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WEST ANTARCTICA: PROBLEM CHILD OF GONDWANALAND

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Abstract. The evolution of West (Lesser) Antarctica and its relation to East (Greater) Antarctica have major implications for global plate interactions, paleoclimate, and paleobiogeography, as well as Gondwanaland reconstruction. Analyses of marine geophysical data still lead to seemingly unacceptable overlap between the Antarctic Peninsula and the South American continent or else to geologically questionable relationships. A review of the relevant geological and geophysical data indicates that the problem lies in microplate movement and crustal thinning within West Antarctica during Gondwanaland breakup in the late Mesozoic and Cenozoic. The available data allow a range of possible reconstructions with West Antarctica subdivided into several discrete or semidiscrete microplates. Final solution of this problem requires additional geological and, particularly, geophysical data from West Antarctica as a whole, and the Weddell Sea-Ross Sea embayment in particular. Meantime, it seems inadvisable to use the present continental outline of Antarctica on the Pacific side of the Transantarctic Mountains in reconstructing Gondwanaland.

ANTARCTICA IN GONDWANALAND

The geologic evolution of West (Lesser) Antarctica and its relation to East (Greater) Antarctica have implications far beyond the confines of Antarctic geology or even the jigsaw puzzle of Gondwanaland reconstruction. Firstly, all investigations of global plate interaction during the late Mesozoic and Cenozoic are faced with the possibility that there may have been a plate boundary within the present continent [see, for example, Molnar et al., 1975; Weissel et al., 1977; Jurdy, 1979; Gordon and Cox, 1980]. Secondly, if indeed more than one plate was involved, then there may have been oceanic circulation between the southeast Pacific Ocean and the South Atlantic Ocean before Drake Passage opened about 30 m.y. ago [Barker and Burrell, 1977]. This would in turn have influenced paleoclimate and hence affects views on possible causes of the onset of Antarctic glaciation and the Cenozoic ice age as a whole. Thirdly, the distribution of fossil marsupials strongly suggests migration of primitive forms between South America and Australasia [Cracraft, 1974; Simpson, 1980]. Antarctic paleogeography must have played a critical role in controlling their movements.

Ever since precise predrift geometric reconstructions have been attempted, West Antarctica has been the 'problem child' of Gondwanaland. In attempting a quantitative fit of Africa and Antarctica, Dietz and

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Sproll [1970] accounted for overlap of the Antarctic Peninsula and Africa by dismissing the peninsula as a 'Mesozoic accretionary belt.' Smith and Hallam [1970] encountered the same problem in their computer fit of all the southern continents and attributed the misfit to distortion of the continental outlines subsequent to breakup of the supercontinent. Reconstruction of Gondwanaland based on recent analysis of marine geophysical data [Norton and Sclater, 1979] still runs into overlap problems with the Antarctic Peninsula superimposed on the Falkland Plateau (Figure 1a).

Although many details have yet to be resolved, the relationships between South America and Africa, India and East Antarctica, and East Antarctica and Australia are now defined to the satisfaction of most students of Gondwana geology. Questions do remain concerning the number and extent of possible Gondwanaland fragments now incorporated in Eurasia and the possibility of strike-slip motion between Antarctica and Australia prior to sea floor spreading, but major controversy revolves only around the relationship of the 'eastern' (Australia, India, East Antarctica) and 'western' (Africa, South America) parts of the supercontinent and around its paleo-Pacific (i.e., Panthalassic) margin from South America through West Antarctica to New Zealand. In the final analysis both major problems center on West Antarctica and are exemplified by the Antarctic Peninsula-Falkland Plateau overlap.

Some of those presenting alternatives to the Norton-Sclater [Norton and Sclater, 1979] analysis of the marine data claim that the geology supports a reconstruction with the Antarctic Peninsula lying on the Pacific side of southernmost South America [Barron et al., 1978; Harrison et al., 1979, 1980; Powell et al., 1980] (see also Figure 1b). This certainly is a geometric fit that overcomes the above mentioned overlap problem, and indeed it has been proposed by Ford [1972a], Ford and Kistler [1980], and Miller [1981] on geologic grounds. Yet geologists who have worked in that part of the world maintain that this solution is in fact at variance with the geologic history that has been worked out there over the past decade [see, for example, Dalziel, 1980; Godoy and Mpodozis, 1980], and recently reported paleomagnetic data tend to support a position for the Antarctic Peninsula closer to the Norton-Sclater fit [Longshaw and Griffiths, 1981].

Here we shall review the field data that make overlap of the Antarctic Peninsula with another continental area appear unacceptable in Gondwanaland reconstruction. We shall also review other evidence that seems to us to rule out any reconstruction dependent on the present geography of Antarctica on the Pacific side of the Transantarctic

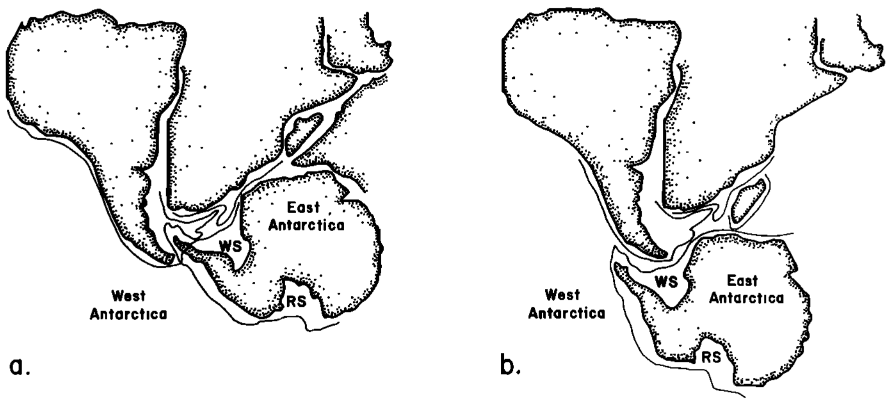

Fig. 1. Gondwanaland reconstruction of (a) Norton and Sclater [1979] and (b) Harrison et al. [1979]. RS is the Ross Sea; WS, the Weddell Sea.

Mountains. We shall present a range of possible alternative solutions and finally point out the type of data required to resolve this important geologic problem.

ANTARCTIC PENINSULA - FALKLAND PLATEAU OVERLAP

It has long been known that continental basement underlies the Paleozoic Table Mountain Sandstone at the southern tip of Africa [Haughton, 1969]. This basement is now known to consist of upper Precambrian metasedimentary rocks intruded by Cambrian granite [Allsopp and Kolbe, 1965]. Recently the continental nature of the eastern tip of the Falkland Plateau was confirmed in the course of the Deep Sea Drilling Project (DSDP) Leg 36 when migmatitic gneiss that proved to be upper Precambrian or lower Paleozoic was cored beneath Jurassic sedimentary rocks at Site 330 [Barker et al., 1976]. Also, the metamorphic complex beneath Devonian strata at Cape Meredith in the Falkland Islands has yielded Precambrian dates [Cingolani and Varela, 1976; Rex and Tanner, 1981]. Hence the South American - African portion of Gondwanaland has a Precambrian or lower Paleozoic continental basement close to its former boundary with Antarctica. Indeed, Precambrian rocks recently dredged from the Agulhas Plateau [Allen and Tucholke, 1981] indicate that the continental basement probably extends to this edge of western Gondwanaland (Figure 2).

