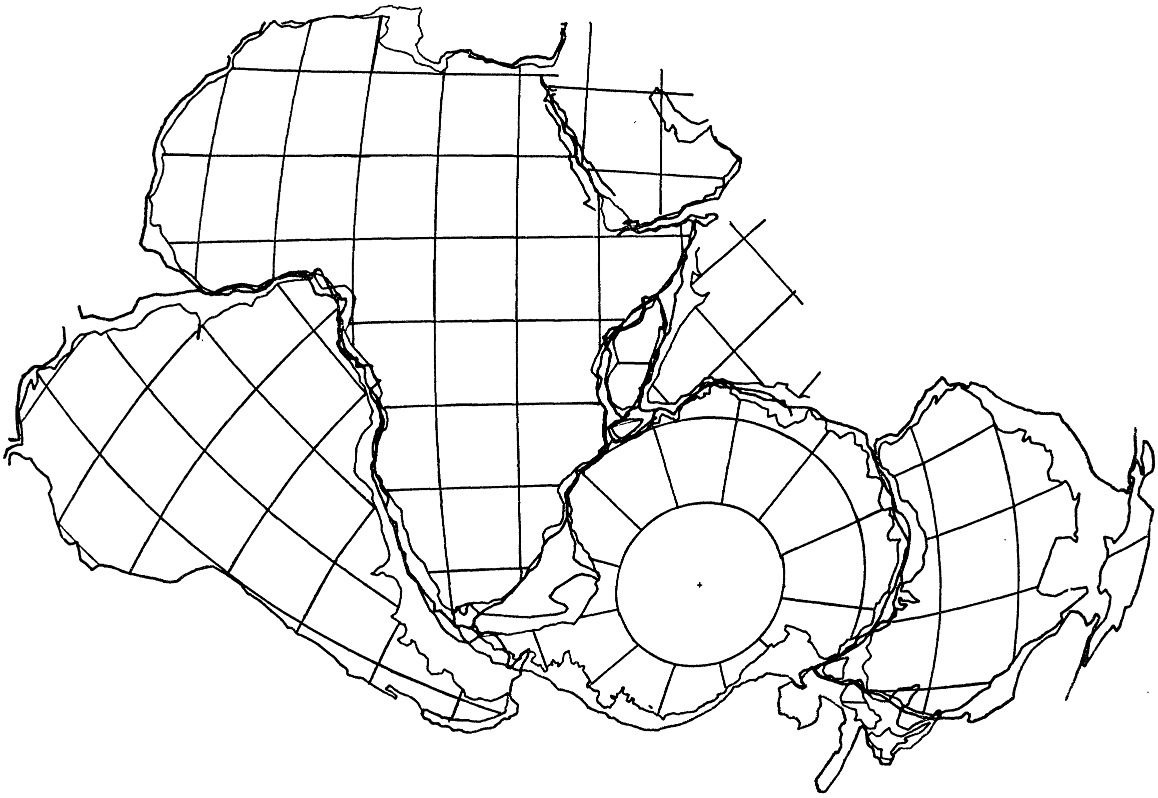

FIGURE 1. Reconstruction of the southern continents, largely at the 500-fathom (910 m) contour. Reproduced, with permission, from Smith & Hallam (1970).

A second widely-used criterion is the matching, latterly by computer, of a representative depth contour on opposing continental slopes, taken to represent the shape of the original break. The pioneer study of the South Atlantic margins (Bullard, Everett & Smith 1965) has been emulated many times, notably by Smith & Hallam (1970 – see figure 1), Dietz & Holden (1970), Dietz & Sproll (1970) and Dietz, Holden & Sproll (1972). A valuable addition has been the recognition by McKenzie & Sclater (1971) that, since sea-floor spreading is essentially symmetric about the spreading axis, mid-ocean ridge earthquakes may also be rotated back onto the margins. The margin-matching criterion used above, however, is subject to several disadvantages. Firstly, the original shapes of some continental margins are very much less distinctive than those of Africa and South America, so that several reconstructions appear equally good to either the eye or the computer. In particular the East Antarctic margin between 30° W and 170° E can be approximated either by the arc of a circle, or by an equi-angular polygon, neither conducive to an unique fit in the absence of other data. To this problem must be added a second, that the present shape of the margin, however defined, may not be the original shape. The eastern margin of Africa, in particular, has experienced considerable and repeated normal faulting since Permian times (Kent 1973, 1974), probably associated largely with the early phase of fragmentation of Gondwanaland; it is likely that in many places the true continental margin lies far from the present 1000 m or 2000 m isobaths.

We may gather together the many strands of geological evidence to form the third general criterion for fitting continents. It would be true to say that, where other, more precise criteria establish a fit, the geologic correlation across the boundary is often very good (see, for example, Hurley 1970, 1973). There are difficulties, however, in using the geology as the primary fitting criterion, at least at those Gondwana margins where this has been attempted. The presence of broad continental shelves introduces an uncertainty into correlations of the land geology and, as down the east coast of Africa, downfaulting associated with fragmentation itself causes burial of the diagnostic older rocks beneath a thick pile of sediments, further separating potentially matching geologic features. Furthermore, there is a tendency, well illustrated along parts of the North and South Atlantic margins, for the break to follow older lineations, so that few older features cross the new margins at a high angle. In general it must be said that although many geological features demonstrate the reality of continental drift, few can be used alone to justify a particular, precise fit.

Palaeomagnetism is the last major criterion, and one which has proved extremely valuable. On the assumption of a geocentric, axially-dipolar magnetic field, relative to which all the continents have moved, the only additional requirement for a complete elucidation of the relative positions of the continents through geologic time is adequate sampling. Needless to say, however, sampling is usually unavoidably inadequate and the governing assumption has been called into question for certain geologic periods. Useful reviews of the topic are given by McElhinny (1973), from which figure 2 is taken, and Creer (1973).

