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The Central Andean rotation pattern: another look

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SUMMARY

Crustal blocks in the Central Andes have experienced vertical-axis rotations through angles ranging up to 50° or more. Blocks located north of the abrupt change in tectonic and geographical trends at Arica, northern Chile (the Arica deflection) have been rotated counter-clockwise; blocks south of the deflection rotated clockwise. Rocks ranging in age from Late Miocene to mid-Jurassic are involved. The palaeomagnetic record of this rotation is referred to as the central Andean rotation pattern (CARP).

In this paper the CARP is investigated using the techniques of palaeomagnetic shape analysis. From this analysis it appears that rotation began in the early Cenozoic, and probably continues at the present time. Cenozoic rotation appears to have occurred without significant northward or southward displacement. For earlier times, however, evidence of displacement is found; the sense of displacement apparently changed at Arica—northward north of the deflection and southward further south. This Mesozoic displacement of crustal material away from Arica appears to have taken place without accompanying rotation.

No existing tectonic model for the CARP explains this two-part history. Several alternative models are suggested, perhaps the least unconvincing of which involve creation of the Arica deflection during the late Mesozoic by subduction of a spreading ridge, or perhaps an island arc or other crustal-thickness anomaly riding on the Nazca (or Phoenix) Plate.

Key words: Andean palaeomagnetism, Andean tectonics, block rotations.

1 INTRODUCTION

The Central Andean rotation pattern (CARP; Somoza *et al.* 1996) is a much-discussed geological phenomenon known almost entirely from palaeomagnetism. Briefly, palaeomagnetic studies have shown that most crustal blocks in and west of the Andes of northern Chile, western Argentina and Peru have undergone vertical axis rotations through angles ranging up to 50° or more. Blocks north of the abrupt change in tectonic trends near Arica, northern Chile (the Arica deflection, at about 19°S) have consistently rotated counter-clockwise, whereas—with several questionable exceptions—blocks south of the deflection have rotated clockwise. Most observers have agreed that little or no displacement along the margin of South America accompanied these rotations. Rocks as young as Late Miocene are rotated. The CARP phenomenon has generated considerable discussion (e.g. Kono *et al.* 1985; Beck 1987, 1998; Beck *et al.* 1994; Somoza *et al.* 1996; Randall 1998; Taylor *et al.* 1998; Lamb 2001; Prezzi & Alonso 2002).

This paper revisits the CARP, using methods of palaeomagnetic shape analysis (Beck 1999a) that illustrate the phenomenon in a useful way and offer effective insight into several remaining questions. In particular, the following will be considered:

(1) Analysis of the CARP requires reliable palaeomagnetic reference poles for stable South America. Such poles have been difficult to obtain (e.g. Roperch & Carlier 1992; Randall 1998; Beck 1999b; Lamb & Randall 2001). Does the choice of reference pole significantly influence tectonic interpretation of the palaeomagnetic data?

(2) Most observers agree that rotations of crustal blocks in the Central Andes were not accompanied by large-scale relative displacements along the continental margin. However, if there is uncertainty in the choice of reference poles, displacements as great as ~500 km could easily escape (palaeomagnetic) detection. Have any displacements occurred, and, if so, when and in what direction?

(3) The pattern of tectonic rotations is the same throughout the Central Andes, regardless of the age of the rocks considered; for example, Miocene rocks show the same rotation pattern as Cretaceous rocks (although the amplitudes of rotation are smaller). When did rotation begin, and is it still going on?

(4) The Arica deflection serves as an effective first approximation to the boundary between clockwise (cw) rotation to the south and counter-clockwise (ccw) rotation to the north. Is it a recent feature representing oroclinal flexure of the Andes (e.g. Kono *et al.* 1985; Isacks 1988), an ancient feature that controls the sense of rotation by influencing the sense of oblique subduction (Beck 1987), or a combination of the two (Beck 1998). Or should we explore other models?

The data used in this paper come from the recent synthesis of Prezzi & Alonso (2002). In all illustrations closed circles will be

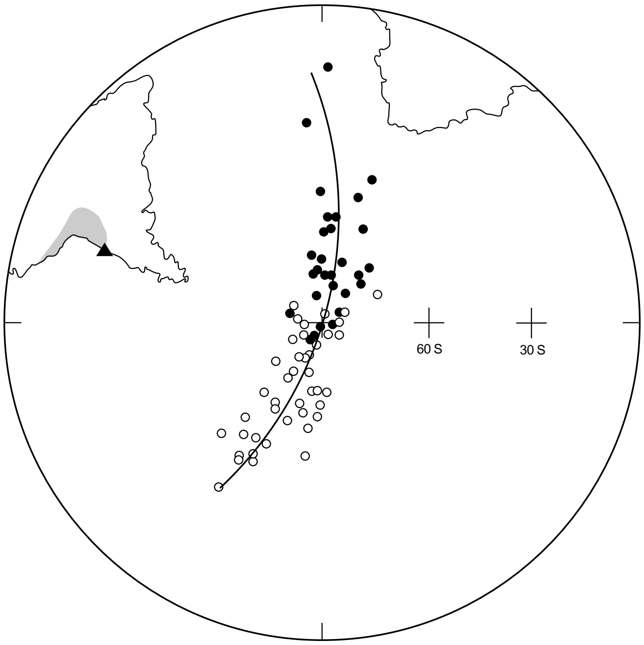


Figure 1. Palaeomagnetic poles from the Central Andes, with best-fit small circle. Solid circles represent poles from locations north of Arica, northern Chile (19° S); open circles are from south of Arica. The triangle indicates the centre of the best-fit circle (Table 1). The shaded area indicates the region of the Central Andean rotation pattern (CARP).

used for poles from rock units north of Arica (NOA) and open circles identify poles from rock units south of Arica (SOA).

2 THE CENTRAL ANDEAN ROTATION PATTERN (CARP): AN OVERVIEW

Seventy-four CARP poles tabulated by Prezzi & Alonso (2002) lie along a small circle with its centre located immediately adjacent to their central Andean sampling area (Fig. 1). Poles from south of the Arica deflection define the western half of the distribution; poles with sampling areas located north of the deflection make up its eastern half. There is minimal overlap between the two subsets. The length of arc subtended at the best-fitting small-circle centre (SCC) (Table 1) is 136.5°. Rock units sampled to create this overall data set range in age from 7 to 177 Ma. Clearly, from this illustration the dominant tectonic process affecting the central Andes has been *in situ* block rotation, with the vast range in rotation amplitude suggesting that relatively small crustal blocks influenced by local geological constraints are involved. The observation that a single well-defined small circle can be fitted to a data set that spans 170 Myr argues that not much apparent polar wander (APW) relative to South America has occurred since the mid-Mesozoic. Finally, if no significant northward or southward relative displacement of the central Andes has occurred (a fact yet to be established), it follows from Fig. 1 that the reference palaeomagnetic pole for interior South America has remained close to the present spin axis since about 175 Ma; that is, that any motion of South America since the mid-Mesozoic has been east-west, in present coordinates. We next look at two related questions: when did the CARP develop, and did it involve any northward or southward relative displacement?

Table 1. Parameters of best-fit small circles discussed in the text.

	λ	ϕ	R	s	N
CARP	28.4°	287.9°	61.8°	4.8	74
All Cenozoic	23.8	291.7	66.0	4.2	45
NOA Cenozoic	27.0	290.4	63.5	4.1	19
SOA Cenozoic	16.1	294.0	73.4	4.3	26
All Mesozoic	27.6	285.2	63.0	5.4	29
NOA Mesozoic	31.0	298.3	53.2	4.1	12
SOA Mesozoic	46.2	288.0	49.2	5.0	17

λ, ϕ, R are respectively S latitude, E longitude and radius of best-fit small circle for data set indicated. s is the root-mean-square deviation from a circle, and N is number of poles in the data set.