Recent field work combined with radiometric dating and a reevaluation of field data compiled by the British Antarctic Survey over many years has resulted in the recognition that the pre-Middle or Late Jurassic basement of the Antarctic Peninsula, South Orkney Islands, and South Shetland Islands comprises rocks of a late Paleozoic to early Mesozoic convergent Pacific margin system [Smellie and Clarkson, 1975; Barker et al., 1976; de Wit, 1977; Dalziel, 1981; Hyden and Tanner, 1981; Smellie, 1981]. This assemblage, which may lie partly on older continental crust [Hamer and Moyes, 1981; Pankhurst, 1981; Smellie, 1981], was deformed, metamorphosed, and uplifted before the deposition of Jurassic to Cretaceous strata that unconformably overlie the basement [Dalziel and Elliot, 1973]. Along the immediate margin are rocks of oceanic affinities such as metachert, mafic volcanic rocks, and ultramafic slices in addition to thick turbidite sequences. Hence the Antarctic Peninsula, at least in part, constitutes an 'accretionary belt,' as maintained by Dietz and Sproll [1970]. Accretion must have occurred, however, before deposition of the Jurassic and Cretaceous cover that is widespread in southern South America as well as the Antarctic Peninsula [Dalziel and Elliot, 1973]. Hence the Antarctic Peninsula must be included in any reconstruction of Gondwanaland, and overlap with the Falkland Plateau or southern Africa does appear to be unacceptable. This contention will become even more compelling if the presence of a lower to middle Paleozoic continental basement in the peninsula is confirmed.

THE PACIFIC MARGIN OF GONDWANALAND

Leaving aside for the moment the detailed geometry of Gondwanaland reconstruction, the upper Paleozoic to lower Mesozoic rocks of the Antarctic Peninsula appear to be part of an ancient Andean-type mountain belt formed along the Pacific margin of the supercontinent prior to fragmentation. The Cape fold belt of southern Africa and Sierra de la Ventana of Argentina constitute parts of a backarc basin (classically a foredeep) of this mountain belt that du Toit [1937] referred to as the Gondwanide orogen.

In South America a fore arc terrain of the Gondwanide orogen can be traced from central Chile to Tierra del Fuego [Dalziel, 1981; Forsythe, 1982] and possibly South Georgia [Tanner and Rex, 1979] (see also Fig-

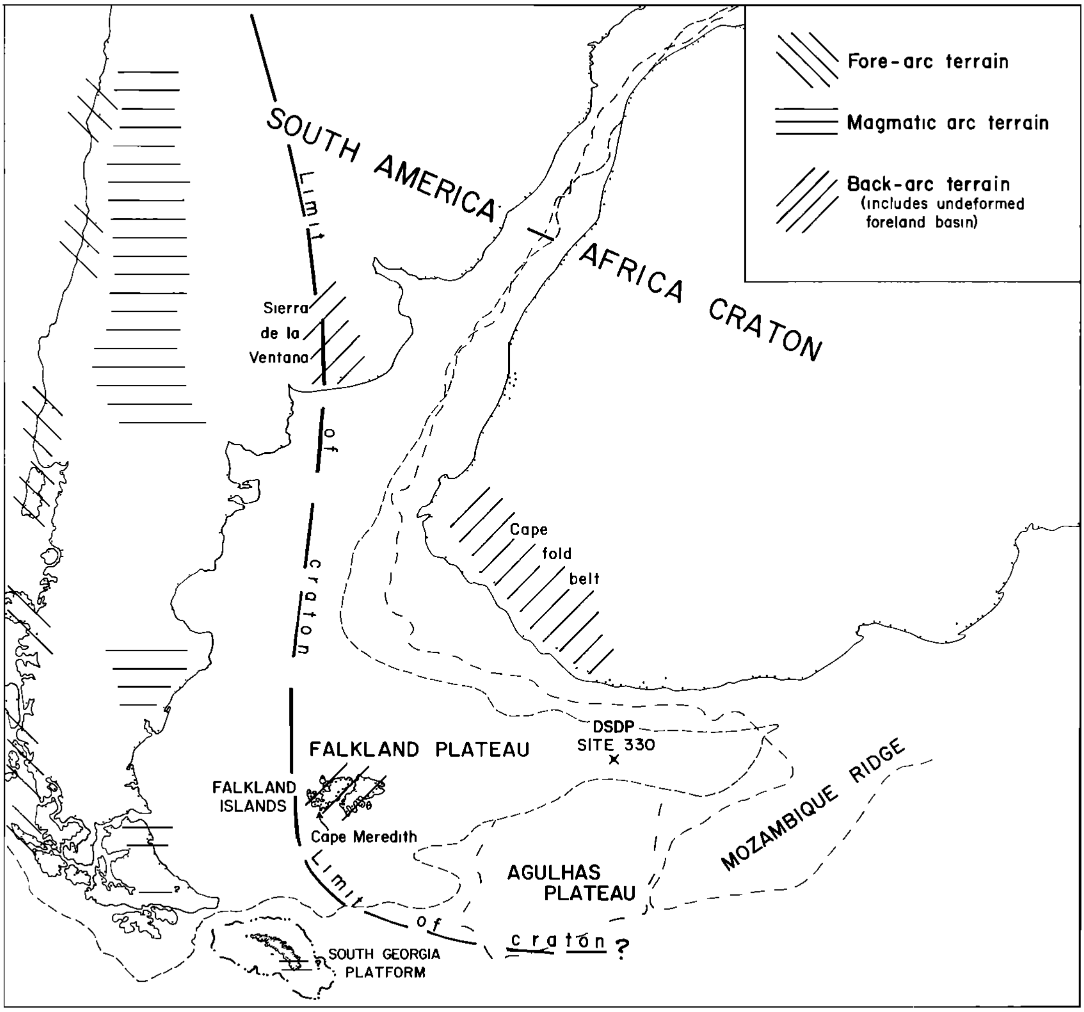

Fig. 2. Map of South America-Africa segment of Gondwanaland (western Gondwanaland) prior to opening of the South Atlantic Ocean Basin, showing location of late Paleozoic to early Mesozoic fore arc, magmatic arc, and back arc terrains. South American data are largely based on the literature research of Forsythe [1982]. Location of Agulhas Plateau is after Allen and Tucholke [1981], location of South Georgia after Dalziel et al. [1975] and Tanner [1981].

ure 2). As mentioned above, it is unconformably overlain by Middle to Upper Jurassic volcanic and sedimentary strata. In Antarctica, Gondwanaland fore arc assemblages have been reported as far south as Alexander Island [Edwards, 1981] (see also Figure 3) but have not yet been positively identified along the Pacific coast to the west of the Antarctic Peninsula, although metamorphosed equivalents may be present in the poorly known Thurston Island area (Figure 3). Still further west, general continuity with the fore arc terrain of the Rangitata orogen in New Zealand has been argued [Hyden and Tanner, 1981], though the timing of deformation and metamorphism varies along strike.

Magmatic arc rocks of late Paleozoic to early Mesozoic age are sparsely distributed in Antarctica but comparatively common in South America and New Zealand [Landis and Bishop, 1972; Tanner and Rex, 1979;

Fig. 3. Map of Antarctica, showing present location of late Paleozoic to early Mesozoic fore arc, magmatic arc, and back arc terrains. AL, Alexander Island; EL, Ellsworth Land; EM, Ellsworth Mountains; HN, Haag Nunataks; JM, Jones Mountains; SOI, South Orkney Islands; SSI, South Shetland Islands; W, Whitmore Mountains.