In figure 2 the Smith & Hallam (1970) reconstruction of Gondwanaland is compared with the best available Phanerozoic palaeomagnetic data from its component continents. The palaeomagnetic poles fall into several groups, each representing a 'quasi-static interval' (Briden 1967) during which the pole apparently hardly moved; polar motion with respect to all continents between these periods was much more rapid. It will be noticed that the African and South American poles, whose relative positions in the Smith & Hallam reconstruction are well-fixed by other means, differ by between 8 and 15°. This separation is a measure of the adequacy of sampling for those continents over that time interval, of the validity of the dipole hypothesis (to some extent) and of the reality of the quasi-static interval (since some poles are from poorly-dated rocks). Sampling is less comprehensive for the east Gondwana continents, particularly for East Antarctica, but the small size of the entire Mesozoic group in figure 2 is some indication of the quality of the Smith & Hallam fit. There is a persistent divergence of Australian palaeopoles of nearly all ages, which cannot entirely be explained by the geology (McElhinny & Embleton 1974), and some suggestion (Creer 1973) of an eccentric dipole field during the Permo-Carboniferous. Also, Gondwanaland may not have had precisely its later shape during the lower Palaeozoic.

In summary, although the palaeomagnetic data provide an overwhelming demonstration of the unity of Gondwanaland through much of the Palaeozoic and Mesozoic, we infer an uncertainty of about 10° in their verification of the Smith & Hallam fit in particular. The uncertainties of the method are such that this figure is unlikely to be reduced by very much over the next few years.

In a later section we exploit this 10° uncertainty by presenting two variants on the Smith & Hallam reconstruction, both compatible with the palaeomagnetic data but with very different consequences for the evolution of southwest Gondwanaland. Firstly, however, we must draw attention to one important point; in the Smith & Hallam model, and in others like it (Dietz & Holden 1970; Dietz *et al.* 1972; Dietz 1973), the Antarctic Peninsula overlays southern Africa.

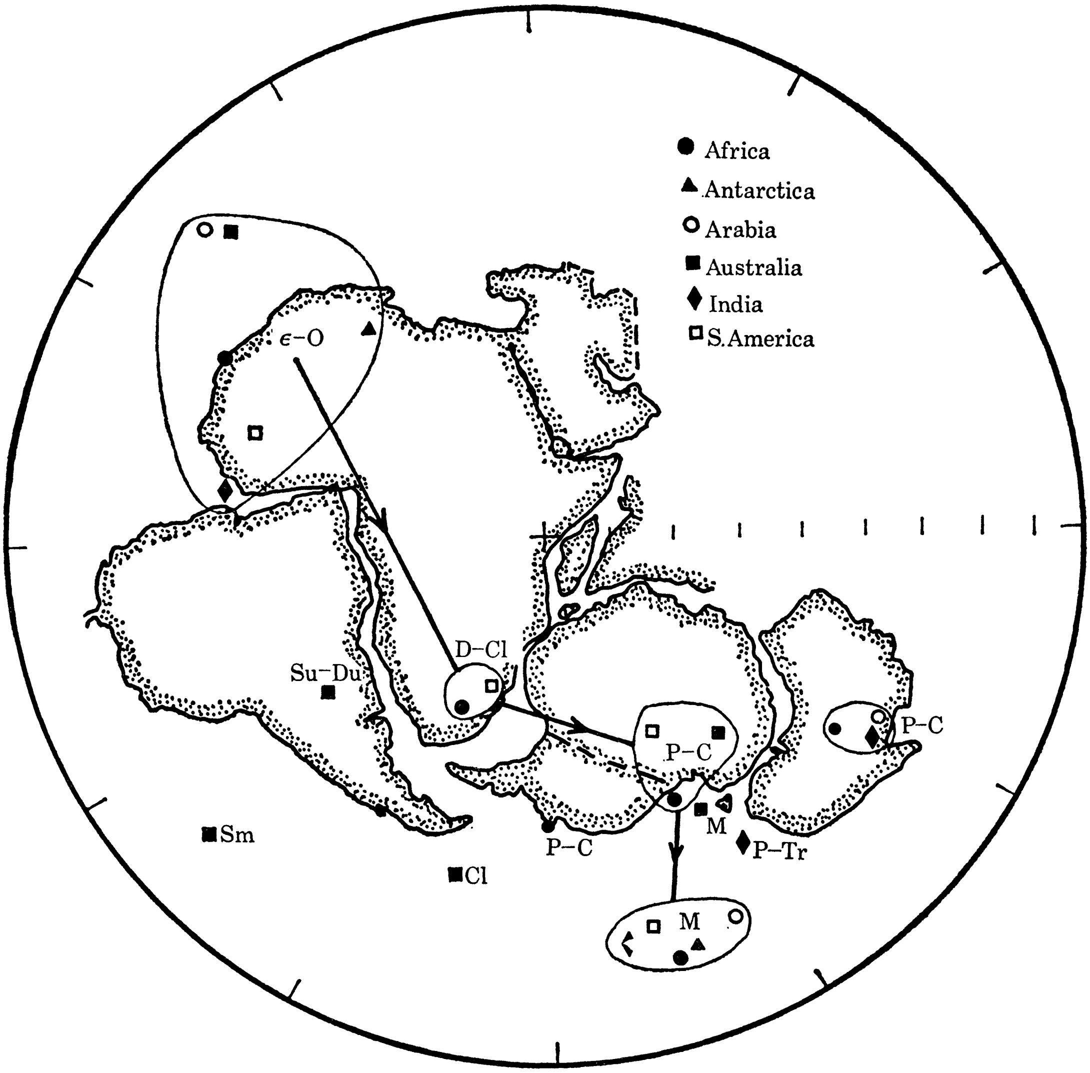

FIGURE 2. Cambrian to Mesozoic palaeomagnetic south poles plotted on the Gondwanaland reconstruction of Smith & Hallam (1970). Groups correspond to 'quasi-static intervals' of Briden (1967). Reproduced with permission from McElhinny (1973).

There is little doubt that the Antarctic Peninsula is built upon an extensive core of pre-break-up continental crust (Adie 1964 and many others) and that the Falkland Plateau is also continental (Barker, Dalziel *et al.* 1977) as far as 40° W. The simplest solution to this unacceptable overlap is to consider that the East Antarctic craton and the marginal orogenic belt of West Antarctica have been part of at least two separate plates for some of the time since Gondwanaland fragmented (Schopf 1969; Elliot 1971; Barker & Griffiths 1972).

New Gondwanaland models – A and B

The two reconstructions which we have generated are shown in figures 3 and 4. Also shown are selected mid-Jurassic palaeomagnetic data as an independent criterion of the validity of the models; these data must be considered next, before the models themselves can be discussed.

