New model for the tectonic history of West Antarctica : a reappraisal of the fit of Antarctica in Gondawana

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New model for the tectonic history of West Antarctica: a reappraisal of the fit of Antarctica in Gondwana

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ABSTRACT

A number of discrete West Antarctic tectonostratigraphic terranes have been proposed to explain regional tectonic events. Due to the very limited exposures of rocks in Antarctica, definition of these terranes has been poor, while speculations on their tectonic history have suffered from the lack of interpretable data. Application of terrane history analytical techniques and a system of data reliability weighting allows a new tectonic model for the evolution of Antarctica to be proposed. This model includes: 1) placement of the Antarctic Peninsula outboard of South America in the early Mesozoic; 2) definition of only four discrete terranes (Antarctic Peninsula Block, West Antarctic Block, South Georgia Block, and South Orkney Block); 3) Late Triassic oblique collision of the Antarctic Peninsula Block with the West Antarctic Block to produce the Ellsworth-Pensacola Orogen; and 4) Jurassic rifting along the West Antarctic-East Antarctic boundary to produce widespread graben development. This model may provide a non-unique solution; however, it is testable and could provide new directions for research in the region.

RÉSUMÉ

Plusieurs terrains tectonostratigraphiques de l'Antarctique Ouest ont été avancés pour expliquer les mouvements tectoniques régionaux. En même temps que la définition des terrains Antarctiques est restée incomplète parceque les roches ne sont pas visibles à la surface, les hypothèses sur l'histoire tectonique de ces terrains ont été rendues difficiles à cause du manque de données. L'application des méthodes d'analyse historique des terrains et d'un système de fiabilité proportionelle des données permet de proposer un nouveau modèle d'évolution de l'Antarctique. Ce modèle comprend: 1) la position de la Péninsule antarctique à l'ouest de l'Amérique du Sud au début du Mésozoïque; 2) l'existence de seulement quatre terrains différents (le bloc de la Péninsule antarctique, le bloc Antarctique Ouest, le bloc de Georgie Sud, et le bloc Orkney Sud); 3) la collision oblique du bloc de la Péninsule antarctique avec le bloc Antarctique Ouest pendant le Trias supérieur, produisant l'orogenèse Ellsworth-Pensacola; et 4) la formation des fossés d'effondrement le long de la frontière Antarctique Ouest-Antarctique Est pendant le Jurassique, produisant le développement général de graben. La solution de ce modèle peut ne pas être unique; cependant ce modèle peut être testé et il peut ouvrir de nouvelles directions de recherche pour cette région.

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CONTENTS

1. Introduction

The fit of Antarctica in Gondwana has long been considered critical to the accuracy of global paleogeographic and tectonic reconstructions (Elliot 1975; DeWit 1977; Barron et al. 1978; Harrison et al. 1979; Powell et al. 1980; Craddock 1982b; Dalziel 1982; Miller 1983; Barron 1987; Lawver & Scotese 1987). The very limited extent of outcrops in West Antarctica has made resolution of this fit problematic. Proposals that West Antarctica is comprised of several tectonostratigraphic (suspect) terranes reflect the complexity of Antarctic geology, but do not presently allow unique solutions to be obtained for the tectonic history of the region (Schopf 1969; Scharnberger & Scharon 1972; Clarkson & Brook 1977; DeWit 1977; Dalziel 1980; 1982; 1983; Harrison et al. 1980; Watts & Bramall 1981; Dalziel & Elliot 1982; Craddock 1983; Dalziel & Grunow 1985; Schmidt & Rowley 1986; Grunow et al. 1987a). Attempts to define the boundaries and tectonic history of these terranes have recently concentrated on geophysical evaluation of subice morphology, the gathering of new paleomagnetic data, geochemical analyses of igneous typologies and calculation of new radiometric dates for critical events (for examples, see references in Cresswell & Vella 1981; Craddock 1982a; Oliver et al. 1983; McKenzie 1987). A wealth of new data have become available, but no consensus on their meaning has yet been forthcoming.

Unfortunately, much emphasis has been placed on non-falsifiable ad hoc hypotheses derived from interpretations of paleomagnetic data and somewhat simplistic arguments about structural heterogeneity. The drawback to the ad hoc approach is that theories proliferate based on a single data set and are thus protected from falsification, while resolution of conflicts between data sets tends to be ignored (YOUNG 1986; WILSON et al., in press). Indeed, conflicts may arise in the actual identification and enumeration of the terranes, such that the defined units themselves are ad hoc and insured against testing by independent methods. However, the application of terrane analysis techniques and a system of data reliability weighting may help resolve conflicts and provide new insights into the tectonic history of West Antarctica. This paper presents a testable alternative model for the Mesozoic evolution of Antarctica and its place in Gondwana based on these insights.

Terrane analysis

Definitions and theory

Tectonostratigraphic terrane analyses and definitions presented here follow the guidelines suggested by CONEY et al. (1980), JONES et al. (1983), SCHERMER et al. (1984), HOWELL et al. (1985) and JONES et al. (1986). Specifically, a terrane is considered "suspect" if its paleogeographic setting is uncertain for a significant period of geologic time. "Terranes" are by definition fault-bounded and are termed "tectonostratigraphic" because their sizes, shapes and structure are due to tectonic processes, while their internal stratigraphic records serve to define them uniquely.

"Terrane analysis" examines key features observable in the stratigraphy and structure of a particular terrane which may serve to constrain that terrane's tectonic history. For example, ophiolite belts, calc-alkaline volcanics, blueschist and melange provide good evidence for ocean basin closure and subduction (MIYASHIRO 1973; HAMILTON 1979; GILL 1981; MOORES 1982; RAYMOND 1984). Geochemically distinct collision-produced granitic suites (LEFORT 1981; HARRIS et al. 1986; PITCHER 1987) can be dated, thus defining times of collision. Successor basins can provide overlap sequences which also constrain the time of accretion (CONEY et al. 1980; HOWELL et al. 1985). Passive margin (drift) sequences can be used to delineate times of rifting (EMERY & UCHUPI 1984). Finally, paleomagnetic and paleobiogeographic data can be used to constrain the changing positions of terranes in time and space (e.g. VAN DER VOO & CHANNELL 1980; TOZER 1982; ENGEBRETSON et al. 1985; HALLAM 1986; HILLHOUSE & MCWILLIAMS 1987; WILSON et al., in review).

Data reliability weighting

Due to the complex nature of regional tectonic analysis, it is both logical and prudent to develop specific rules and procedures for the interpretation of terrane histories. There is enough information to be gleaned from geological studies on terranes and continental blocks to enable one to develop a working model for regional tectonic evolution. However, within any one region conflicts between or within data sets may occur (BOUCOT & GRAY 1983; TAYLOR et al. 1984; COE et al. 1985; HALLAM 1986;

Young 1986; Wilson et al., in review). A useful regional model will only result if data conflicts within and between terranes and regions are resolved. This type of denouement can be achieved through reliability weighting of the various kinds of data.

In order to weigh correctly the relative reliability of some common type of terrane/plate motion data, it is first necessary to comprehend the role of those data in the theory and practice of regional tectonic analysis. As a practical matter it is critical in older Mesozoic interpretations to determine when a terrane may have rifted, when it was subjected to subduction and/or strike-slip processes, where it was on a plate at certain times and when it may have collided with its host continent (Wilson 1987). A vast literature on geologic evidence for various tectonic environments is available, but due to space limitations will be summarized elsewhere (Wilson et al., in prep.). At present, it suffices to say that the principal data types are not always in agreement.

The most common kind of conflict occurs when both paleomagnetic and paleobiogeographic data sets are available for a particular terrane, but do not agree (Boucot & Gray 1983; Taylor et al. 1984; Hallam 1986). In practice, it is clear that both of these data sets can suffer from low resolving power or poorly constrained evidence (e.g. Kellogg & Reynolds 1978; Boucot & Gray 1983; Coe et al. 1985; Jablonski et al. 1985; Tarling 1985; Hallam 1986; Young 1986; Newton 1987; Wilson et al., in press).

An excellent example of such a conflict may be found in the sharply contrasting tectonic histories proposed for the larger Chinese terranes of the late Paleozoic and early Mesozoic. A number of paleomagnetic studies have inferred that the so-called North China, South China and Indochina Blocks did not accrete to Eurasia until sometime in the Jurassic (e.g. McElhinny et al. 1981; Opdyke et al. 1986; Zhao & Coe 1987). However, voluminous vertebrate faunal evidence directly contradicts this scenario and supports much earlier (Permo-Triassic) times of accretion for these large blocks (e.g. Cox 1973; Anderson & Cruickshank 1978; Buffetaut 1981; 1984; Colbert 1986; Wilson et al., in review). Freshwater invertebrate biogeography (Tasch 1981) also supports an earlier accretion time, as does considerable geological evidence (Mitchell 1981; Sengör 1984; Zhang et al. 1984; Yang et al. 1986). In this case (discussed in detail elsewhere) we suggest that the paleobiogeographic data are the more reliable set.

Resolution of such conflicts must be done on a case by case basis, but is greatly facilitated by examination of the relative reliability of each subset (study) making up the data set. For example, paleomagnetic data which do not pass standard stability tests (e.g. reversal test, fold test) may generally be considered less reliable than data which do pass these tests (Tarling 1983; 1985). Likewise, vertebrate paleobiogeographic studies that utilize large, well-preserved and readily identified tetrapod material are superior in resolving power to studies which employ marine invertebrates having planktotrophic larvae (Simpson 1980; Valentine & Jablonski 1983; Jablonski et al. 1985). We suggest that all data types can be objectively judged for quality and then given a relative weighting or rank in the data set. In many such cases it has been our experience that careful evaluation of relative data reliability allows one to eliminate data conflicts consistantly. With these factors in mind, as well as others discussed elsewhere (Wilson et al., in press), we suggest as a guide a system of relative data reliability weighting (in decreasing order) as follows:

1) The most reliable and useful data are "departure" (rift), and "arrival" (collision/suturing) times that are indicated by well-dated and tightly constrained geologic evidence (cf. MOORES 1982; EMERY & UCHUPI 1984; HARRIS et al. 1986; GEHRELS & SALEEBY 1987).
2) Also crucial are well-constrained episodes of strike-slip motion of "known" magnitude and direction, and well-dated geologic evidence that allows inferences to be made about tectonic environment (e.g., subduction) (cf. HAMILTON 1979; GILL 1981; RAYMOND 1984; SAREWITZ & KARIG 1986).
3) Tetrapod paleobiogeography employing large, well-dated, well-preserved and readily identified tetrapod faunal elements; equally important are well-dated fresh water faunal paleobiogeographies such as those based on primary fresh water fish or conchostracans (cf. BUFFETAUT 1981; PATTERSON 1981; TASCH 1987; WILSON et al., in review).
4) High quality paleomagnetic data which record stable remanences measured on clearly identified magnetic mineralogy of known age, and conforming to standards set out in HARRISON & LINDH (1982), LARSON et al. (1982), TARLING (1983; 1985), COGNE et al. (1986), COX & HART (1986), and PIPER (1987).
5) Benthic marine invertebrate paleobiogeography where organisms are considered to have had non-planktotrophic larvae and definition of realms is good; planktonic invertebrate paleobiogeography may also be used, but is characterized by less resolving power (cf. TOZER 1982; ZINSMEISTER 1982; VALENTINE & JABLONSKI 1983; HALLAM 1986; ARCHBOLD 1987; CRAME 1987).
6) Paleomagnetic data of intermediate quality, where questions about stability, time of magnetization, structural corrections and/or high-latitude declination error can not be fully resolved (cf. KELLOGG & REYNOLDS 1978; HARRISON et al. 1982; LARSON et al. 1982; TARLING 1985; WILSON et al., in press).
7) Floral paleobiogeography where definition of realms and dating are good (cf. CHALONER & LACEY 1973; HALLAM 1981).
8) Poorly dated geologic and paleobiogeographic data.
9) Poor quality paleomagnetic data (cf. WILSON et al., in prep.).

Identification and enumeration of terranes

The West Antarctic-Scotia Arc region has been proposed to consist of at least 6 discrete terranes (Fig. 1), namely: 1) the Antarctic Peninsula-Ellsworth Land Block (APB); 2) the Ellsworth-Whitmore Mountains Block (EWB); 3) the Marie Byrd Land Block (MBB); 4) the Thurston Island-Eights Coast Block (TIB); 5) the South Orkney Islands Block (SOB); and 6) the South Georgia Island Block (SGB) (DEWIT 1977; DALZIEL 1982; DALZIEL & ELLIOT 1982; DALZIEL & GRUNOW 1985). Evidence used to define these terranes is summarized in Table 1.

