

## Mesozoic evolution of West Antarctica and the Weddell Sea Basin: new paleomagnetic constraints

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Paleomagnetic data from the Antarctic Peninsula and our recent results from the Ellsworth-Whitmore Mountains block suggest that since the Middle Jurassic these two West Antarctic blocks have undergone little relative movement and together have rotated relative to the East Antarctic craton. New data from Lower Cretaceous rocks from the Thurston Island region of West Antarctica suggest that on the basis of paleomagnetic constraints, the Antarctic Peninsula, Ellsworth-Whitmore Mountains and Thurston Island blocks define a single entity which we call Weddellia; some motion between these blocks is possible within the limits of the paleomagnetic data.

Between the Middle Jurassic and Early Cretaceous, Weddellia remained attached to West Gondwanaland while East Antarctica moved southward (dextrally) relative to Weddellia. From the Early Cretaceous to mid-Cretaceous, Weddellia rotated clockwise  $30^\circ$  and moved sinistrally approximately 2500 km relative to East Antarctica, to its present-day position. We suggest the Early to mid-Cretaceous to be the time of the main if not initial opening of the Weddell Sea.

### 1. Introduction

Reconstructions of Gondwanaland have always been hampered by the uncertainty in positioning West Antarctica [1–3]. Based on geological and geophysical arguments, West Antarctica can be divided into discrete structural blocks that form topographic highs [4–8]: the Antarctic Peninsula block (AP); the Ellsworth-Whitmore Mountains block (EWM); the Haag Nunataks block (H); the Thurston Island–Eights Coast block (TI); and Marie Byrd Land (MBL) (Fig. 1).

Geologically, West Antarctica is quite different from East Antarctica in that the rocks consist primarily of Mesozoic and Cenozoic subduction related intrusives and extrusives (AP, TI and MBL blocks); deformed Paleozoic sedimentary rocks (EWM and MBL blocks); and Middle Jurassic granites (EWM block) [6]. The Haag Nunataks are unique because they represent the

only known Precambrian basement in West Antarctica [7]. East Antarctica consists mostly of Precambrian shield, Paleozoic sedimentary and intrusives rocks (the Transantarctic Mountains) and Middle Jurassic mafic igneous rocks [9].

Available paleomagnetic data from the West Antarctic blocks, except the H block where there are no data; indicates motion of these blocks relative to East Antarctica [10–14]. It has been suggested that the EWM block should be rotated  $90^\circ$  relative to East Antarctica because this would align the structural trends of the Ellsworth Mountains sedimentary rocks with the East Antarctic Transantarctic Mountains sedimentary rocks [4,5]. Cambrian paleomagnetic data [10] from the EWM block support a  $90^\circ$  clockwise restorative rotation relative to East Antarctica but the timing and even the sense of this rotation is not well established.

The geologic history of the EWM and TI blocks was reexamined using geochronology, geochemistry, structural analysis, sedimentology and paleomagnetism by the joint British Antarctic Survey–United States Antarctic Research Program West Antarctic Tectonics project [7,15–19]. The paleomagnetic results from the TI block are presented here and interpreted in conjunction with

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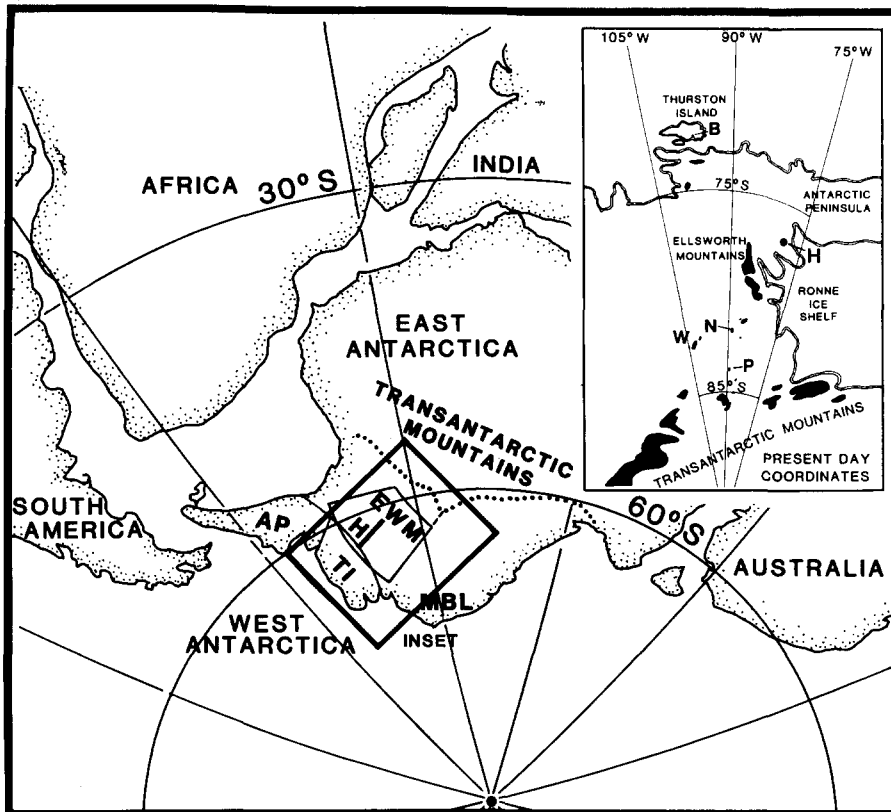


Fig. 1. Gondwanaland reconstruction by Norton and Sclater [3]. West Antarctic crustal blocks [4–8]: AP = Antarctic Peninsula; EWM = Ellsworth Mountains–Whitmore Mountains; H = Haag Nunataks; MBL = Marie Byrd Land; TI = Thurston Island–Eights Coast. Inset shows sample localities in the EWM and TI crustal blocks: B = Belknap and adjoining unnamed nunatak; H = Haag Nunataks; N = Nash Hills; P = Pagano Nunatak; W = Whitmore Mountains.

our earlier reported results [14] from the EWM block.

