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Southernmost South America-Antarctic Peninsula relative plate motions since 84 Ma: Implications for the tectonic evolution of the Scotia Arc region

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Abstract. We have attempted to quantify the relative motion history between southernmost South America (SSA) and the Antarctic Peninsula (AP) by calculating and comparing SSA-Africa, AP-Africa and SSA-AP synthetic flow lines for 84-0 Ma. The flow lines were created using published poles of rotation and plate reconstruction software. The results indicate that since 84 Ma, SSA and AP have moved approximately westward relative to a fixed Africa; however, SSA's rate of westerly motion in that reference frame has been significantly more rapid than AP's rate. Approximately 1320 km of east-west, left-lateral strike-slip displacement and 490 km of north-south, divergent displacement have occurred between the southern tip of SSA and the northern tip of AP since 84 Ma. Increased rates of SSA-AP interplate separation and a change in the angle of plate divergence at approximately 55-40 Ma marked the onset of accelerated continental separation that eventually led to seafloor spreading in the western Scotia Sea at 30 Ma and the development of the Scotia Arc. Increased separation rates between SSA and AP at 55-40 Ma may be related to a global Eocene plate reorganization event. The northeast-southwest oriented western Scotia Sea spreading centers appear to have accommodated all of the SSA-AP interplate motion between 30 and 9 Ma. We suggest that prior to 30 Ma and the opening of Drake Passage, components of interplate strike-slip and divergent motion were accommodated by intracontinental deformation that included strike-slip faulting, counterclockwise tectonic rotation, and continental extension in the southernmost Andes. The results indicate that the opening of the Scotia Sea was caused by plate-scale motions as SSA and AP drifted away from Africa at different velocities along different, nonparallel trajectories. Subduction retreat along the South Scotia Ridge and South Sandwich arc and back arc spreading in the Scotia Sea contributed to the width of separation between SSA and AP across Drake Passage. The results place limits on how SSA-AP relative motion has been temporally and spatially partitioned in the Scotia Arc region.

Introduction

A longstanding problem in the interpretation of the tectonic evolution of the Scotia Arc region (Figure 1) has been constraining the relative motion history between southernmost South America (SSA) and the Antarctic Peninsula (AP) since 84 Ma. Modern plate reconstructions based on paleomagnetic and geologic data [e.g., *Grunow et al.*, 1991] indicate that the northern tip of the AP was located adjacent to the southern tip of SSA along its Pacific margin at 150 Ma (late Jurassic), forming part of Gondwana's active convergent margin (as was first suggested by *de Wit* [1977]). In the southernmost Andes, a progressive mid-Cretaceous-Tertiary orogenic event resulted in collapse and inversion of the Rocas Verdes marginal basin, polyphase deformation, regional metamorphism, and development of the Patagonian fold and thrust belt [*Dalziel et al.*, 1974; *Nelson et al.*, 1980; *Biddle et al.*, 1986]. In the northern two thirds of the AP, this mid-Cretaceous-Tertiary orogenic event is not recorded [*Dalziel and Cortes*, 1972; *Dalziel and Elliot*, 1973; *Katz*, 1973; *Barker et al.*, 1991] suggesting that by mid-Cretaceous time a fundamental break separated the future AP from the future southern tip of SSA. The nature of this break and the relative motion history of the separating continents since the mid-Cretaceous have not been quantitatively constrained previously and have remained speculative.

Three separate paleomagnetic studies of the Patagonian Orocline, the 90° bend in the southernmost Andes (Figure 1), have documented that the orocline is, at least in part, the product of post-mid-Cretaceous counterclockwise rotation [*Dalziel et al.*, 1973; *Burns et al.*, 1980; *Cunningham et al.*, 1991]. It has long been suspected that bending of the southernmost Andes is related to large-scale left-lateral shearing between the South American and Antarctic continents within the Scotia Arc [*Wegener*, 1929; *Carey*, 1955; *Hamilton*, 1964; *Winslow*, 1982; *Cunningham*, 1993]. However, the relative plate motion scenario that would produce the bending has not been constrained.

The Neogene opening of Drake Passage [*Barker and Burrell*, 1977] and seafloor spreading in the western Scotia Sea (Figure

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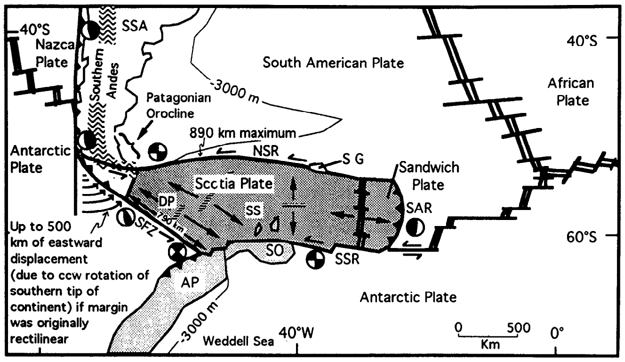

Figure 1. Simplified tectonic map of the Scotia Arc region, southern South America, and part of the Antarctic Peninsula showing major plate boundaries and representative earthquake focal mechanism solutions [*Pelayo and Wiens*, 1989]. Numerical constraints on displacement on some plate boundaries are referred to in text. Open spreading ridges (paired parallel lines) are active; dashed ridges are extinct. Subduction zones are depicted with teeth on upper plate. Abbreviations are SSA, southernmost South America; AP, Antarctic Peninsula; NSR, North Scotia Ridge; SAR, South Sandwich Arc; SSR, South Scotia Ridge; SS, Scotia Sea; DP, Drake Passage; SG, South Georgia; SO, South Orkney block; SFZ, Shackleton Fracture Zone.

