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Decelerating Nazca-South America and Nazca-Pacific Plate Motions

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Abstract. Space geodetic estimates of the rate of Nazca-South America convergence and Nazca-Pacific spreading averaging over several years show that present day rates are significantly slower than the 3 million year average NUVEL-1A model. The implied rates of deceleration are consistent with longer term trends extending back to at least 20 Ma, about the time of initiation of Andes growth, and may reflect consequences of ongoing subduction and construction of the Andes, e.g., increased friction and viscous drag on the subducted slab as the leading edge of South America thickens.

Introduction

Space geodesy compares plate motions averaged over a few years to plate motion models averaged over several million years. In general, present motions [e.g., *Robbins et al.*, 1993; *Larson et al.*, 1997] are similar to models such as NUVEL-1A [*DeMets et al.*, 1994]. One exception, the Caribbean plate [*Dixon et al.*, 1998], presumably reflects model limitations due to inadequate data around the plate margins. It is therefore of interest to investigate discrepancies where the models are better determined, for example Nazca-Pacific motion, one of the best determined relative plate velocities in the NUVEL model, and Nazca-South America motion, an important kinematic boundary condition for Andean tectonics, relatively well determined based on plate circuit closure (e.g., Figures 43 and 44 of *DeMets et al.* [1990]). Initial space geodetic estimates of the rate of Nazca-Pacific spreading and Nazca-South America convergence [*Robbins et al.*, 1993; *Robaudo and Harrison*, 1993] suggested that present-day rates are slower than the 3 million year average rate. *Norabuena et al.* [1998] derived an Euler (angular velocity) vector for Nazca-South America and suggested that present convergence for the central Andes is 12% slower than the NUVEL-1A prediction. New data and a new GPS error model allow a more rigorous investigation.

Data Analysis and Results

We used all available space geodetic data from semi-permanent stations with time series longer than 3.0 years: two very long baseline interferometry (VLBI) sites; one satellite laser ranging (SLR) site; three Doppler Orbitography and Radiopositioning Integrated by Satellite System (DORIS) sites; and seven Global Positioning System (GPS) sites (Table 1; see *Norabuena et al.* [1998] and references therein for descriptions of these techniques). VLBI, SLR and DORIS velocities and uncertainties are from *IERS/CB* [1999]. GPS data were analyzed at the University of Miami following *Dixon et al.* [1997]. GPS velocity and resulting angular velocity uncertainties follow *Mao et al.* [1999], and reflect sampling frequency, total observation time, and both white (no time correlation) and colored (time-correlated) measurement noise.

Velocities relative to ITRF-96 [*Sillard et al.*, 1998] (with one standard error; Table 1) were inverted to define Euler vectors for the South American and Nazca plates, then differenced to define Nazca-South America motion. Site velocities relative to stable South America are shown in Table 2 and Figure 1. Although the two sites on the Nazca plate (Easter and Galapagos Islands) are the minimum necessary to derive an Euler vector, we have at least two data types per island. Each site is far from a plate boundary, so its velocity should be representative of the plate interior. Given independent data types with largely independent errors, we inverted various data subsets to assess consistency. We thus define three Euler vectors for Nazca-South America: GPS

Table 1. Velocities Relative to ITRF-96

Station	Lat.	Lon.	V_n	V_e
	°S	°W	mm/yr	mm/yr
BRAZ(GPS)	15.95	47.88	12.4±1.1	-6.1±1.7
FORT(GPS)	3.88	38.43	13.4±0.8	-5.2±1.5
KOUR(GPS)	5.25	52.81	12.7±1.1	-4.2±1.8
LPGS(GPS)	34.91	57.93	11.5±1.4	-2.4±1.8
KRUA(DORIS)	5.11	52.64	11.5±0.9	-0.7±2.7
EISL(GPS)	27.15	109.38	-7.4±1.0	65.2±1.5
GALA(GPS)	0.74	90.30	14.0±1.7	54.1±3.6
GALD(DORIS)	0.90	89.62	4.3±9.6	49.8±21.1
EASA(DORIS)	27.15	109.38	-7.0±1.5	67.6±1.6
7297(VLBI)	3.88	38.42	11.6±0.7	-2.2±1.7
7097(SLR)	27.15	109.38	-7.0±1.5	67.6±1.6