Forsythe, 1982] (see Figures 2 and 3). There are a few occurrences along the Antarctic Peninsula [Pankhurst, 1981], and more may be present on the eastern continental shelf of the peninsula beneath the Weddell Sea, as suggested by Smellie [1981]. Radiometrically dated plutons of this age are also known in the Jones Mountains [Craddock et al., 1964] and the Whitmore Mountains [Craddock, 1972a,b] (see Figure 3), and other slightly younger plutons on the Ellsworth Mountains - Thiel Mountains ridge and Thurston Island area may be part of the same magmatic arc.

The existence of a late Paleozoic to early Mesozoic magmatic arc is also supported by abundant evidence of contemporaneous volcanism in the sedimentary rocks that form the back arc terrain, principally foreland basins (foredeeps), of the Gondwanide orogen: the Sierra de la Ventana sequence in Argentina, the Karroo Supergroup of the Cape fold belt in South Africa, and the Beacon Supergroup of the Transantarctic Mountains (Figures 2 and 3). In the Karroo, volcanic detritus is found in Permian strata [Elliot and Watts, 1974; Martini, 1974], and the possibility of ash, certainly of volcanic debris, in the overlying Triassic rocks is strongly suggested by the widespread occurrence of laumontite [Fuller, 1971]. The Victoria Group in the Transantarctic Mountains also contains abundant volcanic detritus, although contemporaneous volcanism is not evident until the Middle to Late Triassic [see Elliot, 1975].

The rocks of the fore arc terrain are nearly everywhere intensely and complexly deformed [Dalziel, 1981, 1982a,b; Forsythe, 1982]. In the back arc terrain, foreland folding and thrusting are well documented in the Sierra de la Ventana [Coates, 1969], the Cape fold belt [Haughton, 1969], and the Pensacola Mountains on the margin of the East Antarctic craton [Ford, 1972b] (see Figure 3). The deformation in the Cape fold belt and the Pensacola Mountains took place in the early Mesozoic, although two earlier periods of deformation are also recorded in the Pensacola Mountains [Ford, 1972b].

In contrast, the isolated Ellsworth Mountains (Figure 3), which include a sequence with marked stratigraphic similarities to that of the Cape fold belt, appear to show the imprint of only one deformation for which Craddock [1972a] infers an early Mesozoic age. The most notable feature of the Ellsworths in relation to the Cape fold belt and the Transantarctic Mountains is the orientation of the early Mesozoic tectonic fabric. This is along the length of the mountains and at a high angle to the fabric of the same age in the Pensacola Mountains (Figure 3). Thus it appears that although du Toit [1937] effectively showed the continuity of the back arc terrains and structures of the Sierra de la Ventana and Cape fold belts by closing up the South Atlantic Ocean basin (Figure 2), the distribution of the elements of the Gondwanide orogen in the Antarctic segment of the Gondwanaland supercontinent is more complex (Figure 3).

WEST ANTARCTICA AS A CONTINENTAL MOSAIC

Less than 2% of the bedrock of the Antarctic continent is exposed. In West Antarctica the proportion is slightly higher, but the exposures of the fore arc, magmatic arc, and back arc terrains of the Gondwanide orogen are still very scattered (Figure 3). Apart from the overlap of the Antarctic Peninsula and the Falkland Plateau, there are two principal lines of evidence indicating that the exposed rocks of West Antarctica are the uppermost parts of a mosaic of more or less discrete continental fragments that have moved relative to each other and to the East Antarctic craton. The first line concerns the anomalous position and structural orientation of the Ellsworth Mountains referred to above, and the second concerns the crustal structure and morphology of West Antarctica as a whole.

Rocks exposed in the Ellsworth Mountains range from at least as old as Cambro-Ordovician to Permian in a sequence without obvious stratigraphic breaks, although major disconformities may be present. A thick diamictite of glacial origin and overlying Glossopteris-bearing strata of Permian age form the top of the succession [Craddock, 1969]. As mentioned previously, only one major episode of deformation affects the whole sequence of strata. The absence of the two earlier periods of deformation documented in the Pensacola Mountains and obvious ties to the Gondwana craton margin sequences in the Transantarctic Mountains generally (Glossopteris has not been found in West Antarctica outside the Ellsworth Mountains) led to the suggestion first advanced by

Schopf [1969] that the Ellsworth Mountains were originally located between Africa and the Transantarctic Mountains. In this model the Pensacola Mountains would have lain closer to the Pacific margin of Gondwanaland than did the Ellsworth Mountains, thus accounting for the earlier deformation episodes present in the former but absent in the latter [Ford, 1972b].

Given their isolation, the anomalous structural trend of the Ellsworth Mountains suggests possible rotation during displacement from a position along the Transantarctic Mountains - Cape fold belt - Sierra de la Ventana margin of the Gondwana craton. The strong easterly vergence (present coordinates) of folds in the Ellsworth Mountains [Hjelle et al., 1978; I. W. D. Dalziel, unpublished observations] indicate, when compared with the cratonward vergence in the Cape fold belt and Sierra de la Ventana, that the rotation was counterclockwise. Preliminary paleomagnetic data from lower Paleozoic strata there support a rotation of approximately 90° in this sense [Watts and Bramall, 1981] that would account for the anomalous structural trend.

Subice morphology indicates that the Ellsworth Mountains are topographically connected to a line of nunataks extending southeastwards toward the Thiel Mountains [Drewry et al., 1980; Jankowski and Drewry, 1981] (see Figure 4). Hence restoration of the entire Ellsworth Mountains block to a position along the margin of the Gondwana craton by clockwise rotation would remove the 190-163 m.y. old granitic plutons exposed in these nunataks [Craddock, 1972b; Kovach and Faure, 1978; Webers et al., 1981] from their present close proximity to contemporaneous tholeiitic rocks of the Ferrar Supergroup in the Transantarctic Mountains [Fleck et al., 1977; Kyle et al., 1981]. Indeed, it places the granitic rocks in a position more compatible than their present one with respect to the contemporaneous magmatic arc terrain of the Gondwaide orogen as defined by calc-alkaline igneous rocks in South America and the Antarctic Peninsula and volcanic detritus in southern Africa (Figure 3). Finally, restoration of the Ellsworth Mountains continental block in this way would place the metamorphic rocks of the adjoining Haag Nunataks (Figure 3) that have yielded radiometric dates of approximately one b.y. [Clarkson and Brook, 1977], thereby making them the only known Precambrian crystalline rocks in West Antarctica, close to or within the Precambrian craton of Gondwanaland [Dalziel, 1981]. Hence the geology of the Ellsworth Mountains and the Ellsworth-Thiel Mountains ridge is much better understood by envisaging counterclockwise rotation of a continental fragment than by adhering to a 'stabilist' view.

Although the crustal structure of West Antarctica is as yet imprecisely known, its thickness of 25-30 km (in contrast to 35-40 km for the East Antarctic craton; see summary by Bentley [1973]) and subice morphology broadly support the geologic arguments set forth above. The crustal structure changes abruptly along the front of the Transantarctic Mountains. A deglaciated West Antarctica would be an archipelago whose main land masses would be the Antarctic Peninsula, Thurston Island and part of the Eights Coast, the Ellsworth Mountains including the ridge extending towards the Thiel Mountains, and Marie Byrd Land (Figure 4).

