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Jeffrey T. Freymueller

James N. Kellogg

University of South Carolina - Columbia, kellogg@geol.sc.edu

Victor Vega

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## Plate Motions in the North Andean Region

JEFFREY T. FREYMUELLER,<sup>1</sup> JAMES N. KELLOGG, AND VICTOR VEGA

*Department of Geological Sciences, University of South Carolina, Columbia*

Repeated geodetic measurements with the Global Positioning System (GPS) provide direct measurements of displacements due to plate motions and active crustal deformation in Central America and northern South America, an area of complex interaction of the Nazca, Cocos, Caribbean and South American plates. The displacement rates for the period 1988–1991, obtained from the results of the first three Central And South America (CASA) GPS campaigns, are in general agreement with the predictions of the NUVEL-1 plate motion model, but there are differences in detail between the observations and the model. The Nazca–North Andes convergence rate vector measured by GPS is different from the NUVEL-1 vector at 95% confidence. The difference implies that the North Andes are moving northward relative to South America. The measured convergence between the Caribbean plate and the North Andes suggests that the southern margin of the Caribbean plate is located in the South Caribbean deformed belt. The April 1991 Costa Rica earthquake and the Cocos–Caribbean convergence rate determined by GPS suggest the possibility of significant ongoing deformation between Central America and the stable interior of the Caribbean plate. Our GPS results are consistent with deformation of the overriding plates at the convergent margins of Central and South America and confirm that active convergence is occurring around much of the southern margin of the Caribbean plate, from Colombia west to Costa Rica. Costa Rica and Panamá are not part of the stable Caribbean plate. Instead, the South Caribbean deformed belt and the North Panamá fold belt probably represent the southern margin of the Caribbean plate.

### INTRODUCTION

The CASA (Central and South America) Global Positioning System (GPS) project was inaugurated in 1988 to study plate motions and crustal deformation in Central America and northern South America, a tectonically active area of complex interaction between the Nazca, Cocos, Caribbean and South American plates. There is general agreement that the three plates are converging, but the locations of certain plate boundaries have long been a subject of controversy [e.g., Dewey, 1972; Shagam, 1975; Aggarwal, 1983]. Diffuse seismicity is spread out over a wide area from the Cocos transform fault south of Panamá to the East Andean and Boconó fault systems at the eastern edge of the Andes [Pennington, 1981]. Kellogg *et al.* [1985] have interpreted the tectonics of the region in terms of two additional microplates, Panamá and the North Andes, both of which are subject to internal deformation (Figure 1).

Repeated geodetic measurements with GPS provide direct measurements of the displacements of the individual GPS sites, which can be used to compute rates of plate motion and intraplate deformation. The present CASA network consists of 30 stations in five countries (Figure 1), most of which have been occupied in at least two of the three CASA GPS campaigns. Five sites (Isla Baltra, Isla del Coco, Liberia, Limón and Jerusalem) positioned to measure the velocities of the major plates in the region have been occupied in all three campaigns. This paper concentrates on the plate motion determinations made using these five sites, and two sites (Isla San Andrés and Cartagena) which measure the convergence between the Caribbean plate and the North Andes. The measurements cover a 3-year period, 1988–1991.

<sup>1</sup>Now at Department of Geophysics, Stanford University, Stanford, California.

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The rate of change of baseline vectors, three-dimensional vectors between two sites, measure the rates of motion of the major plates, as well as local or regional deformation at each site. The baseline rate of change vectors are decomposed into components which represent the motion rates in the local north, east and vertical directions. Details of the GPS data analysis and the precision and accuracy of the GPS solutions are given in the appendix. A single baseline is insufficient to compute a pole of relative motion, so the observed baseline rates of change are compared to model rates computed from the NUVEL-1 plate motion model [DeMets *et al.*, 1990; Argus and Gordon, 1991]. Further studies will compute displacement rates for all the sites of the CASA network, to study the internal deformation of the plates.

### REGIONAL TECTONICS

#### *Colombia-Ecuador Subduction System*

Subduction (70 mm/yr) of the oceanic Nazca plate occurs at the western margin of South America, and the trench is seismically active (Table 1). Four large ( $M_s > 7$ ) shallow subduction-related earthquakes have occurred within this area in the last century. The 1906 event ruptured more than 400 km of the trench, from the equator to the north [Kelleher, 1972] (Figure 2). Three smaller events, in 1942, 1958, and 1979 have together ruptured approximately the same length of the trench as did the 1906 event (Figure 2), although the seismic moment of the 1906 event is approximately 5 times as large as the sum of the moments of the smaller events [Kanamori and McNally, 1982]. Based on the seismic record of the last century, Nishenko [1989] estimated the probability of a magnitude 7+ earthquake in these segments of the subduction zone within the next 10 years to be greater than 70%. A magnitude  $M \sim 6.6$  earthquake occurred on November 1991, roughly 100 km to the north of the northern extent of the 1906 rupture (Figure 2).