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Table 2. Velocities Relative to stable South America

Station	V_n mm/yr	V_e mm/yr
South America		
BRAZ (GPS)	-0.1±1.1	-2.1±1.9
FORT (GPS)	1.2±0.9	-1.1±1.7
KOUR (GPS)	0.4±1.2	-0.2±2.0
LPGS (GPS)	-0.4±1.5	-0.2±2.2
KRUA (DORIS)	-0.8±1.0	3.6±2.8
7297 (VLBI)	-0.6±0.9	2.2±1.8
Nazca		
EISL (GPS)	-13.3±1.7	63.9±2.3
GALA (GPS)	5.1±2.3	58.0±3.7
GALD (DORIS)	-4.9±9.7	53.8±21.1
EASA (DORIS)	-12.9±1.8	66.5±2.6
7097 (SLR)	-12.9±1.8	66.5±2.6

data only; all data except GPS; and all available data (Table 3). All three are equivalent within uncertainties, suggesting these data give reliable estimates of present day Nazca-South America motion. The vector based on all data is used in the subsequent discussion.

Discussion

Reference Frame. We assess the stability of our South American reference frame by the misfit of individual site velocities to the rigid plate model (Table 2, Figure 1). The average velocity magnitude for the residuals is 0.7 mm/yr (north) and 1.5 mm/yr (east). The largest residual (3.6 mm/yr east) is at KRUA, the site with the largest uncertainty. Thus the misfits are about the level expected given velocity error. For the 12 data for stable South America (6 stations, two horizontal velocity components each) we compute a reduced χ^2 of 1.09, close to the expected value of unity. This suggests that a rigid South American plate model is appropriate, and that the assigned errors are about right. It also suggests that the influence of the South American reference frame uncertainty on our convergence rate estimate is less than about 3 mm/yr, which is insignificant for this application.

Nazca-South America Motion. Our new Euler vector predicts velocities at the trench (Figure 2) that are similar in azimuth but significantly (95% confidence) slower in rate than the NUVEL-1A prediction, similar to the result of *Norabuena et al.* [1998] and *Angermann et al.* [1999]. Near Lima, Peru (12°S, 79°W) our Euler vector predicts 61±3 mm/yr of convergence at an azimuth of 79°±3°, vs. the NUVEL-1A prediction (75±2 mm/yr at 81°) and that of *Norabuena et al.* [1998] (64±5 mm/yr at 79°±4°). Assuming the NUVEL-1A prediction here accurately represents the 3 million year average velocity, Nazca-South America convergence has slowed over the last 3 million years. Other data also suggest slowing. *Pardo Casas and Molnar* [1987] used plate reconstructions to suggest that convergence off Peru was about 50 mm/yr faster between 20 Ma-10 Ma than for 10-0 Ma, but the difference is near uncertainties. Using new seafloor data, *Somoza* [1998] proposed gradual slowing of convergence after 25 Ma. For a location offshore Peru (12°S) *Somoza's* [1998] data suggest average deceleration is 3.1±1.0 mm/yr per My since 25 Ma, assuming ±15% error in the convergence rates. Since 10 Ma the deceleration has been nearly 6 mm/yr per My, although this latter estimate is more uncertain. Our estimates of present convergence, the NUVEL-1A rate, and *Somoza's* [1998] data are shown in Figure 3, with a least squares line through all data assuming constant deceleration, used to derive the 10 Ma rate in Figure 1.

Nazca-Pacific Motion. Nazca-Pacific spreading is also slowing with time [*Robaudo and Harrison*, 1993]. Table 3 shows the present Nazca-Pacific Euler vector based on our Nazca data ("all data"), and Pacific GPS data from *DeMets and Dixon* [1999]. The present full spreading rate on the ridge at 16°S is 134±3 mm/yr, 11 mm/yr slower than the NUVEL-1A prediction but with essentially identical azimuth. Thus the reduction in Nazca-South America convergence rate over the past 3 million years (12-15 mm/yr; Figure 3) is equivalent within error to the change in Nazca-Pacific spreading. *Tebbens and Cande* [1997] suggest a more gradual slowing of Nazca-Pacific spreading after 20-25 Ma. Together, these data are consistent with a constant rate of deceleration, but again we cannot preclude two stages (more rapid slowing after 5 Ma, Figure 3).

