



Updated Nazca (Farallon)—South America relative motions during the last 40 My: implications for mountain building in the central Andean region

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Abstract — Recently published seafloor data around the Antarctica plate boundaries, as well as calibration of the Cenozoic Magnetic Polarity Time Scale, allow a reevaluation of the Nazca (Farallon)—South America relative convergence kinematics since late Middle Eocene time. The new reconstruction parameters confirm the basic characteristics determined in previous studies. However, two features are notable in the present data set: a strong increase in convergence rate in Late Oligocene time, and a slowdown during Late Miocene time. The former is coeval with the early development of important tectonic characteristics of the present Central Andes, such as compressional failure in wide areas of the region, and the establishment of Late Cenozoic magmatism. This supports the idea that a relationship exists between strong acceleration of convergence and mountain building in the Central Andean region. © 1998 Elsevier Science Ltd. All rights reserved

INTRODUCTION

The Central Andes constitute a type-example of mountain building related to subduction of an oceanic plate beneath a continental margin (e.g. Dewey and Bird, 1970; Jordan *et al.*, 1983). Although it was known early on that the present morphology of the orogen is mainly derived from Late Cenozoic tectonics, the knowledge of the time-space distribution of the Neogene deformation has substantially improved during the last years (Sempere *et al.*, 1990; Jordan *et al.* 1993).

The kinematics of the Nazca (Farallon) and South American plates offer a plate tectonic context to observe the intervening zone of deformation. Since quantitative measurement of relative plate motion can only be performed for pairs of plates separated by a spreading ridge, the Nazca (Farallon)—South America relative convergence must be determined following a plate circuit. Previous studies have used either the Nazca–Pacific–Antarctica–India–Africa–South America circuit (Pilger, 1983) or the Nazca–Pacific–Antarctica–Africa–South America circuit (Pardo Casas and Molnar, 1987). Both of these studies have shown that major changes in rate and direction of relative convergence correlate with major deformational events in the upper plate.

In recent years there has been considerable expansion, refinement, and reevaluation of the seafloor spreading data set related to the Antarctic plate boundaries; including derivation of new reconstruc-

tion parameters (Mayes *et al.*, 1990; Cande *et al.*, 1995; Norton, 1995; Tebbens and Cande, 1997). The geomagnetic time scale for the Cenozoic was also recently revised (Cande and Kent, 1992; 1995). The information reported in these studies is used here to reevaluate the Nazca (Farallon)—South America relative convergence since late Middle Eocene time. This time-span was selected to visualize any possible improvement about the relationship between plate motion changes and Late Cenozoic tectonics in the Central Andean region. The basic characteristics previously noted by Pilger (1983) and Pardo Casas and Molnar (1987) are confirmed in this reevaluation. However, some additional details can be observed.

The new reconstructions suggest that later in the Early Cenozoic the convergence direction changed from NE–SW to nearly E–W, at the time that the convergence rate abruptly increased, reaching the maximum for the time span here considered. This sudden peak in convergence rate is contemporaneous with the onset of major deformation in the Bolivian Altiplano (Sempere *et al.*, 1990) and the establishment of a volcanic arc in the western Central Andes (Jordan and Gardeweg, 1989). Following this sharp change, the convergence rate shows a decay to current values.

METHODOLOGY AND RESULTS

Rotations were calculated with the MAG88 software (Oviedo, 1989). Ages of seafloor anomalies, here referred to as chrons, were assigned according to the

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Cande and Kent (1995) Geomagnetic Polarity Time Scale. Stage rotations and interpolations were obtained according to Cox and Hart (1986). The GMAP program (Torsvik and Smethurst, 1995) was used to observe the convergence direction at the inter-plate boundary.

Plate reconstruction parameters between Nazca and South America for chrons 3, 5, and 5C were obtained through the Nazca-Antarctica-Africa-South America plate circuit, whereas the Nazca (Farallon)-Pacific-Antarctica-Africa-South America circuit was followed for chrons 6, 8, 10, 13 and 18 (Table 1). Finite rotations for the Nazca-Antarctica and Farallon-Pacific-Antarctica reconstructions up to chron 13 were used after Tebbens and Cande (1997). Farallon-Pacific chron 18 reconstruction parameters were taken from Pardo Casas and Molnar (1987), whereas the Pacific-Antarctica rotation for this latter chron was interpolated from the Cande *et al.* (1995) data set.