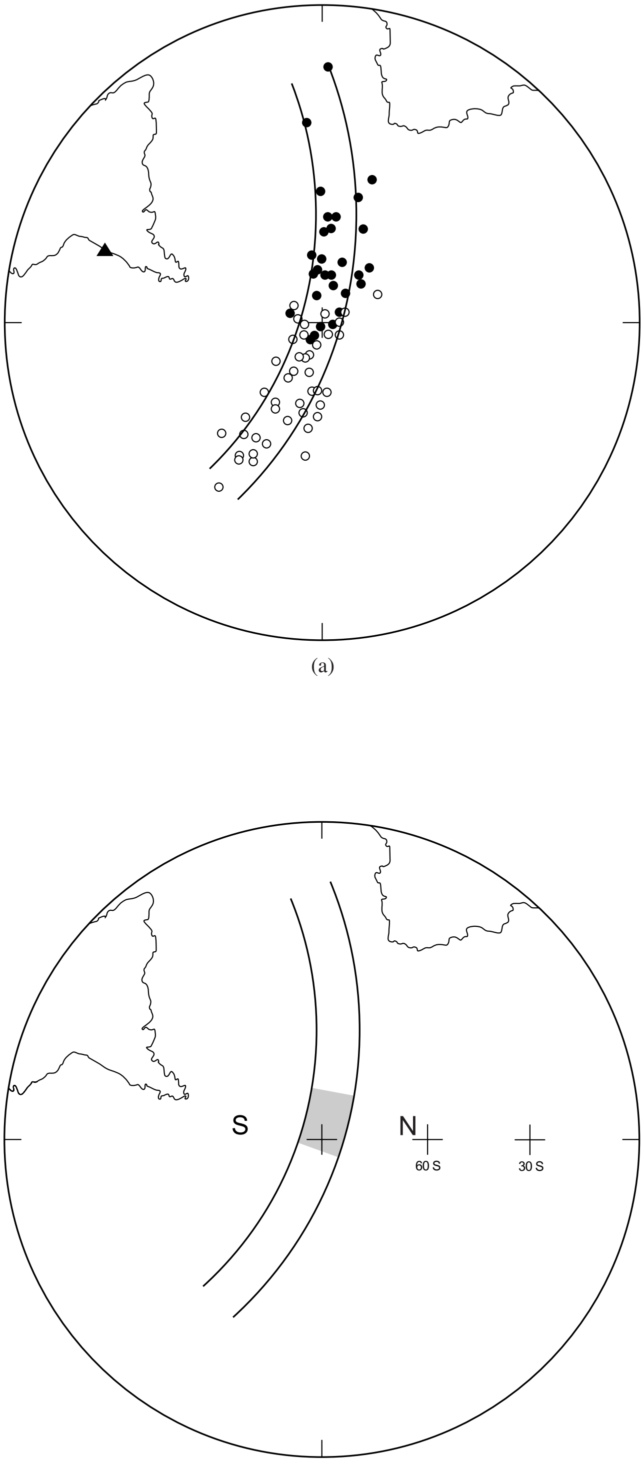
3 NORTH–SOUTH DISPLACEMENT: PALAEOMAGNETIC SIGNATURE

As mentioned earlier, conventional wisdom regarding CARP tectonics has been that displacements have been *in situ* rotations, with very little, if any, accompanying north–south relative motion. This is worth investigating further, if only because it is strikingly unlike the pattern found in coeval rocks from the superficially similar cordilleran belt of North America (e.g. Beck *et al.* 1994). Although displacements of the order of thousands of kilometres seem not to have occurred in the Central Andes, the question of whether smaller displacements are present depends critically on the choice of reference pole. This section explores the nature of palaeomagnetic evidence that might indicate that significant northward or southward displacement has occurred.

The case in which the entire central Andean region has moved either north or south with respect to the continental interior should be relatively easy to detect. In Fig. 2—based on the data of Fig. 1—the field is divided into five regions. The swath shown is formed by two circular arcs centred on the best-fit SCC, with radii $R \pm s$, where R is the radius of the best-fit small circle and s is the root-mean-square difference between each individual pole and the equivalent point on the small circle (Table 1). If the correct reference pole falls within this swath one can reasonably conclude that the displacement has been by and large purely rotational, with no appreciable amount of accompanying north–south displacement. Hereafter, such an arrangement of two parallel small circles will be referred to as a 'pure rotation swath'. The dotted area (based on the small area of overlap of NOA and SOA poles) indicates the region in which the reference pole should lie if the Arica deflection is the point of demarcation between cw and ccw rotations. If the correct reference pole lies outside the swath it follows that—in addition to block rotations—the Central Andean region has been displaced as a whole relative to the stable part of South America, in the sense indicated in Fig. 2(b).

However, it seems more likely that displacements (if any) would be of different sign on either side of the Arica deflection. For instance, judging from palaeomagnetic results from the North American Cordillera, one might expect northward relative motion south of the Arica deflection, where the sense of obliquity seems likely to have been dextral—and the converse north of the deflection. If the displacement is large (∼500 km or greater) there should be a distinct and obvious offset in the CARP pattern (Fig. 3). However, offset resulting from small (∼200 km or less) displacements might not be easily detected.

Finally, it is possible, even likely, that the amount of northward or southward displacement would vary from block to block. For instance, this certainly appears to be the case in the North American analogy (e.g. Beck 1980; Irving & Wynne 1990); separate blocks in that range are separated from one another by faults, often demonstrably strike-slip. Discovery of these tectonically independent blocks


(a)

(b)

Figure 2. Detecting northward or southward displacement. (a) Data from Fig. 1, fitted with two small circles of radii $R = R_0 \pm s$, where R_0 is the best-fit radius (Table 1), and s is the root-mean-square deviation of individual pole positions from the best-fit circle. Symbols as in Fig. 1. (b) Field of (a) divided into five subregions. If the correct reference pole lies in the region labelled N (S), the Central Andes have moved northwards (southwards), with respect to the stable interior of the continent. If the reference pole falls within the 'pure-rotation swath', no significant lateral displacement has occurred, only rotation. Finally, the shaded region indicates the location in which the reference pole must lie if localities north (south) of Arica are rotated counterclockwise (clockwise). See text for further discussion.

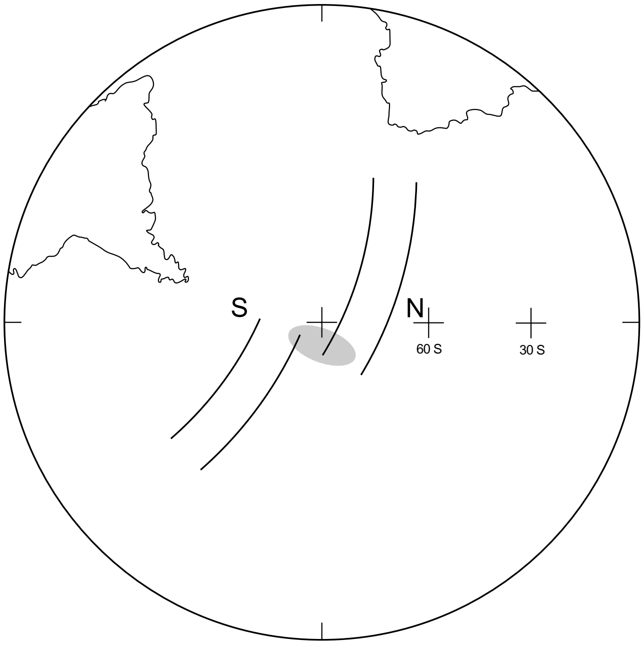


Figure 3. Hypothetical distribution of poles for the situation in which, in addition to rotation, units north (south) of Arica have moved southwards (northwards). Illustration shows individual swaths fitted to NOA and SOA subsets. If the swaths are significantly offset the two regions have moved with respect to one another.

gave rise to the tectonostratigraphic terrane concept (Schermer *et al.* 1984). One reasonable model would correlate the amount of displacement with the amount of rotation; large rotations would accompany large north–south displacements, and vice versa. This—again assuming southward (northward) relative displacement for crustal blocks north (south) of Arica—would serve to rotate the data set and best-fit SCC clockwise (Fig. 4), displacing the SCC away from the mean site location. As shown below, mean site locations and best-fit SCCs tend to be very similar, effectively negating this possibility.