## 2. Sampling

An extensive collection of paleomagnetic cores was obtained from the EWM (480 cores, 77 sites) and TI (728 cores, 114 sites) blocks by West Antarctic Tectonics Project during the 1983–84 and 1984–85 field seasons. Cores were collected by using a gasoline powered, portable diamond-bit coring drill and oriented with a Brunton compass. Sun compass readings were taken at all localities to correct for local magnetic variation. A wide variety of rocks (intrusive, sedimentary and metamorphic), ranging in age from Pre-Cambrian to Jurassic, were samples from the EWM blocks. Paleozoic (?) and Mesozoic plutons, Mesozoic and

Tertiary volcanics, dikes and metamorphic rocks were samples from the TI block. In the case of the igneous rocks an effort was made to collect sites with a variety of textures within individual rock units in the hope that these would have somewhat different cooling histories, hence averaging the effects of secular variation.

Pilot samples from most sites were subjected to demagnetization experiments but special effort was made on the Jurassic units because: (1) a Middle Jurassic paleopole is available for the AP block [13]; (2) dated or presumed Middle Jurassic rocks were samples from both the EWM [16,20] and TI blocks; (3) reference poles for the Middle Jurassic are available from East Antarctica (Ferrardolerites) [21,22]; (4) these reference Jurassic paleopoles for East Antarctica are located in middle latitudes, exceptional for at least late Paleozoic

to Recent time during which the apparent polar wander path tends to be in very high latitudes. Thus, relative rotations can be more readily resolved in the Jurassic than for any other time in this interval using paleomagnetic data.

### 3. Previous paleomagnetic results

Our paleomagnetic results from the EWM block have been presented elsewhere [14]. Briefly, Middle Jurassic coarse-grained, peraluminous granitic plutons from the Pagano Nunatak and Nash Hills (Fig. 1) (Rb/Sr whole rock ages of  $175 \pm 8$  m.y. and  $175 \pm 8$  m.y., respectively) [16] gave stable normal and reversed directions that are antipodal. The Pagano sites have normal polarity whereas the Nash Hills sites have predominantly reversed polarity, except near the margin where baked metasedimentary rocks were magnetically overprinted with a stable normal-polarity direction also found in the granite near the contact. The combined paleopole determined from 8 sites from these 2 localities that are 200km apart is  $235.2^\circ$  E,  $41.2^\circ$  S ( $A_{95} = 5.3^\circ$ ,  $K = 110.2$ ); a paleolatitude of  $47^\circ$  S is indicated for this area of the EWM block. This pole is not significantly different from the Middle Jurassic pole from the AP block [13] but is significantly different from the mean East Antarctic Middle Jurassic pole recalculated by us [14] ( $220.3^\circ$  E,  $54.9^\circ$  S,  $A_{95} = 3.9^\circ$ ,  $K = 97.2$ ,  $N = 15$  localities) (Table 1). In the Nash Hills Cambrian(?) metasedimentary rocks a component of magnetization stable after thermal demagnetization above  $560^\circ$  yielded mean tilt corrected directions of  $D = 21.2^\circ$ ,  $I = 0.8^\circ$ ,  $\alpha_{95} = 8.4^\circ$ ,  $k = 27.6$ ,  $n = 12$  samples (2 sites), corresponding to a pole located at  $292^\circ$  E,  $7.2^\circ$  N. This pole is very

similar to the Late Cambrian pole ( $296^\circ$  E,  $4^\circ$  N) from the Ellsworth Mountains Heritage Group [10] and suggests that little relative rotation occurred within the EWM block.

### 4. New paleomagnetic results

New paleomagnetic data are presented here for the TI block. A dioritic to gabbroic intrusion and cross-cutting mafic and granitic dikes forming Belknap Nunatak and an unnamed nunatak (5 km to the south) were selected for detailed paleomagnetic study (Fig. 1). The intrusive body was thought tentatively to be Jurassic (160 Ma) based on an early K-Ar determination on a pyroxene separate (C. Craddock, personal communication, 1985), but Rb/Sr whole rock dating has now yielded an Early Cretaceous isochron of  $122 \pm 2$  m.y. for the entire igneous complex (I. Millar and R. Pankhurst, personal communication, 1986). A total of 47 independently oriented core samples from 8 sites were drilled at these 2 nunataks. Sun compass readings at each locality required corrections of  $< 3^\circ$  to the magnetic declinations.