The Antarctic Peninsula-Ellsworth Land Block (APB)

The APB has been considered to be separate from the rest of West Antarctica for several reasons. Firstly, there is excellent evidence that the APB formed part of the Pacific margin of Gondwana throughout the Mesozoic, and in this position has experi-

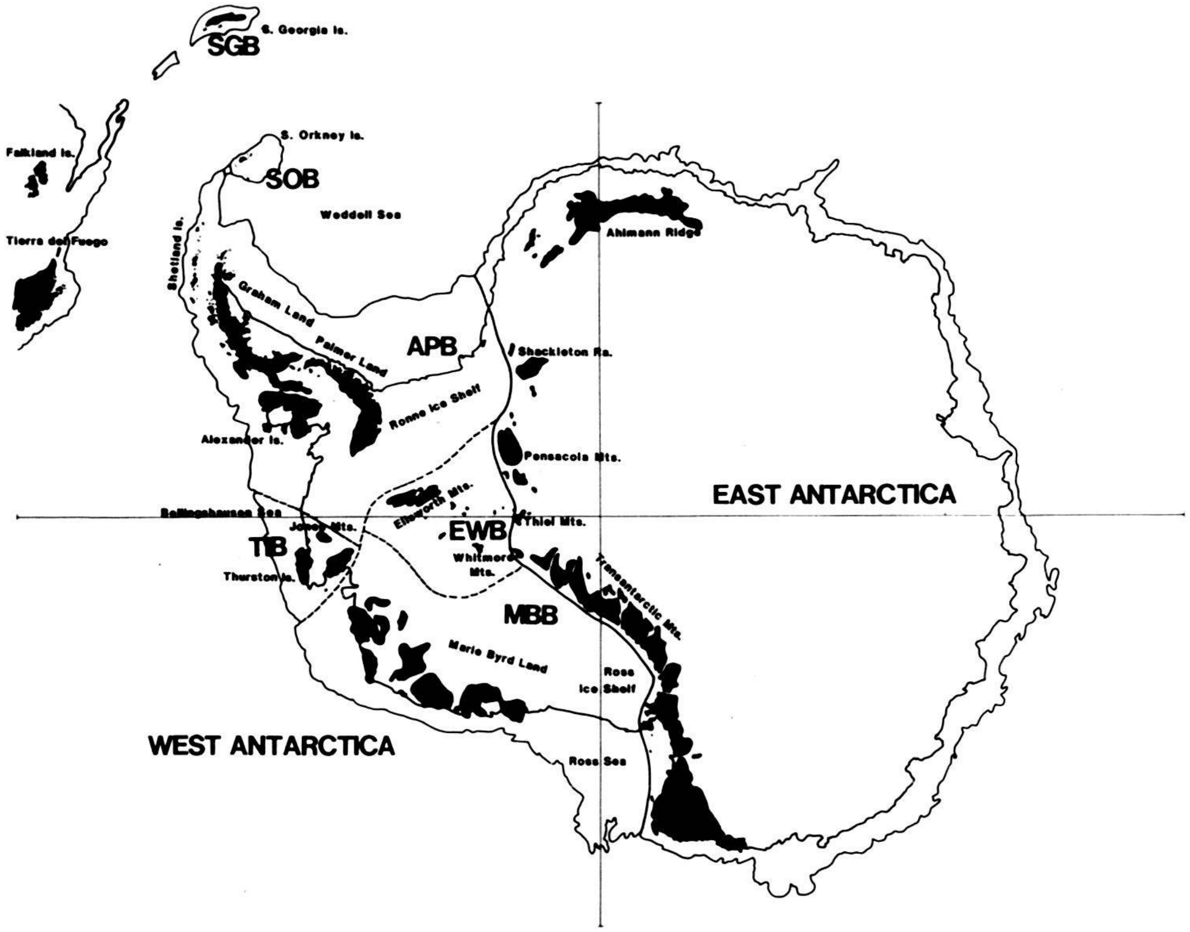

Fig. 1. Location and terrane map of Antarctica. Terranes are those proposed by DALZIEL et al. (1987) and others; note that boundaries are hypothetical. Black patterns represent mapped outcrop areas. APB = Antarctic Peninsula Block; EWB = Ellsworth Whitmore Mountains Block; MBB = Marie Byrd Land Block; SGB = South Georgia Island Block; SOB = South Orkney Islands Block; TIB = Thurston Island-Eights Coast Block.

enced nearly continuous post-Paleozoic subduction (see Table 1; SUAREZ 1976; HARRISON et al. 1979; WEAVER et al. 1981; DALZIEL & ELLIOT 1982; THOMSON & PANKHURST 1983; and many others). This continuous subduction history is reflected by the APB's distinct stratigraphy, which includes fore-arc, arc and back-arc units (ELLIOT 1983). Metamorphic basement rocks with ages ranging from 244 Ma to 386 Ma occur in Graham Land (northern APB) (PANKHURST 1983). Basement rocks in Ellsworth Land may be as old as 500 Ma if the TIB is part of Ellsworth Land (WHITE & CRADDOCK 1987). In any case, granites in Ellsworth Land range from 102 Ma to 230 Ma with most activity in the mid-Cretaceous. The APB's stratigraphy contrasts sharply with the tectonic and stratigraphic evolution of most other parts of Antarctica, but bears some resemblance to that of southern South America (FARQUHARSON 1982; MILLER 1982; SAUNDERS & TARNEY 1982). Based on the strong structural discontinuity (ELLIOT 1983) between the northern (Graham Land) and southern (Palmer Land) portions of the APL, this block could be divided into two sub-terranes (i.e., GLB and PLB; see Figure 2).

Block	L.Pm.	E.Tr.	M.Tr.	L.Tr.	E.J.	M.J.	L.J.	E.K.	L.K.	E.Te.	L.Te.
GLB	?-OP-	OP-OP-O MT-M	P-OP-? T-MT-MT ?-FO	CV-CV AG-AG -MT-MT- -FO-FO-	-CV-CV- -AG-AG- MT-MT FO-FO-?	CV-CV-C AG-AG-A RV-RV-	V-CV-CV G-AG-AG RV-RV-R SS-SS BA-BA-B	-CV-CV- -AG-AG- V-RV-? -SS-SS A-BA-BA	CV-CV-C AG-AG-A MT-BS-M -BA-BA	V-CV-CV G-AG-AG T-BS-MT FO-FO-F MS-MS	-CV -AG -BS O-FO
PLB	?-GL-	GL-?	AG-AG-	CV-CV- AG-AG-A	CV-CV-C G-AG-AG ?-RV-	V-CV-CV -AG-AG- ?-MT-? RF-RF-R ?-BA	-CV-CV- AG-AG-A -RV-? F-RF -BA-BA	CV-CV-C G-AG-AG FO-FO-F SS-SS-? TF-TF-T	V-CV-CV -AG-AG- O F	-CV-CV AG-AG-A	G-AG
SGB						?-BA-B	AG-AG-A A-BA-BA	OP-OP-O G-AG-AG MT-MT-M -BA FO TF	P-OP T -FO -TF-?		
SOB	?-ML-M	L-ML-ML	-? MT- FO- TF-	MT-MT-M FO-FO-F TF-TF-T	T-MT-? O-FO-FO F-TF-?	-?			BS-BS-B	S-BS	
WAB	GL-G	L-GL ?-	?-MT-M FO-FO-F ?-TF-T	CV-CV-C T-MT-MT O-FO-FO F-TF-TF	V-CV-CV RV-RV- RF-RF- CG-CG	RV-RV RF-RF		CV-CV-? AG	-AG	RV- RF-	RV RF
Trn. Ant. Mts.	CO-C GL-G	O-CO LY-LY L-GL			RV-RV- RF-RF-	RV-RV RF-RF				RV- RF-	RV RF
Wed. Sea						?-RV-? RF-RF-R BU-BU-B RS-RS-	F-RF-RF U RS-RS-R	S-RS-RS	-RS	?-RV RF-	-? RF
Sth. Am.	CV-C AG-A	V-CV-CV G-AG-AG	-CV-CV -AG-AG			CV-CV AG-AG ?-BA-BA	-CV-CV- -AG-AG- -BA-BA-	CV-CV-C AG-AG-A OP-OP-O MT-MT-M BA FO TF	V-CV-CV G-AG-AG P T -FO -TF	-CV-CV -AG-AG	

Table 1: Summary Table of tectonic events used in constructing models. Data from various authors in CRESSWELL & VELLA (1981), CRADDOCK (1982a), OLIVER et al. (1983), and McKENZIE (1987). Block abbreviations: GLB = Graham Land Block; PLB = Palmer Land Block; SGB = South Georgia Block; SOB = South Orkneys Block; WAB = West Antarctic Block. Abbreviations for events and data: AG = arc-associated granites; BA = back-arc basin; BS = blueschist metamorphism; BU = breakup unconformity; CG = collision-type granites; CO = conchostracan fossils; CV = calc-alkaline volcanics; FO = folding event; GL = *Glossopteris* flora; LY = *Lystrosaurus* fauna; MS = Marsupial fauna; MT = high T-P metamorphism; OP = ophiolitic rocks; RF = rift-related normal faulting; RS = syn-rift stratigraphic sequence; RV = rift-related volcanism; SS = strike-slip faulting; TF = thrust faulting.

Secondly, certain geophysical evidence (i.e., sub-ice topography, gravity, magnetics and calculated crustal thicknesses) supports the idea that the APB acted as a separate crustal block (MASOLOV et al. 1981; BENTLEY 1983; IVANOV 1983; KADMINA et al. 1983; COGLEY 1984; GARRETT et al. 1987a). The southern boundary of the APB has been described by some of these workers as a rift, while the eastern boundary may be a transform. However, in drawing the southern and eastern boundaries to the APB, the only obvious geologic limits must be the folded and intruded rocks comprising the Ellsworth and Pensacola Mountains, and the oceanic crust comprising the floor of the Weddell Sea. Thirdly, structural data support the identification of the APB as a distinct terrane and suggest that the observed deformation of the southern APB is of contrasting trend and nature relative to tectonic events elsewhere in the Antarctic continent (ELLIOT 1983; ROWLEY et al. 1983; MENEILLY et al. 1987; STOREY et al. 1987). Unfor-