The preinstrumental record of seismicity in this region is incomplete, due to the historically small population on the Pacific coast. Only one event prior to 1906 can be attributed to

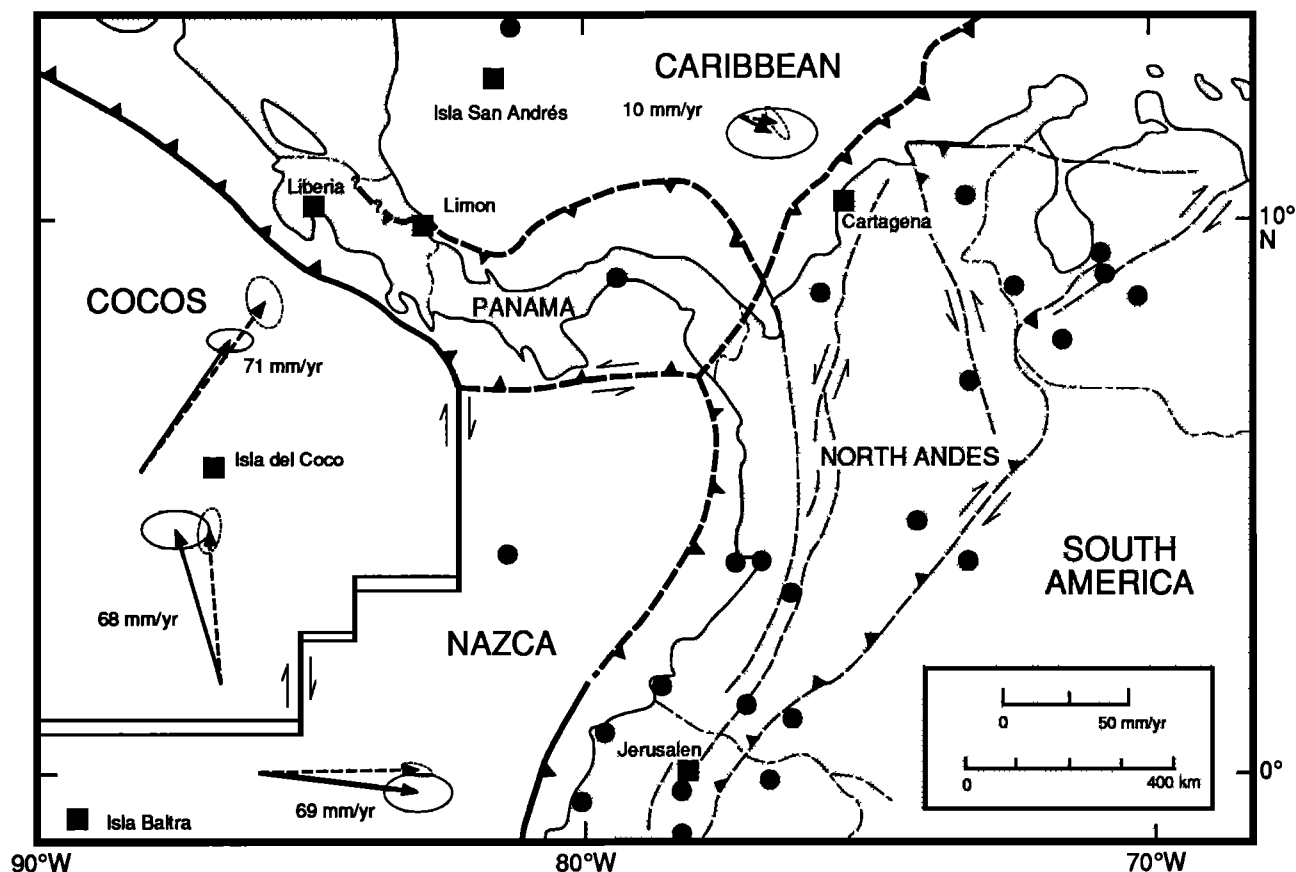


Fig. 1. Observed GPS (solid lines) and model NUVEL-1 [DeMets *et al.*, 1990] (dashed lines) baseline rates of change, with their 95% confidence ellipses. Baseline rates of change measure the relative motions of two GPS sites. The Caribbean-North Andes plate motion is based on only two epochs of GPS data (1988 and 1991), and the uncertainty given is conservative. GPS sites used in this study are indicated by squares; other GPS sites are indicated by circles.

this segment of the trench, an earthquake near Tumaco (Colombia) in 1798, which was large enough to produce notable damage 300 km away in Quito, Ecuador [Comité del Año Geofísico Internacional del Ecuador, 1959]. The damage caused in Quito was similar to the damage caused by the 1979 Tumaco earthquake, but no other information is available to determine the magnitude of this event.

#### *Motion and Deformation of the North Andes*

The North Andes are bounded by the Colombia-Ecuador trench and Panamá on the west, the South Caribbean deformed belt to the north, and the Boconó and East Andean fault zones to the east (Figures 1 and 2) [Bowin, 1976; Pennington, 1981; Kellogg *et al.*, 1985; Adamek *et al.*, 1988]. Within the northern part of the North Andes, significant Cenozoic displacements have occurred on the Oca (right-lateral, east-west trending) and Santa Marta-Bucaramanga (left-lateral, northwest-southeast trending) faults (Figure 2) [e.g., Campbell, 1968; Kellogg, 1984; Mann and Burke, 1984; Mann *et al.*, 1990]. There are no estimates of the slip rates of either of these two faults, but both may be active. The Santa Marta-Bucaramanga fault plays a major role in the vector block model of Dewey and Pindell [1985, 1986]. The Boconó fault, Santa Marta-Bucaramanga fault, and South Caribbean deformed belt define the wedge-shaped "Maracaibo block" which has moved northward relative to stable South America during the

late Cenozoic [Bowin, 1976; Mann and Burke, 1984; Pindell *et al.*, 1988].

