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A tale of two continents: Some tectonic contrasts between the central Andes and the North American Cordillera, as illustrated by their paleomagnetic signatures

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Abstract. Comparison of patterns of paleomagnetic poles from orogenic belts with appropriate reference poles for the craton can help to delineate important large-scale tectonic processes. Comparison of the paleomagnetic signatures of the western Cordillera of North America and the central Andes shows that the western edges of these belts have had profoundly different Mesozoic and Cenozoic histories. Specifically, the North American Cordilleran pattern shows strong evidence of post-middle Cretaceous relative northward displacement of outboard crustal blocks, but there is almost no comparable evidence of margin-parallel displacement in the Andes. We speculate that this may largely be a consequence of a simple difference in shape: the convex-westward western margin of North America facilitates margin-parallel displacement as a response to oblique subduction, whereas the concave-westward margin of South America inhibits it. The patterns of block rotations found along the western edge of the two orogens also are quite different. Nearly everywhere within the western North American Cordillera crustal blocks have rotated clockwise since mid-Cretaceous time, reflecting a pervading state of dextral shear. Within the western Andes of Peru and northern Chile, however, Mesozoic and Cenozoic rocks in Peru (and northernmost Chile) are rotated strongly counterclockwise, whereas rocks of the same age in the remainder of Chile (to about latitude 48°S) are rotated clockwise. A model combining oroclinal bending and block rotations driven by oblique subduction can account for the paleomagnetic observations.

INTRODUCTION

In this paper we contrast the paleomagnetic signatures of the western edge of North America and the westernmost part of the central Andes, concentrating on Mesozoic (especially Cretaceous) and Tertiary data. As is well known, paleomagnetic poles from orogenic belts tend to be scattered, and the tectonic interpretation of any single pole in most cases is discouragingly ambiguous. However, the pattern defined by the paleomagnetic data for an orogenic belt may reflect important tectonic processes that have helped to shape the belt [e.g., Zijderveld and Van der Voo, 1973; Beck, 1976]. The patterns defined by paleomagnetic poles from the Andes and the western Cordillera of North America (hereafter the "Cordillera") are conspicuously different and, as discussed below, probably reflect quite different tectonic histories. We hope that the simple models that emerge from analysis of the paleomagnetic data may be of use in refining syntheses of regional geology.

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CRETACEOUS PALEOMAGNETISM OF THE CENTRAL ANDES AND CORDILLERA

Figure 1 shows Cretaceous paleomagnetic data (as of about mid-1992) for the Cordillera (Figure 1a) and the Andes of Chile and Peru (Figure 1b); Cretaceous poles are used to illustrate differences between the two continents because Cretaceous data sets for both orogenic belts are relatively large and contain many well-determined entries.

Cordillera. The hexagon in Figure 1a represents the mid-Cretaceous reference pole for stable North America [Globerman and Irving, 1988]. The circles represent paleomagnetic poles for mid-Cretaceous rocks from the western Cordillera. Nearly all of these are rotated clockwise with respect to the reference pole. Furthermore, all the Cordilleran Cretaceous studies yield mean inclinations that are less than "expected"; that is, less than they should be had the various sampling sites remained fixed with respect to stable North America since mid-Cretaceous time. This has been interpreted by most investigators [e.g., Beck, 1976, 1991a; Irving et al., 1985] as evidence of relative northward displacement of terranes on the western edge of North America. Such displacements also are strongly supported by paleontological and tectonic studies [e.g., Engebretson et al., 1985; Jones et al., 1972].

Central Andes. Figure 1b shows Cretaceous paleomagnetic (south) poles for the Andes of Peru (open triangles) and Chile (open circles). Hexagons are Cretaceous reference poles. All poles are from the western part of the belt. With two exceptions, Chilean poles lie to the right of the reference poles (as viewed from their sampling sites) and thus suggest clockwise rotation. The exceptions (poles CK18.6 and CK18.8, Table 1) are from rocks located in the extreme north of Chile, essentially within the zone of abrupt bending in topographic and geologic trends at Arica (the Arica deflection; A in Figure 2). All poles north of the Arica deflection (but south of H, the Huancabamba deflection; see Figure 2) lie to the left of the reference poles, suggesting counterclockwise rotation. None of the 12 Cretaceous poles of Figure 1b indicates statistically significant north-south displacement. On the basis of the