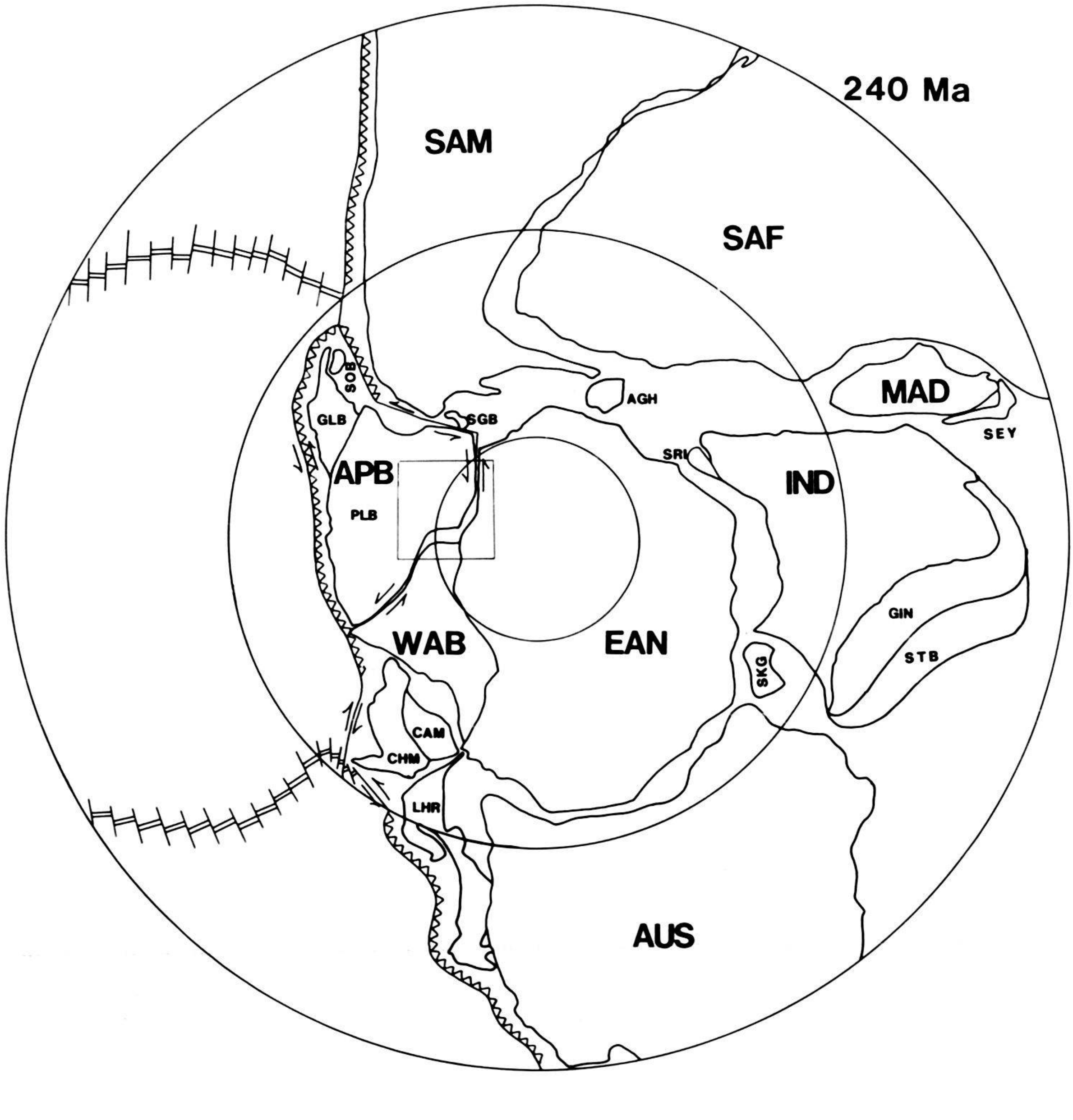

Fig. 2. 240 Ma, Middle Triassic (Anisian) reconstruction showing terranes proposed in this study. Stereographic polar projection, latitude circles at 20 degree intervals. Box denotes location of Figure 3. Note that all plate boundaries are schematic: arrows signify strike-slip relative motion; dragon's teeth represent subduction zones with teeth on upper plate; parallel lines cut by normals denote spreading ridges. See discussion in text. APB = Antarctic Peninsula-Ellsworth Land Block (GLB = Graham Land Sub-block; PLB = Palmer Land Sub-Block); SGB = South Georgia Island Block of DALZIEL (1982); SOB = South Orkney Islands Block of DALZIEL (1982); WAB = West Antarctic Block; AGH = Agulhas Plateau Block; CAM = Campbell Plateau Block; CHM = Chatham Rise Block; GIN = Greater India, the area estimated to have been lost to crustal shortening during collision; LHR = Lord Howe Rise Block; MAD = Madagascar Block; SEY = Seychelles Islands Block; SKG = South Kerguelen Plateau Block; SRI = Sri Lanka Block; STB = South Tibetan (Lhasa) Block.

tunately, there are no vertebrate or invertebrate paleobiogeographic data which can constrain the terrane analysis for the APB.

Paleomagnetic data have been used both to support and to argue against the possibility of oroclinal bending in the APB (DALZIEL et al. 1973; KELLOGG & REYNOLDS 1978; KELLOGG 1980; WATTS et al. 1984). However, the large declination error (delta-95 in the range 10–49 deg.) associated with all high latitude paleomagnetic data limits their usefulness and probably precludes any clear resolution of this problem (KELLOGG & REYNOLDS 1978; VAN DER VOO & CHANNELL 1980; LOWRIE & HIRT 1986). This theoretical limit to the resolving power provided by high latitude paleomagnetic declinations further suggests that all such high paleolatitude data are at best of only intermediate quality in terms of their relative reliability in terrane analysis, and thus must be considered secondary in importance to "arrival time" and any paleobiogeographic data.

Paleomagnetic data also suggest that the APB may have been approximately in its present position since the Jurassic (LONGSHAW & GRIFFITHS 1983; SCHARNBERGER & SCHARON 1982; WATTS et al. 1984). However, this calculated position is relative to Antarctica and is therefore entirely dependent on the particular Gondwana reconstruction and paleomagnetic reference frame used. Thus, use of HARRISON & LINDH'S (1982) paleomagnetic APWP data and BARRON'S (1987) reconstruction rather than NORTON & SCLATER'S (1979) reconstruction gives a different result. The occurrence of a *Glossopteris* flora in the APB (LAUDON et al. 1987) suggests that this terrane was never far from the Gondwana craton during the Permian and Mesozoic.

The Ellsworth-Whitmore Mountains Block (EWB)

The EWB has long been postulated to have a unique tectonic history based on its anomalous structural trend (Fig. 1) and distinct stratigraphic evolution (SCHOPF 1969; CRADDOCK 1975; 1983; CLARKSON & BROOK 1977; WEBERS et al. 1982; CRADDOCK et al. 1986; DALZIEL et al. 1987; STOREY & DALZIEL 1987; VENNUM & STOREY 1987a; 1987b). Thus, the EWB is characterized by a Paleozoic stratigraphy similar to that of the nearby Transantarctic Mountains, but unlike them was subjected to major Early Mesozoic deformation, regional metamorphism and granitic plutonism (see Table 1). The basement of the EWB is currently poorly understood, but may be as old as 1100 Ma if the Haag Nunataks are considered a part of the EWB (MILLAR & PANKHURST 1987). Available geophysical evidence seems to support the proposed continuity of the Ellsworth Mountains and Whitmore Mountains as parts of the same tectonic block (JANKOWSKI & DREWRY 1981; STOREY & DALZIEL 1987).

A major tectonic boundary has been presumed to lie between the EWB and the MBB, as inferred from sub-ice morphology (Byrd Subglacial Basin) and geophysical modeling of magnetic basement types (JANKOWSKI & DREWRY 1981; JANKOWSKI et al. 1983). However, the postulated major extension and volcanism that produced the Byrd Subglacial Basin may not have occurred until the Late Tertiary or even Quaternary, as pointed out by LEMASURIER & REX (1982). Of course, this would imply that the EWB and MBB were not really separate terranes in the Mesozoic. This problem will be discussed further below.

Another major terrane boundary must lie between the EWB and East Antarctica, as suggested by certain structural discontinuities (e.g., no clear evidence for Ross

Orogen tectonism in the EWB), geophysical evidence of faulting along the boundary, crustal thickness calculations and sub-ice morphology (Jankowski & Drewry 1981; Bentley 1983; Craddock 1983; Jankowski et al. 1983; Kadmina et al. 1983). Furthermore, the Triassic vertebrate fauna (of Gondwanan aspect) found in the Transantarctic Mountains has not been reported from the EWB (Anderson & Cruickshank 1978). However, one important tectonic connection between the EWB and East Antarctica seems to have eluded explanation so far. This connection is the nearly coeval early Mesozoic metamorphism, folding and intrusion episode of the Pensacola Mountains of East Antarctica (Table 1; Fig. 2) and the Ellsworth Mountains of the EWB (Ford 1972; Craddock, 1975).

These events are so similar that Craddock (1975) collectively labeled the two mountain belts as the Ellsworth Orogen. Indeed, the two mountain belts may represent opposite sides of a collisional suture; if this is true, then they also provide the most reliable type of evidence available in terrane analysis, that of a well-dated "arrival time". Differences in structural trends between these ranges may or may not be significant, since similar variations can occur within a single range (e.g., the EWB itself; also the Cape and Falklands Fold Belts [Dingle et al. 1983; Storey & Dalziel 1987; Dalziel et al. 1987]). Interestingly, both the EWB and the Pensacola Mountains have been intruded by diabase sills correlative with the Middle Jurassic Ferrar Supergroup of the nearby Transantarctic Mountains (Ford 1972; Vennum & Storey 1987a).

An explanation of the nature and timing of deformation in the Pensacola Mountains and the EWB is of great importance to any tectonic analysis of West Antarctica. In view of this, the implications of several recent geochemical and isotopic dating studies need to be examined. The geochemistry of several granitic intrusions in the EWB suggests that these rocks may be typical examples of collisional granites (Vennum & Storey 1987b). Thus, one suite of intrusives may be characterized as mildly peraluminous, corundum-normative S-type leucogranites similar to post-tectonic collisional granites found in the Himalayas (cf. LeFort 1981; and others). The age of emplacement for this suite ranges from 171 Ma to 182 Ma (Millar & Pankhurst 1987). Another igneous suite consists of deformed, migmatized paragneiss and voluminous pegmatites at Mt. Woollard. These rocks are metaluminous I-type calc-alkaline rocks dated approximately at 200 Ma (Millar & Pankhurst 1987; Vennum & Storey 1987b) which may qualify as typical pre-collision arc intrusions (cf. Harris et al. 1986). Related rocks may include an undated rhyodacite stock in the Martin Hills. The Mt. Seelig granite of the Whitmore Mountains, dated at 190 +/−21 Ma (Millar & Pankhurst 1987), may be related to a late subduction/early collision phase. This intrusive is a slightly metaluminous I-type foliated porphyritic granite. Its chemistry (data from Vennum & Storey 1987b) plots in the syn-collisional field of a Rb vs. (Y + Nb) discrimination diagram (Pearce et al. 1984), but also plots in the volcanic arc field of a Rb/Zr vs. SiO2 discrimination diagram (Harris et al. 1986). Vennum & Storey (1987b), and Dalziel et al. (1987) seem to view the post-tectonic nature of some of the EWB granites as implying that no collisional event could have occurred, but rather emplacement of these rocks was due to an unknown "thermal event". However, this ignores the probable pre-collisional arc setting of the Whitmore Mountains and Mt. Woollard, the probable collisional nature of the post-tectonic granites of the EWB and the obviously compressional folding episodes of the Pensacola Mountains and

EWB. Furthermore, the suite of lamprophyre (minette) dikes reported from the Pensacola Mountains (FORD 1972) is considered a diagnostic feature in post-tectonic collisional environments (THOMPSON et al. 1984).

The excellent work done on Himalayan and Cimmeride collisions may provide an adequate model for the differing phases of collision, and thus an analog for the EWB granites. These well-known collisional events produced separate pre-collisional, syn-collisional and post-collisional granitic suites (LeFORT 1981; PEARCE et al. 1984; HARRIS et al. 1986). The apparent absence of clear syn-collisional granites in the EWB need not imply that they do not exist, since total outcrop represents only 2% of the land area. Nor should their absence be taken to mean that no collision could have taken place, since the Himalayan/Cimmeride analogs imply that co-existence of arc granites, folding, post-collisional granites and lamprophyre dikes actually constitutes de facto evidence of collision. Any such de facto evidence of collision would supercede other data types (e.g. paleomagnetic data) in terrane analysis, since this collision would delineate an "arrival time". The stronger folding observed in the related Pensacola Mountains deformation is best explained by a compressive event (FORD 1972; CRADDOCK 1975). As will be seen in a later section, a plate tectonic model incorporating this collision is credible and may explain some data in other areas.

Paleomagnetic data from two recent studies have been used to substantiate claims about the allochthoneity of the EWB (WATTS & BRAMALL 1981; GRUNOW et al. 1987a). The former study analyzed Cambrian argillites from the Ellsworth Mountains, while the latter study examined Middle Jurassic granitic rocks from several sites in the EWB. Unfortunately, the relative reliability of both studies is questionable in terms of their usefulness in terrane analysis. There are several reasons for this conclusion: 1) the Jurassic study suffers from the ubiquitous problem of high latitude declination error (delta-95 estimated @ 12–18 deg.), which when plotted as an error circle would preclude meaningful interpretation of that study's postulated 15–25 deg. rotation of the EWB; 2) the Jurassic data are from plutonic rocks and thus lack tilt correction (and can not pass a fold test), which fact probably explains their anomalously low calculated paleolatitudes (see GRUNOW et al. 1987a); 3) paleosecular variation probably was not averaged out of the Jurassic data, as shown by high k-parameter values (cf. HARRISON & LINDH 1982); 4) a reversal test would only be passed by one of the Jurassic sites and none of the Cambrian sites; 5) the proper polarity of the Cambrian data is unknown; 6) alpha-95 (cone of confidence) values for the Cambrian study are relatively high (@ 11 deg.) for use in terrane analysis; 7) Cambrian data were collected from a very small sampling area (25 sq. km.) and thus may be "in situ" (locally valid, but regionally invalid) results; and 8) Cambrian data are from severely folded rocks which have almost certainly suffered internal strain reorientation, which has nevertheless not been corrected for (cf. COGNE et al. 1986).