On the east side of the North Andes, right-lateral transpressive movement is taking place on the Boconó and East Andean fault zones. The Boconó fault in Venezuela is principally a right-lateral strike slip fault [Schubert, 1982] which runs through the Mérida Andes. Subparallel thrust faults flank the Boconó fault, and small-scale geodetic networks in the Mérida Andes indicate significant compression normal to the Boconó fault in addition to strike-slip motion [Henneberg, 1983]. The East Andean frontal fault system consists of subparallel westward-dipping faults. Based on a study of focal mechanisms in the East Andean frontal fault system, Pennington [1981] proposed that transpressive right-lateral slip is occurring on these faults, and that the North Andes block is moving NNE relative to the South American plate.

To the south the Ecuadorian Andes include a system of subparallel northeast trending right lateral strike slip faults and north trending thrust faults. The relationships between these faults are not well understood; perhaps the best studied of these faults is the right-lateral strike-slip Pallatanga fault (Figure 2) [Winter and LaVenu, 1988]. The focal mechanism of the magnitude  $M_S \sim 6.9$  earthquake in March 1987 east of Quito indicates pure thrust faulting on a north-south trending fault, while focal mechanisms of two smaller events about 100 km directly to the south show oblique (transpressional) displacement (Table 1 and Figure 2) [Lyon-Caen *et al.*, 1990].

TABLE 1. Summary of Earthquakes Shown in Figures 2 and 3

Date	Latitude	Longitude	Depth	$M_0$ , 10 <sup>20</sup> Nt-m	$M_S$	Area, 1000 km <sup>2</sup>	Slip, m	Source
<i>North Andean Earthquakes</i>								
1 1906	1.0	-81.0	--	200.0	8.7	114.0	5.2	1
2 1942	0.0	-80.0	--	3.2	7.9	7.1	1.3	1
3 1958	1.0	-79.0	--	5.2	7.8	6.6	2.3	1
4 1979	1.6	-79.4	33	29.0	7.7	28.0	2.7	1
5 March 1987	0.06	-77.72	8	0.4	7.0	--	--	2
6 Sept. 1987	-0.90	-77.96	3	0.05	--	--	--	2
7 Sept. 1987	-0.98	-78.04	10	0.005	--	--	--	2
8 Nov. 1991	4.7	-77.5	25	0.7	--	--	--	2
9 Oct. 1992	6.9	-76.7	15	1.1	6.6	--	--	3
10 Oct. 1992	7.1	-76.5	44	7.8	7.2	--	--	3
<i>Costa Rican Earthquakes</i>								
11 March 1990	9.6	-84.9	22	1.0	7.0	--	--	3,4
12 April 1991	9.6	-83.1	17	2.0	7.5	4.5	2.1	4,5
13 Sept. 1992	10.7	-87.7	15	1.6	7.0	1.6	--	3

Prior to 1987, only great earthquakes ( $M > 7$ ) are shown. After 1987, significant or well-studied events are listed. Not all information is available for all earthquakes. Sources are (1) *Kanamori and McNally* [1982], (2) Ines Cifuentes, personal communication, 1992, (3) Harvard CMT solution, 1990, (4) J. Marino Protti-Quesada, personal communication, 1991, and (5) *Plafker and Ward* [1992].

From the short-term seismicity on the Boconó Fault zone in the Venezuelan Andes, *Aggarwal* [1983] deduced a seismic-slip rate of  $10 \pm 2$  mm/yr, and from historical seismicity, slip rates between 8 and 11 mm/yr for the East Andean and Boconó fault systems. *Schubert* [1980] estimated a similar average rate of strike slip motion on the Boconó fault, 8 mm/yr for the last 12,000 years, based on 100-m right-lateral offsets of glacial moraines. *Henneberg* [1983] measured 4.5 mm/yr of slip along the Boconó fault using 6 years of geodetic data. The slip rate on the Pallatanga fault in Ecuador has been estimated as 4-5 mm/yr based on the offset of a glacial moraine [*Winter and LaVenu*, 1988]. The seismic activity of the Iliniza fault (subparallel to and 70 km to the north of the Pallatanga fault) is similar to that of the Pallatanga fault, and it probably has a similar slip rate (Hugo Yepes, Escuela Politecnica Nacional, Ecuador, personal communication, 1991). Based on observed slip rates, *Kellogg et al.* [1985] predicted that relative to the South American plate, the North Andes were moving approximately 10 mm/year toward the northeast.

#### Costa Rica subduction system

The Cocos plate is being subducted beneath the Caribbean plate at the southern Middle America trench. The NUVEL-1 model predicts a subduction rate of 90 mm/yr nearly normal to the trench. The submarine Cocos ridge is being subducted beneath southwestern Costa Rica (Figure 3), and this feature represents the northern boundary of the distinct Costa Rica segment of the trench [*Burbach et al.*, 1984]. The subducted slab in this segment is shallower than in the remainder of the trench to the north, and the slab appears to have been torn due to the effects of the attempted subduction of the buoyant Cocos Ridge.