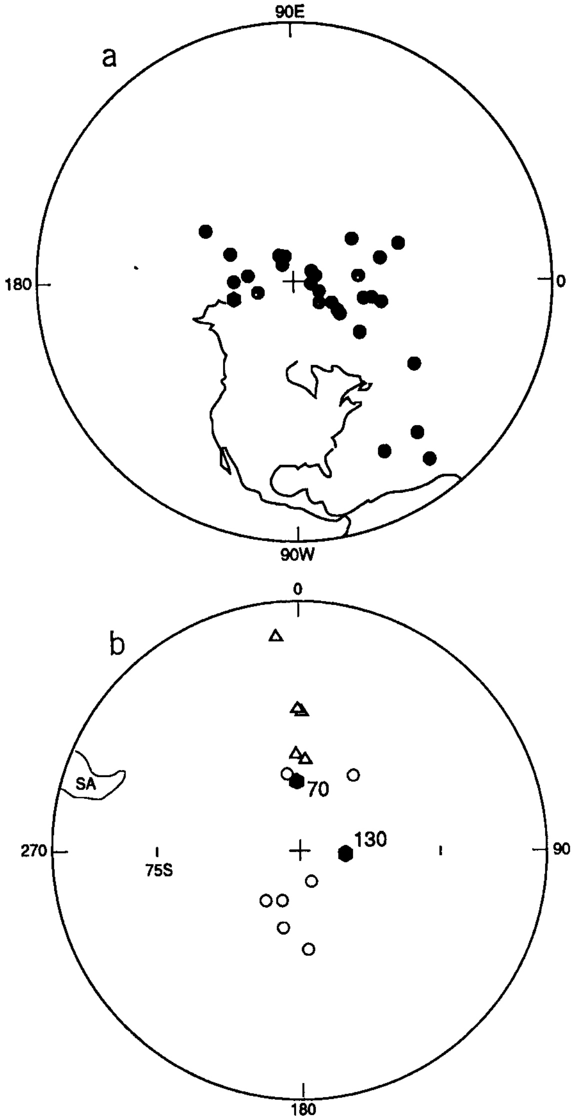

Fig. 1. Cretaceous paleomagnetic poles for (a) the westernmost North American Cordillera and (b) the central Andes. Hexagons are reference poles. Figure 1a, modified from Beck [1991a], illustrates evidence for clockwise rotation and northward relative transport of outboard crustal blocks. In Figure 1b, circles are poles from Chilean rocks and triangles are poles from Peruvian rocks. Figure 1b shows that counterclockwise rotations are common in Peru and clockwise rotations are common in Chile. No north-south transport is indicated. SA is South America.

paleomagnetic data, the Arica deflection (A in Figure 2) appears to have played a very important role in the tectonics of the central Andes. Its significance is discussed in the next section.

However, there is not unanimous agreement about the importance of the Arica deflection. For instance, Oviedo et al. [1991] review paleomagnetic data available to about 1987 and conclude that the difference between Peruvian and Chilean poles shown in Figure 1b is not significant. Using reference poles of that same date, they point out that many paleomagnetic directions from the central Andes have declination values that are not significantly different from the expected values at 95% confidence. When these studies are removed from the data set the pattern of Figure 1b still remains, but it is less obvious. Oviedo et al. [1991] attribute this residual pattern to the effects of rapid apparent polar wander. However, since 1987 the paleomagnetic data set for the central Andes has more than doubled, and most of these later studies have small circles of confidence. Furthermore, the reference path has been enhanced by one important entry [Butler et al., 1991]. After these modifications to the paleomagnetic data set the pattern (clockwise rotations in Chile; counterclockwise rotations in Peru) is more obvious than ever (for additional evidence, see Figure 5). We conclude that the pattern of poles shown in Figure 1b is real, is not an artifact of South American apparent polar wander, and has important tectonic significance.

The Cretaceous paleomagnetic "signatures" of the western margins of western North and central South America thus are very different. The difference with regard to latitudinal (north-south) displacement is illustrated in Figure 3.

WHAT CAUSES THE ANDEAN PATTERN?

There has been much recent interest in this question [e.g., Forsythe et al., 1987; Beck, 1988; Isacks, 1988; Kono et al., 1989]. There are two principal competing hypotheses, which are not mutually exclusive. In both the "indented" nature of the western edge of southern South America and the significance of the Arica deflection are pivotal.

The orocline. The orocline hypothesis as first proposed by Carey [1955] suggests that the Andean chain was originally straight and was bent into its present shape late in its history. As usually conceived, this bending would require extension behind (east of) the orogen. Oroclinal bending by this mechanism makes specific predictions that are easy to test using paleomagnetic data. As shown earlier [Beck, 1988] this original version of the orocline hypothesis is a conspicuously poor fit to the paleomagnetic data. It will not be considered further.

Isacks [1988] has proposed a modified oroclinal model especially adapted to the central Andes. He suggests that oroclinal bending was a consequence of differential crustal thickening during the main (Miocene) phase of Andean orogeny. From calculations based on the thickness of the crust in various transects he predicts maximum bending values of roughly 25° counterclockwise in Peru and 15° clockwise in Chile, measured with respect to undisturbed poles on the craton.