Palaeomagnetic data

As noted above, a particularly close Mesozoic grouping of palaeomagnetic poles results from the Smith & Hallam fit (figure 2). McElhinny (1973) includes within this group data of Triassic to Cretaceous age, where these are available. Since East Antarctic Mesozoic data are confined to the mid-Jurassic, we have only used data from other continents from as close to this period as possible. This greatly reduces the possibility of including data from after Gondwanaland had started to fragment, and lessens the effects of any real polar wander which might have occurred during what McElhinny (1973) and others take to be a quasi-static interval. The mid-Jurassic is in any case well represented on all the southern continents except India, as a result of a prolific intrusion and extrusion of igneous material, presumably associated with the early, pre-movement phase of Gondwanaland fragmentation.

The palaeomagnetic data are listed in table 1 and combined into mean poles, for rotation along with the continents themselves, and displayed in figures 3 and 4.

The South American pole is the mean of 54 sites in 3 main areas for the Chon Aike Formation of intermediate and acid lavas and tuffs (Vilas 1974). At two localities K-Ar ages of 161 and 166 Ma have been obtained (Valencio & Vilas 1970; Creer, Mitchell & Abu Deeb 1971). In Africa, surprisingly in view of the wealth of suitable rocks, the situation is slightly less satisfactory. Ages of between 154 and 190 Ma have been reported from Karoo dolerites (McDougall 1973) and in order to include a sufficiently large number of sites, other (probably related) formations with the same range of ages have been added (see table 1). The Tasmanian dolerites (Irving 1963) provide the Australian pole, from 51 sites. As noted briefly above, Australian data are in general anomalous, suggesting relative movement both within Australia and between there and the remainder of Gondwanaland which is denied by the geologic evidence. The Tasmanian dolerites, however, are contemporaneous and petrologically similar (Compston, McDougall & Heier 1968) to the Karoo rocks and to the Ferrar dolerites which provide the Antarctic pole, and are therefore included here. The Ferrar dolerites (K-Ar ages 147–163 Ma) have been sampled at 60 sites in three areas and the poles group tightly; the Dufek intrusion (Beck 1972) is of the same age (168 ± 5 Ma) but yields a significantly different pole position. This difference is largely eliminated if the dip correction applied by Beck is removed; such a decision may be justified if it is assumed that the differential subsidence of the homoclinal layered gabbro occurred before the body cooled through the Curie temperature of the magnetized minerals. In view of the uncertainty, however, the Dufek pole is neglected here. There are no data of mid-Jurassic age from India nor as yet from West Antarctica, although in this latter area suitable rocks are known to occur.

It should be noted that in obtaining a mean pole for a particular continent, data from table 1 are combined which are apparently significantly different in a few instances. This does not necessarily mean that their combination is unjustified but, perhaps more realistically, that the total scatter of measurements which go to make up one of the poles may not indicate all of the uncertainty with which that pole measures the true pole. The additional uncertainty is usually

TABLE 1. MID-JURASSIC PALAEOMAGNETIC DATA FROM THE SOUTHERN CONTINENTS

	sites	samples	S. Pole positions		ages/Ma	95 (d_m, d_p)°	sources
South America							
Chon Aike P. Deseado	22†	66	84° S	42° E	161	8	Vilas 1974
Chon Aike Camarones	17†	41	82° S	231° E	166 ± 5	12	Creer *et al.* 1971
Chon Aike Reconquista	15†	56	69° S	193° E		13	Vilas 1974
Mean	54†		85° S	197° E		6	Vilas 1974
Africa							
Hoachanas basalts	3	10†	62° S	74° E	168 ± 5	7	Gidskehaug, Creer & Mitchell 1975
Marangudzi ring complex	8	68	70° S	105° E	182–196 ± 10	9	McElhinny, Briden, Jones & Brock 1968 2.49
Mateke Hills ring complex	6	36	59° S	80° E	177 ± 4	9	McElhinny *et al.* 1968 2.50
Stormberg lavas	?4	74†	67° S	98° E	154–190?	15	McElhinny *et al.* 1968 2.28–31
Karroo dolerites	10†	67	66° S	75° E	154–190	13	McElhinny *et al.* 1968 2.48
Mean		255†	67° S	89° E		5	this paper
E. Antarctica							
Ferrar Dol. Ferrar Gl.	5	57	58 °S	218° E		5	Turnbull 1959
Ferrar Dol. Wright, Victoria DV.	46	83	45° S	219° E		4, 3	Bull, Irving & Willis 1962
Ferrar Dol. Beardmore Gl	9	13	59° S	221° E	147–163	20, 18	Briden & Oliver 1963
Ferrar Dol. Whichaway Nun	7	8	54° S	224° E		12, 10	Blundell 1966
Mean	4†		54° S	220° E		8	Beck 1972
Australia							
Tasmanian dolerite	51	132	51° S	160° E	167	6	Irving 1963

† Indicates mode of weighting of mean directions or v.g.ps, where known.

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an undetected geological factor, common to all or most of the samples used; an undetected dip or rotation, a departure from a geocentric axial dipole field, an age difference in a time of polar wander, later re-magnetization and consistent measurement or computation errors could all bias a pole computed from a large number of samples. The published poles are combined in this paper (and throughout the literature) on the understanding that many are probably contaminated, but that their combination should produce a pole more reliable than either alone. It follows however that the computed confidence limits of the combination pole similarly do not always represent all of the uncertainty.

We can now consider model A and model B, concentrating firstly on those features which they have in common.