From the above discussion, it is clear that the EWB was closely related to the Pensacola Mountains in the Mesozoic, but distinctly different from the APB and the rest of East Antarctica. However, the locations and nature of all boundaries except the East Antarctic one are unknown, while the terrane's obvious connection to East Antarctica in the Jurassic suggests that it was separate from East Antarctica only in the Paleozoic. The lack of evidence for Ross Orogen deformation in the EWB does support the probable Paleozoic allochthoneity of the EWB. However, the tectonic history of the EWB cannot be adequately evaluated with presently available paleomagnetic data. No regional model for the early Mesozoic deformation/intrusion event, incorporating the strong evidence for collision, has been presented to date. The occurrence of a *Glossopteris* flora in the EWB suggests it was not far from Gondwana in the late Paleozoic (CRADDOCK 1983). The separation of the EWB and MBB is questionable, and will be evaluated in the following section.

The Marie Byrd Land Block (MBB)

Little is known about the MBB compared to other West Antarctic terranes. There is stratigraphic, faunal and structural evidence that this block was closely connected to the New Zealand/Campbell Plateau/Chatham Rise microcontinent during the earlier Mesozoic (SPÖRLI & CRADDOCK 1981; COOPER et al. 1982; GRINDLEY & DAVEY 1982; SPÖRLI 1987). The oldest dated rocks are 320–350 Ma granites intruding metamorphics in the Ford Ranges, although some nearby sandstones have yielded possibly Early Cambrian microphytoliths (references in GRINDLEY & DAVEY 1982). A calc-alkaline metavolcanic suite, considered on floral dating evidence to be Devonian, may be the oldest such rocks in this part of the circum-Pacific (GRINDLEY & MILDENHALL 1981). Late Jurassic-Cretaceous calc-alkaline volcanics similar to those in the APB are widespread in the MBB, as are mid-Cretaceous calc-alkaline granitic rocks (WADE & WILBANKS 1972; SPÖRLI & CRADDOCK 1981; COOPER et al. 1982). Geophysical data support proposals that the MBB is presently separated from other terranes (i.e. APB and EWB) by graben of probable Tertiary age (MASOLOV et al. 1981; LeMASURIER & REX 1982; KADMINA et al. 1983). However, no geophysical or structural data presently available permit a Mesozoic suture to be drawn between the EWB and the MBB.

The notion that the MBB has acted as a discrete terrane was originally proposed on the basis of paleomagnetic data from Cretaceous rocks (SCHARNBERGER & SCHARON 1972). This early work has since been criticized and labeled unreliable (DALZIEL & GRUNOW 1985). A more recent study (GRINDLEY & OLIVER 1983) produced more reliable results, although no reversal test was possible and tectonic corrections could not be made because the specimens were from igneous rocks. These workers refute the claims of SCHARNBERGER & SCHARON (1972) and suggest that the MBB was at very high latitudes by the Cretaceous. GRINDLEY & OLIVER (1983) further suggest that the MBB could have moved some 200–500 km relative to East Antarctica during the Tertiary as a result of extension. As will be seen below, this is a reasonable hypothesis in light of independent evidence presented by later workers.

The previously mentioned problem of whether or not to consider the MBB as a discrete block can now be resolved on the basis of conventional terrane analysis. The MBB shows stratigraphic and structural similarities to the APB. Faunal evidence and paleomagnetic data support a position for the Mesozoic MBB approximating that proposed by GRINDLEY & DAVEY (1982). No convincing evidence for a Mesozoic suture or boundary between the EWB and the MBB has been reported. Based on the evidence and relative reliability ranking system presented above, it seems quite plausible that the MBB and EWB acted as a single block (which we will call the West Antarctic Block [WAB]) in the Mesozoic and only separated in the Late Tertiary (Fig. 2). The evidence for a Triassic collision event in the WAB does not contradict this scenario, since any inferred suture must lie between the APB and the EWB. Because "arrival" data are deemed to be in the most useful category of evidence used in regional terrane analysis, the Triassic collision data must supersede all other data types presently available.

The Thurston Island-Eights Coast Block (TIB)

The TIB is the smallest and least well-known terrane in West Antarctica (Fig. 1). Outcrops in the area consist primarily of Paleozoic and Mesozoic plutonic rocks intruding probable early Paleozoic gneisses and capped in places by volcanics (WADE & WILBANKS 1972; COOPER et al. 1982; WHITE & CRADDOCK 1987). The Jones Mountains area of the adjacent Eights Coast is comprised of Mesozoic igneous rocks unconformably overlain by Pliocene basalts. Dated granitic rocks in the TIB range in age from 97 Ma to 347 Ma, while the metamorphic basement may be as old as 500 Ma (WHITE & CRADDOCK 1987). Most of the TIB granites are considered by these workers to be of calc-alkaline, I-type affinity, and are therefore indicative of late Paleozoic-Mesozoic subduction. This tectonic history is analogous to that of the MBB area.

Asymmetry in the distribution of gabbros and alkaline granites on Thurston Island leads WHITE & CRADDOCK (1987) to suggest that the TIB has been rotated as a separate block, from an originally different orientation. Geophysical data (MASOLOV et al. 1981; KADMINA et al. 1983) support the existence of a small graben between Thurston Island and the Eights Coast, but this is probably related to the widespread West Antarctic Late Tertiary extension. New paleomagnetic data from Early Cretaceous igneous rocks on Thurston Island suggest that the TIB was part of a united APB-EWB plate by at least Early Cretaceous (GRUNOW et al. 1987b). Although this interpretation is in agreement with the model presented here, it is important to note that these paleomagnetic data are of questionable reliability. For example, tectonic corrections, fold tests and reversal tests are lacking. The reliability of these data also suffers from the usual high-latitude declination error and may not average-out secular variation (i.e., k-parameter values are very high). In view of the weak evidence supporting a discrete TIB terrane and the lack of evidence for bounding sutures of appropriate age, the TIB is here considered to be a part of the APB (see Fig. 2).

The South Orkney (SOB) and South Georgia (SGB) Islands Blocks

These two terranes are relatively well-understood in terms of their tectonic evolution as parts of the Scotia Arc (DALZIEL 1981; 1982; 1984; TANNER 1982; ELLIOT 1983; and others). The close resemblance of South Georgia's Mesozoic stratigraphy and structural evolution to that of the southernmost Andes suggests a pre-Tertiary position for the SGB against South America. Similar constraints apply to the SOB, which must have had a pre-Tertiary position against the northern APB (Fig. 2). Seafloor data from the Scotia Sea and magnetic data from the terranes themselves (GARRETT et al. 1987b) support these general positions; thus it seems a consensus exists on the relative positions and present allochthoneity of these blocks. In view of this apparent consensus, the SGB and SOB are accepted as bona fide terranes without further discussion.

New model for the tectonic evolution of West Antarctica

Continental reconstructions and Gondwana

Plate tectonic reconstructions for the fit of the southern (Gondwana) continents are taken from Barron (1987), but extrapolated back to the Triassic with the following modifications:

1) Continental shapes are corrected for passive margin "de-stretching" using an average beta value of 2 and a 100 km width of crust between the two plates which succumbs to stretching (where beta = 2 is equivalent to 100 km of horizontal stretching), as suggested by Savostin et al. (1986).
2) The present configuration of the continents serves as a base from which stretching and allochthonous terranes have been subtracted. The limits of continental crust (OCB) are taken at the present-day 1,000 fm (2,000 m) isobath following Austin & Uchupi (1982).
3) The fit of Africa and South America is adapted to include two African plates as suggested by Pindell & Dewey (1982). The fit of Madagascar and Africa is taken from Coffin & Rabinowitz (1987). The Seychelles block is fit in the remaining space available at the northern margin of Madagascar. The southern Agulhas Plateau is fit according to rotations published by Martin & Hartnady (1986).
4) India is fit according to Patriat et al. (1982) and Savostin et al. (1986). Sri Lanka is fit according to Katz (1978). South Kerguelen is included in the space between India and Australia (cf. Ramsay et al. 1986).
5) Instead of rotating all of Antarctica, only East Antarctica has been moved using a slightly modified Barron (1987) rotation. West Antarctic terranes have been adapted to reflect the model proposed herein. The model of Grindley & Davey (1982) for New Zealand, the Lord Howe Rise, Chatham Rise and Campbell Plateau is accepted with minor modifications.
6) Rotations of continental masses (Table 2) have all been made in circuits relative to North America, whose position in lat./long. coordinates over time was taken from Harrison & Lindh (1982), and Westphal et al. (1986). All rotations and times were adjusted to agree with the time scales of Forster & Warrington (1985) for the Triassic, and Hallam et al. (1985) as modified by Lowrie & Ogg (1986) for the Jurassic-Paleogene. Maps were reconstructed at 20 MY intervals by computer using a "Hypermap" program provided by E.J. Barron; however, the terranes were drafted-in by hand correcting for changes in shape.

Middle Triassic reconstruction

A new 240 Ma, Middle Triassic (Anisian) reconstruction of the Antarctic blocks is presented in Figure 2. Note that the Bransfield Straits have been closed to bring the South Shetland Islands into a pre-Cenozoic position. Noteworthy also are the restored position of the SOB and the Triassic configuration of the newly defined West Antarctic Block (WAB). The WAB was probably firmly attached to EAN at this time; however, this is mainly based on lack of evidence for any motion. There are no paleomagnetic or paleobiogeographic data of sufficient reliability to resolve this question. The later rifting events along the WAB-EAN boundary do support this model with reliable data,

Block	Time	Lat. (N = +)	Long. (E = +)	Angle (ccw = +)
NAM*	100	0.61	92.22	-20.5
	120	0.55	74.33	-23.8
	140	0.56	57.83	-23.4
	160	0.81	31.33	-14.1
	180	0.55	4.03	-23.8
	200	0.55	4.03	-24.0
	220	0.59	5.93	-21.4
	240	0.48	10.03	-30.0
SAM-NAM	100	4.0	-71.0	-15.0
	120	-15.7	-81.1	-17.5
	140	-33.0	-94.1	-18.5
	160	-51.4	-130.7	-27.8
	180	-53.8	-131.5	-30.8
	200	-54.3	-137.0	-29.9
	220	-54.6	-137.9	-30.5
	240	-54.9	-138.7	-31.0
SAF-NAM	100	-72.3	166.7	-38.9
	120	-65.1	165.6	-54.4
	140	-62.9	163.8	-62.5
	160	-61.5	164.9	-78.1
	180	-62.6	164.5	-81.1
	200	-61.3	163.4	-81.3
	220	-61.3	163.4	-81.9
	240	-61.3	163.4	-82.5
MAD-NAM	100	-72.3	166.7	-38.9
	120	-65.1	165.6	-54.4
	140	-69.4	172.1	-60.2
	160	-66.3	172.0	-74.8
	180	-67.1	172.0	-78.0
	200	-66.0	174.6	-77.9
	220	-65.9	174.7	-78.5
	240	-65.9	174.8	-79.0
IND-NAM	100	-28.5	170.0	-84.1
	120	-28.9	179.4	-102.8
	140	-37.6	176.9	-111.4
	160	-37.9	172.7	-126.1
	180	-38.8	171.5	-128.5
	200	-37.9	171.6	-128.7
	220	-38.0	171.4	-129.2
	240	-38.3	171.0	-130.6
ANT-NAM	100	-57.7	-84.1	-36.1
	120	-58.5	-109.3	-45.7
	140	-59.2	-98.7	-61.2
	160	-60.0	-119.0	-72.5
	180	-60.6	-120.0	-75.7
	200	-60.6	-122.9	-74.8
	220	-60.6	-123.4	-75.3
	240	-60.3	-121.1	-76.8
AUS-NAM	100	-45.5	-135.0	-57.1
	120	-44.7	-142.4	-69.2
	140	-52.3	-136.7	-81.9
	160	-50.9	-146.8	-95.0
	180	-51.6	-147.7	-98.0
	200	-50.9	-149.2	-97.4
	220	-50.9	-149.5	-97.9
	240	-51.8	-145.6	-97.3
AGH-NAM	100	-72.3	166.7	-38.9
	120	-69.2	168.3	-52.3
	140	-72.8	172.6	-57.1
	160	-68.9	174.0	-72.1
	180	-69.7	174.3	-75.3
	200	-68.4	172.0	-75.3
	220	-68.3	172.0	-75.9
	240	-68.3	172.0	-76.4

* North America is rotated according to the APWP derived from paleomagnetic data by HARRISON and LINDH (1982) and WESTPHAL et al. (1986).