Oblique subduction. The second hypothesis advanced to explain the pattern of Andean paleomagnetic poles relies on *in situ* rotation of small crustal blocks, in response to oblique subduction [Beck, 1988]. In this model (Figure 4) the sense of rotation is determined by the sense of obliquity, which reverses at the Arica deflection (assumed to have existed

TABLE 1. Paleomagnetic Poles for the Central Andes

Pole	South Latitude	East Longitude	Age, MA	N	A_{95}	R ± ΔR	P ± ΔP	Reference
					Cenozoic			
PC6.8	63.4°	0.8°	45	20	1.6°	-19.0° ± 8.2°	-1.1 ± 7.9	Mitouard et al. [1990]
PC11.6	73.2°	356.6°	35	9	7.1°	-11.2° ± 10.1°	-2.9 ± 9.6	Macedo-Sanchez et al. [1992]
PC13.5	72.4°	351.5°	10	21	4.5°	-17.0° ± 9.1°	-6.7 ± 8.6	Heki et al. [1985]
PC14.0	84.1°	41.3°	10	16	6.7°	-5.5° ± 9.9°	2.5 ± 9.4	Tsunakawa et al. [1987]
BC17.2	82.7°	350.4°	10	58	3.4°	-6.6° ± 8.9°	-3.7 ± 8.3	McFadden et al. [1990]
BC17.5	83.9°	62.2°	5	25	3.7°	-4.8° ± 8.7°	3.9 ± 8.3	McFadden et al. [1990]
BC22.0	73.5°	212.6°	15	79	2.5°	17.8° ± 9.4°	-1.3 ± 8.0	McFadden et al. [1990]
CC22.8o	51.8°	205.3°	60	15	5.7°	52.7° ± 10.2°	6.9 ± 9.0	Hartley et al. [1992]
CC22.8y	69.0°	181.0°	30	9	8.2°	25.9° ± 11.1°	10.7 ± 10.1	Hartley et al. [1992]
CC27.6	48.8°	211.0°	40	7	5.8°	55.0° ± 13.4°	3.8 ± 9.0	Riley et al. [1993]
CC27.7	74.8°	229.8°	40	6	16.2°	24.3° ± 18.4°	-2.7 ± 14.8	Riley et al. [1993]
					Cretaceous			
PK6.5	52.6°	357.6°	100	3	24.7°	-31.5° ± 21.9°	-9.1 ± 20.7	Heki et al. [1984]
PK10.3	74.9°	4.4°	100	4	8.3°	- 9.4° ± 10.6°	-3.4 ± 10.1	Heki et al. [1984]
PK11.6	65.3°	0.1°	90	30	4.9°	-17.3° ± 11.4°	-4.6 ± 8.7	Macedo-Sanchez et al. [1992]
PK11.8	66.2°	1.4°	100	6	7.8°	-18.3° ± 10.4°	-5.3 ± 9.9	Heki et al. [1984]
PK11.9	73.3°	359.2°	90	12	3.3°	-9.1° ± 8.6°	-3.6 ± 8.2	May and Butler [1985]
CK18.6	77.2°	352.4°	100	19	3.3°	-6.1° ± 8.9°	-6.5 ± 8.2	Heki et al. [1983a]
CK18.8	74.3°	37.5°	125	6	5.1°	-13.4 ± 9.2°	-0.1 ± 8.7	Heki et al. [1983a]
CK23.8	72.6°	176.0°	130	11	6.0°	18.0° ± 9.8°	1.9 ± 9.1	Hartley et al. [1992; Tanaka et al. [1988]; Turner et al. [1984]
CK29.8	79.6°	214.6°	80	17	6.1°	22.7° ± 11.0°	-0.2 ± 9.1	Palmer et al. [1980a]
CK32.8	80.9°	200.2°	120	24	3.4°	13.8° ± 9.6°	-4.4 ± 8.3	Beck et al. [1986]
CK34.7	76.3°	192.5°	100	22	7.1°	23.3° ± 11.7°	1.3 ± 9.6	Beck et al. [1990]
CK43.6	84.2°	159.9°	100	13	5.5°	14.0° ± 12.2°	2.3 ± 8.9	Cembrano et al. [1992]
					Triassic and Jurassic			
CJ18.6	76.4°	357.4°	160	32	4.6°	-14.7° ± 6.6°	-4.3 ± 6.2	Heki et al. [1983b]; Palmer et al. [1980b]; Scanlan and Turner [1992]
CJ19.2	73.9°	62.1°	135	13	9.1°	-11.7° ± 10.8°	8.3 ± 10.5	Heki et al. [1983b]
CJ23.8	62.0°	199.6°	145	10	9.1°	30.4° ± 11.3°	0.0 ± 10.5	Hartley et al. [1988]
CJ25.6	57.5°	217.1°	150*	11	7.0°	35.0° ± 11.0°	-4.9 ± 9.5	Forsythe et al. [1987]
CJ27.5	66.9°	191.6°	155	8	12.7°	23.7° ± 11.7°	-6.9 ± 10.8	Riley et al. [1993]
CT27.5	60.9°	218.3°	220	18	7.8°	28.1° ± 9.0°	-4.5 ± 6.7	Riley et al. [1993]
CJ32.1	84.1°	20.7°	150*	10	4.3°	8.1 ± 10.3°	0.7 ± 8.5	Forsythe et al. [1987]
CT32.1	59.0°	277.5°	220	5	8.7°	11.6° ± 17.0°	-22.7 ± 11.4	Forsythe et al. [1987]
CJ33.0o	85.9°	36.7°	170	8	11.9°	5.7° ± 14.7°	1.7 ± 12.1	Irwin et al. [1987]
CJ33.0y	80.3°	207.8°	145	10	9.5°	11.8° ± 13.0°	-3.9 ± 10.8	Irwin et al. [1987]