4 NORTH–SOUTH DISPLACEMENT: CENOZOIC DATA

At present there is no consensus on the question of the appropriate reference poles to use for analysis of South American tectonics. This is largely the unfortunate result of a paucity of promising palaeomagnetic targets on the South American Craton; Tertiary reference poles are in particularly short supply (Randall 1998). As a result several authors (e.g. Roperch & Carlier 1992; Randall 1998) have responded by 'importing' reference poles from other continents, using standard plate reconstruction parameters to assemble them in South American geographical coordinates. An attempt also has been made to extract valid reference poles from the disturbed regions of the Andean cordillera itself (Lamb & Randall 2001). In this and the following section we compare several recently proposed sets of reference poles with the CARP data set in order to see if there is any evidence of north–south displacement, as would be indicated, for instance, if all choices of reference pole fell outside the pure-rotation swath. The poles tested are summarized in Table 2. Included are poles exclusively from South America (Beck 1999b), South American poles combined with 'imported' African poles (Randall 1998), 'imported' poles from several major plates, including data from purely oceanic plates (Besse & Courtillot 2002),

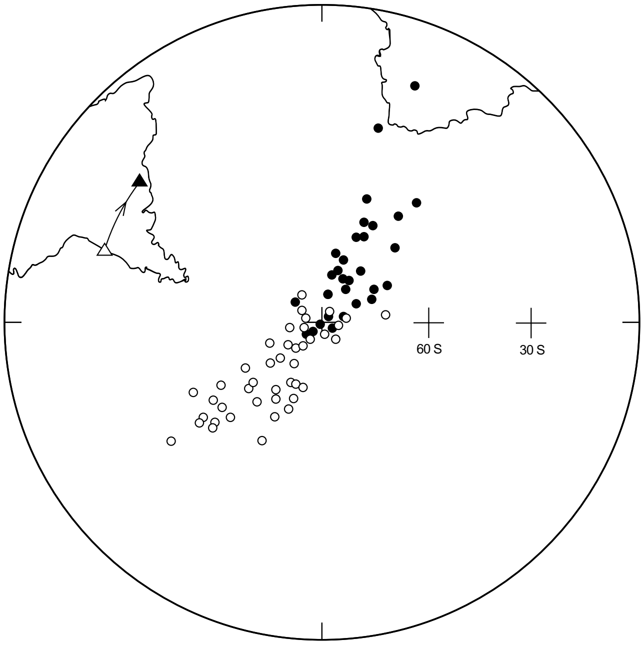
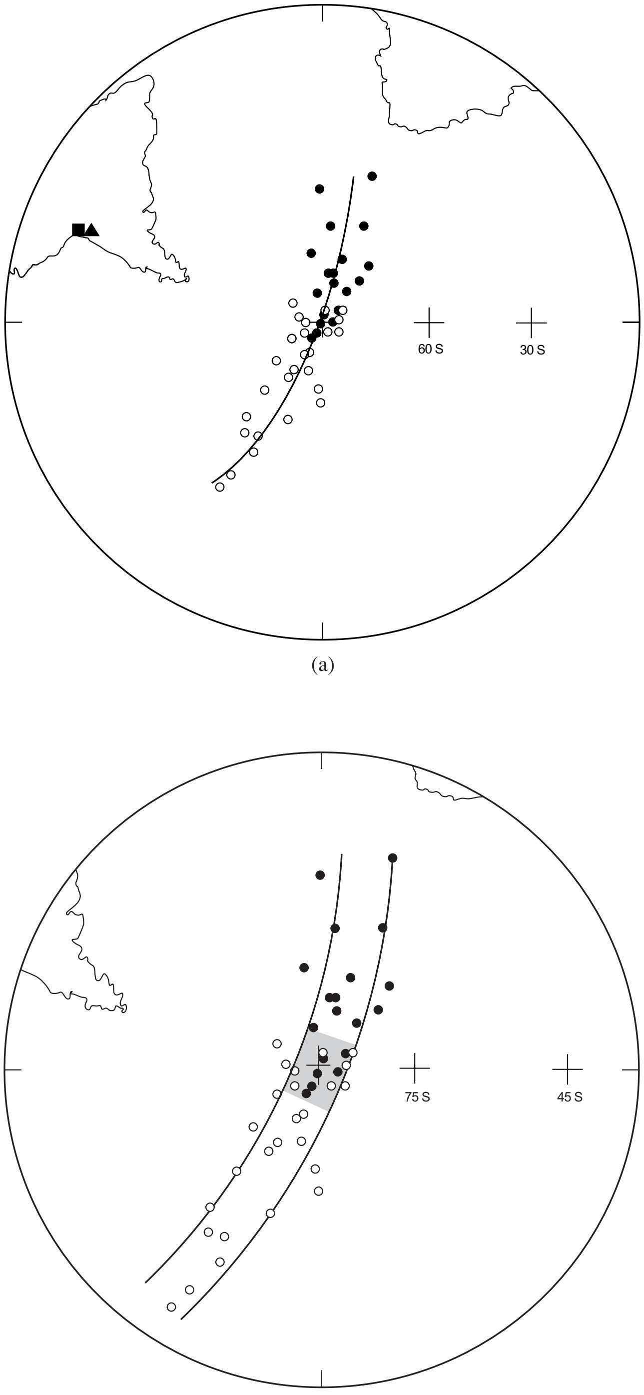


Figure 4. Hypothetical distribution of poles for the situation in which both rotation and variable north–south displacement have occurred, with the amount of displacement varying positively with rotation angle (large clockwise rotation indicates large northward displacement; small counter-clockwise rotation indicates small southward displacement, etc.). The result is to rotate the pattern (in this case, the pattern of Fig. 1) so that the best-fit small circle and mean site location are no longer close together. See text.

Table 2. Palaeomagnetic reference poles for South America.

Age (Ma)	S latitude (°)	E longitude (°)	Reference
20	82.1	311.8	1
5–24	85	310	2
10–20	86	305	3
20–30	83	310	3
40	80	319.5	1
24–66	80	267	2
30–50	84	355	3
70–80	80.8	346.7	4
80	82.3	48.4	1
66–98	83	22	2
80–120	79	40	3
100	87.8	209.2	1
98–144	85	71	2
120	83.9	58.5	1
115–165	88.8	72.4	4
140	77.5	58.2	1

References: 1, Besse & Courtillot (2002); 2, Randall (1998); 3, Lamb & Randall (2001); 4, Beck (1999b).