1) were clearly related to SSA-AP relative plate motions, but the quantification of the relative motion through time has not been well established due to decoupling along the North and South Scotia Ridges (NSR, SSR) [*Barker and Lawver*, 1988; *Dalziel*, 1989; *Barker et al.*, 1991]. Likewise, the relative motion history of South Georgia, a microcontinent that once formed part of the Andes [*Dalziel et al.*, 1975] but is now located 1600 km east of Tierra del Fuego in the South Atlantic (Figure 1), has never been kinematically explained due to uncertainties in the amount of strike-slip motion on the NSR and relative motion between SSA and AP across the Scotia Arc.

In this paper we attempt to shed light on these problems by quantifying SSA-AP relative plate motion since 84 Ma using computer-based plate reconstructions and synthetic flow lines

Method

We have computed a set of synthetic flow lines for SSA relative to Africa and for the AP relative to Africa for the interval 84-0 Ma (Figure 2). We have chosen five individual points in SSA and seven individual points on the AP (Figure 2), and using published finite rotation poles for SSA-Africa and AP-Africa (Table 1) we calculated and plotted backward in time the locations of these points relative to a fixed Africa for every 10 m.y. during the last 84 m.y. Points at 10-m.y. intervals (Figure 2) were linearly interpolated from the control points from Table 1. The control points are based on identified marine magnetic anomalies fom the South Atlantic and Indian Oceans (Table 1). These flow lines were plotted to compare the relative drift of SSA and AP from a fixed southern Africa. Using the finite rotation poles from Table 1, we also calculated a SSA and an AP flow line forward in time from a common starting point at 84 Ma assumed to lie on a common SSA-AP plate boundary at 60°S, 20°W (Figure 3). This point was chosen because it lies between the southernmost SSA and northernmost AP flow lines in Figure 2. Using these two flow lines, we calculated the total displacement between SSA and AP since 84 Ma for this point (Figure 3).

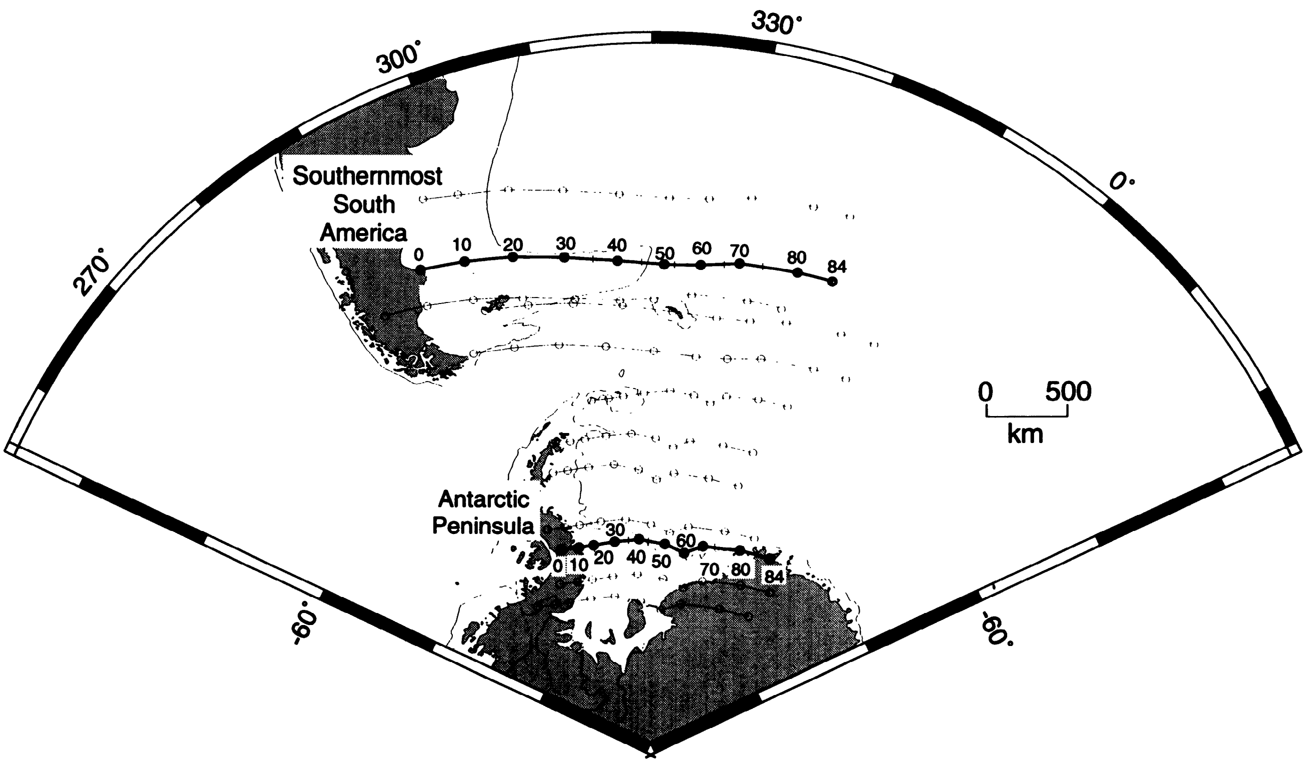

Figure 2. SSA and AP flow lines relative to a fixed southern Africa for the last 84 m.y. Rotation poles that were used to calculate flow lines are given in Table 1. Linearly interpolated 10 m.y. interval locations are shown above two of the flow lines. Flow lines originating from the same continent are approximately parallel, indicating limited rotational spin with respect to Africa since 84 Ma.