Explanation:

Pole designation identifies country (P, Peru; B, Bolivia; C, Chile), geological age (C, Cenozoic; K, Cretaceous; J, Jurassic; T, Triassic), and South latitude of sampling site. Ages are rounded to nearest 5 m.y. and are very approximate in some cases. N is number of sites used in pole calculation. A_{95} is circle of 95% confidence about mean pole. R ± ΔR is rotation and 95% confidence interval, calculated after Beck et al. [1986a]. Positive R is clockwise. P ± ΔP is poleward transport and 95% confidence interval, calculated after same author. Positive P is southward.

* Indicates remagnetized rocks; time of remagnetization poorly known.

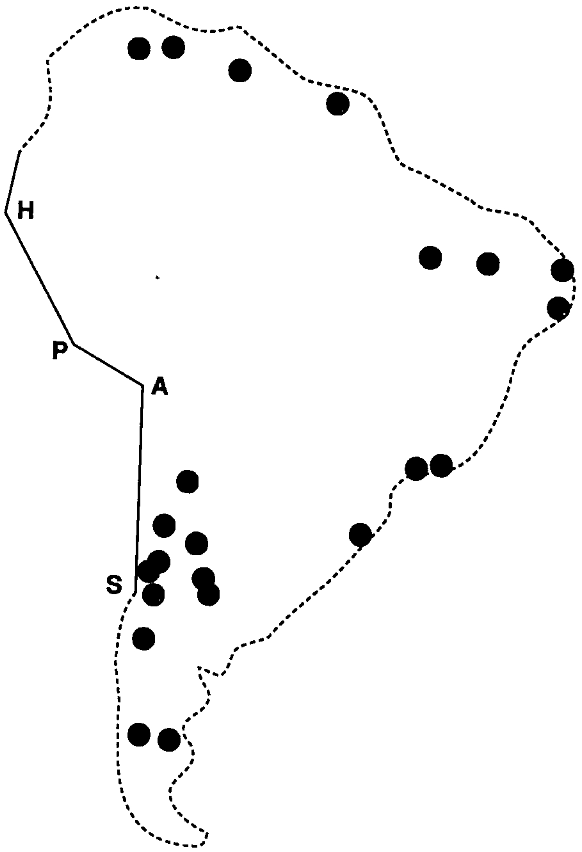

Fig. 2. Cartoon illustrating the "Bolivian orocline." Abbreviations are S, Santiago; A, Arica; P, Pisco; and H, Huancabama. Geologic and topographic trends change abruptly at A, P, and H. Solid circles are locations of areas sampled to construct the reference curve of apparent polar wandering for stable South America.

since early in the continent's history). Several ideas have been advanced to explain how the rotations might be accomplished [e.g., Forsythe et al., 1987; Beck, 1988; Hartley et al., 1992; Irwin et al., 1987], but as yet there are insufficient data to determine which are correct. The small-block rotation model predicts that the amount of rotation will vary from place to place because of differences in local geology, but that, at least for mid-Cretaceous and younger rocks, there ought to be a general dependence of rotation on age of rock unit. Also, if rotations are driven by plate interactions, one might expect the amount of rotation to decrease with distance from the continental margin, as found, for instance, in the Washington-Oregon segment of the Cordillera [Beck et al., 1986a].

The predictions made by the two hypotheses (orocline vs. oblique subduction) thus are quite different, and it should be possible to determine which is more nearly correct by examining the paleomagnetic data. Note that it is quite possible that both processes contribute.

ANALYSIS OF THE PALEOMAGNETIC DATA

The data upon which this section is based are summarized in Table 1. Much recalculation was involved in assembling this compilation, following guidelines used by Beck [1988]. Rotation and poleward transport values given in Table 1 were calculated [Beck et al., 1986a] with respect to the reference poles of Table 2.

Figure 5 tests the Isacks [1988] orocline model. The Isacks model predicts rotations (measured with respect to reference poles from the craton) in the range 10°-20° counterclockwise north of Arica and 5°-10° clockwise south of Arica. Because Isacks envisioned this rotation as occurring during the Miocene, we have plotted Paleogene as well as Mesozoic poles. As seen in Figure 5, the Isacks orocline model is an excellent fit north of Arica but a poor fit to the south. In particular, there is a latitude band within northern Chile (roughly 20°-30°S) where rotations for rocks of all ages are much greater than predicted by the model.