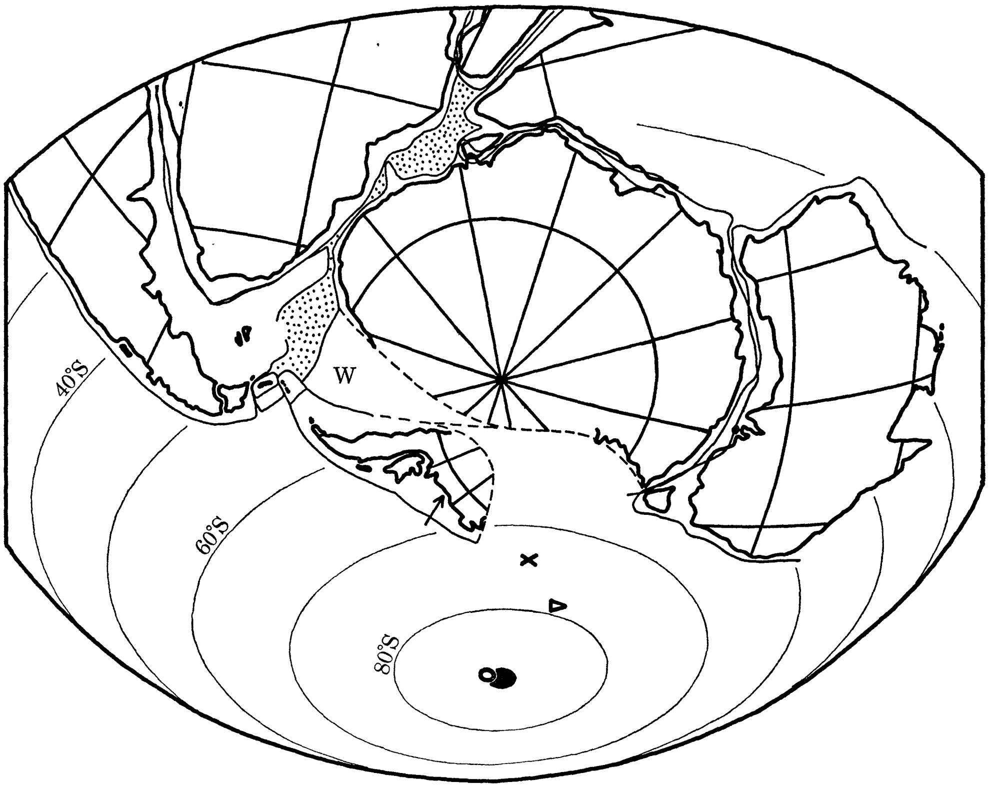

Figure 3. Gondwanaland model A. Pole of projection is mid-Jurassic East Antarctic palaeopole. Mean mid-Jurassic palaeopoles from Australia (×), Africa (○) and South America (▽) also plotted (see table 1). Stippled areas are 'underlap', presumed downfaulted continental crust. For further discussion, see text.

West Gondwanaland

The initial positions and relative motions of South America and Africa are now fairly well known. Ladd *et al.* (1973) and Larson & Ladd (1973) consider that their separation started about 130 Ma ago; Le Pichon & Hayes (1971) detected two main phases of opening, with a change in pole position at about 80 Ma, and confirmed the validity of the Bullard *et al.* (1965) fit of the continental margins. This fit (a 57° rotation of South America about 44° N, 30.6° W) is used to construct West Gondwanaland in both our models, and to combine the African and South American palaeomagnetic data. Unlike Smith & Hallam, we close the small gap in the Bullard *et al.* fit in the southernmost Atlantic, on the assumption (Barker & Griffiths 1972) that the series of Jurassic downfaulted basins in Patagonia (Salado, Colorado, Neuquen and San

Jorge (Zambrano & Urien 1970)) represent a minor flexing of the southern tip of South America which could have produced the observed mismatch. We recognize the continental nature of the Falkland Plateau as far as 40° W, now proved by drilling (Barker, Dalziel *et al.* 1977), and rotate it eastward with South America along the Falkland and Agulhas Fracture Zones to lie tightly along the southeast coast of Africa as far northeast as Durban (see figure 5).

The mean poles for Africa and South America lie about 12° apart. Since the Bullard *et al.* (1965) fit of the margins and the marine magnetic data are more precise, this separation illustrates the degree to which palaeomagnetic data can provide a test of the more speculative parts of Gondwanaland reconstructions.

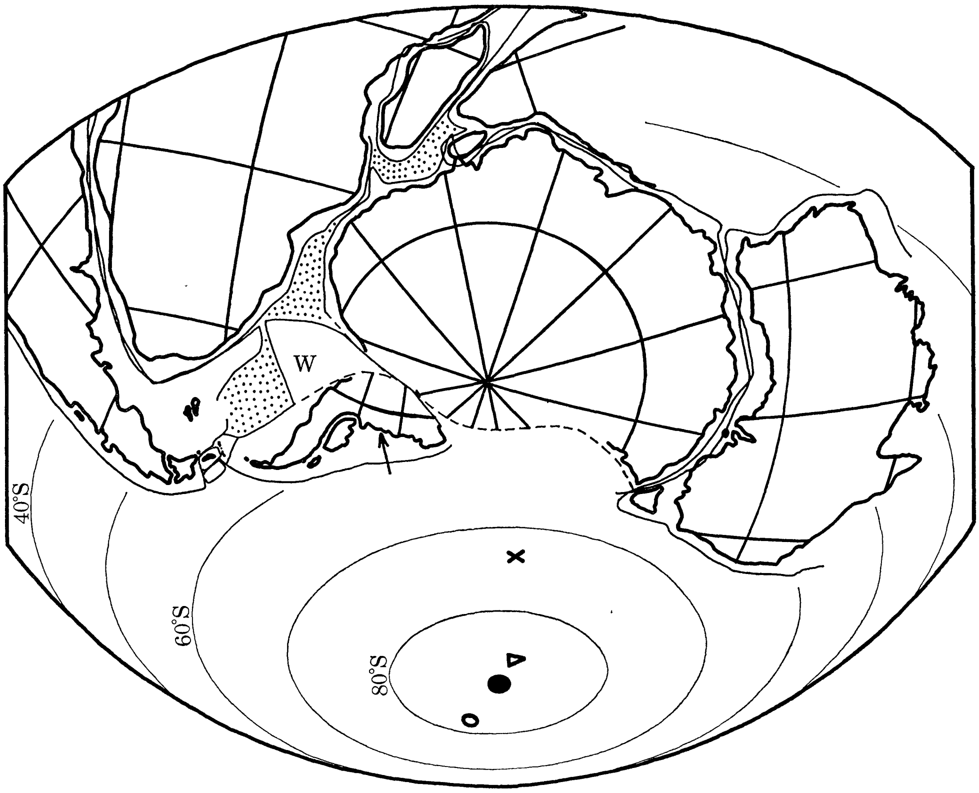

FIGURE 4. As figure 3 above, model B.

East Gondwanaland

Marine magnetic data now indicate clearly that separation of Australia from East Antarctica began at about anomaly 22 time, or 55 Ma (Weissel & Hayes 1972). Australia and its mid-Jurassic palaeopole are rotated back to East Antarctica using the pole and angle of McKenzie & Sclater (1971), 31.6° about 6° S, 40.5° E, which agree closely with those of Weissel & Hayes (1972), slightly less well with those of Smith & Hallam.