Table 2: Finite rotations and paleomagnetic poles used in this study.

however. The shapes of the WAB and APB have been modified to reflect removal of some 300 km of post-Triassic extension. This includes about 250 km of Cenozoic extension along the boundary with East Antarctica associated with uplift of the Transantarctic Mountains and formation of deep graben in the Ross and Weddell Sea areas (HAUGLAND et al. 1985; FITZGERALD et al. 1986; HINZ & KRISTOFFERSEN 1987; KAMP & FITZGERALD 1987; STOCK & MOLNAR 1987). Another 50 km of extension, estimated as resulting from the earlier (Early–Middle Jurassic) failed rifting episode associated with Ferrar Supergroup basic intrusions and graben formation, has also been removed (KYLE et al. 1981; MASOLOV et al. 1981; BENTLEY 1983; DAVEY et al. 1983; ELLIOT et al. 1985; HINZ & KRISTOFFERSEN 1987). This latter estimate is uncertain at present and could be somewhat larger, although even double this value would not affect the model significantly. No attempt has been made to restore crustal shortening which may have accompanied the inferred collision of the APB with the main Antarctic continental mass.

The fit of the Antarctic reconstruction in Middle Triassic Gondwana is also shown in Figure 2. The APB is restored in a position outboard of South America. This position is favored for several reasons: 1) the Antarctic Peninsula does not overlap the Falkland Plateau and is assumed to have suffered no oroclinal bending (cf. BARRON, 1987); 2) it is consistent with a spreading history derived from M-series anomalies identified by BERGH (1977); 3) it is also compatible with the strike of magnetic anomalies in the Weddell Sea (BARKER & JAHN, 1980; LaBRECQUE & BARKER 1981) and the orientation and age of the breakup unconformity along the East Antarctic margin (KRISTOFFERSEN & HAUGLAND 1986; HINZ & KRISTOFFERSEN 1987); and 4) it is consistent with the evidence for later Mesozoic South American back-arc basin evolution (HARRISON et al. 1979; 1980). Although this reconstruction was once controversial (DALZIEL 1980; HARRISON et al. 1980), it now seems to be a workable solution acceptable to a number of authors (FORD & KISTLER 1980; POWELL et al. 1980; DALZIEL 1983; MILLER 1983; BARRON 1987).

The proposed collision (see Fig. 3 for expanded view of collision zone) of the APB with East Antarctica and the WAB is of central importance to this reconstruction. Several components of the hypothetical plate boundaries drawn on Figures 2 and 3 may serve to explain observed features in Antarctica's tectonic history. For example, the oblique nature of the collision, with sinistral strike-slip motion on either side of the Ellsworth-Pensacola collision zone, allows deformation in those regions to be minor in comparison with more orthogonal types of collision belts (cf. CHRISTIE-BLICK & BIDDLE 1985; EISBACHER 1985; KREUZER et al. 1987). Relatively low-intensity deformation is in fact preferable for the Ellsworth Orogen, as pointed out by several workers (e.g. VENNUM & STOREY 1987b). In addition, numerous small overthrusts trending NE–SW have been reported to occur in the western Ahlmann Ridge area of Queen Maud Land (Fig. 1) (SPAETH 1987). These have been interpreted to be a result of the Ross Orogen, but the only time constraints are that thrusting occurred between Cambrian and Middle Jurassic. An Ellsworth Orogen (Triassic) time of deformation is a possible alternative interpretation which fits the model presented here. More specifically, the strike-slip motion produced by oblique collision could have led to the observed deformation in the western Ahlmann Ridge area. However, this interpretation is quite speculative and needs further work.

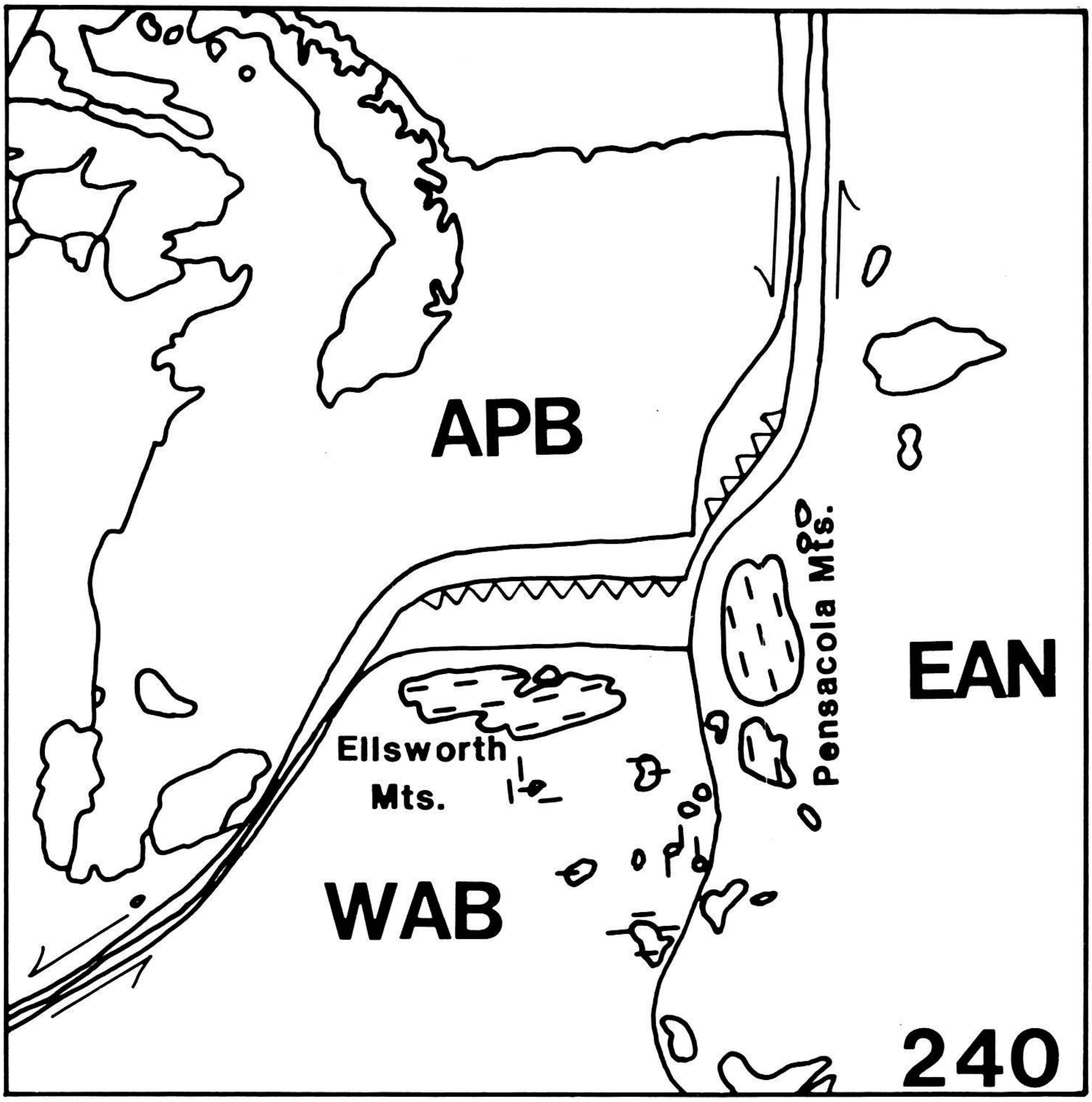

Fig. 3. Expanded-scale map of convergence zones in Middle Triassic reconstruction. Location of box shown on Figure 2. Outcrop areas outlined, with structural trends indicated by dashed line pattern. Structure modified from Ford (1972), Craddock (1983), and Storey & Dalziel (1987). Abbreviations and symbols as in Figure 2; plate boundaries schematic. See text for discussion.

The subduction zone shown adjacent to the Ellsworth Mountains (Fig. 3) is supported by the pre-collisional, calc-alkaline arc nature of the Mt. Woollard and Whitmore Mountains granites (Vennum & Storey 1987b). In the Pensacola Mountains area the plate boundary could have been either strike-slip or more likely oblique subduction (of unknown, but plausibly NW-directed polarity), as shown. The oblique subduction zone drawn along the WAB–APB Pacific margin (Fig. 2) is partially required by strong evidence of subduction in the GLB (e.g. Pankhurst 1983; Thomson & Pankhurst 1983) and partially by geometry, although there is presently no geologic evidence in the WAB that would support the inferred extent of this subduction. However, the lack of evidence could be due in part to the inferred obliquity of the convergence angle and concomitant diminution of magmatism (cf. ASPDEN et al. 1987). Positions of spreading ridges are estimated from global tectonic evidence to be published elsewhere (WILSON et al., in prep.). Separation of the APB into distinct sub-terranes (GLB, PLB) is based on: 1) the obvious structural discontinuity between the blocks (ELLIOT 1983); and 2) the well-documented existence of dextral shear of uncertain, but probable post-Triassic age in the northern PLB (ROWLEY et al. 1983; MENEILLY et al. 1987). The amount of original offset between the PLB and the GLB is unknown, but has been arbitrarily set at 150 km in the present model. The positions of the SOB and SGB are adopted from DALZIEL (1981) and others. Subduction under southern South America is also well-documented (e.g. FORSYTHE 1982; ULIANA & BIDDLE 1987), but the nature of the South American-SGB-PLB boundary shown in Figure 2 is speculative.

Late Triassic reconstruction

A fit of Late Triassic (220 Ma; Norian) Antarctica in Gondwana is presented in Figure 4. The collision of the APB with the WAB and East Antarctica is quite advanced by this time. Subduction has all but ceased, while collision-produced intrusion and deformation have begun, as evidenced by the various radiometrically dated plutons and dikes of the WAB and Pensacola Mountains areas (MILLAR & PANKHURST 1987). Close inspection of Figure 4 suggests that the inferred sinistral strike-slip motion along the APB-East Antarctica boundary could have produced structures typical of a restraining bend system (cf. MANN et al. 1985) in the area of the northern Pensacola Mountains. While there is not enough detailed structural evidence available to evaluate this mechanism fully, it is nevertheless noteworthy that the folding of the Pensacola Mountains occurs in the appropriate position for such a mechanism to operate (cf. CHRISTIE-BLICK & BIDDLE 1985). The Pacific margins of the WAB and APB are much the same as in the 240 Ma reconstruction. The small ocean basin subducting beneath South America in the area east of the GLB has decreased in size considerably by this time, due to the rotation of the APB.