The subglacial morphology of West Antarctica has two further characteristics of importance: firstly, the occurrence of significant areas at depths greater than 1000 m below sea level and attaining maxima of more than 2500 m and secondly, the presence of steep subglacial escarpments. Some question still remains about the extent of glacial overdeepening in the development of the subice morphology, for instance, in narrow troughs on the Weddell Sea side of the Ellsworth Mountains where there are particularly steep escarpments and subglacial depths exceeding 1600 m (Swithinbank [1977]; unpublished data of British Antarctic Survey and Lamont-Doherty Geological Observatory; see Doake et al. [1982]). Nevertheless, the subice morphology does provide

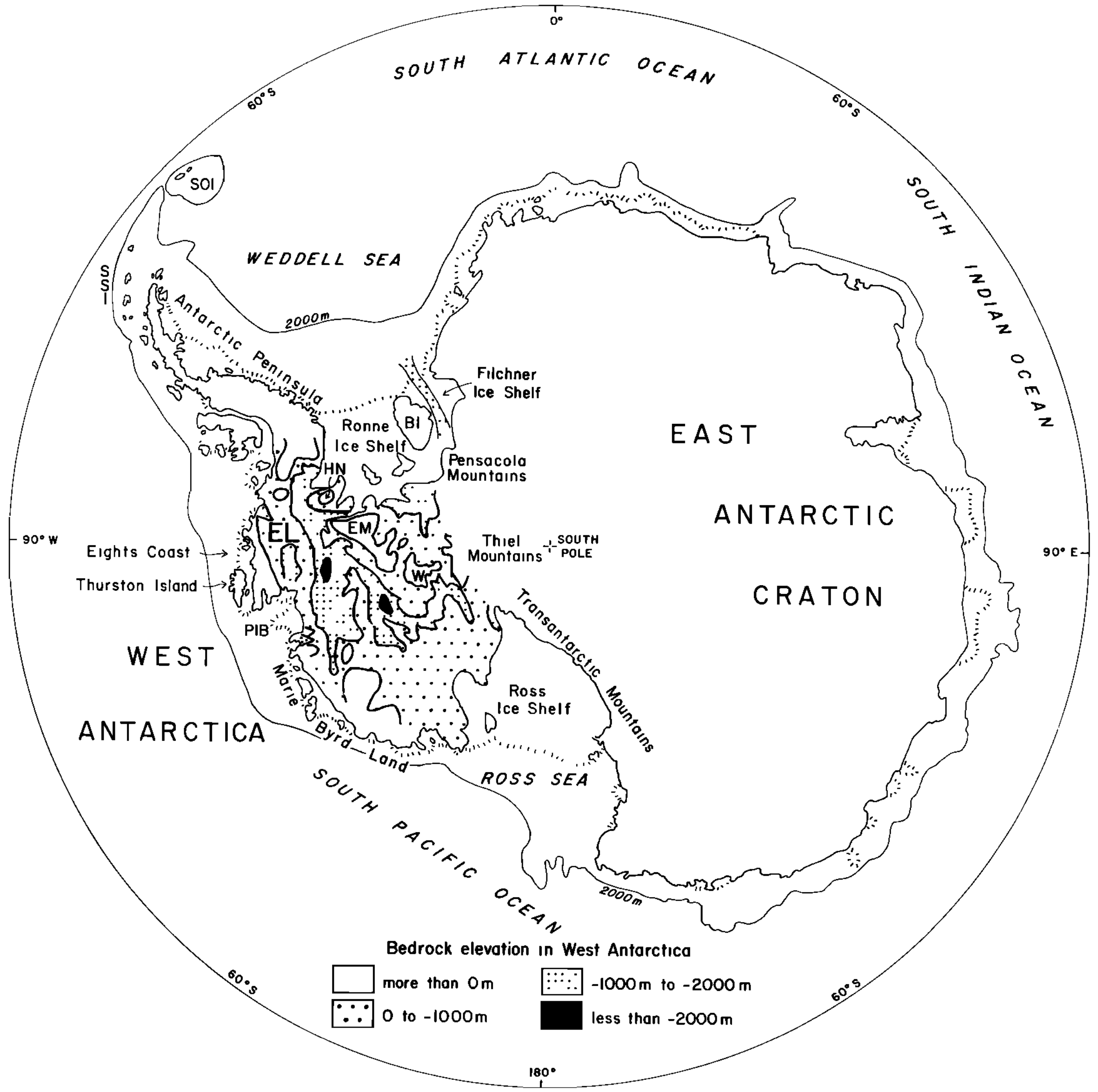

Fig. 4. Subglacial topography of West Antarctica from Bentley [1973], Swithinbank [1977], Behrendt et al. [1980], Jankowski and Drewry [1981], Masolov et al. [1981], and unpublished data of the British Antarctic Survey and Lamont-Doherty Geological Observatory [see Doake et al., 1982]. BI, Berkner Island; EL, Ellsworth Land; EM, Ellsworth Mountains; PIB, Pine Island Bay; SOI, South Orkney Islands; SSI, South Shetland Islands; W, Whitmore Mountains.

a first-order approximation of the boundaries of the crustal fragments making up West Antarctica, for the magnetic signature and the limited data on seismic wave velocities of the rocks in the depressions indicate that they differ from the topographic highs and are probably infilled with undeformed sedimentary and volcanic sequences [Jankowski and Drewry, 1981].

The main subice depression of West Antarctica, the Byrd subglacial basin, runs from the Ross Sea between the Ellsworth-Thiel Mountains ridge to the south and east and Marie Byrd Land, Thurston Island, and the Antarctic Peninsula to the north and west. Deep depressions of more limited extent separate Marie Byrd Land from Thurston Island and the Eights Coast, Thurston Island and the Eights Coast from the Antarctic Peninsula, and the Ellsworth Mountains from the Transantarctic Mountains (Figure 4). Thus, while recognizing the limitations of arguments based on morphology, the subglacial morphology does support the geologic evidence that the Ellsworth Mountains block and the Antarctic Peninsula are microcontinents that may have moved relative to each other, relative to other parts of West Antarctica, and relative to the East Antarctic craton.

From the foregoing brief analysis of West Antarctic geology and morphology it seems clear to us that complete reconstruction of Gondwanaland demands consideration not merely of two former Antarctic plates but indeed perhaps of several former West Antarctic microplates in addition to the single larger one incorporating the East Antarctic craton. It seems to us that the most plausible explanation for the overlap of the Antarctic Peninsula with the Falkland Plateau in the reconstruction based on analysis of marine geophysical data [Norton and Sclater, 1979] (see also Figure 1a) and for the anomalous position and orientation of the Ellsworth Mountains (Figure 3) is that relative motion has occurred of small lithospheric plates incorporating microcontinents.

In this regard it should be noted that although the nature of the crust in the southern and western parts of the Weddell Sea and beneath the Ronne Ice Shelf is poorly known, the bathymetry and magnetic signature of the northern and eastern parts of the Weddell basin indicate unequivocally its oceanic character there [LaBrecque and Barker, 1981]. Hence any relative motion between the microplates incorporating the Antarctic Peninsula and the Ellsworth Mountains presumably took place by the normal mechanisms of continental rifting and sea floor spreading, contemporaneous with the fragmentation of Gondwanaland and the development of the southern oceans. The presence throughout the Transantarctic Mountains of the Jurassic mafic igneous rocks of the Ferrar Supergroup, including the Dufek layered intrusion in the Pensacola Mountains [Behrendt et al., 1981; Kyle et al., 1981] seems to support this view of major rifting throughout West Antarctica.