In March and April of 1990, two months after the second measurement campaign, a series of five shallow earthquakes, the largest being  $M_S \sim 6.9$ , and three others being larger than  $M_S \sim 6.0$ , ruptured portions of the trench from southern

Nicaragua south to Panamá. The first and largest event (focal mechanism plotted in Figure 3) occurred just south of the tip of the Nicoya peninsula, approximately on a line between Liberia and Isla del Coco. Based on the seismic moment and the approximate area of the aftershock zone, the principal event had close to 2 m of slip. Elastic dislocation modeling predicts that this earthquake caused only a small displacement (roughly 2 cm) at Liberia, located  $\sim 100$  km from the epicenter. Model displacements at Limón and Isla del Coco were insignificant.

On the Caribbean margin of Costa Rica and Panamá, convergence between the stable Caribbean plate and the Central American arc occurs on the North Panamá fold belt. The North Panamá fold belt comes on land north of Puerto Limón. The subaqueous part of the fold belt, off the northern coast of Panamá, consists of young sediments being deformed into anticlinal folds. Multichannel seismic and SeaMARC II surveys show undeformed oceanic crust dipping landward beneath folded sediments of the deformed belt [*Lu and McMillen*, 1983; *Silver et al.*, 1990]. A two-dimensional density model constructed from refraction interval velocities predicts landward-dipping oceanic crust beneath the North Panamá fold belt [*Kellogg et al.*, 1991]. Earthquake focal mechanisms and seismicity suggest a poorly defined Wadati-Benioff zone dipping about 50 degrees to the southwest beneath the Panamá fold belt [*Wolters*, 1986; *Adamek et al.*, 1988].

The April 1991 Costa Rica earthquake ( $M_S \sim 7.4$ ) occurred on the Caribbean coast of Costa Rica shortly after the 1991 measurements were made (Figure 4). The earthquake was a thrust event on a plane striking between  $102^\circ$  and  $120^\circ$  and dipping between  $17^\circ$  and  $30^\circ$  to the southwest [*Güendele et al.*, 1991; *Plafker and Ward*, 1992; *Goes et al.*, 1993]. The fault is one of a system of faults that make up the northwest extension of the North Panamá fold belt. The earthquake produced up to 20-30 cm of uplift along the coast, measured by uplift of coral reefs and other shoreline features [*Plafker and Ward*, 1992] and