Table 1. Finite Rotation Poles Used to Generate Synthetic Flow Lines in Figure 2

Time, Ma*	Anomaly	Latitude, °N	Longitude, °E	Angle, deg.	Reference
			Antarctic Peninsula-Africa		
6.0	3a	16.58	-23.15	1.18	L. A. Lawver (unpublished data, 1991)
10.5	5	8.2	-49.4	1.53	*Royer and Chang* [1991]
20.5	6	10.7	-47.9	2.78	*Royer and Chang* [1991]
35.5	13	12.0	-48.4	5.46	*Royer and Chang* [1991]
42.7	18	17.1	-46.6	7.22	calculated from *Müller et al.* [1993]
50.3	21	10.3	-42.9	8.77	*Royer et al.* [1988]
68.5	31y	1.1	-41.6	11.84	*Royer et al.* [1988]
73.6	32	-1.8	-41.4	13.47	*Royer et al.* [1988]
80.2	33	-4.70	-39.7	16.04	*Royer et al.* [1988]
84.0	34y	-2.6	-38.1	17.91	calculated from *Müller et al.* [1993]
			South America-Africa		
8.9	5	59.99	-38.89	3.13	*Shaw and Cande* [1990]
19.4	6	58.07	-37.42	7.04	*Shaw and Cande* [1990]
26.9	8	57.16	-35.34	9.98	*Shaw and Cande* [1990]
35.3	13	56.63	-33.91	13.38	*Shaw and Cande* [1990]
44.7	20	57.62	-32.07	17.58	*Shaw and Cande* [1990]
51.9	22	59.3	-31.59	20.08	*Shaw and Cande* [1990]
58.6	25	61.07	-31.49	22.30	*Shaw and Cande* [1990]
66.7	30	63.3	-33.45	24.77	*Shaw and Cande* [1990]
74.3	33	63.11	-33.81	27.93	*Shaw and Cande* [1990]
80.2	33r	62.91	-34.19	30.97	*Shaw and Cande* [1990]
84.0	34	61.59	-34.15	33.5	*Shaw and Cande* [1990]

* All sources used the Decade of North American Geology timescale [*Kent and Gradstein* 1986]

The database used for the SSA flow lines consists of magnetic anomaly and finite pole calculations by *Shaw and Cande* [1990] for 84-0 Ma. No anomaly data and therefore no flow rates are available for the interval 118.7-84 Ma corresponding to the Cretaceous magnetic quiet interval, and thus our analysis is limited to the 84-0 Ma interval. The database used for the AP flow line is the East Antarctica-Africa magnetic anomaly data base and finite pole calculations from

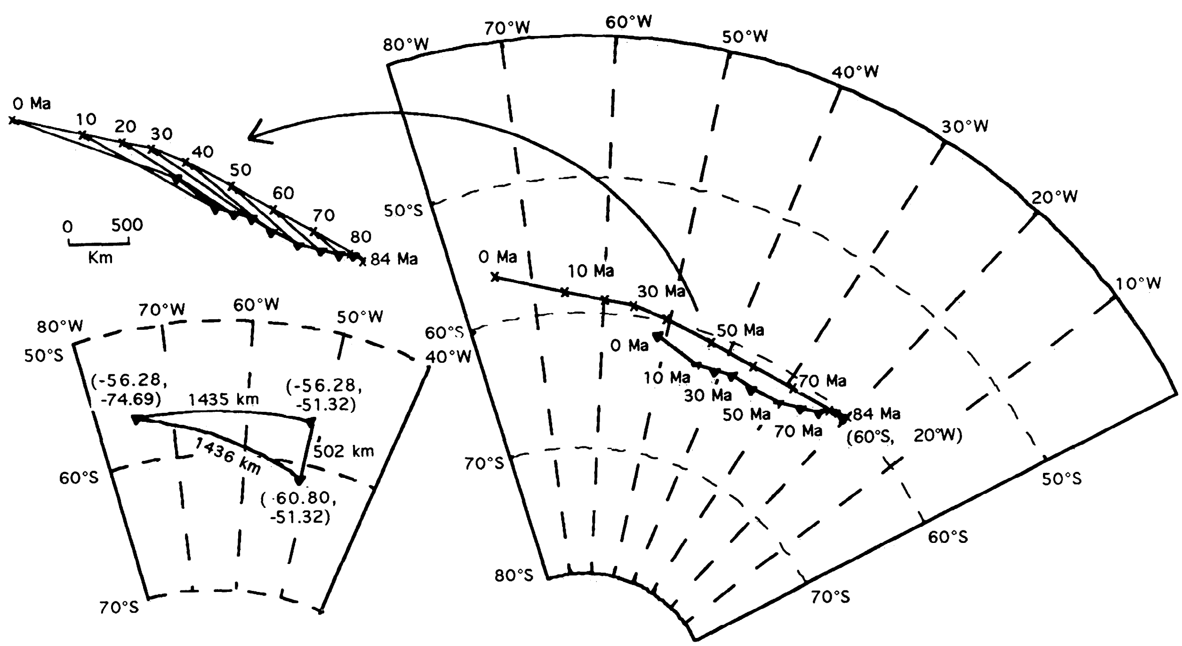

Figure 3. SSA and AP flow lines plotted forward in time from a common starting point (-60.00, -20.00) assumed to lie along a common SSA-AP plate boundary at 84 Ma. Finite rotation poles from Table 1 were used to plot the flow lines forward in time from the 84 Ma starting point. The diagram at top left shows displacement vectors connecting points of the same age between flow lines, which track the increasing separation and change in direction between SSA and AP. The smaller plot at bottom left shows the final N-S and E-W components of separation between the 0 Ma end points of the two flow lines. The final separation between the two flowlines is approximately 1436 km of NW-SE displacement.

Table 2. SSA-AP 84-0 Ma Flow Line Data for Northern Tip of AP (Keeping SSA Fixed)

Time, Ma	Latitude, °N	Longitude, °E	Distance, km	Azimuth	E-W Component, km	N-S Component, km
0	-61.00	-50.00				
10	-60.67	-53.33	180	103	180(E)	40(S)
20	-60.04	-57.48	240	109	230(E)	70(S)
30	-59.06	-60.82	220	122	190(E)	110(S)
40	-58.07	-63.50	190	127	160(E)	110(S)
50	-57.73	-65.76	140	107	130(E)	40(S)
60	-58.04	-67.92	130	76	130(E)	30(N)
70	-57.28	-70.05	150	124	130(E)	80(S)
80	-56.71	-72.58	120	114	150(E)	60(S)
84	-56.62	-72.88	20	119	20(E)	10(S)

Calculated distances between 10 m.y. flow line points are rounded to the nearest 10 km. Total distance is 1390 km; total displacements are 1320 km eastward and 490 km southward.