Early Jurassic reconstruction

An Early Jurassic (200 Ma; Sinemurian) reconstruction of Gondwana is presented in Figure 5. Deformation associated with the APB collision was probably complete by this time, but the majority of the resulting post-collisional granites in the WAB were not yet emplaced. Suturing of the APB to Antarctica is considered to have been complete by Sinemurian, which situation is reflected by the absence in Figure 5 of a plate boundary between these blocks. Almost the entire Pacific margin of Gondwana was probably undergoing subduction at this time (cf. PANKHURST 1983; HARRINGTON & KORSCH 1985; WILSON et al., in press). The close proximity of the GLB and SOB to southern South America is consistent with a position that allows for the later opening of the Weddell Sea and the absence, in the Early Jurassic, of a marginal basin behind the APB (HARRISON et al. 1979; DALZIEL 1983). No collision is implied by the close

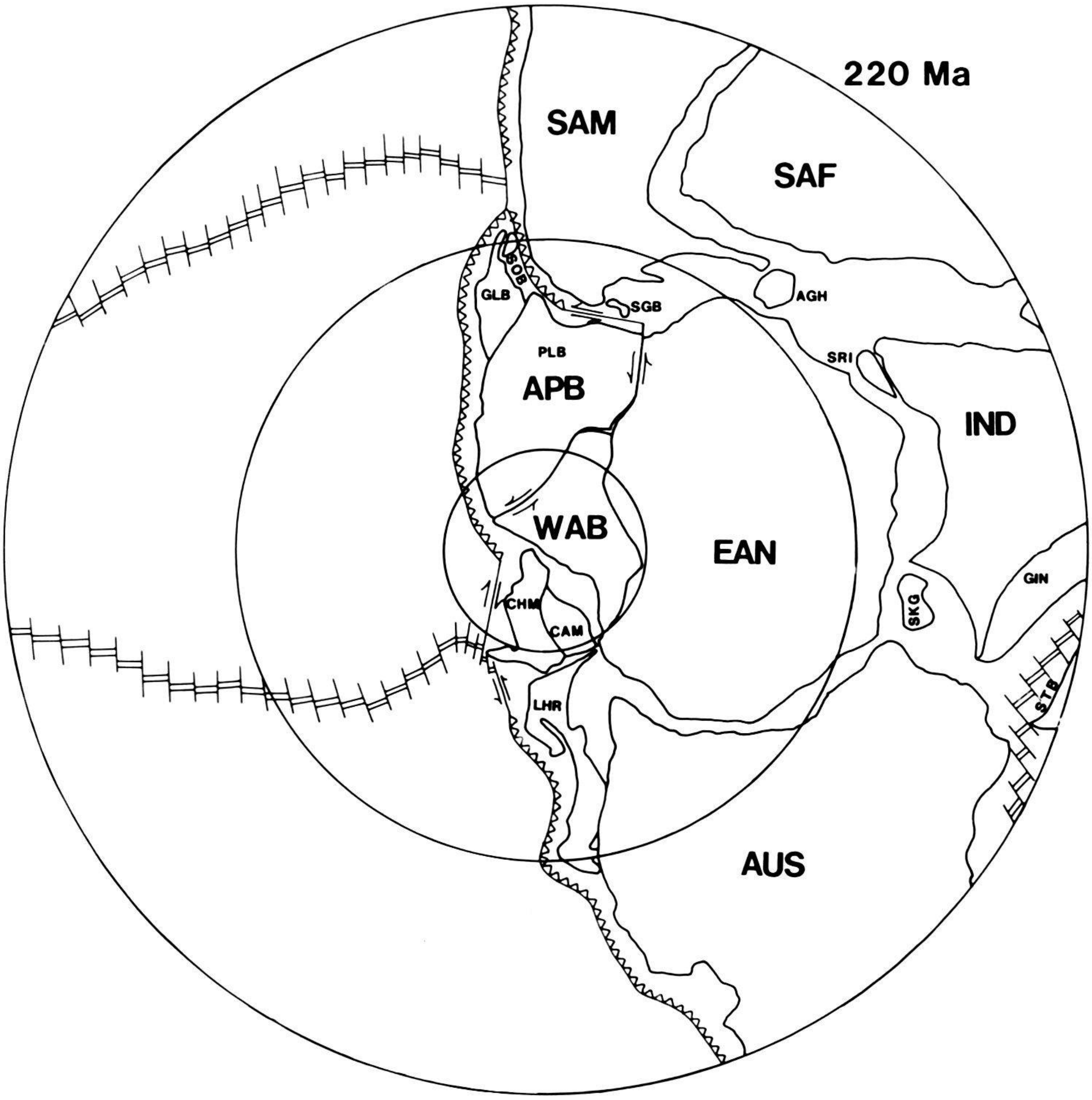

Fig. 4. 220 Ma, Late Triassic (Norian) reconstruction. Abbreviations and symbols as in Figure 2; plate boundaries schematic. See text for discussion.

proximity of these crustal blocks; rather, inferred Triassic subduction of sea floor separating the GLB–SOB and South America (Fig. 4) has merely ceased as a result of the plate reorganization attendent upon collision of the APB.

Late Early Jurassic reconstruction

Figure 6 shows a reconstruction of Antarctica in Gondwana for 180 Ma (Toarcian; late Early Jurassic). This figure suggests that the principal change in plate tectonic milieu, as compared to the 200 Ma reconstruction, is the inferred initiation of a tri-radiate rift system in western Gondwana. Two of the rift arms form a partial boundary be-

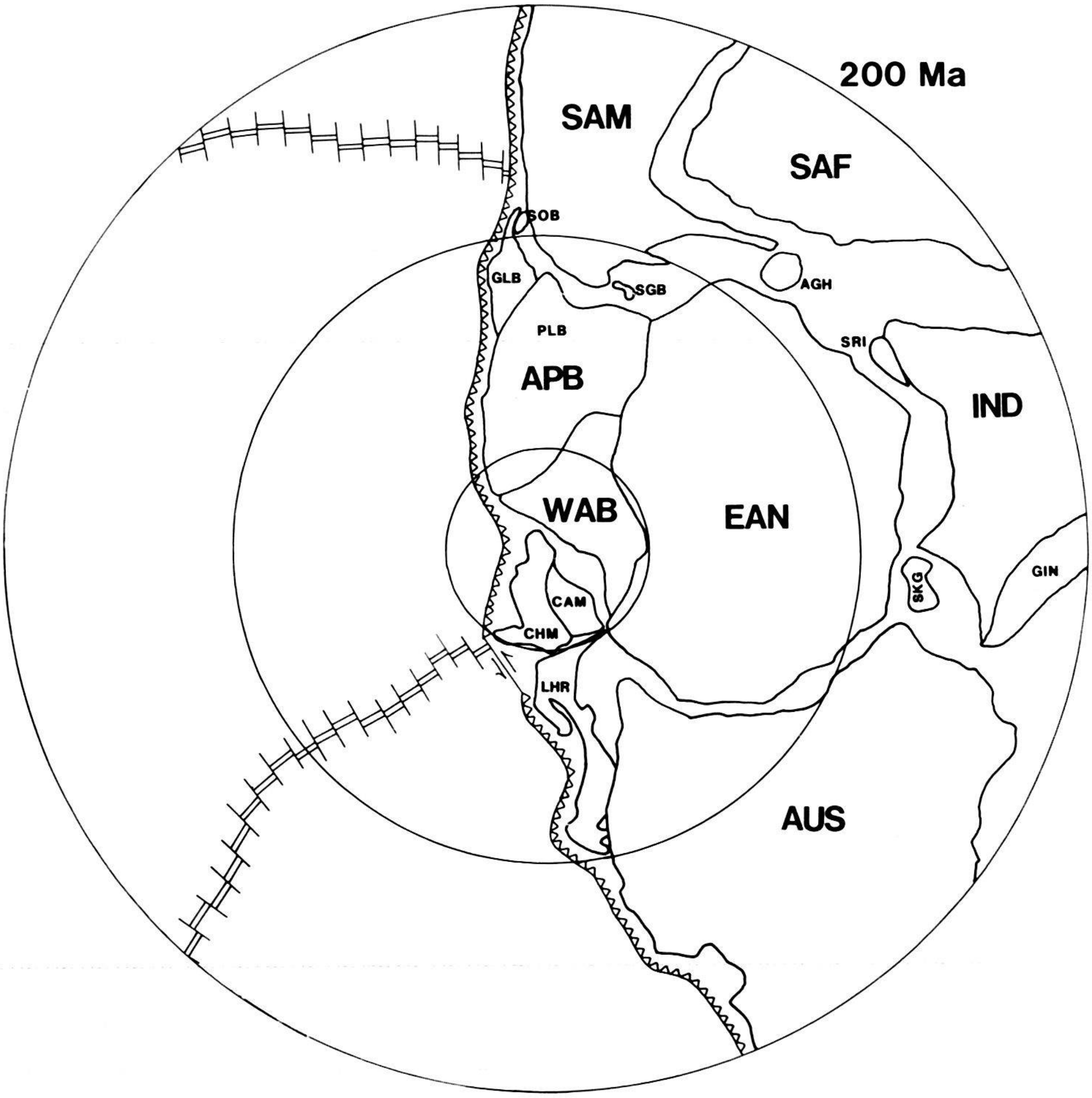

Fig. 5. 200 Ma, Early Jurassic (Sinemurian) reconstruction. Abbreviations and symbols as in Figure 2; plate boundaries schematic. See text for discussion.

tween South America and Antarctica, while a third arm extends into the interior of Antarctica from the Weddell Sea to the Ross Sea. The incipient tri-radiate rift interpretation was proposed by Ford & Kistler (1980) to explain the distribution of dated Ferrar Supergroup tholeiitic magmatism in Antarctica. These authors identified two chemically distinct sub-systems in the widespread Ferrar-correlative intrusions: 1) a Transantarctic Mountains unit in mid-plate, stretching from the Ross Sea to north of the Pensacola Mountains; and 2) a Weddell Sea unit spanning the area from the Theron Mountains to the Weddell Sea. The Weddell Sea sub-system may also include intrusions related to the easternmost rift arm, which ran parallel to the Queen Maud coast (cf. Spaeth 1987). This sub-system has affinities with the Karoo intrusions of

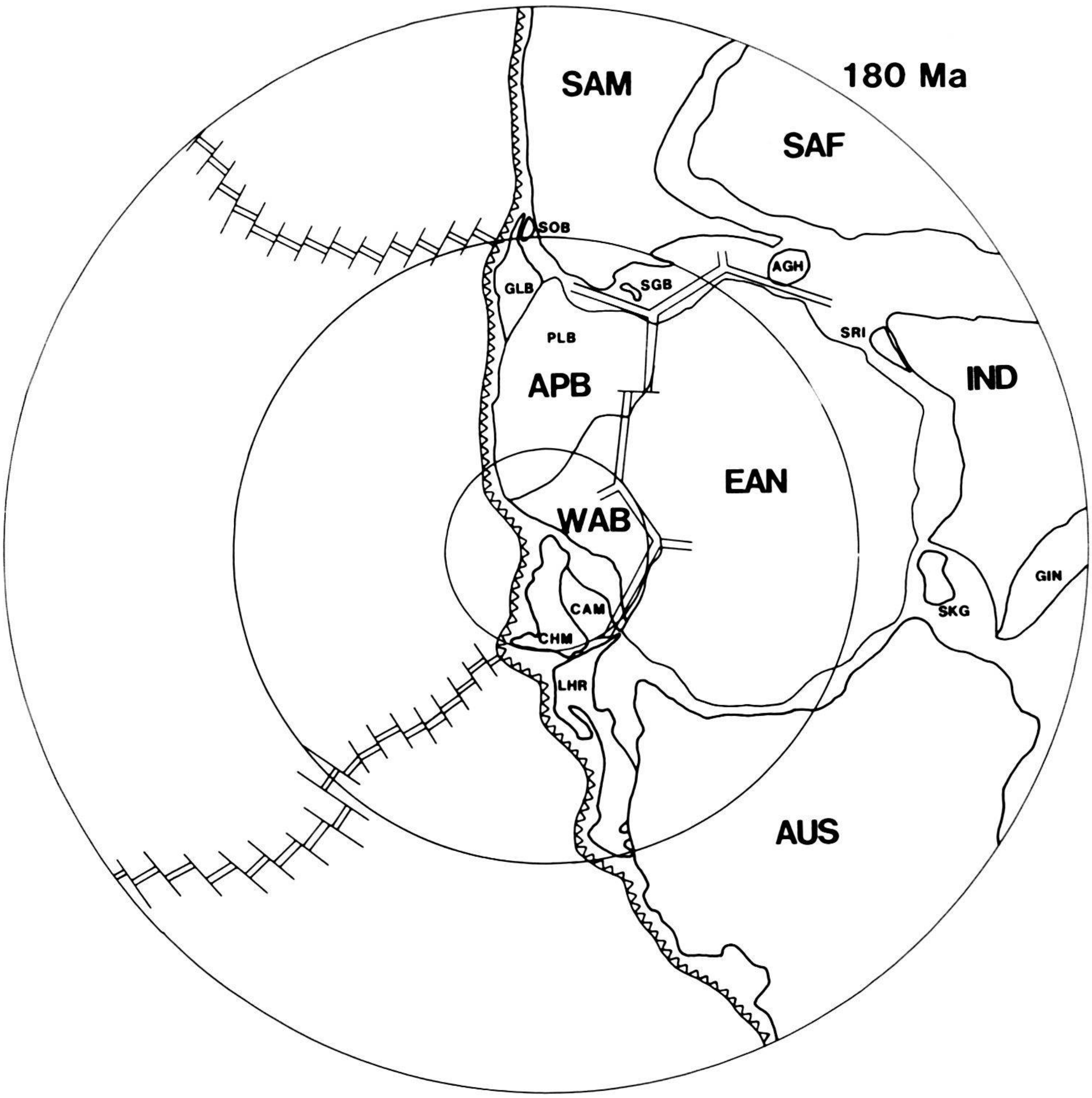

Fig. 6. 180 Ma, Late Early Jurassic (Toarcian) reconstruction. Abbreviations and symbols as in Figure 2; plate boundaries schematic. See text for discussion.