Because it makes so few specific predictions the small-block, oblique-subduction model is difficult to test. If oblique subduction has gone on since well back into the Mesozoic more-or-less as depicted in Figure 4, then one might expect older poles to show more rotation than younger poles. Calculations based on data in Table 1 show that this is not the case; the mean rotations for Cenozoic (21.8° ± 17.4°), Cretaceous (16.4° ± 7.1°), Jurassic (18.1° ± 10.7°), and Triassic (19.9° ± 11.7°) rock units are statistically identical. Thus, if small-block rotations have been dominant, they must have taken place mainly in late Cenozoic time. Very young (10 Ma or younger) rock units have significantly smaller rotations (8.5° ± 5.7°) than do the older rock groups.

We also tested whether or not the amount of rotation was related to distance from the continental margin, with a negative result. In places (e.g., near Copiapo, Chile [Riley et al., 1993]) rotations are significantly greater near the coast than inland, but elsewhere this is not the case. A regression line fitted to the entire data set shows no significant correlation between rotation and distance from the continental margin. Thus, if local block rotations have occurred, the shear responsible must have been distributed over a wide section of South American continental crust.

SPECULATIONS ON THE CAUSE OF THE ANDEAN ROTATIONS

The Isacks [1988] version of the orocline model fits so well north of Arica that it would be difficult to argue that it is wrong. However, it is a poor fit south of Arica, especially in the latitude range 20°-30°. Also, clockwise rotations in Chile are found far south of the zone where the Isacks model should have its effect [Cembrano et al., 1992], probably associated with the Liquiñe-Ofqui fault zone [Hervé and Thiele, 1987]. Thus it also would be hard to argue that shear-driven small-block rotations have not occurred. We offer a simple compromise model that combines the two (Figure 6). The key to our ideas, which are at most a small modification of the Isacks [1988] model, is the observation that oroclinal bending would increase the likelihood of shear-