Royer and Chang [1991], *Royer et al.* [1988], and *Müller et al.* [1993] for the period 84-0 Ma. Paleomagnetic data indicate that the AP was fixed to East Antarctica during that period [*Watts et al.*, 1984; *Grunow et al.*, 1991, *Grunow*, 1993]. Thus we assume that the poles for East Antarctica-Africa relative motion can be used for AP-Africa relative motion for the 84-0 Ma interval.

All rotation pole sources used the same Decade of North American Geology (DNAG) timescale [*Kent and Gadstein*, 1986]. We assume a 1°-2° error in pole locations [*Royer and Chang*, 1991] and have resolution of the order of tens of kilometers for our flow line 10 m.y. points. A north-south and east-west coordinate reference frame was used to compute north-south and east-west components of displacement because SSA-Africa and AP-Africa flow lines are approximately latitudinal for 84-0 Ma (Figures 2 and 3). Rates of SSA-AP relative motion were computed from the values of relative displacements for a given time interval (Table 2).

After constraining SSA and AP motion relative to a fixed Africa, we plotted the motion of AP relative to a fixed SSA using widely available plate reconstruction software for a three plate circuit (Figures 4-6). Because the AP has rotated slightly relative to SSA since 84 Ma, calculations of AP-SSA relative motion are dependent on which points on each continent are chosen. Therefore there is not a unique solution to the amount of separation between SSA and AP during the last 84 m.y. Thus only the relative motion of the northern tip of the AP (present coordinates at 61°S, -50°W) relative to the southern tip of SSA was calculated back to 84 Ma to best constrain the history of SSA-AP separation across what is now the Scotia Arc (Figure 6). For visual clarity, AP-SSA relative motion for 80-40 Ma and 40-0 Ma are plotted separately (Figures 4 and 5). It is

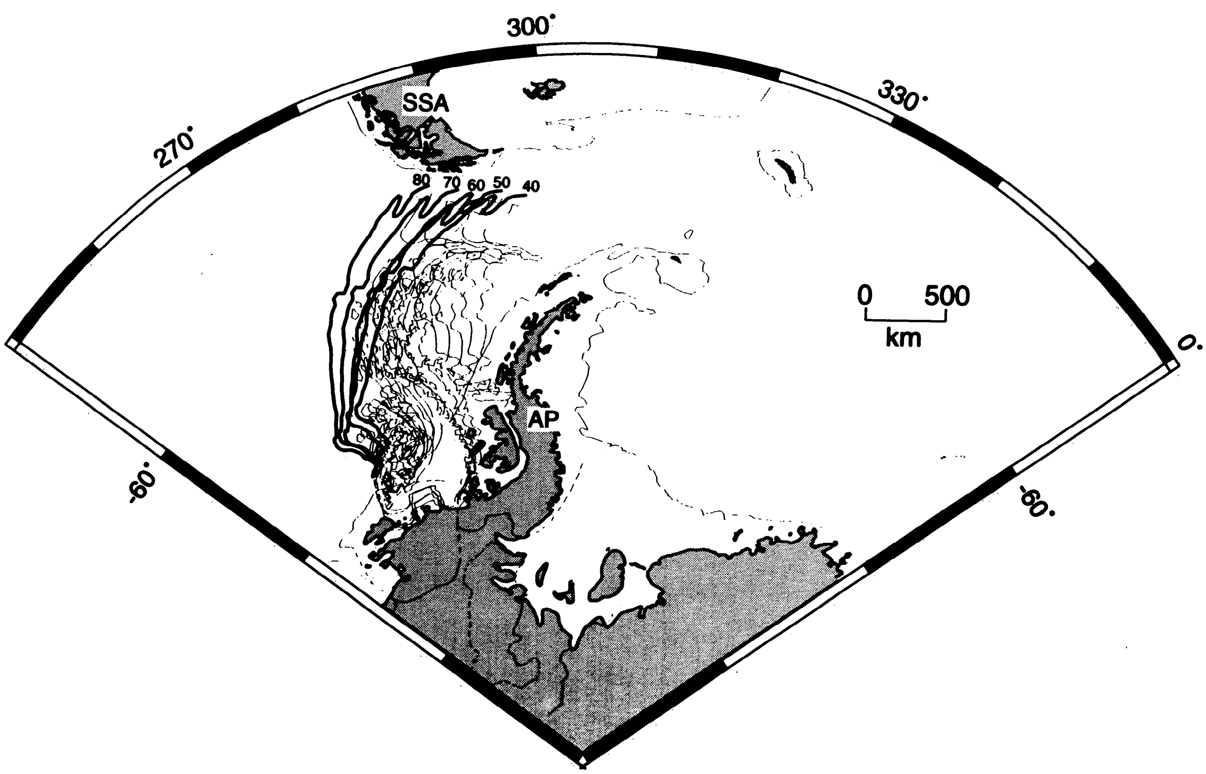

Figure 4. AP motion for 80-40 Ma relative to a fixed SSA. Western margin of AP is highlighted for clarity.