The natural remanent magnetization (NRM) of the samples was measured on either a cryogenic magnetometer or a computerized fluxgate spinner magnetometer. NRM intensities ranged between  $10^1$  and  $10^2$  A/m, typically higher in the more mafic lithologies. Samples were progressively demagnetized in a minimum of 5 steps up to a peak alternating field (AF) of 100 mT. The demagnetization data were plotted on vector end-point diagrams [23] and characteristic directions were calculated by using principal component analysis [24].

A single component of magnetization, upward

TABLE 1  
Paleomagnetic poles

Location	Age (Ma)	Long. ( $^\circ$ E)	Lat. ( $^\circ$ S)	$K$	$A_{95}$	Reference
AP block	175	238.0	48.0	–	9.5	[8]
EWM block	174	235.2	41.2	110.2	5.3	[9]
Combined Middle Jurassic AP-EWM mean pole	175	237.0	45.8	111.5	6.4	[9]
East Antarctica	160–180	220.3	54.8	97.2	3.9	[8]
TI block	122	232.0	49.0	233.1	7.9	this paper

$K$  = estimation of Fisher's [43] precision parameter;  $A_{95}$  = radius of circle at the 95% confidence level for mean pole position.

pointing to the southwest, was consistently found in 5 sites at the unnamed nunatak and 1 site at Belknap Nunatak (total of 34 samples; Fig. 2a and b). The magnetizations at these 6 sites are of normal polarity and very high stability. Since the

directions depart from the present-day field and only a single component is present, we assume that this is an original magnetization acquired during cooling. Three different rock units (diorite/gabbro, a diabase dike and a 5-m-wide granitic dike with xenoliths of the diorite) gave the same directions. Although the precise time elapsed between emplacement of these various lithologies is not known, it seems reasonable to assume that sufficient time is represented to average the effects of secular variation.

Two of the 8 sites proved unsuitable for the final analysis. These sites (12 samples) are dominated by very low coercivity components, the samples typically retaining less than 10% of their original intensity at 20 mT (Fig. 2c). Several samples contained a partial magnetic overprint component that was oriented northeast and upward pointing (Fig. 2d), but a more stable, possibly primary component could not be adequately resolved because it was retained only in the last 5–10% of the magnetization.

Our unit mean direction of  $D = 133.7^\circ$ ,  $I = -75.6^\circ$ ,  $\alpha_{95} = 4.4^\circ$ ,  $k = 233.1$ , for the TI block was determined by combining sample means (Fig. 3) to produce 6 site means; the 6 site means were combined to produce the unit mean (Table 2).

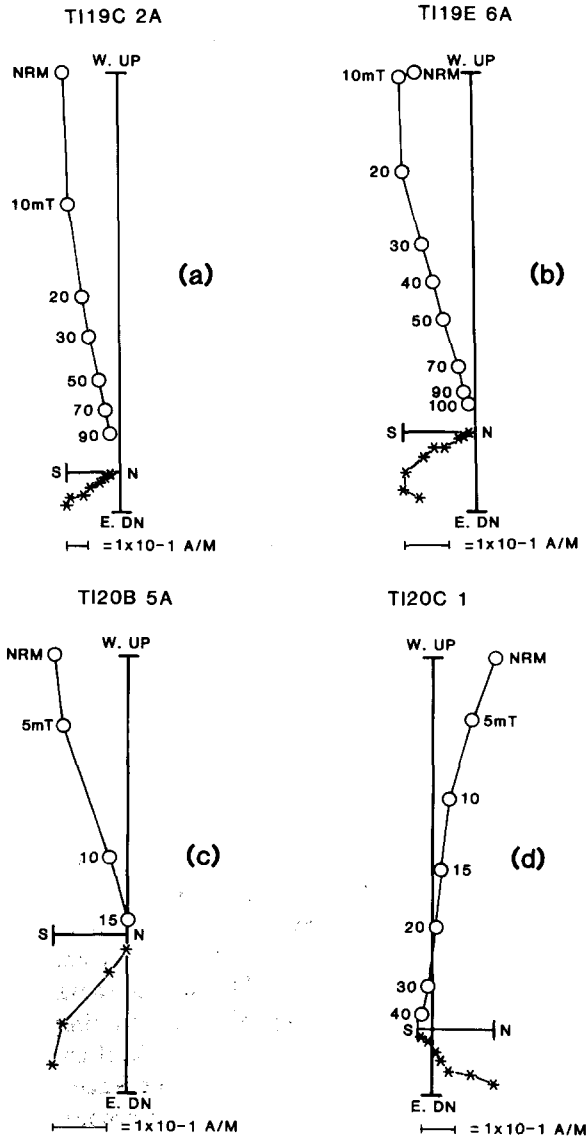


Fig. 2. Orthogonal projection of vector end-points [17] showing demagnetization behavior of samples from Belknap Nunatak and the unnamed nunatak. Open circles (stars) are projection on vertical (horizontal) planes at indicated levels (in mT) of AF cleaning. (a) Diorite from unnamed nunatak. (b) Granitic dike from unnamed nunatak. (c) Low-coercivity mafic dike from Belknap nunatak. (d) Overprinted fine-grained gabbro from Belknap Nunatak.