(a)

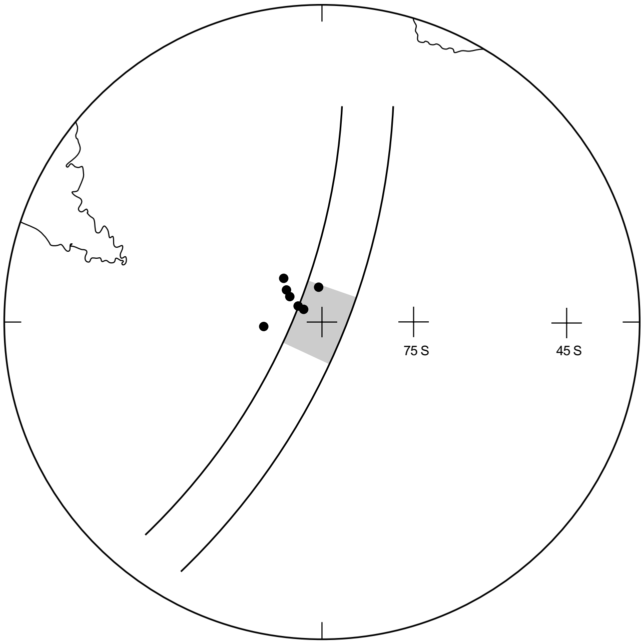
(b)

Figure 5. Cenozoic palaeomagnetic poles from the Central Andes. (a) Cenozoic data set, from Prezzi & Alonso (2002). Symbols as in Fig. 1; the square is the mean site location. (b) Pure-rotation swath fitted to the data of (a); see caption for Fig. 2(b) (note change of scale). (c) Location of Cenozoic reference poles suggest southward displacement of the central Andes. (d) Lack of offset of swaths for NOA and SOA subsets suggests that no differential displacement has occurred.

and South American cratonal poles combined with directions extracted from inclination data from the disturbed zone of the Central Andes (Lamb & Randall 2001).

Prezzi & Alonso (2002) list 45 poles in the age range 0 to 65 Ma. These yield a well-defined small circle (Fig. 5a; parameters in Table 1). The angle subtended by this Cenozoic swath at the centre of the best-fit small circle is 98.3°, roughly 40° less than the maximum amplitude of the entire CARP data set illustrated in Fig. 1. The best-fit SCC lies within the Central Andes, reinforcing the conclusion that *in situ* rotation of crustal blocks has been the dominant type of displacement affecting the region.

There is a slight overlap of NOA and SOA poles near the centre of the swath (Fig. 5b); several of these overlapping poles come from



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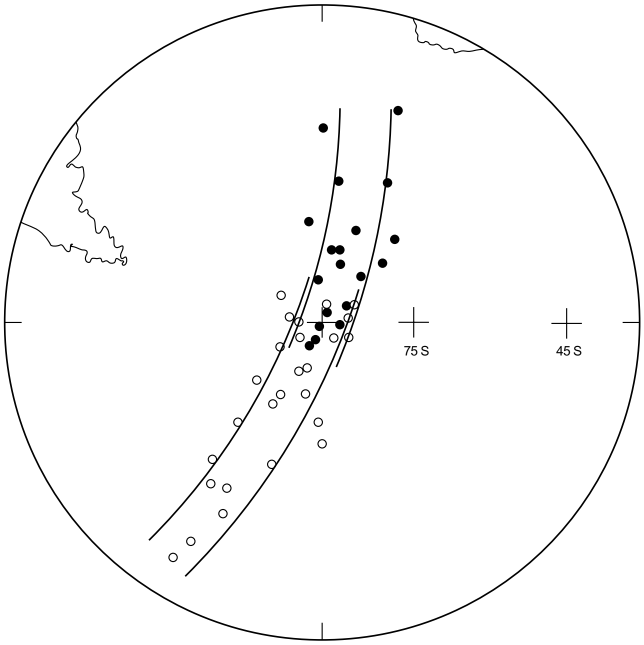


(d)

Figure 5. *(Continued.)*

rock units located within the Arica hinge zone, and several others are from very young rock units which have had little time to rotate significantly. As explained earlier, this area of overlap can be used as an estimate of the region within the pure-rotation swath that the correct reference pole must lie if rotation is purely ccw NOA and cw SOA.

Superimposing the seven Cenozoic reference poles from Table 2 on the Cenozoic pure-rotation swath yields some surprising and perhaps somewhat tenuous evidence (Fig. 5c) to suggest that the Central Andes have moved relatively southwards a few degrees, presumably since late in the period. However, of the seven poles shown, three fall within the swath, and these are poles based wholly or in part on data from South America itself. Of the remaining four, several have 95 per cent confidence circles that partially overlap the swath. Thus it is possible that the appearance of southward displacement arises because of small inaccuracies in the parameters used to import poles from other continents into the South American framework (as suggested, for instance, by Randall 1998). If southward displacement has occurred it is of the order of a few hundred kilometres.

The question of whether the sense of displacement changes at the Arica deflection can be answered in the negative with fair certainty. In Fig. 5(d), swaths have been fitted individually to both NOA and SOA Cenozoic subsets; these show essentially no offset (compare Fig. 3), suggesting no differential displacement. Finally, close proximity (3.6°) of best-fit SCC and mean site location argues against the kind of variable displacement illustrated in Fig. 4.

5 NORTH–SOUTH DISPLACEMENT: MESOZOIC DATA

Repeating this same process with Mesozoic data yields several interesting observations. Despite the fact that the poles involved represent a age span of 100 Myr, they can all be fitted with a small circle (Fig. 6a; Table 1) with an rms error of only 5.4°. The total angle subtended by the Mesozoic swath at the best-fit SCC is 123.0°, about 25° greater than in the Cenozoic example. The nine choices of Mesozoic reference pole from Table 2 plot—with one marginal exception—within the pure-rotation swath, and most within the shaded area indicating that the Arica deflection is the dividing point between cw and ccw rotation (Fig. 6b). This casts further doubt on the suggestion in the previous section that the Central Andes may have been displaced southwards relative to the stable continental interior.

However, comparing the NOA and SOA Mesozoic subsets produces an interesting and unexpected result. From Fig. 6(c) it is clear that the two subsets are displaced from one another, and moreover in such a way as to suggest that crustal blocks NOA have moved relatively northwards and blocks SOA relatively southwards. This is precisely the opposite sense of displacement that one would infer from the North American analogy. The fact that dividing the Mesozoic set into subsets based on location north or south of Arica produces a slightly better small-circle fit (Table 1) argues that the situation shown in Fig. 6c is real. Clearly, this observation (if valid) calls for a modification of current tectonic models for the Central Andes. Palaeomagnetic evidence for possible displacement away from the Arica deflection has been noted previously (e.g. Beck *et al.* 1994; Randall 1998).

If crustal blocks from the Central Andes were displaced laterally away from the Arica deflection during the Mesozoic (and/or early Cenozoic?), evidence should be found in the geological record. A detailed discussion of Central Andean geology is obviously beyond the scope of this paper. Southward displacement of crustal blocks SOA could have been accomplished by displacement along the many mapped faults dissecting the Chilean coastline, many of which are sinistral (e.g. Brown *et al.* 1993; Taylor *et al.* 1998). Much less is known about the structure of the Peruvian Andes, but its complexity and the linear nature of mapped structural elements (e.g. Cobbing 1974; Caldas 1983) suggest the possibility of margin-parallel strike-slip faults within that section of the Andean cordillera. It is hoped that detailed geological studies in both Chile and Peru can be directed at the problem of lateral terrane displacement.