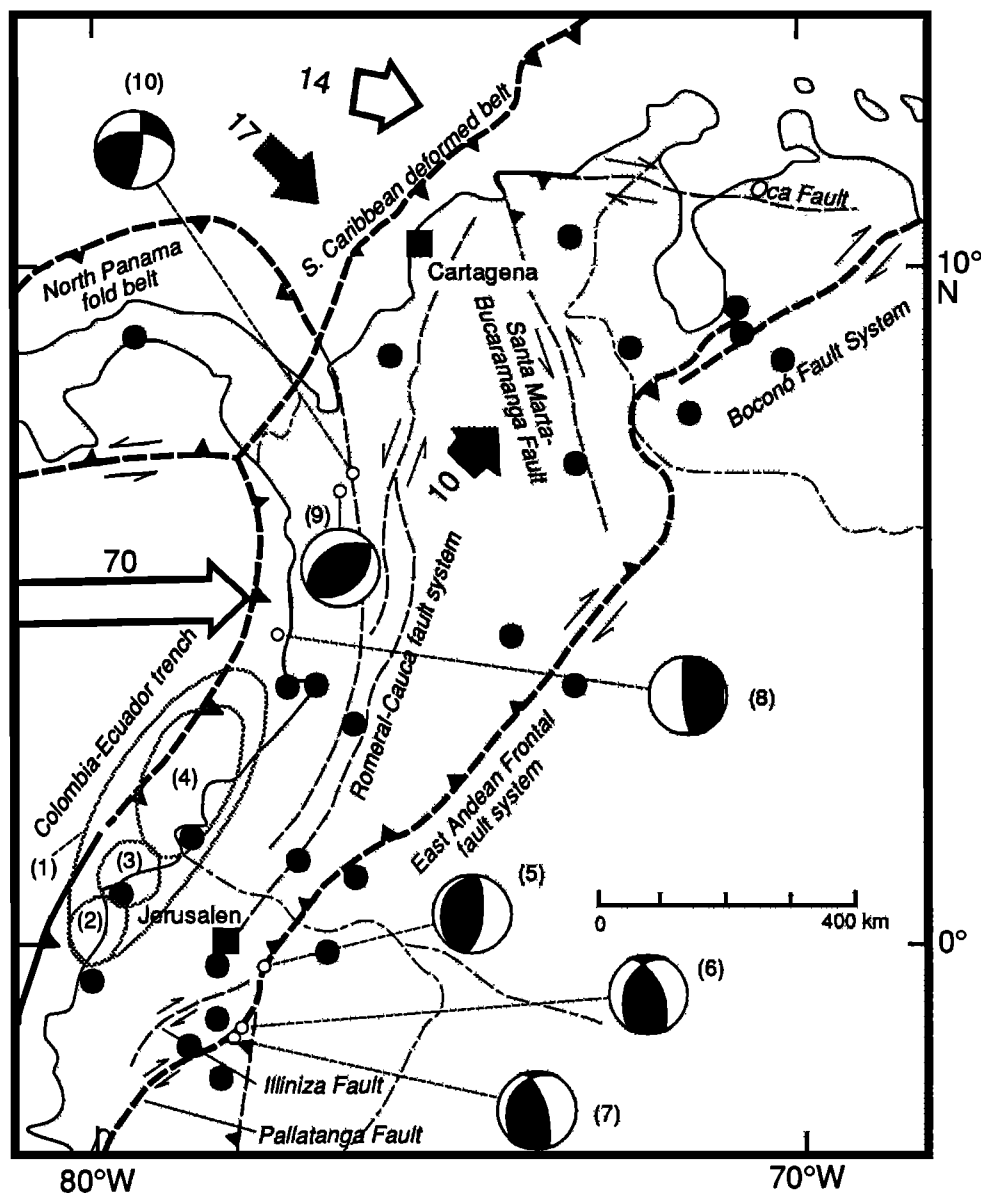


Fig. 2. Tectonic features and boundaries of the North Andes block. All plate velocity vectors are relative to the South American plate, except the grey vector which represents the Caribbean-North Andes vector of Kellogg *et al.* [1985]. Focal mechanisms or aftershock zones are shown for 10 significant earthquakes in the region. The numbers next to each focal mechanism or aftershock zone refer to Table 1. Earthquakes 1-7 occurred prior to the 1988 GPS campaign, and 8-10 after the 1991 campaign.

by repeated geodetic leveling [De Obaldia *et al.*, 1991]. Vertical coseismic displacements of a similar magnitude have been measured using GPS [Lundgren *et al.*, 1991], and almost 2 m of horizontal coseismic displacement were observed at Puerto Limón [Lundgren *et al.*, 1991]. The horizontal displacement at Limón observed with GPS is not in accord with a dislocation model based on the vertical displacement data, and may be due in part to local seaward slumping in response to the earthquake [Pflafer and Ward, 1992].

#### Southern Caribbean Plate Boundary Zone

The location of the southern margin of the Caribbean plate has been the subject of considerable controversy. It has been placed as far south as the Boconó and East Andean fault systems, and as far north as the South Caribbean deformed belt

(Figure 2). The southern margin of the Caribbean plate is now generally accepted to be a distributed zone of deformation, although there remains disagreement over how much of the North Andes should be considered "Caribbean." The principal part of the plate boundary zone consists of a series of deformed belts along the Caribbean coast of South and Central America, including the South Caribbean deformed belt, the North Panamá fold belt and the Leeward Antilles [e.g., Pindell and Barrett, 1990; Mann *et al.*, 1990].

In Colombia, the South Caribbean deformed belt includes the Sinú and San Jacinto belts (Figure 2), consisting of up to 12 km of Tertiary turbidites, carbonates, and fluvial and lacustrine sediments [Duque-Caro, 1979; Duque-Caro, 1984]. The wedge of sediments has a very low topographic slope ( $\leq 2^\circ$ ) [Toto and Kellogg, 1992]. Toto and Kellogg [1992] interpreted the Sinú and San Jacinto belts as an accretionary wedge similar to

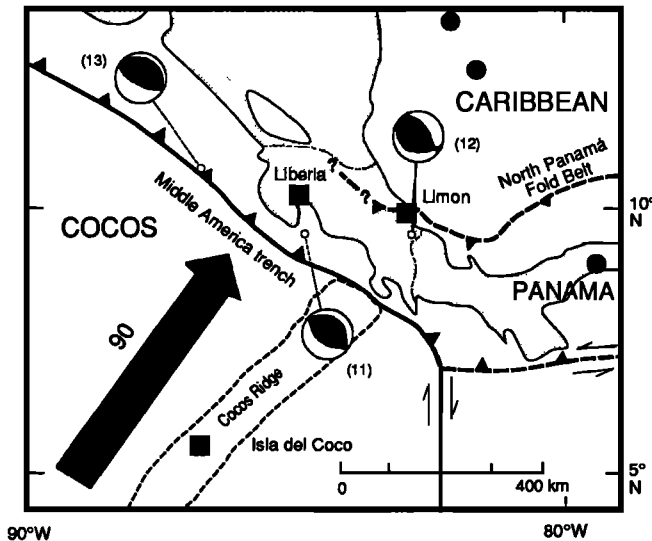


Fig. 3. The Costa Rica subduction system. Focal mechanisms are shown for the 1990 Gulf of Nicoya earthquake ( $M \sim 6.9$ ), the 1991 Valle de Estrella earthquake ( $M \sim 7.4$ ), and the 1992 Nicaraguan earthquake ( $M \sim 7.0$ ). The numbers next to each focal mechanism refer to Table 1.

the Barbados, Makran and Cascadia wedges, with pore pressures approaching lithostatic. The high pore pressures and low slip rate explain the low rate of seismicity in the wedge.

Multichannel seismic profiles across the South Caribbean deformed belt show evidence for active folding of the youngest sediments and show that Caribbean acoustic basement has underthrust the deformed belt [Lu and McMillen, 1983; Lehner *et al.*, 1983; Ladd *et al.*, 1984]. Kellogg and Bonini [1982] have interpreted a zone of earthquakes dipping  $20^\circ$  to the southeast beneath the continent [Dewey, 1972; Pennington, 1981] as a weakly defined Wadati-Benioff zone resulting from the slow underthrusting of Caribbean crust. Kellogg *et al.* [1985] used a block vector model to estimate the convergence rate between the Caribbean and North Andes to be 17 mm/yr, to the southeast. Dewey and Pindell [1985, 1986] find a similar convergence direction between the Colombian basin and the Maracaibo block. Mann and Burke [1984] argue for northerly directed convergence between the Caribbean and the Maracaibo block.