Reconstruction parameters of the Antarctica-Africa pair for chrons 5, 6 and 13 were directly obtained from Norton (1995), whereas rotations for chrons 3, 5C, 8, 10 and 18 were determined by interpolating

Norton's data set. Reconstruction parameters of Cande *et al.* (1988) were used for the Africa-South America plate pair.

Small circles defined by stage rotations were used to determine mean convergence rate for discrete time intervals, as well as to observe the paleoconvergence direction at several points near the present plate boundary zone.

The obtained Nazca (Farallon)-South America reconstruction parameters for the last 40 my are listed in Table 2. The magnitude and timing of mean convergence rate at 22°S (northern Chile) are illustrated in Fig. 1a, with data from other latitudes indicating similar information (see Table 2). The Nazca-South America convergence pole of the NUVEL-1A global plate motion model (DeMets *et al.* 1994) may be the best estimate for current plate motions. Accordingly, the rate predicted by the NUVEL-1A model is also given at the bottom of Table 2 and indicated in Fig. 1a.

Temporal changes in convergence obliquity at 12°S (central Perú) and 22°S (northern Chile) are depicted in Fig. 1b. These values were calculated by ignoring any possible Late Cenozoic rotation of the leading edge of South America with respect to the craton (e.g. Isacks, 1988). Slightly different obliquity is expected for early times if such a rotation took place (see discussion in Beck *et al.* 1994).

The results suggest around 5–8 cm/yr of NE-SW convergence during the late Early Cenozoic, which abruptly increased up to near 15 cm/yr between chrons 10 and 8 (i.e. 28.3–25.8 Ma), at which time a change to a roughly E-W direction occurred. A regime of relatively high convergence rate was sustained between 20 and 11 Ma (Fig. 1a). The drop in the late Late Cenozoic could have started either between chrons 5C and 5 (16–11 Ma) or chrons 5 and 3 (11 and 5 Ma). The former possibility implies a gentle decrease in convergence velocity, whereas the latter suggests a more abrupt decrease. The correspondence between the mean convergence rate since chron 3 and that predicted by NUVEL-1A model is noticeable (Table 2, Fig. 1a), suggesting that velocities close to the current value were reached at least around 5 my ago.

Convergence appears to have been dextral during the late Early Cenozoic, being slightly oblique in Perú and moderately oblique in Chile (Table 2; Fig. 1b). A change to slightly sinistral convergence in Perú and nearly orthogonal convergence in Chile is linked to the sudden increase in convergence rate between chrons 8–6. A further change between chrons 6–5C is determined by the relatively low latitude of the corresponding stage pole (Table 2), and could reflect either problems with determination of chron 6 reconstruction for the Farallon-Pacific pair (Pardo Casas and Molnar, 1987) or accommodation of a major plate

Table 1. Plate Circuit, Total Reconstructions

Chron	Lat.	Long.	angle	source
Nazca to South America-NUVEL1-A				
	56.00	−94.00	0.72	a
Farallon to Pacific				
18	68.51	−123.50	−36.52	b
Pacific to Antarctica				
18	74.85	−54.58	32.50	c
Nazca (Farallon) to Antarctica				
3	48.23	−99.75	−2.81	d
5	52.66	−99.42	−7.26	d
5C	53.01	−99.39	−11.10	d
6	46.64	−97.33	−15.22	d
8	51.10	−98.30	−20.70	d
10	55.21	−104.50	−22.15	d
13	55.43	−117.59	−23.68	d
Antarctica to Africa				
3	11.47	−43.84	0.79	c
5	11.47	−43.84	1.59	e
5C	7.94	−39.14	2.32	c
6	6.41	−37.16	2.91	e
8	8.23	−38.00	4.08	c
10	8.73	−39.25	4.59	c
13	9.44	−39.90	5.59	e
18	11.60	−41.16	7.19	c
Africa to South America				
3	60.00	−39.00	−1.21	f
5	60.00	−39.00	−3.15	f
5C	59.50	−38.00	−5.75	f
6	59.50	−38.00	−7.05	f
8	59.00	−36.00	−10.00	f
10	57.00	−35.00	−11.05	f
13	57.50	−34.00	−13.38	f
18	57.50	−32.50	−15.80	f