South Africa, and both may be related to the eventual breakup of the Gondwana continents. The Transantarctic sub-system is in a position and has a chemistry compatible with its being the expression of a failed rift (cf. Burke 1976; 1977; Ford & Kistler 1980; Emery & Uchupi 1984).

Geophysical studies support the existence of possibly Jurassic rifts in the Weddell Sea sector, although structural overprinting of these graben by major rifting in the Cenozoic is probably common (Masolov et al. 1981; Hinz & Kristoffersen 1987). The reported ages of most reliably dated intrusions from throughout Antarctica fall in the range from 180–160 Ma, although a few are as old as 204 Ma (Ford & Kistler 1980; Kyle et al. 1981; Elliot et al. 1985). An alternative interpretation presented by

SCHMIDT & ROWLEY (1986) and adopted by GRUNOW et al. (1987b) invokes dextral strike-slip of some 500–1,000 km to explain the occurrence of the Jurassic tholeiites. However, this model is based mostly on assumptions about geometry, which are in turn based on a Gondwana fit rejected here. No structural evidence (e.g. folding, transpressional basins, etc.) of such major strike-slip displacement has come to light, nor do sea floor data require such motion.

Middle Jurassic reconstruction

A Middle Jurassic (160 Ma; Callovian) reconstruction is presented as Figure 7. The major feature of note remains the tri-radiate rift system in western Gondwana. The failed rift arm in Antarctica essentially ceased extensional motion shortly after this time; consequently, crustal stretching totaling an arbitrary but reasonable estimate of 50 km has been added to the WAB and APB on Figure 7 to reflect the Jurassic rifting episode. Tholeiitic intrusions continue to be emplaced in the Middle Jurassic of Antarctica, but the major activity occurred before 160 Ma (ELLIOT et al. 1985). The early formation of "back-arc" basins in the PLB and southern South America (BRUHN et al. 1978; FORSYTHE 1982; DALZIEL 1983) may have resulted from this postulated rift system, one arm of which eventually opened the Weddell Sea.

Late Jurassic reconstruction

Figure 8 presents a 140 Ma (Kimmeridgian) Late Jurassic reconstruction of Antarctica in Gondwana. India has just separated from Gondwana, while Madagascar has moved a considerable distance south, opening the Somali Basin behind it (PATRIAT et al. 1982; COFFIN & RABINOWITZ 1987). The Weddell Sea Basin has also begun to open by Late Jurassic time (LaBRECQUE & BARKER 1981; HINZ & KRISTOFFERSEN 1987), which is consistent (HARRISON et al. 1979; DALZIEL 1983) with reports of "back-arc" basin development in the APB and SGB during this period. Basalt dikes and sills in the PLB were apparently emplaced as a result of this regional extension (MENEILLY et al. 1987).

A portion of the same rift system that opened the Weddell Sea could have continued to the north into Patagonia; however it would have changed character northward to become a true back-arc basin (BRUHN et al. 1978; and others). In any case, there is good sedimentological evidence indicating that the GLB arc was small and mostly submergent at this time, and that active back-arc extension was not occurring in close proximity to the GLB (FARQUHARSON 1982). This is compatible with the interpretation offered here. Subduction probably continued all along the Pacific margin of Gondwana during the Late Jurassic (e.g. SPÖRLI 1987; ULIANA & BIDDLE 1987).

Early Cretaceous reconstruction

A reconstruction of Antarctica in Gondwana for 120 Ma (Hauterivian) in the Early Cretaceous is presented as Figure 9. India continues to move northward, while Madagascar has reached its present-day position relative to Africa (COFFIN & RABINOWITZ 1987). Spreading continues in the Weddell Sea and in the back-arc basin of Patagonia (DALZIEL 1981). However, three factors now add considerable complexity to the

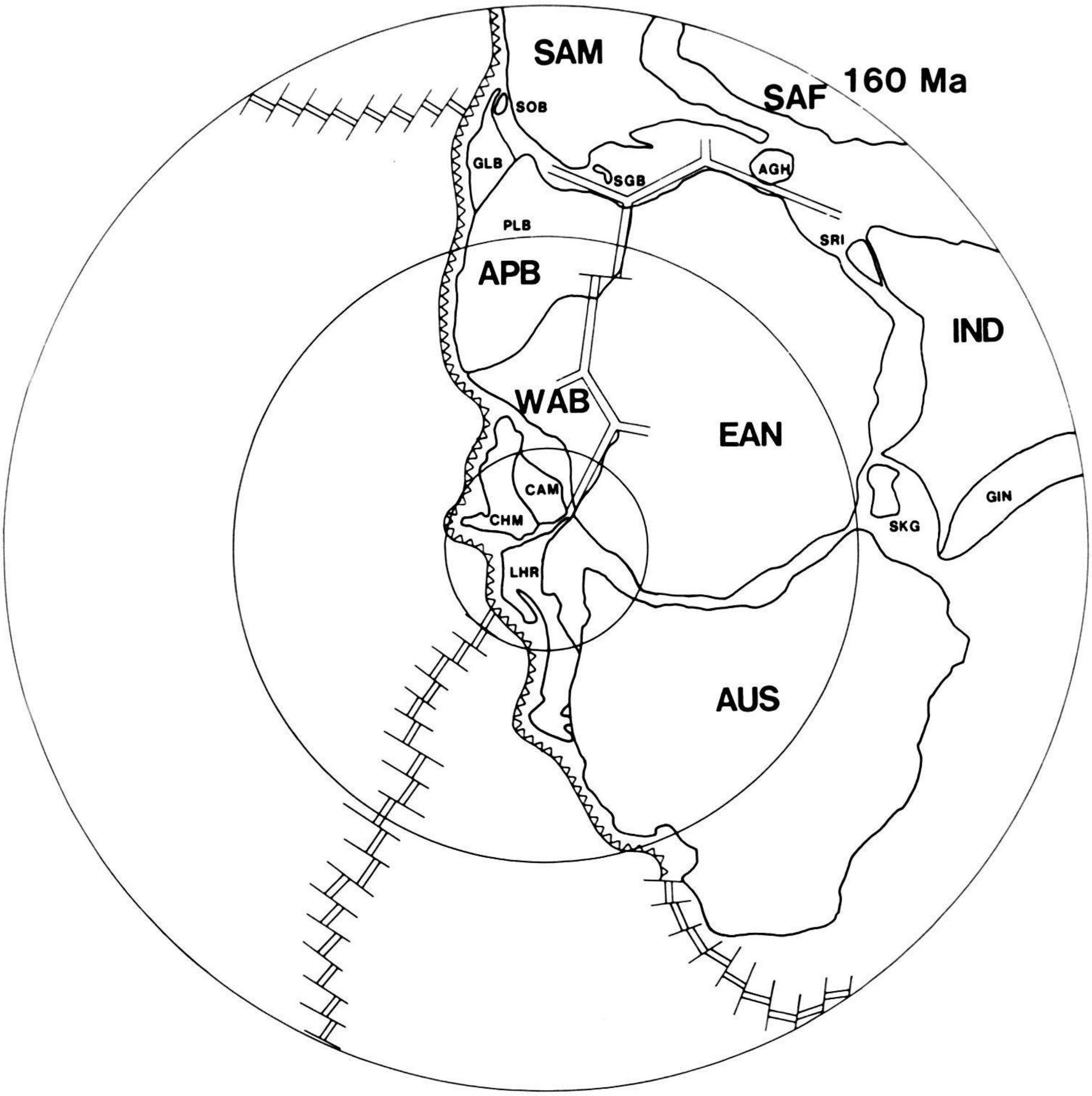

Fig. 7. 160 Ma, Middle Jurassic (Callovian) reconstruction. Abbreviations and symbols as in Figure 2; plate boundaries schematic. See text for discussion.

picture: 1) strong Early Cretaceous compression in the PLB is coupled with a nearly complete lack of deformation in the GLB (Elliot 1983); 2) there is good evidence of dextral strike-slip in the boundary area between the GLB and the PLB, although the timing of this is presently obscure (Rowley et al. 1983; Meneilly et al. 1987); and 3) continued back-arc spreading in South America, in spite of the opening gap between South America and the APB, makes a single arc explanation unlikely. Thus, in order to satisfy kinematic and geometric requirements of the foregoing evidence, it seems necessary to invoke a second west-facing subduction zone east of the APB (Fig. 9), and an east-facing subduction zone along the Weddell margin of the PLB driven by a short-lived spreading center. Other explanations are possible (Elliot 1983) but difficult to

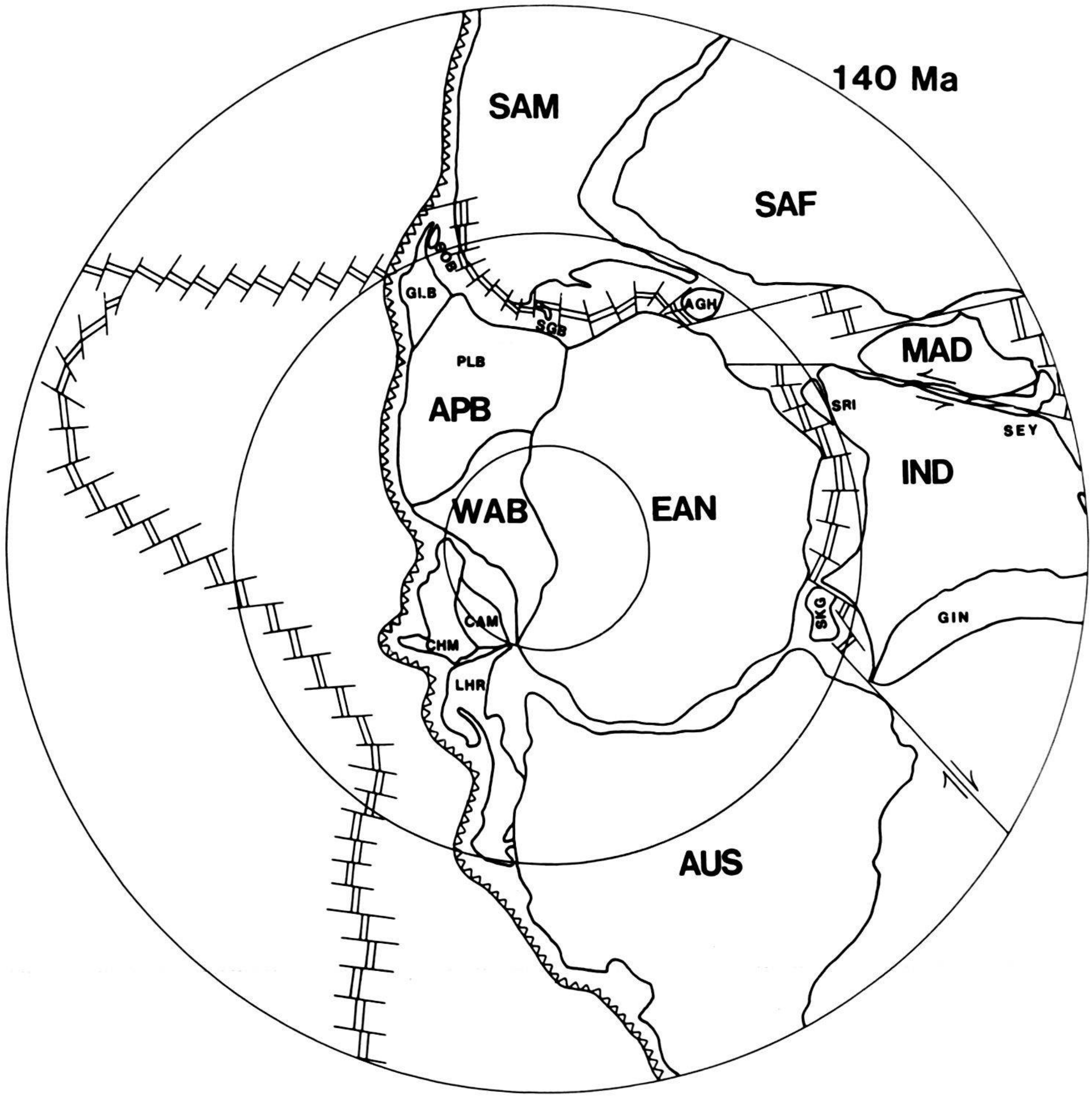

Fig. 8. 140 Ma, Late Jurassic (Kimmeridgian) reconstruction. Abbreviations and symbols as in Figure 2; plate boundaries schematic. See text for discussion.

envision given the geometry of major blocks and rifts shown in Figure 9. The GLB portion of the APB arc became emergent and was marked by voluminous activity at this time (e.g. Farquharson 1982). Again, subduction is inferred to have continued along the entire Pacific margin of Gondwana (e.g. Thomson & Pankhurst 1983; Harrington & Korsch 1985).