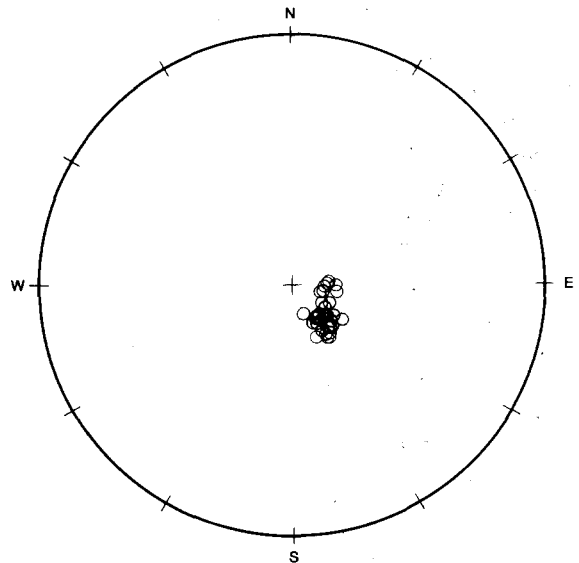


Fig. 3. Equal area projection of characteristic cleaned mean sample directions from Belknap Nunatak and unnamed nunatak. Open symbols are on the upper hemisphere. 1 sample rejected from 35 samples.

TABLE 2

Belknap Nunatak and unnamed nunatak (72°26'S, 97°45'W)

Site	Lithology	$n/N$	$D$ (°)	$I$ (°)	$k$	$\alpha_{95}$ (°)	Pole	
							long. (°E)	lat. (°S)
TI19A	layered gabbro	6/6	93.9	-78.1	1009.8	2.1	210.4	60.6
TI19B	mafic dike	6/6	145.2	-70.3	1162.5	2.0	236.9	39.1
TI19C	diorite/gabbro	6/6	132.1	-75.7	625.1	2.7	231.2	49.2
TI19D	diorite	4/4	141.9	-73.7	888.4	3.1	236.3	44.6
TI19E	granitic dike	5/6	143.2	-75.1	1173.3	2.2	238.0	46.7
TI20A	diorite	7/7	130.9	-77.2	288.3	3.6	231.9	51.8
Mean	$N = 6$ sites	34/35	133.7	-75.6	233.1	4.4	232.0	49.0 $A_{95} = 7.9^\circ$

$n/N$  = number of samples used in site mean calculation/total number of samples;  $k$  = estimation of Fisher's [43] precision parameter;  $\alpha_{95}$  = radius of error circle at the 95% confidence level;  $A_{95}$  = radius of circle at the 95% confidence level for the mean pole position; the mean paleopole position is derived from the 6 individual poles.

This direction corresponds to an Early Cretaceous paleomagnetic south pole for the TI block at 232°E, 49°S ( $A_{95} = 7.9^\circ$ ,  $K = 72.9$ ) for  $N = 6$  site mean virtual geomagnetic poles (Table 1) and a paleolatitude of 62.8°S. The TI pole falls near the Middle Jurassic EWM (235,2°E, 41.2°S) and AP(238°E, 48°S) poles, even though it is younger by 50 m.y.

## 5. Discussion of paleomagnetic results

There are three possibilities to explain the close correspondence of the Early Cretaceous TI pole with the AP and EWM Middle Jurassic poles: (1) the TI rocks by tectonic or intrusive activity have been tilted in just such a way to make an (unknown) Early Cretaceous paleomagnetic direction correspond to the Middle Jurassic one in the AP and EWM blocks; (2) the TI rocks have not been tilted but the TI block moved separately from AP and EWM blocks such that the correspondence of paleopoles is coincidental, (3) the paleomagnetic pole was nearly stationary from the Middle Jurassic to the middle Early Cretaceous with respect to all three structural blocks.

The first explanation (tilting) is a possibility difficult to disprove. Tilt corrections have not been applied in any of the West Antarctic studies because the poles have been determined by analysis of intrusive rocks for which the paleohorizontal cannot be documented. However, the remarkable similarity in the AP and EWM poles, obtained from very similar age rocks sampled over a large

region, implies to us that little tilting has occurred in these areas. Indeed, the structure of the Paleozoic sedimentary country rocks of the EWM block as a whole indicates no positive evidence for tilting since the emplacement of the paleomagnetically identical Nash Hills and Pagano Nunatak plutons. The folds are upright, the hinge lines are sub-horizontal [17]. At present, there are no other Early Cretaceous poles (pre-122 Ma) from East or West Antarctica to compare with the TI pole. Nonetheless, we feel that it would be unlikely that the TI rocks would be tilted just the right amount and about the right axis for the stable magnetic directions to end up nearly the same as the Middle Jurassic directions from the AP and EWM blocks.

The second possibility (a location for the TI block exotic to West Antarctica and East Antarctica) places the TI block as an isolated entity somewhere in the Pacific west of southern South America or perhaps adjacent to East Gondwanaland (Australia). Definitive geologic arguments cannot be made to support or reject this possibility, although the rocks of the TI block, including those sampled, are not unlike the rocks of the Mesozoic-Cenozoic magmatic arc forming the presently adjoining Antarctic Peninsula. If exotic, the TI block would have had to experience a rather fortuitous plate motion history to account for the coincidence in paleopoles.