Magnetic anomalies can only be used in mapping the northward movement of India away from Antarctica back to about 72 Ma (McKenzie & Sclater 1971) but India appears from reasonable extrapolation of those data to have separated from Enderby Land about 100 Ma ago (Sclater, von der Borch *et al.* 1974). In this respect our reconstruction is more akin to that of Dietz (1971 – figure 3D), avoiding the unfortunate consequence of Smith & Hallam's model of requiring Ceylon to approach India during drift. It should be noted in passing that this position for India invalidates our earlier Gondwanaland reconstruction (Barker & Griffiths

1972, Figure 15), making it impossible for East Antarctica to take up the position then suggested, relative to West Gondwanaland.

There are no mid-Jurassic palaeomagnetic data from India, so the East Gondwanaland poles are those from the similar Ferrar and Tasman dolerites; the former is used as the pole of the reconstruction in figures 3 and 4, so that the 10° latitude lines indicate mid-Jurassic palaeolatitudes and orientations for each reconstruction and measure the scatter of the palaeopoles. The Australian and East Antarctic palaeopoles are separated by about 17°, a significant difference incompatible with the known geology, as noted above. In combining East and West Gondwanaland data, the Antarctic pole is taken to be the more important.

Madagascar and the East African margin

There remains considerable controversy over the position of Madagascar (figure 5) in Gondwanaland; it is variously supposed to have lain (*a*) in its present position relative to Africa

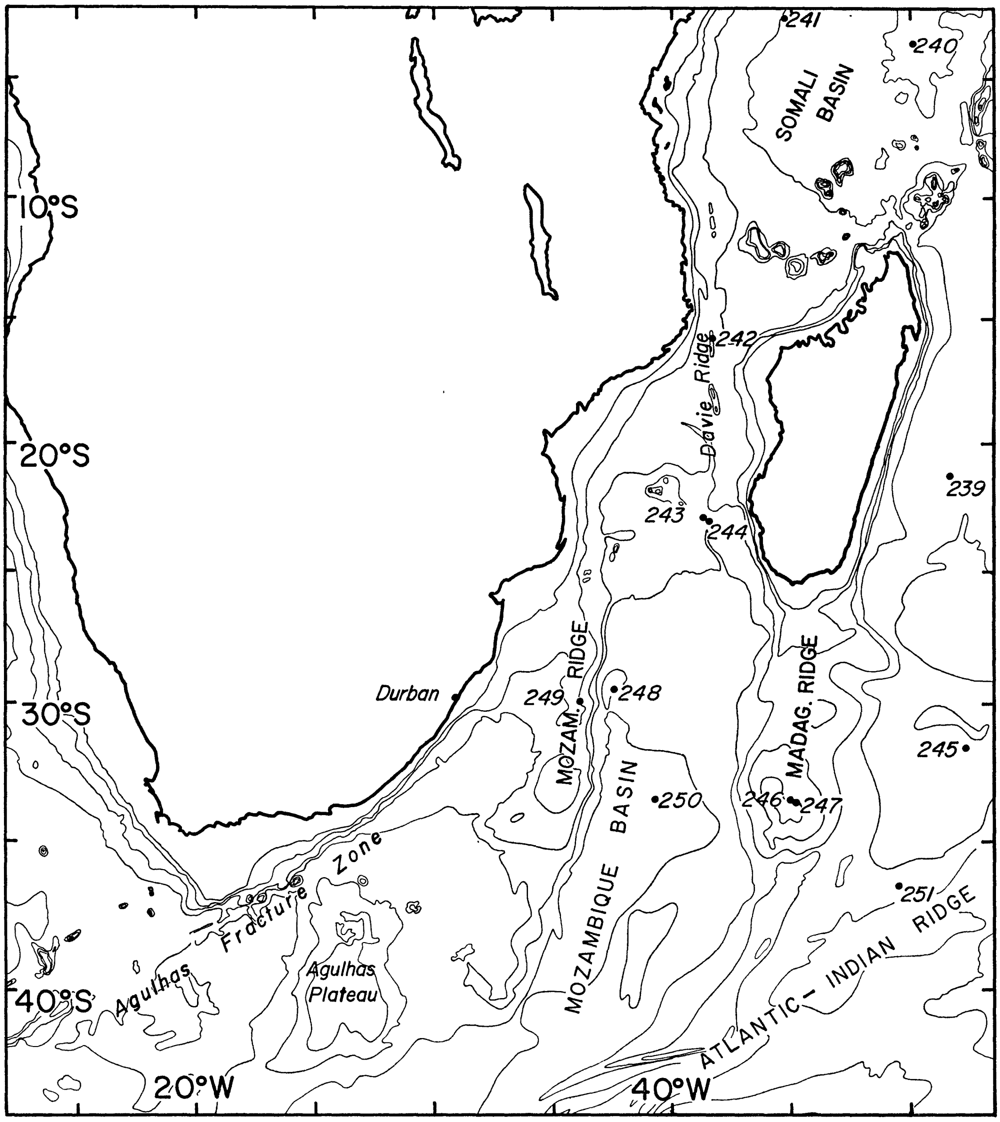

Figure 5. Bathymetric chart of East African margin. Isobaths are at 1 km intervals; numbers indicate DSDP sites. Redrawn from Simpson (1974).

(Dixey 1960; Kent 1973), (*b*) off the Mozambique margin to the southwest (Flores 1970) and (*c*) to the northwest alongside Kenya and Tanzania (du Toit 1937; Smith & Hallam 1970 and most authors). The debate has been prolonged because much of the evidence adduced involves comparisons of episodes of faulting, marine transgression, and intrusion which were essentially related to the early stages of Gondwanaland break-up and followed a similar pattern all the way along the East African margin.

Although we do not regard Embleton & McElhinny's (1975) endorsement as conclusive, we have taken the northern position here, being influenced also by the oceanic appearance of the Somali and Mozambique Basins and the similarity of the Mozambique and Davie Ridges to fracture zones, the latter indicating the direction of movement of Madagascar away from Africa. Accepting this, drilling at site 241 (Simpson, Schlich *et al.* 1974) in the Somali Basin indicates that separation of Madagascar from Kenya and Tanzania took place before the Turonian.