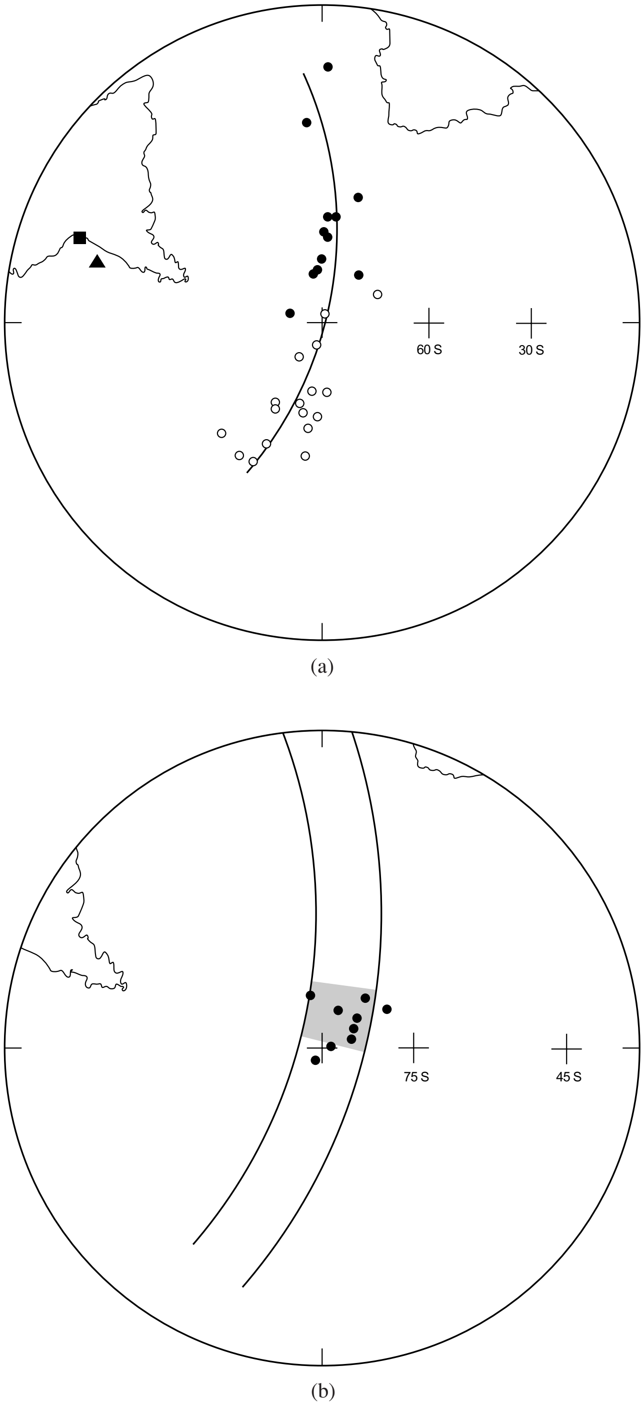


Figure 6. Mesozoic palaeomagnetic poles from the Central Andes. (a) Mesozoic data set from Prezzi & Alonso (2002). Symbols as in Fig. 5(a). (b) Mesozoic reference poles indicate that no overall displacement of the Central Andes with respect to the interior of South America has occurred. (c) Displacement of swaths for NOA and SOA subsets suggests that Mesozoic localities NOA have moved relatively northwards; localities SOA have moved southwards.

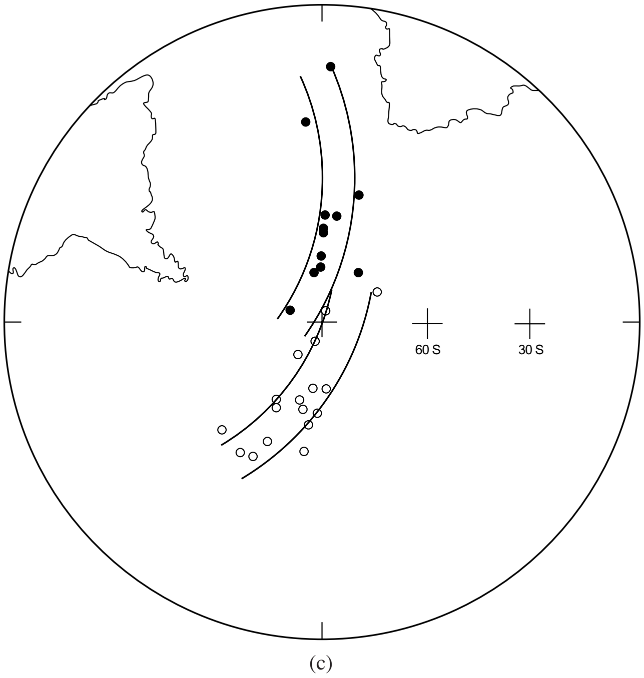


Figure 6. *(Continued.)*

6 WHEN DID THE ROTATION OCCUR?

As suggested earlier, if one judges from the total amplitude of rotation (as measured by the angle subtended at the best-fit SCC), it appears that rotation began late in the Mesozoic. However, total amplitude depends entirely on ‘outliers’—poles at the extreme ends of the swath. In particular, the length of the Mesozoic swath is strongly influenced by a single result on 177 Ma rocks from Chala, Peru (Roperch & Carlier 1992), for which Prezzi & Alonso (2002) calculate a rotation of nearly 90°. Without this one entry the total amplitudes of Mesozoic and Cenozoic subsets are quite similar. Probably a better way to determine when the rotation process began is to calculate the mean rotation for various subsets; this figure should be roughly the same for all subsets older than the beginning of rotation, but should decrease thereafter. Results of such a series of calculations are shown in Fig. 7, from which it appears that rotation actually began in the early Cenozoic, perhaps about 50–60 Ma. The fact that rocks as young as Late Miocene are rotated suggests that rotation is still active. The overall amplitude of rotation NOA and SOA appears to be roughly the same for the entire data set (Fig. 1).

Note that the rotations shown in Fig. 7 are computed with respect to the mean site location, calculated as the Fisher (1953) mean of individual site locations tabulated by Prezzi & Alonso (2002). The reference pole used also differs slightly for each calculation. In view of the uncertainty regarding reference poles discussed earlier, a reference pole derived from the distribution itself was used. This lies on a small circle centred on the mean site location, and is positioned at the centre of overlap of NOA and SOA poles, or, if no overlap occurs, between the closest poles from each subset. Mean locations and reference poles are summarized in Table 3.

A complication in this analysis arises from the fact, suggested by G. Taylor (personal communication, 2003), that the geographical distribution of site ages is not homogeneous; older rocks tend to be concentrated near the continental margin, younger rocks in the Andean cordillera, etc. Beck (1998) shows that there is no correlation between the amount of rotation and the distance from the plate margin on the part of Peruvian sites (NOA), but that a slight positive correlation does exist SOA. This does not negate the conclusion that rotation probably began early in the Cenozoic, but it complicates the tectonic interpretations given below.