## RESULTS

Displacement rates were computed for the Isla Baltra/Jerusalén (Nazca-North Andes plates), Isla Baltra/Isla del Coco (Nazca-Cocos) and the Isla del Coco/Liberia (Cocos-Caribbean or Cocos-Panamá) baselines based on the GPS baseline estimates from 1988, 1990 and 1991. Each baseline was considered independently. The computed displacement rates and their uncertainties are based on a weighted linear fit of the GPS solutions as a function of time for each baseline (Figure 4). The weights used were determined from the formal uncertainties of each estimate and an estimate of magnitude of the potential systematic errors (Appendix). The uncertainties due to the potential systematic errors make up a significant part of the error budget (Appendix, Table A2). The reduced chi-square statistics for the linear fits ranged from 0.44 to 1.29, indicating that the scatter of the data about the best fit line is

fairly consistent with the given uncertainties. Notice that in Figure 4 all estimates from a given campaign frequently lie either above or below the best fit line. This is an indication that all estimates from a given campaign are slightly biased due to systematic errors, but the reduced chi-square statistics suggest that the uncertainties used are reasonable, and that our uncertainties have accounted sufficiently for these systematic errors.

Since only two epochs are available for the Isla San Andrés/Cartagena (Caribbean-North Andes) baseline, the displacement rate is the difference between the two solutions divided by the time elapsed between the experiments (3.05 years). The uncertainty in the rate for this baseline is based on the mean formal precision of each experiment's solution, with the uncertainty due to the possible systematic error sources described above added in quadrature. This is a conservative approach that reduces the chance of interpreting systematic errors as plate motions. We feel it is appropriate to observe caution in the assessment of uncertainties for baselines with only two occupations.

The observed baseline displacement rates are in general agreement with the predictions of the NUVEL-1 plate motion model, but there are significant differences on most baselines; only for the Nazca-Cocos spreading rate do the NUVEL-1 predictions lie within the 95% confidence ellipses of the GPS baseline rates (Figure 1, Table 2). The plate motion model predictions and their uncertainties are shown with dashed lines. Notice that for the Cocos-Caribbean convergence rate, the uncertainty in the GPS estimate is smaller than the uncertainty in the NUVEL-1 model. No significant vertical motions were observed at any sites. A summary of the GPS and NUVEL-1 displacement rates is given in Table 2.

## DISCUSSION

Differences between our GPS baseline rates and the predictions of the NUVEL-1 model for those baselines may be explained in four possible ways: (1) systematic biases in the GPS solutions which change systematically with time, (2) deficiencies in the NUVEL-1 model, (3) motion of the GPS sites with respect to the stable plate interiors, or (4) temporal variations in motions of certain stations due to the effects of the earthquake cycle. We consider the third and fourth possibilities to be the most likely.

Systematic biases in the GPS solutions which bias the baseline rates are possible, but unlikely for two reasons. First, we have been very conservative in assigning uncertainties which consider the magnitudes of potential systematic errors. Second, when baselines have been observed multiple times over several years, the systematic errors would have to change linearly with time to bias the baseline rates. This is a primary reason for assigning very conservative uncertainties to the Isla San Andrés/Cartagena baseline which has been measured only in 1988 and 1991.

Deficiencies in the NUVEL-1 model are also possible; for example, the motion of the Caribbean plate is poorly constrained relative to other plates by the types of data used in the NUVEL-1 model. Three years of GPS data have determined the relative motion of Liberia and Isla del Coco more precisely than does the NUVEL-1 model. Also, the NUVEL-1 model is probably less reliable at convergent plate boundaries than at extensional or transform boundaries, due to the lack of reliable data which directly measure convergence rate and direction.