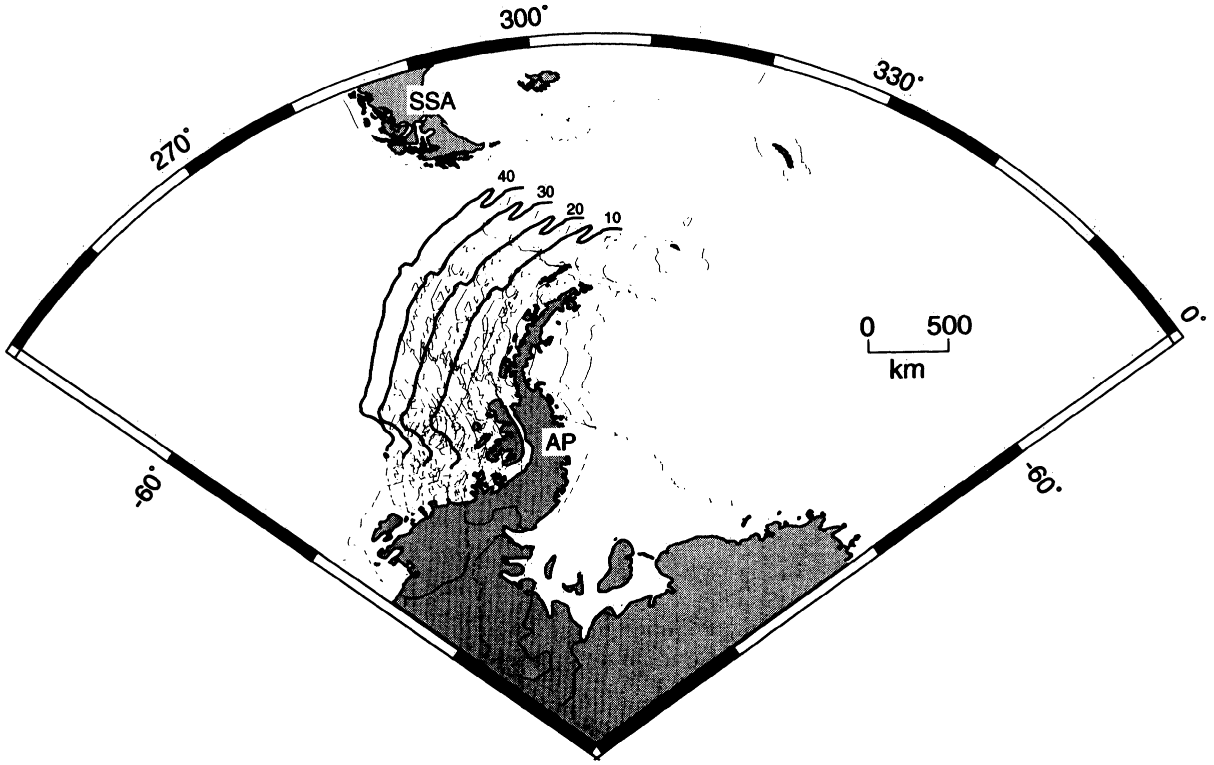

Figure 5. AP motion for 40-0 Ma relative to a fixed SSA. Western margin of AP is highlighted for clarity.

possible that local deformation of the northern tip of the AP may have occurred during the last 84 m.y. However, we believe it has not significantly affected the calculated locations of the 10 m.y. points in Figure 6 because existing paleomagnetic data indicate that the northern tip of the AP has not been oroclinally bent during the last 84 m.y. [*Watts et al.*, 1984; *Grunow et al.*, 1991; *Grunow*, 1993].

Results

The finite rotation poles that were used to calculate the synthetic flow lines in Figure 2 are of the order of 60°-90° away from the calculated flow lines (Table 1). Thus the flow lines in Figure 2 are close to being great circles, and rotational spin between SSA and AP for the 84-0 Ma period is small. Flow lines starting from the same continent plot approximately parallel to each other (Figure 2). The SSA-Africa and AP-Africa flow lines indicate that since 84 Ma, SSA and AP have moved approximately westward relative to a fixed Africa (Figures 2 and 7). SSA's rate of westerly motion in that reference frame has been more rapid than AP's rate (Figures 2, 3) and SSA and AP have also diverged in a north-south sense since 45 Ma (Figures 2-7). Overall, SSA-AP relative motion has been dominated by east-west left-lateral strike-slip interplate shear with a lesser component of interplate north-south divergence since 84 Ma (Figures 3, 6, and 8 and Table 2). Approximately 1436 km of northwest-southeast separation is calculated for SSA-AP relative motion from the common starting point assumed to lie along a common SSA-AP plate boundary at 84 Ma (Figure 3). This is in close agreement with the 1390 km of northwest-southeast separation calculated from the AP-SSA-fixed flow line in Figure 6 (Table 2). The numbers differ slightly because they are location dependent. Summation of components of east-west and north-south relative motion for 10 m.y. intervals of the AP-SSA-fixed flow line in Figure 6 indicates that 1320 km of east-west left-lateral strike-slip motion and approximately 490 km of north-south divergent motion occurred since 84 Ma. A plot of rates of east-west left-lateral relative motion for each 10 m.y. interval from 84-0 Ma in Figure 6 indicates that east-west strike-slip interplate motion has been highest during the last 40 m.y. (Figure 8). Rates of north-south divergent motion between SSA and AP were highest during 40-20 Ma (Figure 8). An increase in east-west and north-south rates of separation occurred between SSA and AP between 55-40 Ma. Control points at 44.7, 51.9, and 58.6 Ma for SSA relative motion and at 42.7, 50.3, and 68.5 Ma for AP relative motion are sufficient to generate confidence that this represents a real and important change (Table 1).

Figures 4 and 5 visually represent how the AP has been drifting toward the E-SE relative to a fixed SSA during the last 84 m.y. During the 84-40 Ma interval, AP was pivoting about a point near the base of the AP relative to a fixed SSA and the northern tip of the AP was swinging past the southern tip of SSA in a clockwise sense. This interplate motion was dominantly left-lateral strike-slip (Figures 6 and 8). During the 40-0 Ma interval, AP has drifted as a more rigid, nonspinning block toward the E-SE relative to SSA (Figure 5). SSA-AP interplate motion during the 40-0 Ma interval has also been dominated by left-lateral interplate strike-slip but with an important component of north-south interplate divergence.