Causes for Deceleration. The negative buoyancy of subducting oceanic lithosphere is thought to be a major driving force for plate motion ("slab pull"; *Forsyth and Uyeda*, [1975]). Younger lithosphere is warmer and more buoyant than older lithosphere, so the force

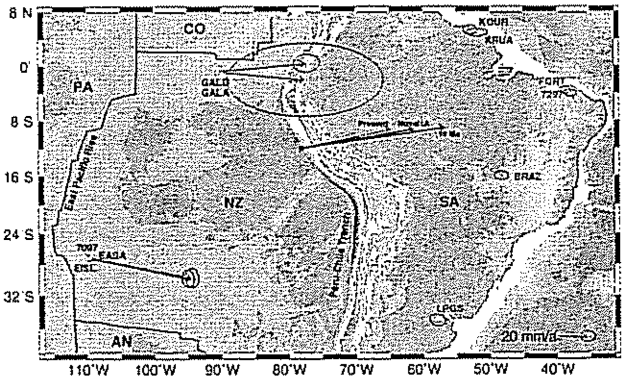

Figure 1. Space geodetic velocities relative to South America for DORIS, GPS, SLR and VLBI sites on the Nazca (NZ) and South American (SA) plates. Error ellipses are 95% confidence regions. Convergence vectors calculated at the trench (12°S) shown for Present (this study), 3 Ma average (NUVEL-1A) and 10 Ma (Figure 3) assuming no change in azimuth from 3 Ma to 10 Ma, but offset slightly for clarity.

Table 3. Euler(Angular Velocity) Vectors

Source	Lat. °N	Lon. °W	ω (°/myr)	σ_{max}	σ_{min}	Azm (°)	σ_ω (°/myr)
Nazca-South America[1]							
NUVEL-1A[2]	56.0	94.0	0.72	3.6	1.5	-10.0	0.02
Larson et al.,1997	43.8	84.8	0.74	9.1	5.5	-18.0	0.07
Norabuena et al., 1998	40.6	90.5	0.71	6.2	3.1	-7.4	0.033
Angermann et al., 1999	48.8	91.7	0.59	4.0	1.9	-3.3	0.014
This study: GPS	43.8	96.6	0.624	11.3	2.1	7.9	0.037
Non-GPS	62.8	85.9	0.589	7.8	2.3	18.2	0.009
All data	47.4	93.7	0.624	6.1	2.4	7.1	0.017
Nazca-Pacific[1]							
NUVEL-1A[2]	55.6	90.1	1.36	1.8	0.9	-1.0	0.02
This study: All data	53.2	90.6	1.27	3.1	1.3	18.0	0.016

[1] Counterclockwise motion of first plate relative to second. Pole error ellipse specified by semi-major (σ_{max}) and semi-minor (σ_{min}) axes in degrees (2D one standard error). σ_ω is 1D one standard error in rotation rate, ω. Azm is azimuth of semi-major axis, degrees clockwise from North.

[2] DeMets et al. [1994].

due to negative buoyancy decreases for younger subducting lithosphere. Westward motion of South America relative to the East Pacific Rise causes the mean age of subducting Nazca lithosphere to decrease with time, decreasing slab pull, and perhaps slowing Nazca-Pacific spreading and Nazca-South American convergence. This scenario predicts that the area of the Nazca plate should decrease with time. To quantify this "age effect", we use finite rotation data [*Pardo Casas and Molnar*, 1987], and determine the distance between the East Pacific Rise and the South America trench through time. At the latitude of Easter Island, the ridge crest was about 800 km further west of South America 25 My ago than today. Thus the present subducting crust (mean age 40 Ma) is about 10 My younger than the crust 25 My ago (mean age 50 Ma), assuming a half spreading rate of 8 cm/yr. This age change predicts an average change in lithospheric density of about 0.18% using any standard subsidence curve [*Parsons and Sclater*, 1977; *Stein and Stein*, 1992; *Harrison*,