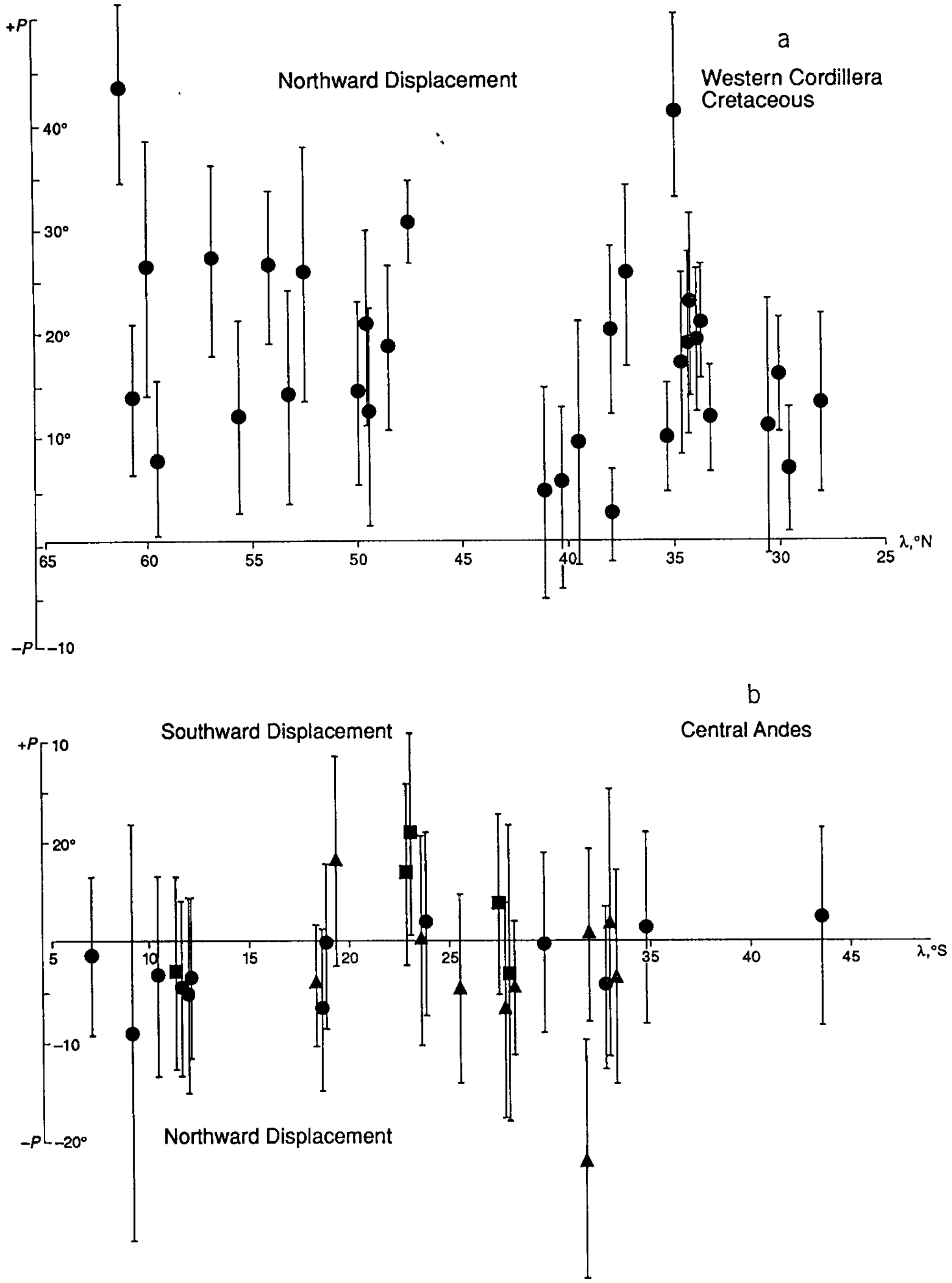

Fig. 3. Diagram illustrating the difference between the (a) western Cordillera and (b) central Andes with respect to margin-parallel (north-south) displacement of crustal blocks. Ordinate (P) is "poleward transport," calculated by comparing observed and reference paleomagnetic poles [Beck et al. 1986a]. Abscissa is latitude of sampling site. The 95% error bars are shown. In Figure 3a only Cretaceous data plotted; note that all P values are positive (suggesting northward transport) and that only four (from the Sierra Nevada block) are not significantly different than P=0 at 95% confidence. Figure 3b shows all Mesozoic and Paleogene data for the central Andes (squares, Paleogene; circles, Cretaceous; triangles, Triassic and Jurassic). Note that only a single study is significant from P=0 at 95% confidence. Margin-parallel displacement thus is not supported for the central Andes. The tendency for Cretaceous and Paleogene poles in Peru to cluster on the "northward displacement" side of the P=0 line is curious and unexplained.

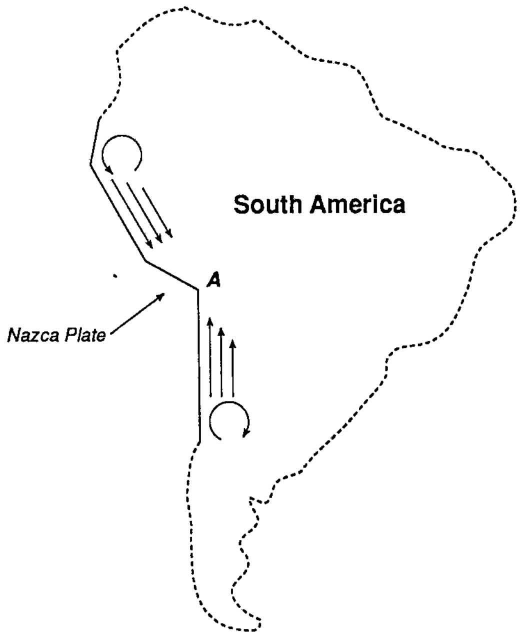

Fig. 4. Cartoon showing how the sense of obliquity changes at Arica (A). If oblique convergence causes shear in the overriding plate, it should be in the direction indicated and should produce rotations in the sense shown.

driven rotation south of Arica but decrease it to the north.

We concur with Isacks [1988] that the South American margin was curved prior to the latest phase of Andean orogeny, although not so sharply curved as it is at present. At least since Eocene time the central Andes were fronted by the Nazca plate, which prior to the Miocene converged with South America in a strongly north-oblique direction [Cande and Leslie, 1986; Pardo-Casas and Molnar, 1987]. In pre-Eocene time, west central South America may have been in contact with the Aluk plate [Cande and Leslie, 1986], the direction of whose motion with respect to South America is unknown. However, the abundance of mid-Cretaceous and younger magmatic rocks in Peru and north and central Chile argues for convergence for at least the last 100 m.y., and the shape assumed for the South American plate margin would then assure that such convergence must have been more dextral in Chile than in Peru. Thus we feel safe in assuming a pattern of plate interaction roughly as depicted in Figure 4 since mid-Cretaceous time.

Given this type of plate interaction, before oroclinal bending convergence ought to have been strongly right-oblique south of Arica. North of Arica, because of the curvature of the South American plate margin, convergence would have been more nearly margin-normal (Figure 6a). Thus it follows that, pre-orocline, any small-block rotations that occurred would have been generally clockwise in Chile but nonexistent (or small) in Peru. Moreover, as Figure 6 illustrates, oroclinal bending by the Isacks model would increase obliquity in northern Chile but decrease it in southern Peru. Thus as oroclinal bending progressed, shear-driven clockwise rotations would die out altogether (or perhaps reverse) in southern Peru but would be enhanced in Chile. This model predicts fairly uniform, small, counterclockwise rotations in Peru (conforming to the Isacks model) but much greater and more scattered amounts of clockwise rotation (orocline plus shear) in northern Chile. This is of course exactly what is observed. This model also may account for the fact that large strike-slip faults are well known in Chile but apparently are far less prominent in Peru.

WHY ARE THE WESTERN CORDILLERA AND CENTRAL ANDES SO DIFFERENT?