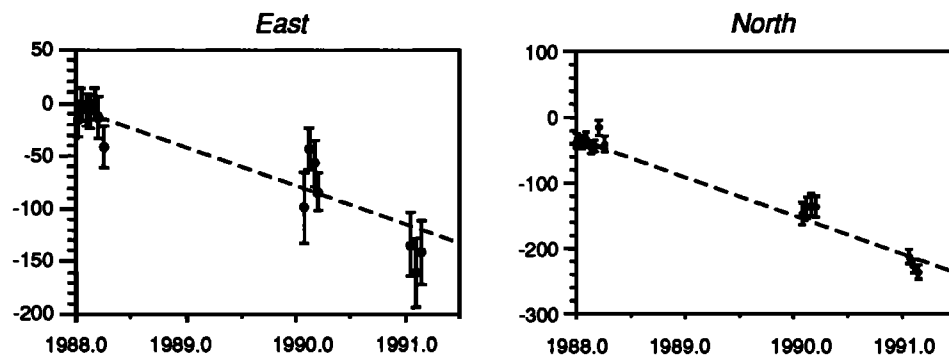
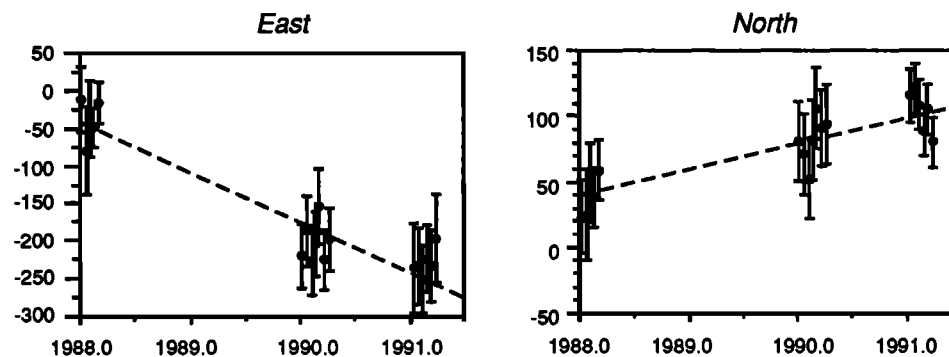
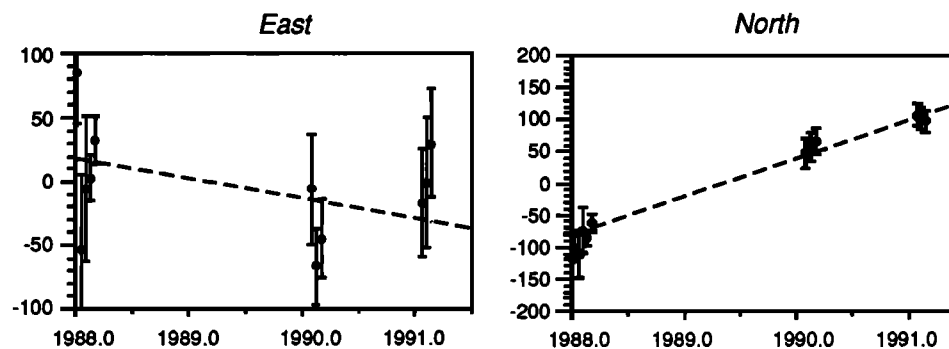
**Cocos / Liberia (Cocos-Caribbean)****Baltra/Jerusalen (Nazca-North Andes)****Baltra / Cocos (Nazca-Cocos)**

Fig. 4. Baseline solutions as a function of time for three baselines which measure relative motion of the major plates. The horizontal separation of solutions for each campaign has been exaggerated to show the individual solutions.

Nevertheless, the NUVEL-1 model is in good agreement with geodetic measurements in many parts of the world, and it represents well the motions of the stable plate interiors on a global basis [DeMets *et al.*, 1990; Gordon and Stein, 1992].

Application of the NUVEL-1 model to specific sites is possible only when each site can be placed unambiguously on a stable plate. In plate boundary zones or other regions of active deformation, we would expect that the motion of GPS sites would differ from the motion predicted by NUVEL-1. A considerable body of evidence, summarized in the first section, suggests that the North Andes region is moving relative to

South America. We expect that baseline rates of change involving sites in the North Andes (Jerusalen and Cartagena in this study) will differ from the predictions of the NUVEL-1 model by the amount that those sites are in motion relative to the South American plate.

Temporal effects of the earthquake cycle may have affected the GPS baseline rates, but the magnitude of these effects is small for the baselines considered. The two large earthquakes in Costa Rica both had substantial coseismic offsets but caused only small displacements at the sites used in this study. An elastic dislocation model for the March 1990 magnitude 6.9

TABLE 2. Observed Displacement Rates  
Compared With Predictions of NUVEL-1 Plate Motion Model.

Baseline	NUVEL-1		GPS		$\chi^2_v$
	East	North	East	North	
Isla Baltra / Jerusalem	-70±4	-1±2	-68 ±7	15 ±5	0.44
Isla Baltra / Isla del Coco	-4±3	65±5	-15 ±6	66 ±4	1.11
Isla del Coco / Liberia	-54±4	-73±6	-40 ±3	-59 ±2	1.29
Isla San Andrés / Cartagena	-14±3	3±4	-11 ±10	7 ±6	--

The motion of the second station relative to the first station is given. Since these baselines are mostly oriented in the direction of relative plate motion, negative displacement rates indicate convergence and positive rates divergence. The  $\chi^2_v$  column gives the reduced chi square statistic of the linear fit to the GPS measurements.

earthquake was computed based on fault parameters derived from the Harvard Centroid Moment Tensor solution and a solution of the University of California, Santa Cruz based on local and teleseismic data (J. M. Protti-Quesada, personal communication, 1991). The model predicts 20 mm of southward motion at Liberia (located ~100 km from the epicenter), and insignificant displacements at Limón and Isla del Coco. The 1991 earthquake occurred 2 months after the 1991 measurements. The Limón site, located close to the 1991 epicenter, was not used in this study.

Nazca-North Andes convergence is measured by the baseline from Baltra to Jerusalem (1323 km). Jerusalem (on the North Andes microplate) has a northward component of motion relative to South America, so Baltra appears to be moving southward relative to the NUVEL-1 Nazca-South America prediction. If the entire difference between the GPS estimate and NUVEL-1 were due to motion of the North Andes, the North Andes microplate would be moving relative to South America at a rate of  $16 \pm 5$  mm/yr toward  $353 \pm 25^\circ$ . Kellogg *et al.* [1985] predicted the motion of the North Andes microplate relative to South America to be roughly 10 mm/yr toward  $55^\circ$ . If the predicted northeastward motion of the North Andes is added to the GPS displacement rate, the NUVEL-1 model would lie within the 95% confidence ellipses of the GPS estimate. Although the inferred motion of Jerusalem is directed more northward than predicted, the difference is not significant at the 95% confidence level.