Specific changes in SSA-AP relative motion (Figure 6) match well with magnetic anomaly and fracture zone trends and Geosat gravity data for the northern Weddell Sea. A small angular change between the 10-20 and 20-30 Ma intervals in

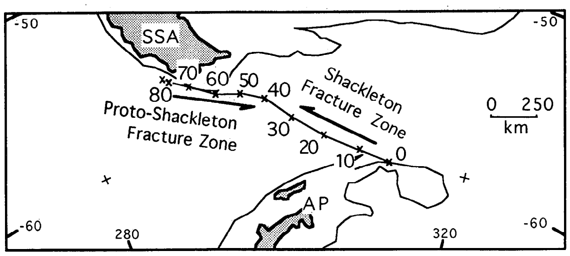

Figure 6. Motion of northern tip of AP relative to fixed SSA for 84-0 Ma. Proto-Shackleton Fracture Zone is the proposed name for the left-lateral fault system that accommodated the clockwise swing of the northern tip of the Antarctic Peninsula past the southern tip of SSA during 84-40 Ma.

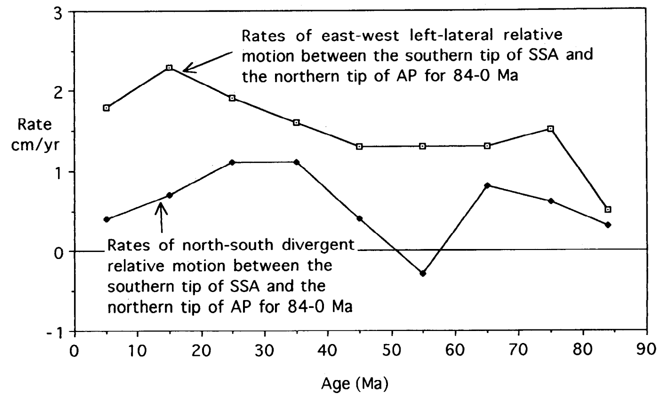

Figure 8. Plot showing rates of east-west, left-lateral strike-slip relative motion and north-south divergent relative motion between SSA and AP for 84-0 Ma. Data taken from Figure 6 and Table 2.

Figure 6 is consistent with plate motion changes on the SSA-AP plate pair east of the Scotia Arc at 20-24 Ma as documented by *Barker and Lawver* [1988] and by Geosat data [*Gahagan*, 1988]. A reported change in SSA-AP motion at approximately 50 Ma [*Livermore and Woollett*, 1993] roughly coincides with the acceleration in plate separation we report for the 55-40 Ma period (Figure 8) and the change in SSA-AP plate motion at 50-40 Ma visible in Figure 6. Our data clearly indicate differential motion between the northern tip of the AP and the southern tip of SSA during the entire 84-0 Ma period (Figures 4 and 5). *Livermore and Woolett* [1993] suggest that the northern tip of the AP and the southern tip of SSA may have been locked together during the 65-49 Ma period. Our data indicate that during this period there was minor north-south relative motion between the continents but that substantial east-west left-lateral strike-slip motion was continuing between the separating continents (Figures 6 and 8).

Implications

The results of this study indicate that relative to Africa, SSA has been outpacing AP since 84 Ma in its westerly drift and this has led to an east-west left-lateral strike-slip sense of relative motion with a lesser north-south divergent component of relative motion between the two continents. Since 84 Ma, approximately 1320 km of east-west, left-lateral, strike-slip and 490 km of north-south divergent motion (Table 2) have been accommodated between the southern tip of SSA and the northern tip of AP across the Scotia Arc. Both components of separation may have been accommodated in various locations by different mechanisms. We believe that it is most likely that east-west strike-slip and north-south divergent components of interplate motion were dominantly accommodated by (1) seafloor spreading in the Scotia Sea and left-lateral motion along the Shackleton Fracture Zone (SFZ), (2) by left-lateral and divergent motion along a fault system that must have existed to accommodate the initial separation of AP from SSA prior to seafloor spreading in the Scotia Sea (Figure 6), and (3) by internal deformation in SSA and within some of the continental fragments that were a part of the formerly linked SSA-AP continent but are now scattered around the periphery of the Scotia Plate (e.g., South Georgia and the South Orkney block, Figure 1). We are not able to calculate how the total motion has been partitioned, but we can suggest some probable limits. We will consider the partition of the motion forward in time since 84 Ma.

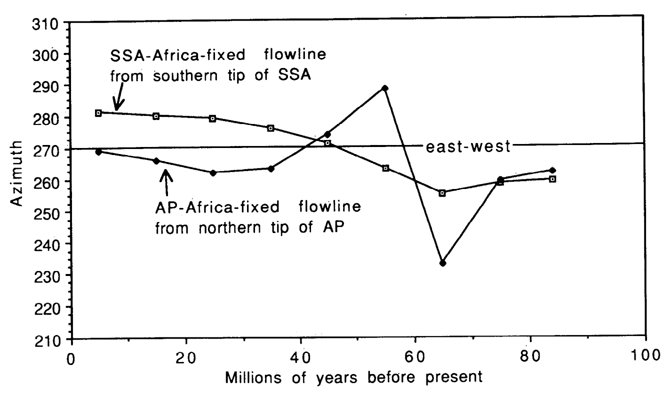

Figure 7. Azimuth versus age plot for 84-0 Ma for southernmost SSA and northernmost AP flow lines shown in Figure 2.

84-50 Ma

Between 84-50 Ma and prior to the Mid-Tertiary opening of the Scotia Sea, the future continental regions of SSA and AP were not yet physically separated despite the fact that they were connected to larger plates that were moving in different directions at different velocities. Thus an intracontinental plate boundary existed between what are today SSA and AP. During this period, approximately 430 km of east-west left-lateral interplate motion and 120 km of north-south divergence between SSA and the AP are indicated by the flow line data (Table 3). This relative motion must have been accommodated by intracontinental deformation within the still-connected SSA and AP. Oroclinal bending, strike-slip faulting and continental fragmentation in the southernmost Andes were occurring at this time [*Winslow*; 1982, *Cunningham et al.*, 1991; *Cunningham*, 1993] and probably represent a deformational response to the interplate motion. If one assumes a rectilinear trend for the Patagonian batholith/Pacific margin prior to development of the orocline, then up to 500 km of eastward displacement of the southern tip of the continent has occurred (Figure 1). If the margin was originally curved, then the amount of strike-slip motion that was accommodated in the region was greater or less than 500