The presence of downfaulted continental basement on the Falkland Plateau, certainly at 3.2 km and probably at more than 5 km below sea level, implies that the 1000 m or 2000 m contour along the east African margin need not define the continental edge. Figure 5, a section of a recent bathymetric chart of the southeast Atlantic and southwest Indian Oceans by Simpson (1974), shows that parts of the Mozambique Channel and Natal Valley below 2 km could be downfaulted continent, as could the Mozambique and Madagascar Ridges to 30° S and the Agulhas Plateau, on account of their elevation above the surrounding ocean. The plans of leg 25 in these respects were unfortunately not successful; basalt with oceanic affinities was drilled at site 249 on the Mozambique Ridge (Simpson, Schlich *et al.* 1974), above Hauterivian to Valanginian siltstones and claystones, but the shipboard party was not convinced that true basement had been reached and leave open the possibility of an underlying continental crust. Both model A and B require the Mozambique Ridge to be oceanic, the latter less certainly however, and the line of its steep eastern margin to indicate the direction of initial separation of Africa from East Antarctica.

It is not clear how the line of the Davie Ridge extends to north and south; it may not be homopolar with the eastern margin of the Mozambique Ridge. We assume that, during the initial separation of the Gondwana continents, Madagascar remained behind with India as Africa moved northward, but that there may at that time have been a very small movement of Madagascar/India away from East Antarctica, before the major separation started 100 Ma ago.

Models A and B treat differently the other possible continental occurrences off East Africa; in both models the Madagascar Ridge is assumed continental, but in model A it lay originally between the central Mozambique margin (15 to 20° S) and the Princess Ragnhild Coast of East Antarctica, in Model B between southeast Madagascar and the same. We follow Scrutton (1973) in assuming the Agulhas Plateau to be oceanic, since leg 36 drilling data from site 328 in the Malvinas Outer Basin argue against its having been originally an eastward extension of the Falkland Plateau (Barker, Dalziel *et al.* 1977).

The Scotia Sea and the South America–Antarctic Peninsula link

More recent work in the Scotia Sea supports an earlier contention (Barker 1970 and figure 6) that it had evolved almost entirely in the last 40 Ma. It now appears that about 30 Ma ago Drake Passage was closed and Elephant I. lay opposite Cape Horn (Barker & Burrell, in preparation). The eastern Scotia Sea is known to have formed entirely by secondary extension behind the South Sandwich island arc and trench (Barker 1972) in the last 8 Ma. However, the central Scotia Sea is more complex, comprising a mixture of small areas of oceanic crust with varying magnetic anomaly orientations, together with elevated regions of less obvious oceanic affinities. We believe this central undated region to be merely a more complex complement to Drake Passage opening, perhaps involving an east-facing subduction zone ancestral to the South Sandwich trench, although de Wit (in press) has suggested that it is of early Cretaceous age, and an eastward extension of the marginal basin found in the Andean Cordillera of southern Chile (Dalziel, de Wit & Palmer 1974).

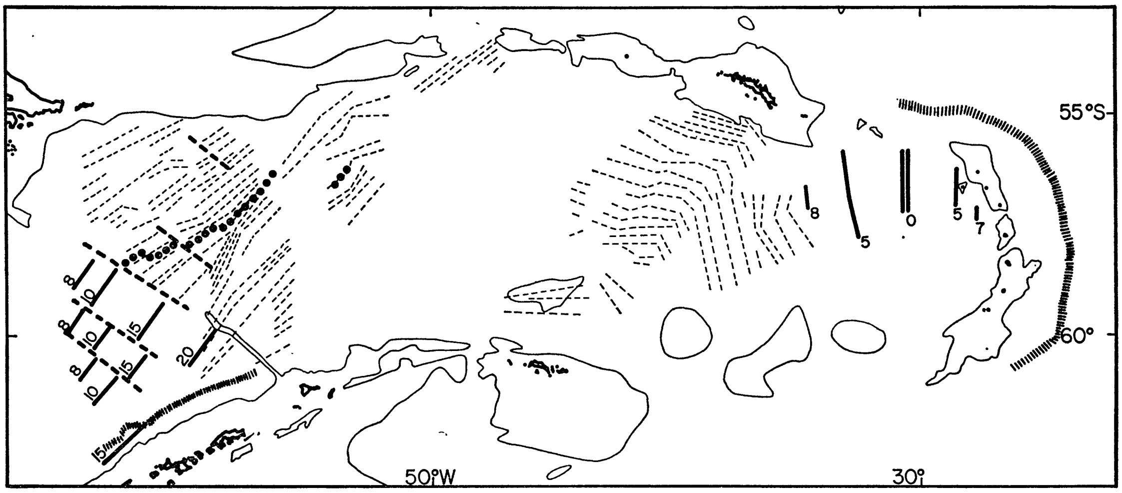

Figure 6. Ocean floor in the Scotia Sea, showing magnetic lineations, identified and unidentified, deduced from older data. 2000 m isobath defines areas of continental and intermediate crustal structure. Reproduced with permission from Barker (1970).

Depositional conditions at the Falkland Plateau and Malvinas Outer Basin sites drilled during leg 36 of the Deep Sea Drilling Project, and much additional data throughout the Southern Ocean, suggest that before about 30 Ma ago there was no deep-water connection between the Pacific and Atlantic Oceans (Barker, Dalziel *et al.* 1977). This has reinforced previously held views that a continuous continental connection existed between South America and Antarctic Peninsula (Hawkes 1962; Dalziel & Elliot 1971; Barker & Griffiths 1972; de Wit, in press), until it was fragmented and dispersed along the north and south Scotia Ridge as Drake Passage opened. The shape and length of the connection, however, was in dispute. We consider that the aggregate size of the limited number of identifiably continental fragments, all of which appear to have formed part of a recognizable Pacific margin sequence, combined with the requirement that the barrier remained continuous, places strict limits upon the length of the connection. Thus it is a condition of both models, and their evolution, that the distance between Cape Horn and Elephant I. remained small (500 km or less) until 30 Ma ago, the region acting as a hinge for rotation of the Antarctic Peninsula with respect to South America following Gondwanaland fragmentation.

Boundaries of an Antarctic Peninsula plate

It has been pointed out, above, that the most reasonable way of reconciling a Gondwanaland reconstruction with the continental nature of the Falkland Plateau is to accept relative motion of East and West Antarctica; of the latter, we can restrict our interest to the Antarctic Peninsula, since there is evidence (Scharon, Shimoyama & Scharnberger 1969; Scharnberger & Scharon

1971) that Marie Byrd Land at least has moved independently, and it is likely that several small plates have formed and reformed since the initial fragmentation. Hence, the remainder of West Antarctica is not shown in figures 3 and 4. This in turn leads us to neglect the position of New Zealand also; its closest link is with West Antarctica and, unlike other remote parts of Gondwanaland which we *have* considered, its position does not affect our argument.