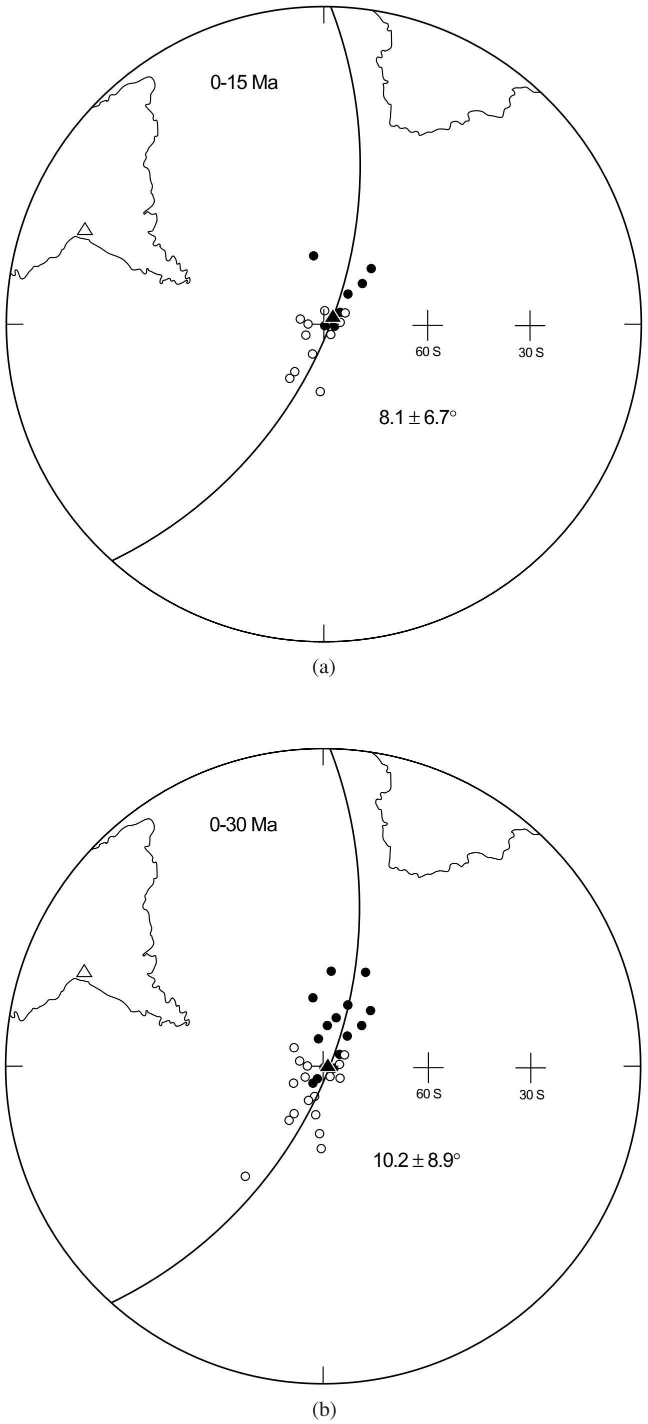


Figure 7. Mean rotations for different age groups of CARP data indicate that rotation began in the early Cenozoic. Mean rotation and its standard deviation are indicated on each diagram. The hollow triangle is the mean site locality; the solid triangle is the reference pole (Table 3). For discussion of reference poles see text.

7 SOME SPECULATIONS ON TECTONIC MODELS

If inferences drawn from the observations discussed above are correct, it follows that to account for the CARP a set of tectonic processes with the following characteristics is required:

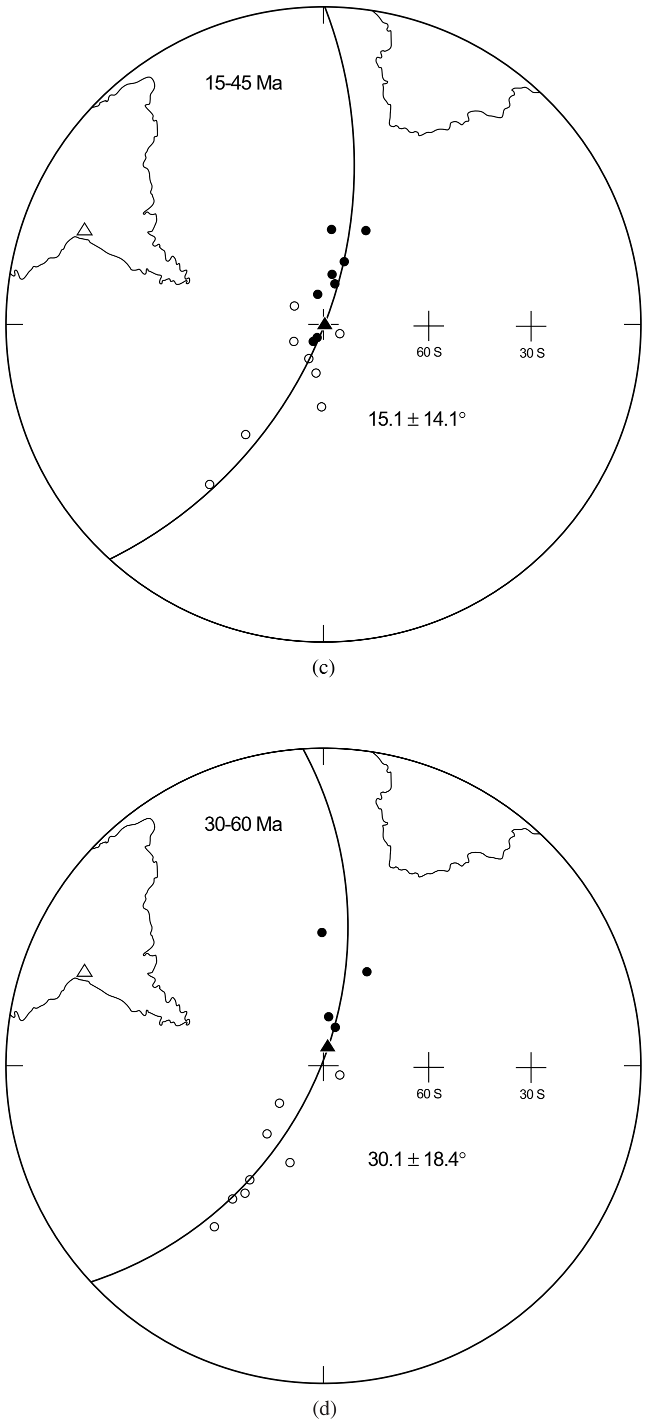
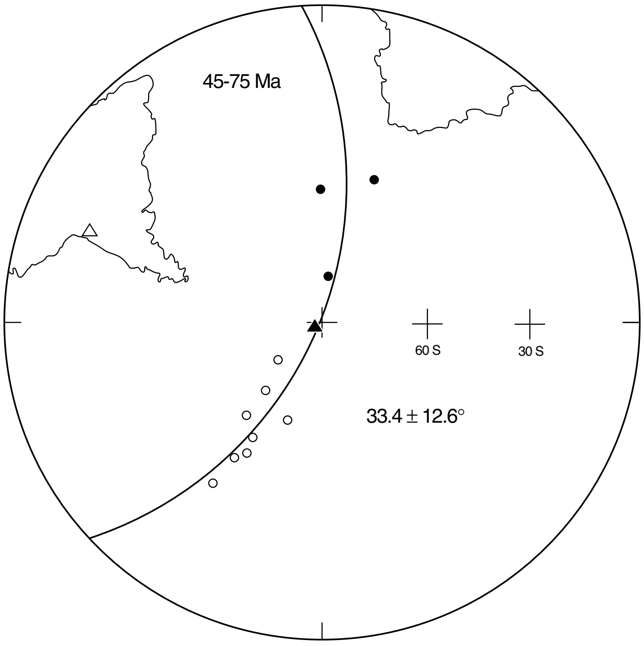


Figure 7. *(Continued.)*

(1) It produced widespread ccw rotations of crustal blocks located north of the Arica deflection, and equally widespread cw rotations further south.

(2) Although it produced a consistent sense of rotation over broad regions, it operated in such a way as to allow neighbouring blocks to rotate by different amounts.

(3) During the Mesozoic it produced movement of crustal material away from the Arica deflection—northward NOA, southward SOA—apparently without significant accompanying block rotations. If the uneven geographical distribution of site ages discussed



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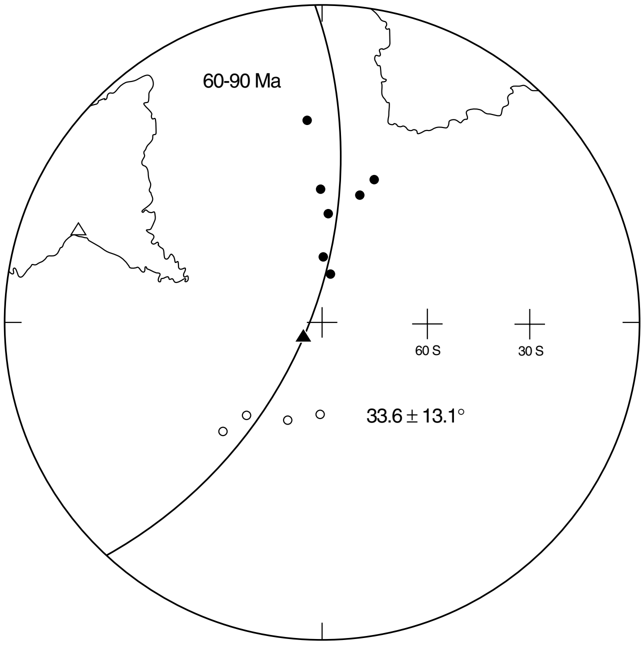

(f)

Figure 7. *(Continued.)*

in the previous section is correct, this displacement of crustal material may have been confined to the immediate plate margin.