DISCUSSION: TOWARDS A PERFECT GONDWANALAND

From the standpoint of the geology of southern South America, South Africa, and Antarctica it is our belief that the fit of Norton and Sclater [1979] based on marine geophysical data is basically correct in all respects except for the West Antarctic geography and hence the Antarctic Peninsula - Falkland Plateau overlap. Leaving aside questions concerning the interpretation of the marine data, we believe that the geologic and geophysical data from Antarctica discussed above rule out the simplistic approach of fitting southern South America into the Weddell Sea [Ford, 1972a; Barron et al., 1978; Harrison et al., 1979, 1980; Powell et al., 1980]. As argued by Dalziel [1980] and Godoy and Mpodozis [1980], the geology of southern South America is also difficult to reconcile with this solution as are the paleomagnetic data [Longshaw and Griffiths, 1981]. The fit arrived at by Norton and Sclater is essentially the same as that suggested by du Toit [1937] on purely geologic grounds and by Smith and Hallam [1970] on the basis of geology and quantitative geometric reassembly of the continental outlines.

For the reasons set out in the previous section, we believe that the solution to the Antarctic Peninsula-Falkland Plateau overlap problem and hence the ultimate solution to the reconstruction of a 'perfect' Gondwanaland, lies in recognizing that West Antarctica consists of a number of discrete or semidiscrete microcontinental blocks that probably moved relative to one another and to the East Antarctic craton during the breakup of the Gondwana supercontinent and the development of the southern oceans.

Few data are available to constrain the extent, let alone the original position, of the individual blocks. Nevertheless, certain limits can be placed on these questions at the present time, and we shall attempt to set them out.

Antarctic Peninsula

The geology of the Antarctic Peninsula clearly indicates that it was part of the immediate Pacific margin of Gondwanaland before breakup. Indeed, detailed structural studies in the pre-Late Jurassic fore arc terrain of the South Orkney Islands and South Shetland Islands indicate that the present Pacific margin of the Antarctic Peninsula may be closely related to the early Mesozoic margin [Dalziel, 1982a,b].

Morphologically and geologically, the Antarctic Peninsula extends south into the region known as Ellsworth Land (Figure 4). Given the sigmoid shape of the peninsula, it is tempting to appeal to oroclinal bending [Carey, 1958] to explain, at least in part, its overlap with the Falkland Plateau. Paleomagnetic data strongly indicate, however, that the eastward bend in the critical northern section existed before the end of the Mesozoic [Dalziel et al., 1973; Kellogg and Reynolds, 1978]. Although limited data can be taken to suggest that westward oroclinal bending of the southern extremity has taken place [Kellogg, 1980], this does not resolve the problem of overlap with the Falkland Plateau.

The original orientation of the Antarctic Peninsula microcontinental block with respect to the South American, African, and East Antarctic segments of the Gondwana supercontinent is at present constrained only by unpublished paleomagnetic data and by the fact that it was part of the active Pacific margin before breakup. It must have been located Pacificward of the Falkland Plateau, southern Africa, and the East Antarctic craton, for these areas contain no rocks of the prebreakup magmatic arc terrain. Paleomagnetic data are reported to indicate an original position south of Cape Horn and an original orientation roughly comparable to its present one [Longshaw and Griffiths, 1981].

Thurston Island - Eights Coast

This small continental block is poorly exposed and has been little studied. As mentioned above, it seems to have been part of a Gondwanaland margin magmatic arc before breakup and possibly also exposes part of the fore arc terrain seen in the South Orkney and South Shetland Islands. Hence, although it seems to be separated from the Antarctic Peninsula by a significant morphological break, it was probably originally located close to the base of the peninsula.

Ellsworth Mountains

It is clear that the Ellsworth Mountains form part of a crustal block extending south as far as the Thiel Mountains and west as far as the Whitmore Mountains (Figure 4). The block is bounded to the east and west by major depressions. The subice morphology suggests the possibility of significant structural breaks within the block [Jankowski and Drewry, 1981] (see Figure 4). As outlined above, the Ellsworth Mountains must have been located along the margin of the East Antarctic craton. The fold vergence and paleomagnetic data indicate restoration to their original position by clockwise rotation. Restoration in this fashion is supported by the geology of the surrounding nunataks, such as the Whitmore Mountains and the Haag Nunataks, as discussed above. In the simplest reconstruction of this zone, therefore, the Ellsworth Mountains microcontinent, together with the Haag Nunataks and several other upstanding crustal blocks that core ice rises on the Ronne Ice Shelf

[Doake et al., 1982] would lie adjacent to Berkner Island against the margin of the East Antarctic craton. This is, however, regarded as an unlikely reconstruction because it conflicts with the fact that the rocks of the Ellsworth Mountains have undergone only one episode of deformation in contrast with more than one for the rocks of the Pensacola Mountains.

Therefore the Ellsworth Mountains block must have been translated, presumably from the north, as well as rotated. Such translation implies that the Ellsworth Mountains were a link between the Cape fold belt and the Transantarctic Mountains as suggested by Schopf [1969] and must therefore be compatible with geological and geophysical data from the Ronne Ice Shelf region (Figure 4). Although the subglacial trough beneath the Filchner Ice Shelf has been interpreted as a rift [Masolov et al., 1981] and there is a deep depression between the Ellsworth Mountains and the Pensacola Mountains [Jankowski and Drewry, 1981], data for the critical part of the Ronne Ice Shelf between Berkner Island and the Antarctic Peninsula are totally lacking.

Marie Byrd Land

This continental block is separated from the Ellsworth Mountains block by the deep subice basin, mentioned above, and from the Thurston Island - Eights Coast block by the narrow but profound depression beneath the Pine Island glacier (Figure 4). The geological history of Marie Byrd Land is poorly known because of the fragmentary record. Nevertheless the record of Paleozoic and Mesozoic igneous, metamorphic, and metasedimentary rocks, together with reasonable reconstructions based on closure across the Pacific-Antarctic ridge before Early Cretaceous time, support it having been part of the Pacific margin of Gondwanaland.

The morphology of the Byrd subglacial basin (Figure 4), together with preliminary geophysical results indicating that volcanism was involved in its development [Jankowski and Drewry, 1981], suggests that this depression also had an extensional origin. Indeed, Cenozoic alkaline volcanism is widespread in Marie Byrd Land. This in turn suggests that Marie Byrd Land may have undergone some translation and rotation with respect to the East Antarctic craton. The paleomagnetic test of the early Tertiary circuit between the Pacific, Antarctic, and Indian plates, carried out by Gordon and Cox [1980], indicates that movement between Marie Byrd Land and East Antarctica has indeed occurred.

New Zealand

The original location of the New Zealand microcontinent is also part of the West Antarctic problem. The sea floor spreading history of the Pacific-Antarctic ridge indicates that New Zealand originated as part of the Pacific margin of Gondwana in the vicinity of the present Ross Sea [Molnar et al., 1975; Weissel et al., 1977; Grindley and Davey, 1981]. Moreover, the petrology of the Beacon Supergroup in the Transantarctic Mountains requires the presence of an active magmatic arc during Triassic time at least in the region now occupied by Marie Byrd Land, the Ross Ice Shelf, and the Ross Sea [see Elliot, 1975]. Such an arc was present in New Zealand [Landis and Bishop, 1972], and as previously mentioned, the Rangitata orogen has been considered a continuation of the late Paleozoic to early Mesozoic fore arc terrain of the Antarctic Peninsula area [Hyden and Tanner, 1981]. Therefore, despite uncertainties concerning their exact original locations, Marie Byrd Land and the present New Zealand microcontinent appear to be the only likely fragments of this portion of the active convergent Pacific margin of Gondwana in the late Paleozoic to early Mesozoic.