Late Early Cretaceous reconstruction

Figure 10 presents an Albian (100 Ma; late Early Cretaceous) reconstruction of the southern continents. The breakup of Gondwana was by this time at an advanced stage,

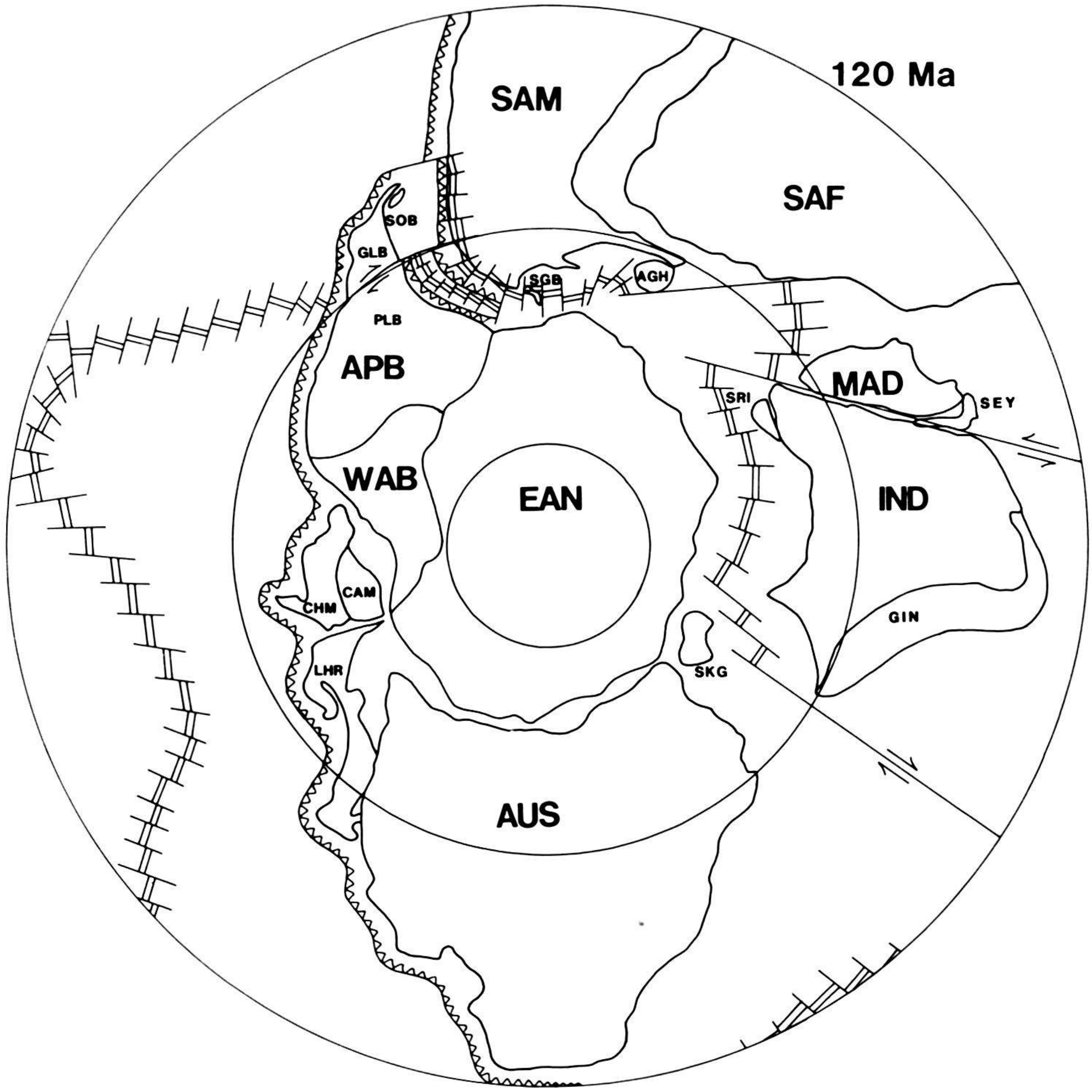

Fig. 9. 120 Ma, Early Cretaceous (Hauterivian) reconstruction. Abbreviations and symbols as in Figure 2; plate boundaries schematic. See text for discussion.

as shown by the opening of the South Atlantic, the northward flight of India and the incipient spreading between Australia and Antarctica (BARRON 1987). The Falkland Plateau and the Agulhas Plateau have separated from one another, and the South Kerguelen Plateau has separated from Antarctica (MARTIN & HARTNADY 1986; RAMSAY et al. 1986; MUNSCHY & SCHLICH 1987).

Continued motion of South America and Antarctica has resulted in substantial subduction of the small basin behind the GLB, the closure of the South American back-arc basins and the emplacement of ophiolites in the SGB and elsewhere (HARRISON et al. 1979; DALZIEL 1981; 1983). The Weddell Sea is bounded on the west by an inferred sinistral transform which allows the APB to slide past South America. A

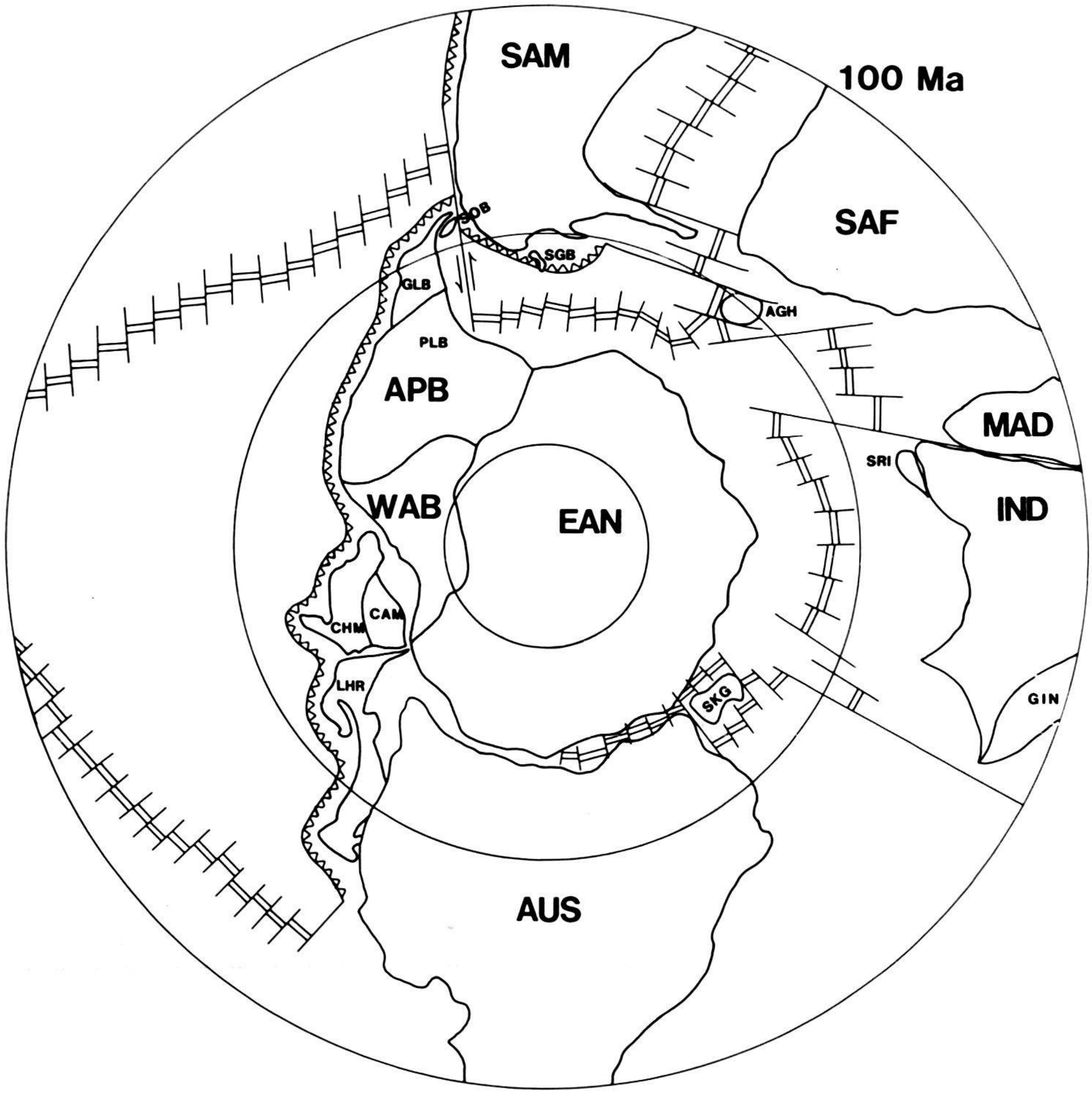

Fig. 10. 100 Ma, Late Early Cretaceous (Albian) reconstruction. Abbreviations and symbols as in Figure 2; plate boundaries schematic. See text for discussion.

short-lived subduction zone is inferred to have formed the northern border of the Weddell Sea and to have taken up convergence required by motion of the major blocks. This convergent boundary may also explain the observed emplacement of SGB and other ophiolites. Strike-slip motion of the GLB has ended and this block is inferred to have reached its present-day orientation. Compression in the PLB has also ended, and with it the presumed associated east-facing subduction system.

The alternative model of Grunow et al. (1987b) calls for some 2,500 km of sinistral strike-slip along the West Antarctic–East Antarctic boundary during the mid-Cretaceous. This huge amount of translation would require average motion of some 10 cm/yr along the inferred fault. However, there is again no structural evidence to support such motion. Thus, although one would expect significant Cretaceous deformation (similar in style to that of the San Andreas System) to occur all along the trend of the Transantarctic Mountains, none is observed. Furthermore, a recent survey of global plate boundaries came up with an average rate of motion for analogous major transforms of only 2 cm/yr (JARRARD 1986), and even the San Andreas transform moves no faster than 5.6 cm/yr. Thus the inferred rate of motion for this postulated major transform seems rather high. For the reasons just discussed we do not include major transform motion of West Antarctica in the mid-Cretaceous in our model. From this point on, the tectonic evolution of Antarctica and the Scotia Arc seems well understood (e.g. DALZIEL 1984) and relatively non-controversial; therefore no further reconstructions are deemed necessary at this juncture.

Discussion

In our view, the simultaneous application of terrane analysis techniques and integrated data reliability weighting is a necessary prerequisite to any meaningful interpretation of large-scale tectonic evolution. Certainly the reconstructions presented here are quite different from previous attempts, although the same data base has been used to formulate models. Nevertheless, much of what we propose is not uniquely defined. Therefore, in the context of the present study it is important to assess the usefulness of such an admittedly speculative effort. Detailed structural analysis and geochemical characterization of the important igneous typologies may go a long way toward testing the theory of a collision between the APB and the Antarctic craton. New geophysical data from critical areas identified in the reconstructions presented here could confirm or deny the inferred locations and nature of terrane boundaries. New fossil discoveries could aid in confirming the identification and paleogeographic analysis of proposed terranes. Alternative interpretations may result from such efforts, but if they are based on proper terrane analysis methods and reasonable plate tectonic scenarios, progress will have been made toward improving our understanding of Antarctic and Gondwanan history.

Conclusions

West Antarctic terranes proposed in previous studies have been poorly defined and may not accurately reflect the tectonic evolution of Antarctica. An alternative suite of tectonic reconstructions has been assembled in the present study using well-established terrane analysis techniques and data reliability weighting. The new model places the Antarctic Peninsula outboard of South America in the early Mesozoic. Only four terranes are defined as comprising West Antarctica: the Antarctic Peninsula, West Antarctic, South Georgia and South Orkney Blocks. Late Triassic oblique collision of the Antarctic Peninsula Block with the West Antarctic Block is invoked to explain the features of the Ellsworth-Pensacola Orogen. Finally, a Jurassic rifting event is inferred to have produced widespread development of graben along the West Antarctic–East Antarctic boundary. Although the solutions presented in this model are not unique, they are testable and falsifiable, and thus should serve to focus further research.

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