The third and favored explanation (little apparent polar wander) for the very close similarity in the Early Cretaceous TI pole and the Middle Jurassic AP and EWM poles accepts the data at

face value and incorporates the conservative assumption that the TI block remained part of the tectonic unit formed by the AP and EWM blocks, i.e., the AP-EWM-TI blocks were essentially one paleomagnetic entity between at least 175 and 122 m.y. ago. The Precambrian Haag Nunataks have been left in their present relative position with respect to the AP and EWM blocks because it is a geologically acceptable position [8] and there are no paleomagnetic data to support an exotic location. We propose to call this group of geologically and paleomagnetically related blocks, Weddellia [25]. Indirect arguments must be made for Weddellia's existence since there are no Middle Jurassic TI poles and no middle Early Cretaceous AP or EWM poles, i.e., no poles of similar age common to all three structural blocks exist to allow a paleomagnetic test.

## 6. Plate tectonic setting

In considering the tectonic setting of Weddellia during the Jurassic and Cretaceous, we have chosen to use the Norton and Sclater [3] reconstruction of Gondwanaland because their reconstruction fits the Gondwanaland paleomagnetic data closely [27] and provides the necessary rotation poles. Recent refinements of the Gondwanaland reconstruction [28] do not appreciably affect our position for Weddellia and would require using several different sources to obtain all of the rotation poles. We have determined a mean paleomagnetic pole for Africa, Australia and East Antarctica for the period 165–180 Ma. This more precisely coincides with the age of the AP-EWM Middle Jurassic poles, compared to the Gondwanaland paleopole for the Triassic and Jurassic periods combined calculated by Norton and Sclater [3]. We have excluded South American poles from the analysis of Gondwanaland mean poles because Mesozoic poles from South America tend to fall very close to the present-day field [27], making it difficult to distinguish between Mesozoic paleomagnetic directions and present-day overprints in the absence of appropriate fold tests.

There are seven African paleomagnetic poles that fall within the prescribed age constraints [29] giving a mean Middle Jurassic pole for Africa at  $77.7^\circ\text{E}$ ,  $65.2^\circ\text{S}$  ( $A_{95} = 5.1^\circ$ ,  $K = 138.6$ ). Two Middle Jurassic poles from Australia [27] yield a

mean paleomagnetic pole at  $180.5^\circ\text{E}$ ,  $51.1^\circ\text{S}$  ( $A_{95} = 15.1^\circ$ ,  $K = 249.3$ ); the study of the Kangaroo Island Basalts [30] was excluded because it is based on only two sites. For East Antarctica, we use the Middle Jurassic pole listed earlier which is based on 15 separate studies ( $220.3^\circ\text{E}$ ,  $54.9^\circ\text{S}$ ).

Using Norton and Sclater's finite rotation poles for closure and rotating the Middle Jurassic poles for Australia and Africa into an Antarctic reference frame, we found that the mean Middle Jurassic paleomagnetic pole of these continents is well defined at  $219.7^\circ\text{E}$ ,  $56.8^\circ\text{S}$ , ( $A_{95} = 3.1^\circ$ ,  $K = 1550$ , for  $N = 3$ ). This close agreement of poles indicates that the Norton and Sclater reconstruction provides a good general description of the predrift configuration of Gondwanaland, for a time when the position of East Gondwanaland (Australia, East Antarctica, India) to West Gondwanaland (Africa and South America) is not well constrained by sea-floor data.

The only Gondwanaland poles of similar age to the TI block (130 Ma to 110 Ma) come from Africa [27]. African middle Early Cretaceous poles [29] ( $83^\circ\text{E}$ ,  $56.6^\circ\text{S}$ ,  $A_{95} = 11.9^\circ$ ,  $K = 108$ ,  $N = 3$ ) are not significantly different from the African Middle Jurassic ones, i.e., little apparent polar wander has occurred between about 180 and 110 Ma. This is consistent with our assumption that Weddellia had remained part of West Gondwanaland from the Middle Jurassic to the Early Cretaceous.

## 7. New tectonic models

Weddellia's tectonic evolution during the Middle Jurassic and Early Cretaceous has been divided into two scenarios: (1) rigid Weddellia—no relative motion between the AP-EWM-TI blocks; (2) mosaic Weddellia—motion allowed between the AP-EWM-TI blocks. Paleomagnetically we cannot distinguish between these possibilities of Weddellia's Mesozoic plate motion history and believe that the actual evolution of Weddellia could lie somewhere between the two models.

The first scenario assumes that there has been virtually no relative motion between the AP, EWM and TI blocks. Rigid Weddellia's 175 Ma position is shown in Fig. 4a, based on the combined AP-EWM Middle Jurassic pole of  $237^\circ\text{E}$ ,  $45.8^\circ\text{S}$  ( $A_{95} = 6.4^\circ$ ,  $K = 111.5$ ,  $N = 6$  localities), and is