An obvious choice for the boundary of East Antarctica is the abrupt scarp of the Transantarctic Mountains, marked also by a sub-ice topographic depression and sharp changes in crustal structure (Heezen, Tharp & Bentley 1972; Bentley & Clough 1971) and thickness (Woollard 1962).

The southern and eastern boundaries of the Antarctic Peninsula are rather less certain; Wade & Wilbanks (1971) and Munizaga (1971) consider that Ellsworth Land, including Thurston I. and the Jones Mts, resembles the Antarctic Peninsula more closely than it does Marie Byrd Land, and cite a 1 km-deep subglacial trough at about 105° W as the dividing line. On the other hand a similar trough meets the Pacific margin at about 82° W in the centre of Ellsworth Land (arrowed in figures 3 and 4). We have taken the former trough as boundary of the Antarctic Peninsula plate, but the consequences of choosing the more easterly trough (model C) are also discussed below, in parenthesis. This southern boundary is taken to curve northwards close to the south coast of Ellsworth Land, to join the eastern margin of the Antarctic Peninsula at the Weddell Sea.

A totally unknown area, presumed continental because shallow, separates the well-defined East Antarctic and Antarctic Peninsula plates at the head of the Weddell Sea (marked area W in figures 3 and 4). This area does *not* include the Ellsworth Mts, which comprise a strongly folded, thick sedimentary sequence akin to the Beacon Supergroup of the Transantarctic Mts (Craddock 1969), but with a structural trend perpendicular to both that range and Ellsworth Land. Schopf (1969) considers the Ellsworth Mts to have been displaced from an initial position within the Transantarctic Mts, north of the Pensacola Mts.

Contrasts between models A and B

The prime difference between the models lies in the locations of East Antarctica relative to Africa, a distance of about 900 km in a direction essentially along the boundary between them. These locations thus exploit the greater part of the uncertainty in the palaeomagnetic data, as the pole positions in figures 3 and 4 indicate. However, the locations are not arbitrary, but match discrete discontinuities along the African and East Antarctic margins; provided the assumption of a northerly position for Madagascar holds, these are, if not the only positions, certainly the most likely.

The consequences of this difference for the southwestern margin of Gondwanaland are quite marked. In model A the eastern end of the Falkland Plateau touches the East Antarctic margin near Cap Norvegia, closing off entirely the mouth of the Weddell Sea; in model B the Falkland Plateau only half-closes the Weddell Sea and the Antarctic Peninsula is able to lie much more nearly perpendicular to East Antarctica than in model A, thus changing the palaeopole position. The mid-Jurassic palaeolatitude of the peninsula is broadly similar in both models (55–70° S model A, 54–61° S model B) but the palaeo-declinations (300–255° model A, 340–285° model B) differ by a measurable 30–40°. The head of the Weddell Sea, area W, does not move with respect to East Antarctica in model A (figure 3), although it is obvious that it could be made to do so in order to reduce the area of presumed downfaulted continental crust lying between it and the Falkland Plateau. The west side of area W is a strike-slip boundary with the Antarctic Peninsula. In contrast, the whole of area W rotates with the Antarctic Peninsula in model B, along its eastern margin with East Antarctica. In model B it is reasonable for the Ellsworth Mts to have moved, with area W, from an initial position north of the Pensacola Mts, as Schopf (1969) suggests; in model A this becomes impossible, and an initial location for the Ellsworth Mts along the strike of the Transantarctic Mts nearer to the Ross Sea becomes likely.

As is obvious from figure 3, model A is not significantly affected by the choice of either the 105° W or 82° W trough as the base of the Antarctic Peninsula. Use of the former in model B, however, prevents the peninsula from lying closer to the Falkland Plateau than shown in figure 4, because it is too long. If the 82° W boundary is used ('model C') the peninsula could be made to lie very much closer, as de Wit (in press) suggests, but there would then be difficulty in producing the quite large, presumed continental area W, which has to come from the vicinity of the Falkland Plateau since sources on the Ross Sea side are barred by the peninsula itself. Model B, as drawn in figure 4, includes a large area of downfaulted continental material south of the Falkland Plateau, the whereabouts of which are today unknown, unless it lies in the inaccessible eastern Weddell Sea. Also in model B, the northern part of the Mozambique Ridge (not including site 249) is continental.

It is worth noting that in both model B and its variant, model C, the initial shape of the Pacific margin of southwest Gondwanaland could have been a smooth curve from South America to the base of the Antarctic Peninsula, without the suggestion of an original cusp as shown in figure 4. Model C is testable, since the mid-Jurassic palaeo-declination on the Peninsula would be different again from those of models A and B. It should be noted too, that only for the Middle Jurassic is there presently a large collection of palaeomagnetic data from other parts of Gondwanaland with which Antarctic Peninsula data may be compared. In the earliest Cretaceous the Gondwana continents started their independent motions, and the magnetic pole appears to have moved relative to all. Thus, although the peninsula has a wealth of post-Middle Jurassic igneous rocks, unambiguous interpretation of their palaeomagnetism may be difficult.

Evolution of models A and B

There are geometric constraints which, if they do not require it, at least suggest that the relative motion of Africa and East Antarctica began at the same time as South Atlantic opening. Certainly Africa alone could not have started to move away from the remainder of Gondwanaland, on either model, and there is no evidence that either South America or Antarctica made a lone early departure. The sketch illustrating the early separation, figure 7 (*a* and *b*), assumes that all of the spreading started at the same time, about 130 Ma. Only the first episodes of downfaulting on the Falkland Plateau, in the Magellan Basin and along the East African margin, and the associated volcanism, were earlier.