(4) This lateral displacement of crustal blocks ceased by about 65 Ma; some time shortly thereafter a new tectonic regime produced local *in situ* rotations of crustal blocks without significant lateral displacement.

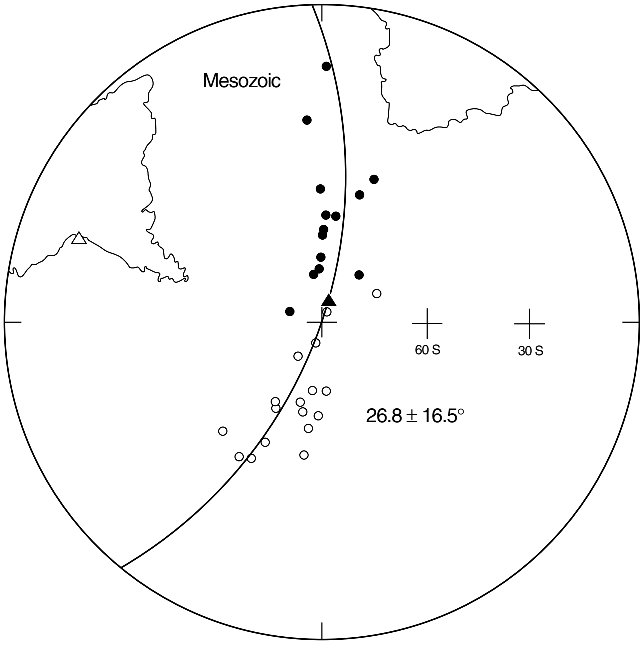

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Figure 7. *(Continued.)*

Table 3. Parameters for small circles and mean rotation calculations (Fig. 7).

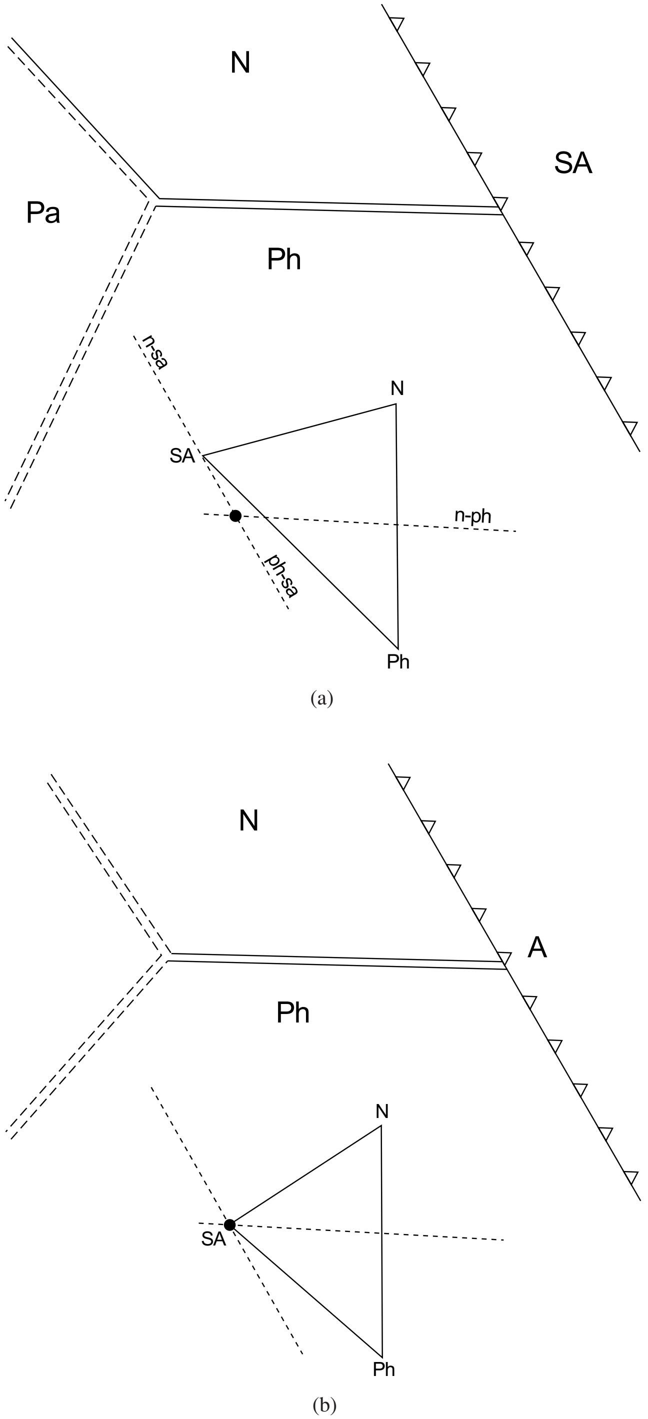
Subset	λ_s (°)	ϕ_s (°)	R (°)	rms (°)	λ_p (°)	ϕ_p (°)
0–15 Ma	20.0°	291.6°	70.8°	4.23°	88.0°	44.6°
0–30 Ma	19.4	291.1	70.6	4.18	89.8	201.7
15–45 Ma	18.9	290.5	70.3	3.99	88.4	231.6
30–60 Ma	22.7	291.8	66.5	4.10	84.3	12.6
45–75 Ma	22.6	291.7	65.6	4.05	88.0	265.7
60–90 Ma	18.6	290.5	68.2	6.04	84.3	235.5
Mesozoic	21.2	289.0	68.6	5.81	84.5	15.8

λ_s, ϕ_s are respectively S latitude and E longitude of the mean site; R is the radius of the best-fit circle for the subset indicated, centred on λ_s and ϕ_s; rms is the root-mean-square deviation from the small circle; λ_p, ϕ_p are respectively S latitude and E longitude of the reference pole.

Randall (1998) neatly summarizes existing CARP models (his Fig. 7), none of which satisfies these four observations; although they generally yield the correct sense of rotation, they entail either no relative displacement or a small amount of displacement in the wrong sense.

What is needed is a two-part model, the two parts separated by an important tectonic transition in the Late Mesozoic or early Cenozoic. Two possible candidate-scenarios are Mesozoic subduction of a spreading ridge between the Nazca (Farallon) and Phoenix (Aluk) plates, or of an aseismic ridge or oceanic plateau riding on the Nazca (or possibly Phoenix) Plate. These are discussed below. Other models are surely possible.