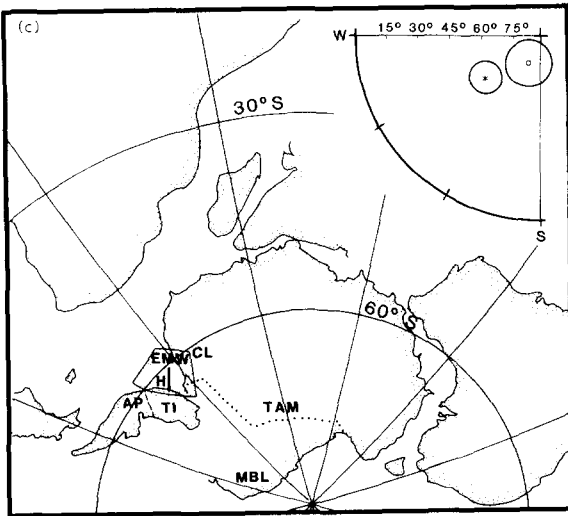
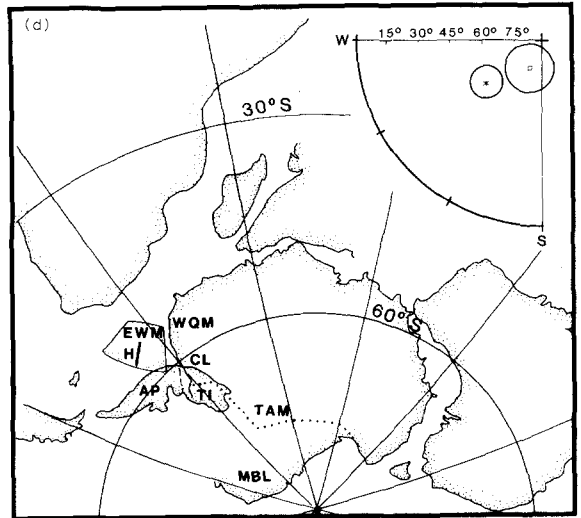
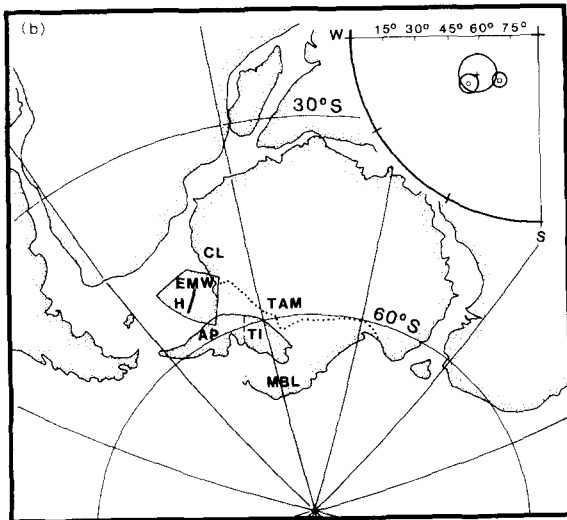
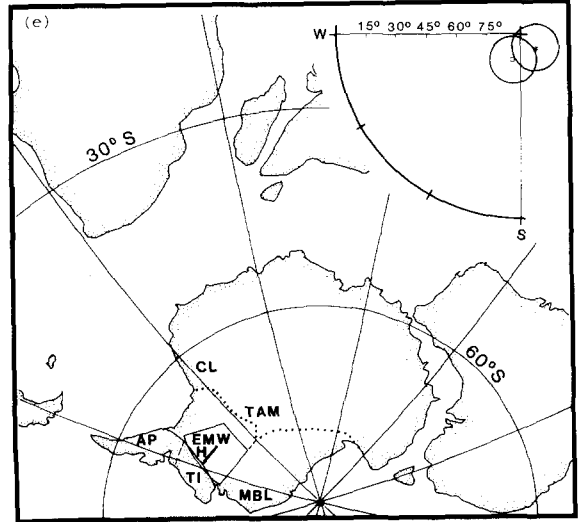
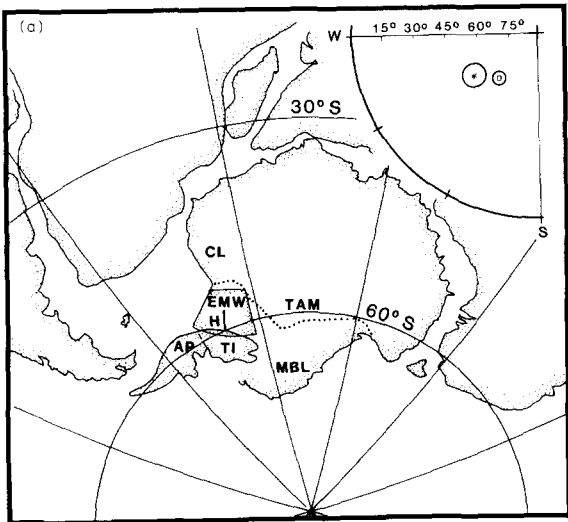


Fig. 4. The reconstructions are based on the Norton and Selater [3] rotation poles for positioning the continents. The 175 Ma reconstructions use our new Middle Jurassic Gondwanaland reference pole. The 122 Ma (anomaly M1) reconstructions use the Segoufin and Patriot [34] position for Madagascar with respect to Africa. The 100 Ma reconstruction is interpolated between those for anomalies 34 and M0. In all these reconstructions Marie Byrd Land is retained in its present position with respect to East Antarctica. The boundaries of the EWM, AP and TI blocks are schematic. On the EWM block the line represents the position of the Ellsworth Mountains and H shows the position of the Precambrian Haag Nunataks. The dotted line represents the Transantarctic Mountains (*TAM*); *CL* indicates the position of Coats Land and *WQM* represents the position of western Queen Maud Land. The inset in each figure shows an equal angle stereographic projection of the relevant paleomagnetic poles for Weddellia and East Antarctica with their associated circles of 95% confidence. (a) Middle Jurassic position for rigid Weddellia.