Clearly we are not yet in a position to precisely reconstruct the

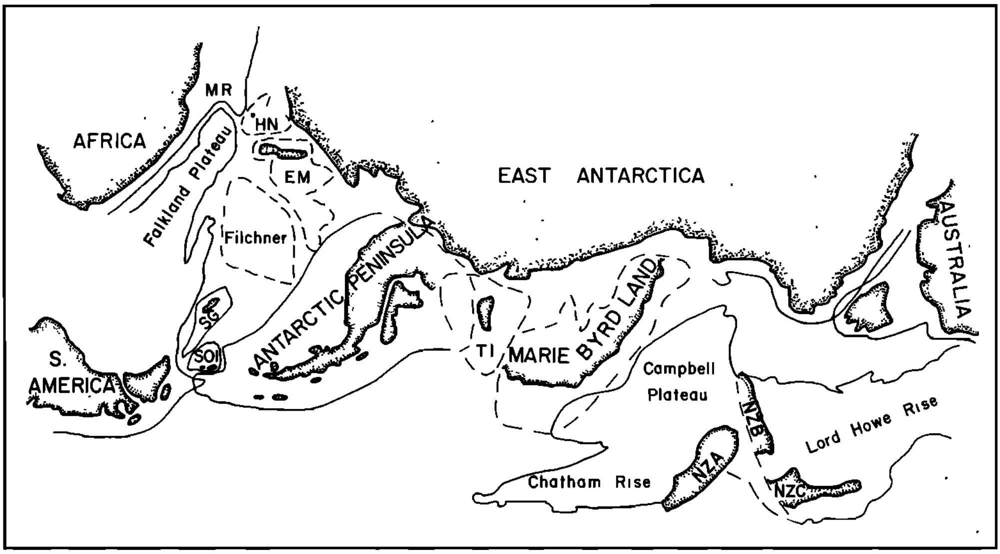

Fig. 5. One possible reconstruction of part of the Pacific margin of Gondwanaland based on the results of the Reunite Gondwanaland Workshop. See text for discussion. EM, Ellsworth Mountains block; HN, Haag Nunataks; MR, Mozambique Ridge; NZA, NZB, NZC, parts of New Zealand; SG, South Georgia; SOI, South Orkney Islands; TI, Thurston Island block.

Pacific margin of Gondwana from southern South America through West Antarctica to New Zealand. In order to work out the original relationships of the unquestionably continental areas of West Antarctica to the East Antarctic craton as well as to each other, new data are required: (1) geophysical data including magnetics, detailed bathymetry, gravity, subice topography, and refraction and reflection seismics throughout West Antarctica and the Weddell Sea - Ross Sea embayment in particular, (2) geologic and paleomagnetic data from the base of the Antarctic Peninsula, the Thurston Island - Eights Coast area, the Ellsworth Mountains - Thiel Mountains subglacial ridge, and Marie Byrd Land, and (3) geologic and geophysical data on the nature of the Transantarctic Mountains front.

Attempts to reconstruct the Pacific margin of Gondwanaland, recognizing the existence of several microplates in West Antarctica, have so far been limited to the Scotia arc region [Barker et al., 1976; de Wit, 1977; Dalziel et al., 1981]. The reconstruction involving the entire Antarctic margin of Gondwanaland, shown in Figure 5, emerged from a workshop convened by Louis Nicolaysen of the Bernard Price Institute of the University of Witwatersrand, South Africa and is similar to that being incorporated in the first geologic map of the Gondwanaland supercontinent [de Wit et al., 1982]. While illustrating the type of solution required for reconstruction of the Pacific margin of Gondwanaland, it also illustrates some remaining major difficulties. Foremost is a 'space' problem. It is difficult to find room along the immediate Pacific margin for the Antarctic Peninsula, Thurston Island - Eights Coast, Marie Byrd Land, and New Zealand blocks, especially taking into account the Chatham Rise and Campbell Plateau. Second, there are as yet no firm constraints on the amount of crustal extension between Marie Byrd Land and the East Antarctic craton, and third, there are few constraints on the reconstruction of the Weddell Sea area.

The original orientation and position of the Antarctic Peninsula are critical for the magnitude of the space problem. The Antarctic Peninsula must have been located between two end member positions, as illus-

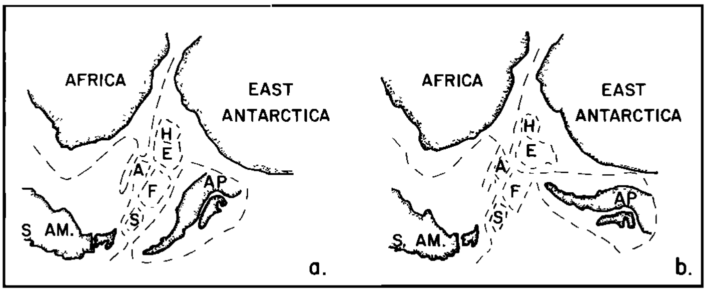

Fig. 6. Reconstructions of Gondwanaland in the Weddell Sea - South Atlantic Ocean area, demonstrating alternative positions for the Antarctic Peninsula. See text for discussion. A, Agulhas Plateau; AP, Antarctic Peninsula; E, Ellsworth Mountains block; F, Filchner block; H, Haag Nunataks; S, South Georgia.

trated in Figure 6. Because there is no evidence for Gondwanian magmatic arc rocks along the southern (present coordinates) margin of the Falkland Plateau, yet the Karroo rocks contain contemporaneous volcanic debris, a reconstruction with the Antarctic Peninsula along the West Gondwanaland margin seems more likely (Figure 6a). Paleomagnetic data are also reported to favor such a reconstruction [Longshaw and Griffiths, 1981]. It reduces, but does not eliminate, the space problem (Figures 5 and 6).

Four general possibilities have been suggested to account for the space problem. One has the whole of the Pacific margin microplate system shifted left-laterally with respect to the Gondwana craton along the Transantarctic Mountains front - Australian eastern continental margin. Another has East Gondwanaland rotated anticlockwise with respect to West Gondwanaland. A third requires one or more of the microplates to be allochthonous. The fourth, paradoxically perhaps, allows larger areas for the individual microplates of West Antarctica and hence a less 'closely packed' reconstruction than that shown in Figure 5. This would help to eliminate the striking and entirely hypothetical oroclinal bend between the Chatham Rise and Thurston Island in the reconstruction shown here [G. W. Grindley, personal communication, 1980].

We know of no compelling evidence in favor of any one of those four possibilities. Nevertheless, we believe the solution does lie in the microplates constituting the Pacific margin and that they will be critical in the solution that will eventually emerge for this remote, enigmatic, but important sector of Gondwanaland.

CONCLUSIONS

The available geologic, paleomagnetic, marine, and airborne geophysical data indicate that West Antarctica consists of several discrete or semidiscrete microcontinental blocks. Motion of these blocks relative to each other and relative to the East Antarctic segment of the Gondwana craton appears to have taken place during the late Mesozoic to early Cenozoic. This seems to explain Antarctic Peninsula-South America overlap but rules out the use of the present continental outline of Antarctica on the Pacific side of the Transantarctic Mountains in Gondwanaland reconstruction.

Without new geologic and geophysical data from the Weddell Sea-Ross Sea embayment, in particular, it seems to us unlikely that any definitive reconstruction of the West Antarctic portion of the Gondwanaland margin is going to emerge, let alone that we can go ahead and solve the more important problems of global plate interaction, paleoclimate, and paleobiogeography that depend on understanding the relationship of East and West Antarctica throughout the Mesozoic and Cenozoic.

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REFERENCES

Allen, R. B., and B. E. Tucholke, Petrography and implications of continental rocks from the Agulhas Plateau, southwest Indian Ocean, Geology, 9, 463-468, 1981.