From a paleomagnetic point of view, the most conspicuous difference between the histories of the westernmost (arc and forearc) part of the central Andes and the Cordillera since mid-Mesozoic time concerns evidence of margin-parallel displacement of blocks of continental crust. In the westernmost Cordillera most paleomagnetic studies yield paleolatitudes that are "wrong" (usually too low) when compared to the paleolatitude of interior North America [e.g., Beck, 1976, 1991a]. In South America this is not the case; only two studies have P values different from zero at 95% confidence (Figure 3b and Table 1). Thus the paleomagnetic picture suggests that North American terranes have moved fairly freely along the continental margin (since

TABLE 2. Anchor Points for South American Reference Apparent Polar Wander Path

Age, Ma	South Latitude	East Longitude	A_{95}	Reference
230	82.7°	285.5°	7.4°	Beck [1988]
160	89.0°	271.1°	4.6°	Beck [1988]
130	83.8°	96.4°	3.4°	Bellieni et al. [1983
70	78.7°	358.4°	6.3°	Butler et al. [1991]
50	85.1°	303.2°	10.0°	Riley et al. [1993]
0	90.0°	-------	10.0°	present dipole

Reference poles for rotation calculations (Table 1) were determined by interpolation between these tie points. A_{95} values for 50 Ma and present poles were assigned arbitrarily. For all interpolated poles, A95 values also set arbitrarily at 10.0°.

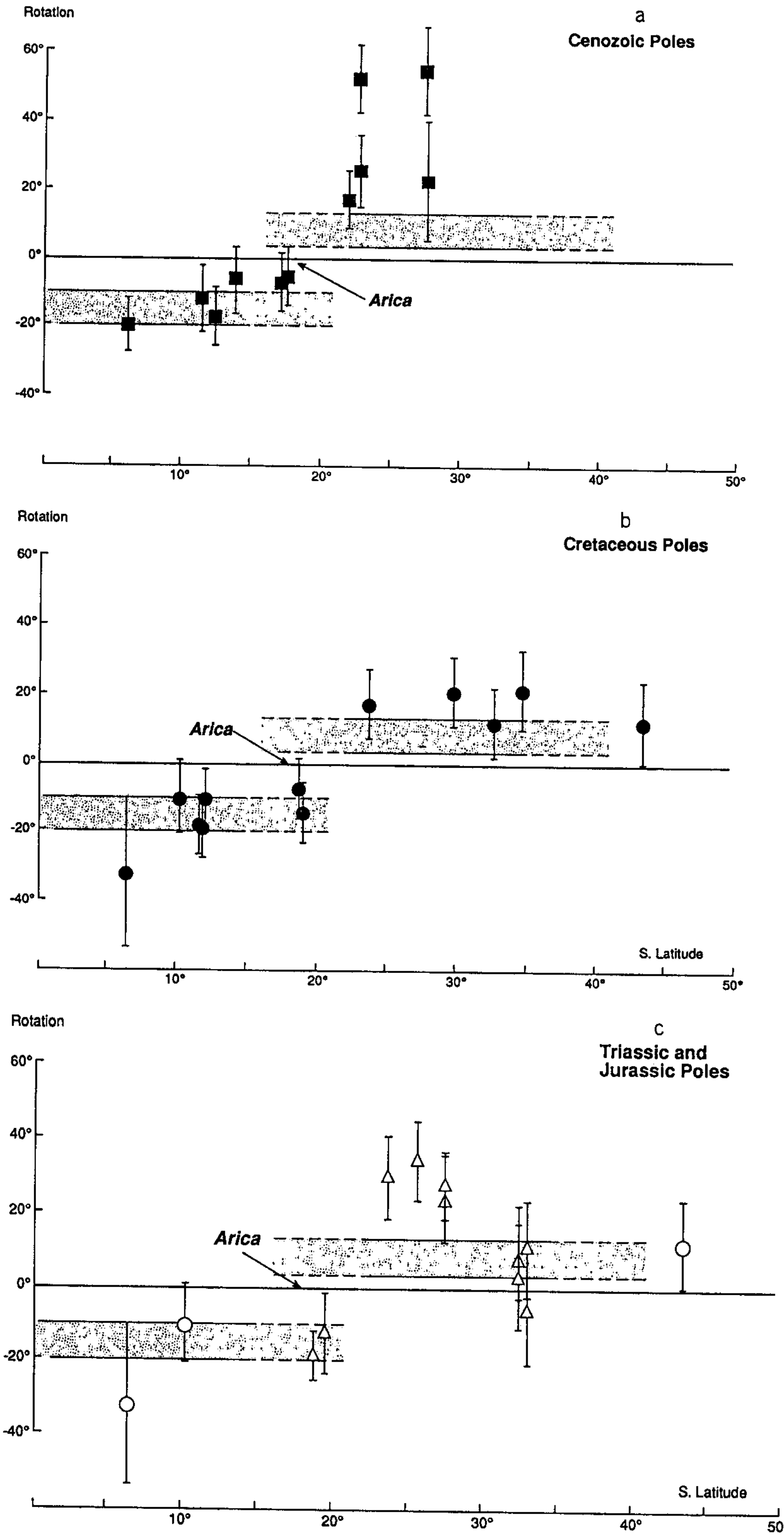

Fig. 5. Paleomagnetic test of the Isacks [1988] orocline for (a) Cenozoic; (b) Cretaceous; and (c) Triassic and Jurassic. Ordinate is rotation [Beck et al. 1986a], calculated with respect to reference poles from the South American craton; abcissa is latitude of sampling site. Shaded region is amount of rotation predicted by the Isacks model. The 95% confidence intervals shown.