constrained by the observed paleolatitudes at the sample localities in the AP and EWM blocks of  $54^{\circ}\text{S}$  and  $47^{\circ}\text{S}$ , respectively. The limits of the paleomagnetic error must be used to avoid the apparent overlap of the AP block with South America forced by the paleolatitude constraints of the AP and EWM blocks. The predicted overlap could largely be due to widespread extension of continental crust in South America and/or rigid Weddellia after the emplacement of the AP and EWM plutons on which the poles are based, rather than with major problems in the Gondwanaland reference poles [3,31,32]. This reconstruction also uses the maximum amount of rotation allowed by the paleomagnetic data to achieve the more northerly position of the EWM block. The Ellsworth Mountains structural trend strikes at high angle into East Antarctica, south of Coats Land in Fig. 4a.

An alternative Middle Jurassic reconstruction (mosaic Weddellia) more exactly restores the individual mean paleopoles from the AP and EWM

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lia i.e., little relative motion between the AP, EWM and TI blocks. Equal angle plot shows rigid Weddellia mean pole (\*) and East Antarctic mean pole ( $\square$ ). (b) Middle Jurassic position for mosaic Weddellia i.e., uses the individual AP and EWM paleomagnetic poles. Equal angle projection shows individual mean poles of the AP block (+), EWM block ( $\circ$ ) and East Antarctica ( $\square$ ). (c) The 122 Ma position for a rigid Weddellia using the TI paleomagnetic pole. Note the dextral strike-slip motion ( $\approx 650$  km) required along the EWM/East Antarctica boundary since the Middle Jurassic. Equal angle plot for rigid Weddellia: mean Early Cretaceous paleopole for Weddellia (\*) and East Antarctica ( $\square$ ); the East Antarctic pole was obtained by rotating the African mean Early Cretaceous pole ( $83^{\circ}\text{E}$ ,  $56.6^{\circ}\text{S}$ ) into East Antarctic coordinates. (d) The 122 Ma position for mosaic Weddellia. Note the dextral strike-slip motion ( $\approx 650$  km) required along the EWM/East Antarctica and TI/East Antarctica boundaries since the Middle Jurassic. Equal angle plot for Early Cretaceous mosaic Weddellia: the TI block pole represents Weddellia (\*) and the African Early Cretaceous mean pole rotated into East Antarctic coordinates represents the East Antarctic paleopole ( $\square$ ). (e) At 100 Ma, Weddellia was in its present-day position with respect to East Antarctica. Note the  $\approx 2500$  km of sinistral strike-slip motion needed along the EWM/East Antarctica boundary and a clockwise rotation of  $\approx 30^{\circ}$  relative to East Antarctica since 122 Ma. Dextral strike-slip motion is needed between the AP-TI/EWM blocks since 122 Ma in the case of the mosaic Weddellia reconstruction (Fig. 4d). Equal angle plot shows the mid-Cretaceous mean paleopoles for Weddellia (\*) based on the AP block pole [38] and East Antarctica ( $\square$ ) based on the Australian mean mid-Cretaceous pole ( $153^{\circ}\text{E}$ ,  $52^{\circ}\text{S}$ ) [27] rotated into East Antarctic coordinates.

blocks to the mean Gondwanaland pole. This forces the AP and EWM blocks to move as separate but adjacent structural units (Fig. 4b). The Ellsworth Mountain sedimentary succession would then strike into the continental shelf adjacent to Coats Land.

Between about 155 and 122 Ma, East Gondwanaland (including East Antarctica) moved south by approximately 650 km with respect to West Gondwanaland (including Weddellia) as a result of the opening of the Somali and Mozambique basins [32–36] (Fig. 4c and d). Unacceptable overlap between the EWM and AP-TI blocks is created if, during this interval, the EWM block moved with East Antarctica rather than with the AP and TI blocks. Hence, either a rigid or a mosaic Weddellia remained essentially fixed with respect to West Gondwanaland during this time. The position of Weddellia's EWM block relative to East Antarctica changed along a dextral transform zone, either starting south of Coats Land and ending up adjacent to Coats Land (Fig. 4a and c) or starting near Coats Land and ending up adjacent to western Queen Maud Land (Fig. 4b and d). If Weddellia was not a rigid tectonic entity, an equivalent amount of dextral transcurrent motion would be required along the AP/TI boundary with East Antarctica between the Middle Jurassic (Fig. 4b) and the Early Cretaceous (Fig. 4d).

Paleomagnetic data from mid- to Late Cretaceous rocks of the Antarctic Peninsula [37,38] suggest that the AP block, and hence we assume the rest of Weddellia, had moved to its present-day position relative to East Antarctica by about 100 m.y. ago. This leaves approximately 22 m.y. for either rigid or mosaic Weddellia to have moved from its middle Early Cretaceous (122 Ma; ca. M1 time [39]) position in Fig. 4c or d, to the mid-Cretaceous (100 Ma) one in Fig. 4e. We suggest this motion may be associated with the main opening of the Weddell Sea. An older age for the opening has been previously suggested on the basis of magnetic anomalies in the Weddell Sea [40,41], but the anomalies if correctly identified [42] may record creation of smaller, older pieces of ocean floor. At an estimated spreading rate of 0.6 cm/yr [40], approximately 250 km of Weddell sea-floor would have been created between M29 (160 Ma) and M1 (122 Ma); this small motion is



outside the resolution of the paleomagnetic data.