Allsopp, H. L., and P. Kolbe, Isotopic age determinations of the Cape granite and intruded Malmesbury sediments, Cape Province, South Africa, Geochim. Cosmochim. Acta, 29 (10), 1115-1130, 1965.

Barker, P. F., and J. Burrell, The Opening of Drake Passage, Marine Geol., 25, 15-34, 1977.

Barker, P. F., I. W. D. Dalziel, et al., The evolution of the southwestern Atlantic Ocean Basin: Leg 36 data, in Initial Reports of the Deep Sea Drilling Project, vol. 36, edited by S. W. Wise Jr., U.S. Government Printing Office, Washington, D.C., 1976.

Barron, E. J., C. G. A. Harrison, and W. W. Hay, A revised reconstruction of the southern continents, Eos Trans. AGU, 59 (5), 436-449, 1978.

Behrendt, J. C., D. J. Drewry, E. Jankowski, and M. S. Grim, Aeromagnetic and radio echo ice-sounding measurements over the Dufek intrusion, Antarctica, J. Geophys. Res., 86, 3014-3020, 1981.

Bentley, C. R., Crustal structure of Antarctica, Tectonophysics, 20 (1-4), 229-240, 1973.

Carey, S. W., A tectonic approach to continental drift, Proc. R. Soc. Tasmania, 89, 255-288, 1958.

Cingolani, C. A., and R. Varela, Investigaciones Geologicas y Geocronologicas en el extremo Sur de la Isla Gran Malvina, Sector de Cabo Belgrano (Cabo Meredith), Islas Malvinas, Actas Congr. Geol. Argent., 6, 1976.

Clarkson, P. D., and M. Brook, Age and position of the Ellsworth Mountains crustal fragment, Antarctica, Nature, 265, 615-616, 1977.

Coates, D. A., Stratigraphy and sedimentation of the Sauce Grande Formation, Sierra de la Ventana, Southern Buenos Aires Province, Argentina, in Gondwana Stratigraphy, pp. 799-819, International Union of Geological Sciences Symposium, UNESCO, Paris, 1969.

Cracraft, J., Continental drift and vertebrate distribution, Ann. Rev. Ecol. Systemat., 5, 215-261, 1974.

Craddock, C., Geology of the Ellsworth Mountains, Antarctic Map Folio Ser., folio 12, sheet 4, edited by C. Craddock and V. Bushnell, Am. Geogr. Soc., New York, 1969.

Craddock, C., Antarctic tectonics, in Antarctic Geology and Geophysics, edited by R. J. Adie, pp. 449-455, Universitetsforlaget, Oslo, 1972a.

Craddock, C., Geologic map of Antarctica. Am Geogr. Soc., New York, 1972b.

Craddock, C., T. W. Bastein, and R. H. Rutford, Geology of the Jones Mountains area, in Antarctic Geology, edited by R. J. Adie, pp. 171-187, North Holland, Amsterdam, 1964.

Dalziel, I. W. D., Comment on Mesozoic evolution of the Antarctic Peninsula and the southern Andes by C. G. A. Harrison, E. J. Barron, and W. W. Hay, Geology, 8, 260-261, 1980.

Dalziel, I. W. D., Pre-Jurassic history of the Scotia Arc region, in

Antarctic Geoscience, edited by C. Craddock, University of Wisconsin Press, Madison, Wisconsin, 1981.

Dalziel, I. W. D., Structural evolution of a Gondwanaland margin subduction complex, southern Scotia Ridge, Antarctica, submitted to J. Geol. Soc. London, in press, 1982a.

Dalziel, I. W. D., Deformation of Gondwanaland margin fore-arc basin deposits, southern Scotia Ridge, Antarctica, submitted to J. Geol. Soc. London, in press, 1982b.

Dalziel, I. W. D., and D. H. Elliot, The Scotia Arc and Antarctic Margin, in The South Atlantic, The Ocean Basins and Margins, vol. 1, edited by A. E. M. Nairn and F. G. Stehli, pp. 171-245, Plenum Press, New York, 1973.

Dalziel, I. W. D., R. Kligfield, W. Lowrie, and N. D. Opdyke, Palaeomagnetic data from the southernmost Andes and the Antarctandes, in Implications of Continental Drift to the Earth Sciences, vol. 1, edited by D. H. Tarling and S. K. Runcorn, pp. 87-101, Academic, New York, 1973.

Dalziel, I. W. D., R. H. Dott, Jr., R. D. Winn, Jr., and R. L. Bruhn, Tectonic relations of South Georgia Island to the southernmost Andes, Geol. Soc. Am. Bull., 86, 1034-1040, 1975.

Dalziel, I. W. D., D. H. Elliot, D. L. Jones, J. W. Thomson, M. R. A. Thomson, N. A. Wells, and W. J. Zinsmeister, The geological significance of some Triassic microfossils from the South Orkney Islands, Scotia Ridge, Geol. Mag., 118, 15-25, 1981.

de Wit, M. J., The evolution of the Scotia Arc as a Key to the Reconstruction of Southwestern Gondwanaland, Tectonophysics, 37, 58-81, 1977.

de Wit, M. J., M. Jeffrey, H. Bergh, and L. O. Nicolaysen, Geologic map of Gondwanaland, Bernard Price Institute of Geophysical Research, University of the Witwatersrand, Johannesburg, in press, 1982.

Dietz, R. S., and W. P. Sproll, Fit between Africa and Antarctica: A continental drift reconstruction, Science, 167, 1612-1614, 1970.

Doake, C. S. M., R. D. Crabtree, and I. W. D. Dalziel, Airborne echo-sounding in Ellsworth Land and Ronne Ice Shelf, Antarct. J. U.S., in press, 1982.

Drewry, D. J., D. T. Meldovan, and E. Jankowski, Radio echo and magnetic sounding of the Antarctic ice sheet, 1978-79, Polar Rec., 20, 43-57, 1980.

du Toit, A. L., Our Wandering Continents, Oliver and Boyd, Edinburgh, 1937.

Edwards, C. W., Further paleontological evidence of Triassic sedimentation in Western Antarctica, in Antarctic Geoscience, edited by C. Craddock, University of Wisconsin Press, Madison, Wisconsin, 1981.

Elliot, D. H., Gondwana basins of Antarctica, in Gondwana Geology, edited by K. S. W. Campbell, pp. 493-536, Australia National University Press, Canberra, 1975.

Elliot, D. H., and D. Watts, The nature and origin of volcaniclastic material in some Karroo and Beacon rocks, Trans. Geol. Soc. South Africa, 77, 109-111, 1974.

Fleck, R. J., J. F. Sutter, and D. H. Elliot, Interpretation of discordant $^{40}Ar/^{39}Ar$ age spectra of Mesozoic tholeiites from Antarctica, Geochim. Cosmochim. Acta, 41 (1), 15-32, 1977.

Ford, A. B., Fit of the Gondwana continents: Drift reconstruction from the Antarctic continental viewpoint, 24th International Geological Congress, Montreal, August 1972a.

Ford, A. B., Weddell orogeny: Latest Permian to early Mesozoic deformation at the Weddell Sea Margin of the Transantarctic Mountains, in Antarctic Geology and Geophysics, edited by R. J. Adie, pp. 419-425, Universitetsforlaget, Oslo, 1972b.

Ford, A. B., and R. W. Kistler, K-Ar age, composition, and origin of Mesozoic mafic rocks related to Ferrar Group, Pensacola Mountains, Antarctica, N.Z. J. Geol. Geophys., 23, 371-390, 1980.

Forsythe, R. D., The late Paleozoic to early Mesozoic evolution of southern South America: A plate tectonic interpretation, submitted to J. Geol. Soc. London, in press, 1982.