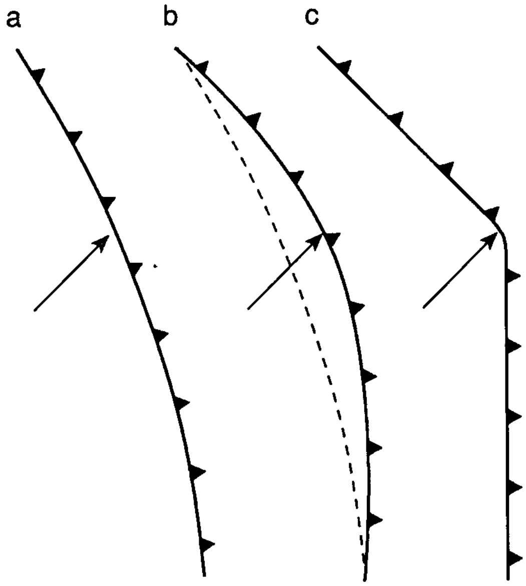

Fig. 6. Consequences of oroclinal bending after the Isacks [1988] model. (a) Pre bending shape of continental margin is slightly concave westward. Arrow is direction of convergence, which is right-oblique everywhere but decreasingly so northward. (b) As bending progresses, convergence becomes more oblique to the south but less oblique to the north. (c) With bending complete, high obliquity in the south facilitates small-block clockwise rotations. In the north, small-block rotations are inhibited by low obliquity, or perhaps become counterclockwise.

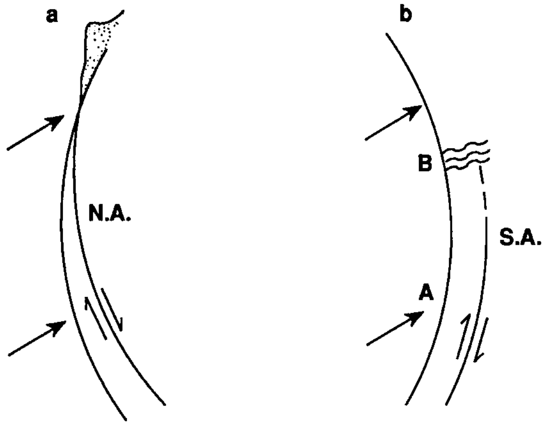

Fig. 7. Effect of shape of continental (plate) margin on coast-parallel displacements. In Figure 7a, convex curvature causes obliquity to increase in direction of transport, whether that is north or south. In Figure 7b, concave shape produces a buttress which impedes coast-parallel transport. See text. NA is North America; SA is South America.

about 135 Ma, entirely northward). South American terranes, on the other hand, have remained essentially fixed in the coordinate system of the continent, although some have undergone large rotations. We suspect that to a first approximation this difference is a result of the different shapes of the two continents (Figure 7).

Elsewhere [Beck, 1986, 1991b; Jarrard, 1986] it has been argued that the ability of oblique subduction to induce margin-parallel displacement (transport of crustal blocks along the margin of a continental plate) depends, among other factors, upon the angle of obliquity. Everything else equal, the greater the obliquity, the greater the probability that margin-parallel displacement will occur. In particular, for any set of circumstances there exists a critical obliquity below which detachment and margin-parallel transport will not occur. Thus the (convex westward) outline of North America is ideal for margin-parallel displacements, because it assures that under most circumstances obliquity will increase in the direction of displacement, whether that happens to be north or south. Central South America, on the other hand, probably was concave westward throughout most of Mesozoic and Cenozoic time. Thus, irrespective of whether the sense of oblique convergence was dextral or sinistral, obliquity would decrease in the direction of potential terrane transport. Thus, although conditions might favor margin-parallel displacement at some point on the plate margin (A in Figure 7b), conditions further along the margin (B in Figure 7b) would prevent motion. The resulting buttress might be partially overcome (as by thickening the crust at B), but the amount of displacement would be severely limited. We suspect that even the small amount of curvature postulated for the pre-orocline central Andes (e.g., Figure 6a) would be enough to retard or prevent terrane displacement, and as the orocline developed conditions would become progressively less favorable. This also might help explain why the long, topographically impressive zones of probable strike-slip faulting in Chile (Liquiñe-Ofqui and Atacama faults) show so little displacement when compared to their North America counterparts.

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