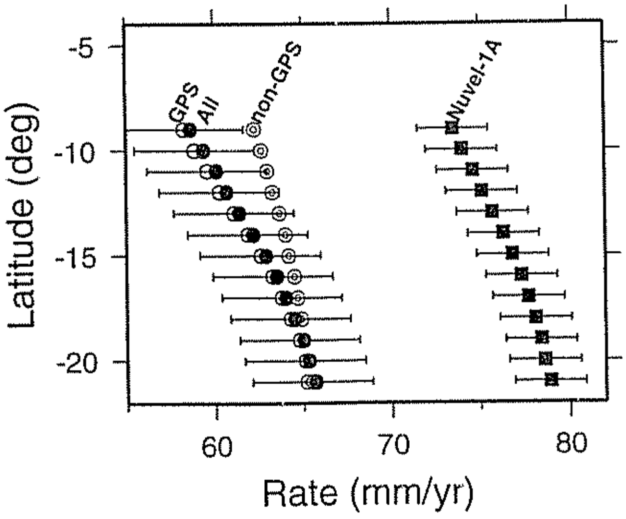

Figure 2. Predicted latitudinal variation of Nazca-South America convergence rate along the Peru-Chile trench, from GPS (open circle), non GPS (concentric circles), all data (solid circle) and the NUVEL-1A model (solid square, *DeMets et al.*, [1994]). Error bars (one standard error) shown for NUVEL-1A and GPS.

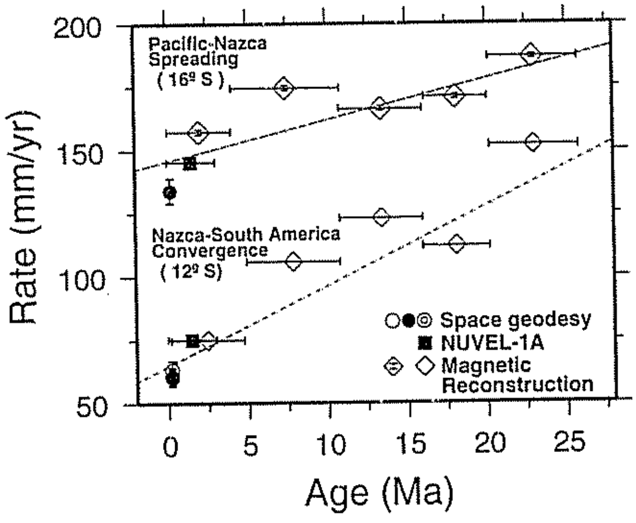

Figure 3. Plate motion rates for last 25 Ma: Nazca-Pacific spreading (top), Nazca-South America convergence (bottom). Horizontal lines show averaging interval, vertical lines show uncertainty (one standard error) if known (NUVEL-1A uncertainty negligible at this scale). Diamonds from magnetic reconstruction (partly filled, Nazca-Pacific, *Tebbens and Cande*, [1997]; open, Nazca-South America, *Somoza* [1998]), remaining symbols as in Figure 2. Dashed line is unweighted least squares fit through all data. At present, half spreading rate (Pacific-Nazca)≃Nazca-South America convergence rate, but at prior times it was slower, consistent with migration of trench towards ridge for last 25 Ma.

1998], less than 10% of the total change in density over the entire age range of oceanic lithosphere, 180 Ma. Thus, while the age effect contributes to deceleration, we suspect it is not the major factor.

The most significant tectonic change in the region for the last 25 Ma is the growth of the high Andes and greatly thickened crust along western South America. Crustal thickness here reaches 70 km [*James*, 1971]; 30-45 km is typical for continental crust [*Rudnick and Fountain* [1995]. Continental mountain building is a consequence of plate convergence, but may also influence convergence by feedback. For example, convergence slowed following India-Eurasia collision and generation of the Himalaya, due to the difficulty of subducting buoyant continental lithosphere [*Molnar et al.*, 1993]. Andean growth has been linked to faster Nazca-South America convergence at 20-25 Ma [*Pardo Casas and Molnar*, 1987]. Slowing convergence since then could be related to the same process. Perhaps rapid oceanic subduction cools sub-lithospheric mantle, increasing its strength and resistance to subduction (this effect would be partly counteracted by the greater density of the subducted slab). Another important effect could be the increased drag between subducting and overiding plates as the leading edge of South America thickens, possible enhanced by "flat slab" subduction. While all mountain belts are growth-limited by surficial and crustal processes (erosion, lateral spreading of overthickened crust) perhaps Andean mountain belts, which may owe their initiation to rapid subduction of oceanic lithosphere, are fundamentally limited by feedback slowing of subduction; the process contains the seeds of its own demise.

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