Table 3. Calculated Limits on Accommodation of SSA-AP Relative Motion Between Southern Tip of SSA and Northern Tip of AP Along Plate Boundaries and Within Tectonic Regions Within Scotia Arc for 84-0 Ma

	Motion Type	Displacement, km		
		0-50 Ma	50-84 Ma	0-84 Ma
Flow line data	east-west strike-slip	890	430	1320
	north-south divergence	370	120	490
Western Scotia Sea spreading centers and Shackleton Fracture Zone (active during ~30-9 Ma)	east-west strike-slip	440†	0	440†
		700‡		700‡
		180†	0	180†
	north-south divergence	440‡		440‡
Proto-Shackleton Fracture Zone (proposed activity during 30-84 Ma)	east-west strike-slip	0-290§	0-430	0-720¶
	north-south relative motion	0-190§	0-120	0-310¶
Continental South America and continental blocks previously connected to SSA	east-west strike-slip	0-500	0-500	0-500
	north-south relative motion	0-190	0-120	0-310
North Scotia Ridge (proposed maximum period of activity; 0-50 Ma)	east-west strike-slip	0-890	0	0-890
	north-south relative motion	?*	0	?*
South Scotia Ridge (strike-slip activity since 20 Ma)	east-west strike-slip	0-410	0	0-410
	north-south relative motion	?*	0	? *

* Some convergence (transpression) is presently being accommodated along the NSR [*Ludwig and Rabinowitz*, 1982], while some divergence (transtension) is presently being accommodated along the SSR [*Pelayo and Wiens*, 1989]. How much has occurred is unknown.
† Calculated from flow line data in Table 2.
‡ Measured.
§ Displacement during 30-50 Ma.
¶ Displacement during 30-84 Ma.

km. Based on consideration of rotated paleomagnetic directions in SSA [*Dalziel et al.*, 1973; *Burns et al.*, 1980; *Cunningham et al.*, 1991] and documented evidence for left-lateral strike-slip faulting in the region [*Winslow*, 1982; *Cunningham*, 1993], we interpret 500 km to be a best approximation of an upper limit for accommodation of left-lateral interplate motion within the southern region of the South American continent. Continental deformation in the southernmost Andes including oroclinal bending was probably structurally linked to a left-lateral strike-slip fault system that must have existed between the future SSA and AP to accommodate separation of the AP from SSA and remove their latitudinal overlap [*Cunningham et al.*, 1991; *Grunow et al.*, 1992]. This system we call the proto-Shackleton Fracture Zone (Figure 6). Because the proto-Shackleton Fracture Zone would have had a west-northwesterly trend (Figure 6), motion along it can be divided into an east-west left-lateral strike-slip component and a north-south divergent component. Although it is impossible to quantify motion along this proposed structure, it seems reasonable to suggest that it may have accommodated a significant fraction of total SSA-AP relative motion for the 84-50 Ma period. The proto-Shackleton Fracture Zone may have also marked a mid-Late Cretaceous tectonic boundary between progressive contractional, transpressional, and possibly transtensional deformation in the southernmost Andes and the relatively undisturbed northern AP [*Dalziel and Elliot*, 1973].

50-0 Ma

The flow line data for the 50-0 Ma interval (Tables 2 and 3) indicate that continental separation between SSA and AP that eventually led to seafloor spreading in the western Scotia Sea and development of the Scotia plate accelerated between 55 and 40 Ma when an increase in north-south divergence and east-west strike-slip motion occurred between SSA and AP (Figure 6). During this period, SSA-AP divergence also increased as SSA-Africa motion became more west-northwesterly while AP-Africa motion was west-southwesterly (Figures 2 and 7). It is worth noting that the timing of this change in rate and angle of plate separation coincides approximately with the initial India-Eurasia collision [*Patriat and Achache*, 1984], the approximate age of the bend in the Hawaii-Emperor seamount chain [*Clague et al.*, 1989], and a documented increase in spreading rates between Antarctica and Australia [*Lawver et al.*, 1992] and thus may be part of a larger, global-scale plate reorganization event.

Between 50 and 30 Ma and prior to the onset of seafloor spreading in the western Scotia Sea, the SSA-AP flow line data predict that 290 km of east-west left-lateral strike-slip motion and 150 km of north-south divergent motion occurred between the two plates (Tables 2 and 3). During this period, it is likely that pre-seafloor-spreading continental extension between SSA and AP and continued strike-slip motion along the proto-Shackleton Fracture Zone accommodated both components of displacement.

Between 30 and 9 Ma, components of east-west left-lateral and north-south divergent interplate motion between SSA and AP have been accommodated by the now extinct northeast trending central and western Scotia Sea spreading centers within the Scotia Plate. This motion has been tracked by the SFZ that forms the western boundary to the Scotia Sea spreading centers and Scotia plate (Figure 1). Approximately 440 km of north-south separation and 700 km of east-west separation can be measured from the south-ernmost tip of SSA to the northernmost tip of the AP (using the 3000-m bathymetric contour as the edge of the continent (Figure 1). However, the flow line data indicate that only approximately 440 km of east-west, left-lateral SSA-AP interplate motion and only approximately 180 km of north-south divergent interplate motion occurred during the 30-9 Ma interval during which the spreading centers were active [*Barker and Burrell*, 1977, Table 3]. Thus the present north-south width of the Scotia Sea and amount of left-lateral offset along the Shackleton Fracture Zone are not explained solely by SSA-AP relative motion. Counterclockwise rotation of the southernmost tip of SSA could have resulted in some northward displacement of the southernmost tip of SSA relative to the northern tip of the AP during the last 30 m.y., causing additional seafloor spreading in the western Scotia Sea. However, more importantly, south-southwest-ward subduction retreat of the magmatic arc that existed along the southern boundary to the Scotia Sea (SSR) [*Barker and Lawver*, 1988] may have caused a significant amount of back arc extension in the Scotia Sea independent of SSA-AP relative motion.