Note: North latitude, East longitude and counterclockwise rotations are positive. Sources of rotations: a, DeMets *et al.*, (1994); b, Pardo Casas and Molnar (1987); c, interpolated for this study; d, Tebbens and Cande (1997); e, Norton (1995); f, Cande *et al.*, (1988)

Table 2. Relative Motions of Nazca with respect to South America, Middle Eocene-Recent

Chron	Age (Ma)	Total Reconstruction			Forward Motion Stage			Mean Convergence Rate			Mean Convergence Azimuth		
		Lat.	Long.	Angle	Lat.	Long.	Angle	12°S	22°S	30°S	12°S	22°S	30°S
3	4.9	59.85	255.91	-3.45	59.85	255.91	3.45	7.5	7.8	7.8	77	74	75
5	10.8	62.45	260.63	-9.23	63.79	264.09	5.79	10.6	10.9	10.9	82	79	80
5C	16.0	63.24	263.60	-15.15	64.04	268.80	5.93	12.3	12.7	12.6	84	81	82
6	20.2	57.69	263.42	-19.94	41.16	259.31	5.07	11.2	12.5	13.0	71	67	69
8	25.8	61.81	263.15	-27.44	72.71	270.22	7.68	15.2	15.2	14.9	87	84	85
10	28.3	65.36	258.72	-29.57	71.74	113.92	2.92	11.2	9.9	8.6	—	—	—
13	33.0	67.66	244.76	-32.41	52.33	146.70	4.28	8.2	6.8	6.0	57	56	49
18	40.0	68.66	228.42	-36.47	53.36	146.46	5.44	7.1	5.8	5.2	59	57	51

Note: North latitude, East longitude and counterclockwise rotation are positive. Forward motion stage rotations describe the motion of the oceanic plate toward a fixed South America for each considered interval. Mean convergence rates are given in cm/yr. Mean convergence azimuths in current South American coordinates are given in degrees to the East. Current convergence rates, as predicted by NUVEL-1A model (DeMets *et al.* 1994), at 12, 22 and 30°S are 7.5, 7.9 and 8.0 cm/yr, respectively

boundary reorganization in the southeast Pacific at 20 Ma (Tebbens and Cande 1997). Younger Nazca–South America reconstructions suggest slight obliquity at the interplate boundary, being dextral in Chile and sinistral in Perú (Fig. 1b).

Thus, recent improvements of seafloor data in the southern Pacific and Indian oceans confirm the more important characteristics of the Late Eocene–Recent kinematics in the South American subduction zone previously defined by Pilger (1983) and Pardo Casas and Molnar (1987). It can be considered, however, that the new rotations (Table 2) are slightly more precise, since they are based on new, high quality seafloor data, along with a recently calibrated time scale. The incorporation of confidence intervals (as Pardo Casas and Molnar did) could prevent any possible overinterpretation of the results. Unfortunately, no information is available to develop this latter approach.

DISCUSSION

The East Pacific rise reached the North American subduction zone during Oligocene time, being progressively subducted beneath the continental lithosphere (e.g. Hamilton, 1987; Crowell, 1987). This event appears to have heralded a major plate boundary reorganization in the Pacific basin. Outstanding Late Oligocene events are the breakup of the Farallon plate into the Nazca and Cocos plates (e.g. Herron and Heirtzler, 1967; Mammerickx and Klitgord, 1982), the initiation of spreading in the Japan Sea (Jolivet *et al.*, 1992), and a drastic decrease in Pacific–Vancouver (North Pacific) spreading rates (Cande and Kent, 1992).

Contemporaneous events in the southeast Pacific are an increase in spreading rate and change in spreading direction on the Pacific–Farallon (Nazca)

ridge (Mayes *et al.*, 1990; Tebbens *et al.*, 1997) and near 40° clockwise rotation of the Chile ridge axis (Tebbens and Cande, 1997). The Late Oligocene–Early Miocene kinematic changes observed in the western South America subduction zone (Fig. 1) are likely related to this plate reorganization.