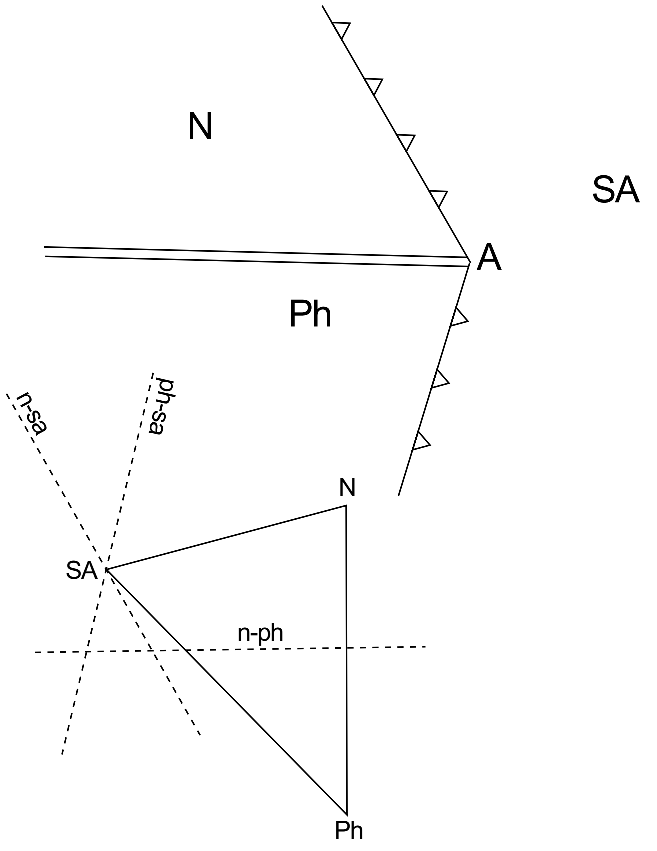
If subduction of the Nazca–Phoenix ridge caused the observed displacements away from the Arica deflection, it probably follows that the ridge remained stationary at or near that point for at least several tens of millions of years. This suggests two alternative possibilities; either long-continued subduction of the ridge caused the Arica deflection (the ridge acting as a rigid indenter), or the Arica deflection—already in existence—somehow acted as a ‘trap’ to hold the ridge in place. For instance, in the situation shown in Fig. 8a the N–SA–Ph triple junction will migrate southwards along the western South American margin. However, a slight change in relative subduction velocities will be sufficient to stop it in its tracks (Fig. 8b); for so long as this situation persists the ridge will subduct end-on



(a)

(b)

Figure 8. Displacement of South American crustal material away from the Arica deflection caused by subduction of the Nazca-Phoenix ridge. (a) The upper diagram shows plate configuration: N, Nazca Plate; SA, South American Plate; Ph, Phoenix Plate; Pa, Pacific Plate. The lower diagram shows relative velocities; dashed lines are the framework in which the configuration of the two plates indicated does not change. the large dot shows the relative velocity of the N–SA–Ph triple junction, which is southwards along the SA plate boundary. (b) Same as (a) except that a change in relative velocities causes the triple junction to be stationary in SA coordinates. (c) Like (a) except that the Arica deflection is assumed to pre-date ridge subduction. The velocity diagram shows that this configuration is unstable and that the deflection cannot act as a 'trap' to hold the N–Ph ridge in place relative to South America. For a refresher on the analysis of triple junctions see McKenzie & Morgan (1969).



(c)

Figure 8. *(Continued.)*

at the same point. Subduction velocities might change because of changing obliquity of convergence as the ridge moves southwards, possibly associated with a change in the age of subducting material. Or perhaps a seamount chain or other piece of thickened crust slowed Phoenix subduction when it reached the trench. Possible effects of long-continued ridge–trench collision would be mostly thermal and magmatic, but tectonic consequences also are predicted (e.g. Forsythe & Nelson 1985; Thorkelson 1996). For instance, heating associated with a long-lived slab window might weaken the overriding (South American) lithosphere, permitting indentation of the continental margin and flow of lithospheric material away from the point of ridge impact.

The second alternative—that a pre-existent Arica deflection served to 'trap' the ridge—seems less likely; as shown in Fig. 8(c), an abrupt change in the trend of the subduction zone (without an accompanying change in convergence velocities) would destabilize the N–Ph–SA triple junction, probably resulting in continued migration of the point of ridge collision to the south.

A second possibility is illustrated in Fig. 9, which shows a hypothetical seamount chain on the Nazca (or Phoenix) Plate approaching the Andean subduction zone. Increased buoyancy of Nazca lithosphere associated with the seamount chain would act to decrease the subduction angle in the vicinity of point A. A set of processes might then occur (e.g. Isacks 1988) that would result in thermal thinning of the overriding lithosphere, local compressive thickening of the South American crust, and gravitational extrusion of crustal material radially away from the locus of maximum thickening—the latter perhaps similar to the tectonic situation on either side of the Himalayan indenter today. The geometry during subduction of this hypothetical

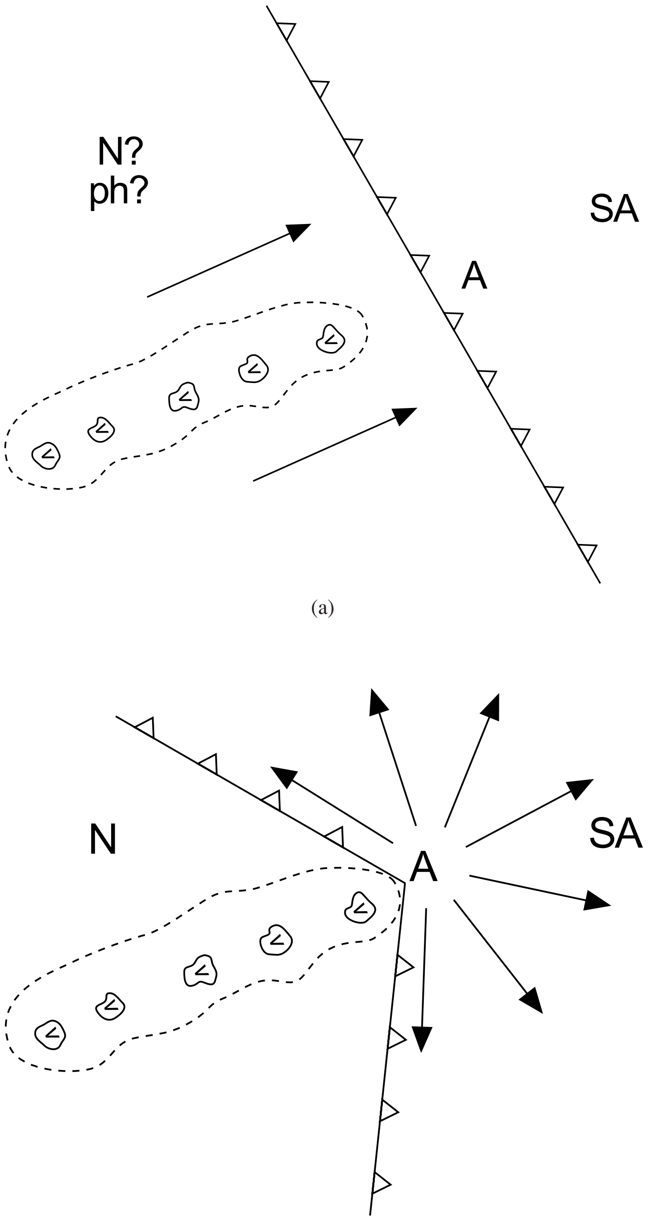


Figure 9. Creation of the Arica deflection (A) by subduction of a seamount chain. The subducting plate could be either the Nazca Plate or the Phoenix Plate. To create A and displace SA crustal material in the manner indicated in the figure subduction must be substantially normal to the SA plate boundary.

seamount chain (Fig. 9b) is kinematically, but perhaps not dynamically, similar to modern subduction of the Emperor seamount chain into the kink formed by the intersection of the Kurile and Aleutian subduction zones.

This highly speculative discussion leaves several important questions unanswered: (1) why was there no rotation of crustal blocks during extrusion of material away from the Arica deflection during the Mesozoic and (2) what caused the rotations that occurred—without lateral transport—during the bulk of the Cenozoic? The answer to both questions may lie in the thermal state of the lithosphere. During the earlier phase of deformation the South American lithosphere is postulated to have been thermally thinned and softened, whereas in the latter stage, during subduction of the Nazca Plate, it was much cooler, hence thicker and less fluid. Fluid flow directed radially outward from a point source at Arica during the first phase would drive northward displacement NOA, southward displacement SOA, and perhaps compression in the eastern hinterland—but it would not cause rotation. Later, oblique Nazca subduction might possibly provide an engine for ccw rotation NOA and cw rotation SOA, by the mechanism described in England & Wells (1991) and Beck (1998). Little or no lateral motion would accompany these rotations because the abrupt change in trend of the plate margin at Arica would provide an effective buttress against such displacements.

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