Since 9 Ma and the cessation of seafloor spreading in the Scotia Sea, SSA-AP relative motion has probably been accommodated by left-lateral strike-slip faulting in Tierra del Fuego and along the NSR and by transtension along the SSR [*Pelayo and Wiens*, 1989]. Calculations of SSA-AP relative motion are unaffected by the late Tertiary development of the Scotia Plate [*Barker et al.*, 1991]. However, the partitioning of Scotia Plate-SSA and Scotia Plate-AP relative motions is difficult to quantify. This is because the western Scotia Sea floor, although apparently coupled to SSA along a passive continental margin southeast of Cape Horn, is on the south side of the NSR and its on-land extension in Tierra del Fuego [*Winslow*, 1982]. In addition, the Scotia Sea floor is separated from the AP by the SSR and a transtensional fault system at the western end of the SSR [*Pelayo and Wiens*, 1989].

The approximately 890 km of left-lateral SSA-AP interplate motion between 50 and 0 Ma (Table 3) has important implications for the history of eastward translation of South Georgia away from SSA (Figure 1). Because seafloor spreading in the Scotia Sea only began at approximately 30 Ma [*Barker and Burrell*, 1977], the modern NSR is not generally considered to have been much older than 30 Ma in its role as the northern boundary to the young seafloor generated in the Scotia Sea. (The fault system may be older because prior to actual seafloor spreading, significant displace-ments probably occurred as the continent extended and fragmented, and the flow line data indicate an increase in interplate east-west strike-slip motion at approximately 55-40 Ma (Figure 8).) Thus if South Georgia's eastward translation relative to SSA was along the NSR, then it presumably occurred during the last 50 m.y. (We speculate that 50 Ma is an upper limit for initial left-lateral displacements along the NSR). However, only approximately 890 km, or 55% of South Georgia's 1600 km of apparent eastward displacement relative to SSA, can be accounted for by SSA-AP relative motion along the NSR during the last 50 Ma (Table 2). Therefore either at least 45% or more of South Georgia's apparent eastward translation relative to SSA must be accounted for by another mechanism besides strike-slip translation along the NSR, or South Georgia's restored original position must have been farther east of Cape Horn than originally proposed [*Dalziel*, 1981]. It is possible that South Georgia's translation path involved a combination of strike-slip and rift-drift motion, or more likely, South Georgia moved eastward as an upper plate to the easterly migrating SSR-South Sandwich Arc subduction zone at an independent rate faster than SSA-AP relative motion [*Barker et al.*, 1991; *Royden*, 1993; P. Barker, personal communi-cation, 1993].

Paleomagnetic data indicate that the apparent orocline on the Antarctic Peninsula either is a primary bend or was formed by oroclinal rotation prior to 110 Ma [*Watts et al.*, 1984; *Grunow et al.*, 1991; *Grunow*, 1993]. Therefore this regional feature does not appear to have formed as a result of SSA-AP relative motions since 84 Ma. The amount of displacement on the SSR that forms the southern boundary to the western Scotia Sea spreading centers and the Scotia plate is unknown. The SSR apparently formed as a magmatic arc prior to becoming a transform boundary at around 20 Ma [*Barker and Lawver*, 1988]. The SSA-AP flow line data indicate that since 20 Ma, 410 km of east-west left-lateral strike-slip motion has occurred between SSA and AP. Thus a maximum value of 410 km for left-lateral strike-slip displacement along the SSR is proposed, although we believe the true value is considerably less because the NSR was active during this time and was accommodating some of the SSA-AP relative motion east of the southern tip of SSA.

In summary, during the last 84 m.y., SSA and AP have followed non parallel drift trajectories at different rates relative to Africa. This difference has caused approximately 1320 km of east-west left-lateral strike-slip separation and 490 km of north-south divergence between the southern tip of SSA and the northern tip of AP in what is today the Scotia Arc region (Table 3). Between 30 and 9 Ma, all SSA-AP relative motion appears to have been accommodated by seafloor spreading in the western Scotia Sea. Uncertainties with Scotia Plate-SSA and Scotia Plate-AP motion make it difficult to quantify total displacement along the NSR and SSR. However, an upper limit of 890 km of left-lateral strike-slip motion for the NSR and 420 km for the SSR is proposed.

Prior to 30 Ma and the onset of seafloor spreading in the Scotia Sea, most SSA-AP interplate motion was accommodated by intracontinental deformation within the SSA continent, by left-lateral strike-slip faulting along a proposed proto-Shackleton Fracture Zone, and possibly by motion between continental blocks that later separated from SSA and the AP and were dispersed along the periphery of the Scotia Arc. Intracontinental deformation within SSA related to SSA-AP interplate motion included left-lateral strike-slip faulting, counterclockwise continental rotation, transpression, and probably transtension. The proto-Shackleton Fracture Zone may have separated mid-Late Cretaceous poly-phase deformation in the southernmost Andes from relative tectonic quiescence in the northern AP.

The data presented here match well with previous models of Scotia Arc evolution and indicate that the Scotia Arc region can, at first order, be viewed as a complication of SSA-AP relative plate motions. The opening of Drake Passage by seafloor spreading in the western Scotia Sea was a passive response to the gradual pulling away of SSA from the AP. Although the western Scotia Sea appears to have occupied a back arc setting related to a proposed mid-Late Tertiary subduction zone along the South Scotia Ridge [*Barker et al.*, 1991], we believe the initial opening of the Scotia Sea was caused by larger-scale plate motions as SSA and the AP drifted away from Africa at different velocities along diverging trajectories. Changes in drift direction and increased rates of east-west left-lateral and north-south divergent relative motion at 55-40 Ma led to final SSA-AP separation and eventual seafloor spreading in the Scotia Sea. The results provide limits on how SSA-AP interplate motion has been temporally and spatially partitioned during the last 84 m.y.

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