Early Cenozoic magmatism and deformation in the Central Andes were mainly concentrated in the present forearc region, although evidence of uplifted zones far inland has been reported (Kennan *et al.*, 1995). The sudden change of plate convergence kinematics during Late Oligocene time is coeval with a generalized eastward shift and widening of the locus of main tectonic activity, and beginning of formation of the modern Central Andes. Outstanding events are the establishment of the Late Cenozoic magmatic activity (Sébrier *et al.*, 1988; Jordan and Gardeweg, 1989; Soler and Bonhomme, 1990; Mpodozis, *et al.* 1995) and the onset of compressional failure in wide areas of the region (Sempere *et al.*, 1990; Sempere *et al.* 1994). It is worth noting that the start of Late Cenozoic deformation along the Central Andes was diachronous (Sempere *et al.*, 1990; Marrett *et al.*, 1994; Jordan *et al.*, 1993), suggesting that additional controls, perhaps related to upper plate heterogeneities, may have existed. It could be considered, however, that *strong acceleration* of convergence during Late Oligocene time was a factor contributing to mountain building in the Central Andean region.

The slowdown of convergence rate since Late Miocene time roughly correlates with the last deformational phase in the orogen. This phase is characterized by the progressive end of internal deformation in the Altiplano–Puna region, acceleration of plateau uplift, and eastward jump of deformation to the Subandean and Sierras Pampeanas regions (Benjamin *et al.*, 1987; Roeder, 1988; Isacks, 1988; Gubbels *et al.*, 1993; Kley *et al.*, 1997). The Pliocene–Quaternary

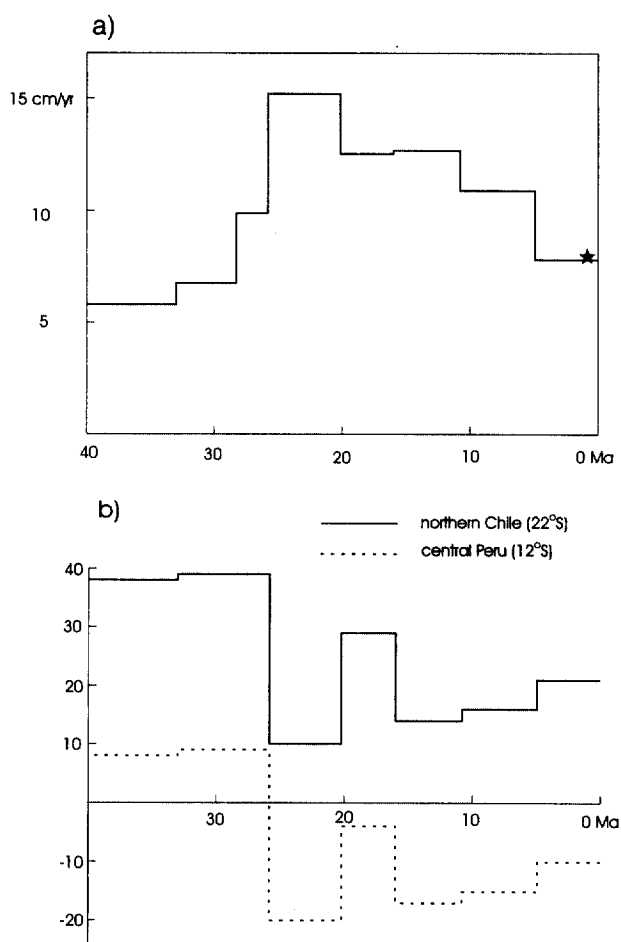


Fig. 1. a) Mean convergence rate at 22°S, 40 Ma to Recent. The curve for other latitudes along the Central Andean margin show similar shape (see values in Table 2). Note the sharp increase between 28.3 and 25.8 Ma. The Late Neogene decay could be either rather gradual (as shown) or more abrupt if a drop is located between 10.8 and 4.9 Ma. Star indicates the present convergence rate value as predicted by the NUVEL-1A model (DeMets *et al.* 1994). b) Convergence obliquity in central Peru at 12°S (dotted line) and in northern Chile at 22°S (solid line). Positive (negative) values indicate dextral (sinistral) convergence. See the text for discussion.

change in stress kinematics documented in the Puna region could be related to this slowdown of convergence rate, as Marrett *et al.* (1994) hypothesized.

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