Fuller, A. O., The occurrence of laumontite in strata of the Karroo System, South Africa, in Proceedings and Papers: Second I.U.G.S. Symposium on the Stratigraphy and Paleontology of the Gondwana System, edited by S. H. Haughton, pp. 159-167, Pretoria Council for Scientific and Industrial Research, 1971.

Godoy, E., and C. Mpodozis, Comment on 'Mesozoic evolution of the Antarctic Peninsula and the southern Andes,' Geology, 8, 261-262, 1980.

Gordon, R.G., and A. Cox, Paleomagnetic test of the early Tertiary plate circuit between the Pacific basin plates and the Indian plate, J. Geophys. Res., 85, 6534-6546, 1980.

Grindley, G. W., and F. J. Davey, Some aspects of the reconstruction of New Zealand, Australia and Antarctica, in Antarctic Geoscience, edited by C. Craddock, University of Wisconsin Press, Madison, Wisconsin, 1981.

Hamer, R. D., and A. B. Moyes, Petrogenesis of garnet-bearing volcanic rocks of the Antarctic Peninsula Volcanic Group from Trinity Peninsula, Geol. Soc. London Newsl., 10 (5), 11, 1981.

Harrison, C. G. A., E. J. Barron, and W. W. Hay, Mesozoic evolution of the Antarctic Peninsula and the southern Andes, Geology, 7 (8), 374-378, 1979.

Harrison, C. G. A., E. J. Barron, and W. W. Hay, Reply to 'Comment on "Mesozoic evolution of the Antarctic Peninsula and the southern Andes,"' Geology, 262-263, 8, 1980.

Haughton, S. H., Geological History of Southern Africa, Geological Society of South Africa, Johannesburg, 1969.

Hjelle, A., Y. Ohta, and T. S. Winsnes, Stratigraphy and igneous petrology of southern Heritage Range, Ellsworth Mountains, Antarctica, Skr. Nor. Polarinst. 169, 1-43, 1978.

Hyden, G., and P. W. G. Tanner, Late Paleozoic-early Mesozoic fore-arc basin sedimentary rocks at the Pacific margin in West Antarctica, Geol. Rundsch., 70, 529-541, 1981.

Jankowski, E. J., and D. J. Drewry, The structure of West Antarctica from geophysical studies, Nature, 291, 17-21, 1981.

Jurdy, D. M., Relative plate motions and the formations of marginal basins, J. Geophys. Res., 84 (B12), 6796-6802, 1979.

Kellogg, K. S., Paleomagnetic evidence for oroclinal bending of the southern Antarctic Peninsula, Geol. Soc. Am. Bull., 91 (7), 414-420, 1980.

Kellogg, K. S., and R. L. Reynolds, Paleomagnetic results from the Lassiter Coast, Antarctica, and a test for oroclinal bending of the Antarctic Peninsula, J. Geophys. Res., 83, 2293-2299, 1978.

Kovach, J., and G. Faure, Rubidium-strontium geochronology of granitic rocks from Mt. Chapman, Whitmore Mountains, West Antarctica, Antarct. J. U.S., 13, 17-18, 1978.

Kyle, P. R., D. H. Elliot, and J. F. Sutter, Jurassic Ferrar Supergroup tholeiites from the Transantarctic Mountains, Antarctica, and their relationship to the initial fragmentation of Gondwana, in Gondwana V, edited by M. M. Cresswell and P. Vella, pp. 283-287, A. A. Balkema, Rotterdam, 1981.

LaBrecque, J. L., and P. F. Barker, The age of the Weddell Basin, Nature, 290, 489-492, 1981.

Landis, C. A., and D. G. Bishop, Plate tectonics and regional stratigraphic-metamorphic relations in the southern part of the New Zealand geosyncline, Geol. Soc. Am. Bull., 83, 2267-2284, 1972.

Longshaw, S., and D. H. Griffiths, A paleomagnetic study of some rocks from the Antarctic Peninsula and its implications for Gondwanaland reconstruction, Geol. Soc. London Newsl., 10 (5), 8-9, 1981.

Martini, J. E. J., On the presence of ash beds and volcanic fragments

in the greywackes of the Karroo System in the southern Cape Province (South Africa), Trans. Geol. Soc. S. Africa, 77 (2), 113-116, 1974.
Masolov, V. N., R. G. Kurinin, and G. E. Grikurov, Crustal structures and tectonic significance of Antarctic rift zones (from geophysical evidence), in Gondwana V, edited by M. M. Cresswell and P. Vella, A. A. Balkema, Rotterdam, 1981.
Miller, H., Palaozoische und fruhmesozoische Orogenesen am pazifischen Rand Gondwana, Geol. Rundsch., 70, 519-528, 1981.
Molnar, P., T. Atwater, and J. Mammericky, Magnetic anomalies, bathymetry and the tectonic evolution of the South Pacific since the Late Cretaceous, R. Astron. Soc. Geophys. J., 40 (3), 383-420, 1975.
Norton, I. O., and J. G. Sclater, A model for the evolution of the Indian Ocean and the breakup of Gondwanaland, J. Geophys. Res., 84 (B12), 6803-6830, 1979.
Pankhurst, R. J., Rb-Sr studies of igneous rocks from the Antarctic Peninsula, Geol. Soc. London Newsl., 10 (5), 11-12, 1981.
Powell, C. M., B. D. Johnson, and J. J. Veevers, A revised fit of East and West Gondwanaland, Tectonophysics, 68 (1-4), 13-29, 1980.
Rex, D. C., and P. W. G. Tanner, Precambrian age for the gneissose basement in the Falkland Islands, in Antarctic Geoscience, edited by C. Craddock, University of Wisconsin Press, Madison, Wisconsin, 1981.
Schopf, J. M., Ellsworth Mountains: Position in West Antarctica due to sea floor spreading, Science, 164, 63-66, 1969.
Simpson, G. G., Splendid Isolation: The Curious History of the South American Mammals, Yale University Press, New Haven, Connecticut, 1980.
Smellie, J. L., A complete arc-trench system recognized in Gondwana sequences of the Antarctic Peninsula region, Geol. Mag., 118, 139-159, 1981.
Smellie, J. L., and P. D. Clarkson, Evidence for pre-Jurassic subduction in western Antarctica, Nature, 258, 701-702, 1975.
Smith, A. G., and A. Hallam, The fit of the southern continents, Nature, 225, 139-144, 1970.
Swithinbank, C. W. M., Glaciological research in the Antarctic Peninsula, Phil. Trans. R. Soc. London Ser. B, 279, 161-183, 1977.
Tanner, P. W. G., The geological evolution of South Georgia, in Antarctic Geoscience, edited by C. Craddock, University of Wisconsin Press, Madison, Wisconsin, 1981.
Tanner, P. W. G., and D. C. Rex, Timing of events in an Early Cretaceous island arc-marginal basin system on South Georgia, Geol. Mag., 116, 167-179, 1979.
Watts, D. R., and A. M. Bramall, Paleomagnetic evidence for a displaced terrain in western Antarctica, Nature, 293, 638-642, 1981.
Webers, G. F., C. Craddock, A. M. Rogers, and J. J. Anderson, Geology of the Whitmore Mountains, in Antarctic Geoscience, edited by C. Craddock, University of Wisconsin Press, Madison, Wisconsin, 1981.
Weissel, J. K., D. E. Hayes, and E. M. Herron, Plate Tectonics synthesis: The displacements between Australia, New Zealand, and Antarctica since the Late Cretaceous, Mar. Geol., 25, 231-277, 1977.

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