Recent geophysical investigations in the Weddell Sea [41] have found two collinear basement structures; the Andenes Escarpment and the Explora Escarpment. Kristoffersen and Haugland [41] suggest that these two linear basement highs are mid-Jurassic rift-related structures and form a continuous basement ridge across the Weddell Sea. This interpretation would preclude post-rift motion between East Antarctica and Weddellia. Given the differences in basement morphology, structure and magnetic signature between the lineaments and the uncertainty in age, we feel that the Andenes and Explora Escarpments have not been conclusively proven to be the same feature and of mid-Jurassic age.

Our interpretation implies that rigid or mosaic Weddellia moved sinistrally 2500 km from the Early to mid-Cretaceous along the EWM/East Antarctic boundary, i.e., 10 cm/yr, possibly along the same transform boundary along which 650 km of dextral motion is suggested to have occurred between the Middle Jurassic and Early Cretaceous. The fast rate of motion along the Weddellia/East Antarctica boundary could be lessened if sea-floor spreading was initiated in the Weddell Sea prior to 122 Ma and was not paleomagnetically discernible. The postulated motion of Weddellia is equivalent to a clockwise rotation of 30° about a rotation pole located near the northern tip of the Antarctic Peninsula. Previously we proposed a clockwise rotation of 15–20° for the combined AP and EWM blocks [14]. Delay of this rotation until 122 to 100 Ma as suggested by our new data, however, requires a larger rotation to compensate for the earlier dextral relative movement of Weddellia with regard to East Antarctica.

A more complex opening history of the Weddell Sea is required if mosaic Weddellia (Fig. 4d) is correct. Apart from the sinistral motion along the EWM block's eastern boundary with East Antarctica, an additional 1000 km of dextral transcurrent motion would be needed on the EWM/AP boundary between the Early Cretaceous and mid-Cretaceous.

## 8. Conclusions

In conclusion, at least three of the West Antarctic structural blocks (AP, EWM, and TI)

appear to have acted as a paleomagnetic entity of closely related blocks, Weddellia, whose motion opened the Weddell Sea since the Early Cretaceous. A reconstruction with a rigid Weddellia assumes little or no relative motion between the AP-EWM-TI blocks and creates a very simple scenario for opening the Weddell Sea (Fig. 4a and c) but is near the limit of experimental error in the paleomagnetic data. A reconstruction with a mosaic Weddellia allows motion between its blocks, i.e., AP and EWM blocks (Fig. 4b and d) by strictly using the individual mean poles, but creates a complex opening history for the Weddell Sea. For this second scenario, approximately 1000 km of dextral motion would be required between the AP and EWM blocks during the 122 to 100 Ma interval (Fig. 4d and e).

In either reconstruction, the EWM block is located north and east of the AP block in the Middle Jurassic and the structural trend of the Ellsworth Mountains remains at a high angle to the Transantarctic Mountains and Cape Fold Belt at this time. Geologic and paleomagnetic data [4,6,10] suggest approximately 90° of rotation between the Ellsworth Mountains and the Transantarctic Mountains in East Antarctica. Although the Middle Jurassic paleomagnetic results from the AP [13] and EWM [14] blocks do not indicate a 90° rotation relative to East Antarctica, rotation of the Ellsworth Mountains may have occurred prior to the Middle Jurassic.

The boundary between East Antarctica and Weddellia in either the rigid or mosaic model is broadly a transcurrent fault zone that has had first dextral and then sinistral motion. The first motion was related to the Mozambique and Somali spreading centers moving East Antarctica southward in the Late Jurassic and earliest Cretaceous while Weddellia remained attached to West Gondwanaland. The subsequent sinistral motion, associated with the opening of the Weddell Sea after 122 Ma, moved Weddellia into its present position with respect to East Antarctica by the mid-Cretaceous. In the case of mosaic Weddellia, dextral translation is needed between the EWM block and the AP-TI blocks (Fig. 4c–e), in addition to the sinistral motion between mosaic Weddellia and East Antarctica. The actual position of the strike-slip zone or zones separating Weddellia from East Antarctica must be between

Pagano Nunatak and the Transantarctic Mountains. This strike-slip zone could be the plate boundary between the southwest Indian Ocean spreading centers and the Pacific Ocean floor. Our tectonic model for either rigid or mosaic Weddellia also suggests that any physiographic connection between the Pacific Ocean and either the Southwest Indian Ocean or the embryonic South Atlantic Ocean was highly restricted until 122 Ma. Paleomagnetic poles of Early Cretaceous age from the AP and EWM blocks and of Middle Jurassic age from the TI block are needed to further test the existence of Weddellia in the Mesozoic.

The position of the fifth West Antarctic crustal block, MBL, is unknown for the Jurassic and Early Cretaceous. A "greater" West Antarctica that includes MBL cannot be ruled out but appears unlikely because the Late Cretaceous pole of MBL [12] does not fall on the common apparent polar wander path of either East Antarctica or Weddellia. Without older poles from MBL the question of its Jurassic or Early Cretaceous position cannot be documented.

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