Models A and B have in common the opening of the South Atlantic, with the Falkland Plateau clearing Africa about 100 Ma ago (Barker, Dalziel *et al.* 1977), and the northeastward movement of Africa away from a part of East Antarctica along the line of the eastern margin of the Mozambique Ridge. The age of the basal sediments at site 249 on the Ridge is consistent with this scheme. Also in both cases the third spreading arm, which was creating the floor of the Weddell Sea, extended westward as far as the marginal basin of the southern Andes (Dalziel *et al.* 1974), crossing South Georgia and perhaps also the South Orkney Is. block

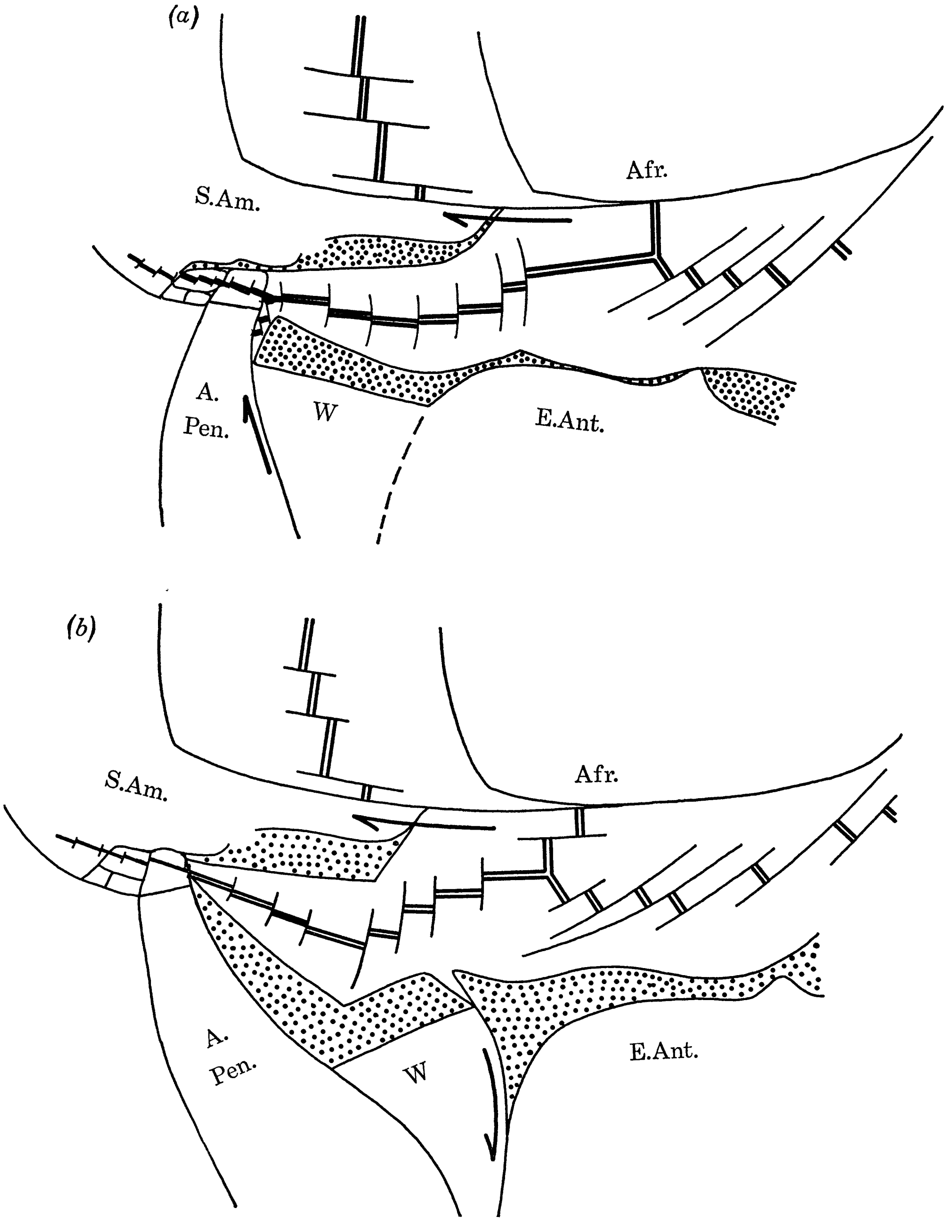

FIGURE 7. Sketch of possible early evolution of Gondwanaland models A and B, showing spreading centres and (stippled) areas of pre-fragmentation downfaulted continental crust.

(Harrington, Barker & Griffiths 1971). The extension of this centre into South America was apparently short-lived and the small marginal basin so produced was compressively deformed in the mid-Cretaceous (Dalziel *et al.* 1974). It becomes possible to see this as a consequence of the hinging of the Antarctic Peninsula.

It is the necessary differences in the evolution of models A and B, however, which are crucial. In model A the Weddell Sea opened by the relative rotation of South America and East Antarctica about a pole in the Pacific not far west of Cape Horn. Magnetic anomalies in the Weddell Sea will today be oriented slightly north of east and, opposite area W, will be without major offset. In model B the Weddell Sea opened by motion of the Antarctic Peninsula away from South America; anomalies near the head of the Weddell Sea will be oriented northwest–southeast in present coordinates, obliquely to the margin, and will have frequent offsets. Farther east in the Weddell Sea, the most southerly anomalies will be oriented north-northwest, reflecting the separation of Africa from East Antarctica. In both models a belt of downfaulted continental material occupies the southernmost Weddell Sea; for model B the belt is thicker in the east and, with the plate geometry as drawn (figure 7*b*), the certainty arises later of compression at the northern end of the East Antarctic–Antarctic Peninsula plate boundary and hence perhaps of the cessation of relative motion.

Conclusions

It should be stressed that A and B are not the only models which can be constructed, although they are among the most likely, and that their evolution in the way described above is not inevitable. Figure 7 is based on relatively simple motions of all the plates concerned, although it is known that South Atlantic opening involved at least two poles of opening, with different rates, that Indian Ocean opening probably was discontinuous (McKenzie & Sclater 1971; Simpson, Schlich *et al.* 1974) and that Weddell Sea opening itself probably stopped before Scotia Sea opening started. Nevertheless, this comparison of the models has demonstrated that they do have *different* consequences for

(1) the palaeo-declination of mid-Jurassic rocks on the Antarctic Peninsula and

(2) the orientation of magnetic anomalies in the Weddell Sea. Moreover it has demonstrated the converse, that these two measurable parameters together will probably provide a unique solution to the major unsolved problem of the reconstruction of Gondwanaland.

Note added in proof (December 1976). Recent palaeomagnetic studies have strengthened the basis of our models. More extensive sampling of the Karroo Supergroup on Madagascar (McElhinny, Embleton, Daly & Pozzi 1976) has given convincing support to an original northern position, as proposed by Du Toit (1937) and assumed (crucially) by us. Also, resampling of the classic Australian Mesozoic sites by Schmidt (1976) has brought the Jurassic palaeopole to within 6° of the East Antarctic pole of figures 3 and 4, confirming a second assumption, that the latter better represented East Gondwanaland than the original anomalous Australian palaeopole of table 1.

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