Convergence between the Cocos and Caribbean plates is measured by the baseline between Isla del Coco on the Cocos plate and Liberia (595 km) or Limón (636 km) in Costa Rica. The geodetic monument used at the Limón site was destroyed and reset between the 1990 and 1991 experiments, so only the baseline to Liberia is used here. No significant motion was observed between Limón and Liberia during the period 1988-1990. The observed convergence rate of 71 mm/yr is only 78% of the 91 mm/yr predicted by the NUVEL-1, but the direction of motion is almost identical to that predicted by the plate motion model. If the NUVEL-1 Cocos-Caribbean relative motion vector is correct, then the observed convergence rate would be consistent with the hypothesis that the stations in Costa Rica are moving northeastward relative to the stable Caribbean plate. Relative to Isla San Andrés, which is presumably located on the stable Caribbean plate, Liberia moved northward at a rate of  $14 \pm 6$  mm/yr during the period 1988-1991. The 1991 Costa Rica earthquake occurred on a shallow southwestward-dipping thrust consistent with

Caribbean crust underthrusting Central America [Plafker and Ward, 1992], further supporting this hypothesis.

The March 1990 magnitude 6.9 earthquake probably did not produce significant deformation at either of the sites that make up this baseline. According to an elastic deformation model, 20 mm of southward motion is predicted at the Liberia station. Removing the model coseismic displacement from the GPS estimates for 1991 would improve the fit of the baseline estimates about a line (chi-square of 1.05 rather than 1.29) and produce slightly better agreement with the NUVEL-1 model's predicted direction of convergence ( $0.1^\circ$  away from the NUVEL-1 direction rather than  $2.4^\circ$ ). The results shown in Figure 1 do not remove the model displacement of Liberia. Additional GPS data in Costa Rica, taken in 1990 and 1991 but not used in this study, will allow a more reliable estimate of the coseismic displacement of Liberia [Niemeier *et al.*, 1993].

Isla San Andrés on the Caribbean plate moved southward at a rate of  $7 \pm 6$  mm/yr and eastward at a rate of  $11 \pm 10$  mm/yr relative to Cartagena on the northern coast of Colombia. As mentioned above, the uncertainties for this baseline are conservative because the baseline has been occupied only twice. Given the large uncertainties, the observed convergence is consistent with both the NUVEL-1 Caribbean-South America relative motion prediction and the Kellogg *et al.* [1985] Caribbean-North Andes prediction. Most of the convergence in the South Caribbean plate boundary zone must be taken up offshore, north of Cartagena.

The rate of seafloor spreading at the Galápagos Rise is measured by the baseline between Isla Baltra on the Nazca plate and Isla del Coco on the Cocos plate (754 km). Relative to Isla Baltra, Isla del Coco has a larger westward component of motion than the NUVEL-1 model predicts, but the difference is not significant at the 95% confidence level. The scatter of the estimates for the east component of this baseline is much larger than for any other baseline. The north component of this baseline is much better determined, and the rate agrees with the NUVEL-1 prediction to within 1 mm/yr.

Additional occupations of the network will significantly improve the uncertainties in the GPS-derived plate motion rates. With the first three occupations, the uncertainty in the Cocos-Caribbean (Panamá) vector from GPS is comparable to the uncertainty for the same vector in the NUVEL-1 model, and with future occupations GPS can be expected to determine relative plate motions in the region with a precision comparable to or better than that of the NUVEL-1 plate motion model. Initial GPS results presented here are consistent with



deformation in the overriding plates at the Colombia-Ecuador and Middle America trenches. We expect that in the future GPS data from the full CASA network will resolve details of active slip partitioning within the complex North Andean and Central American plate boundaries.

#### APPENDIX ANALYSIS OF THE GPS MEASUREMENTS

The GPS data were analyzed using the GIPSY software [Lichten and Border, 1987; Blewitt, 1989; Sovers and Border, 1990; Blewitt, 1990]. Details of the analysis are given in Freymueller [1991]. Each day of data was analyzed independently, using data from all stations in the CASA region and from a tracking network of sites distributed over almost half the globe (Figure A1). Carrier phase data were used, along with pseudorange data when they were available, to estimate station coordinates, corrections to the satellite orbits, time-varying tropospheric path delays at each station, and the carrier phase ambiguities and receiver and satellite clock errors (independently for each epoch). When possible, the carrier phase ambiguities were resolved to integer values using the method of Blewitt [1989], which produces a dramatic improvement, of a factor of 2-4 or more, in the precision and accuracy of GPS solutions [Dong and Bock, 1989; Blewitt, 1989]. Due to a change of receiver types between the 1988 and 1990 experiments, most ambiguities in the 1990 and 1991 solutions could not be resolved (none were resolved for the stations considered here) [Freymueller, 1992].

Estimating corrections to the GPS satellite orbits using data from a tracking network is necessary to obtain a sufficient level of precision for tectonic studies. For a network the size of the CASA network, orbit improvement results in a factor of 5-10 increase in precision. Using a standard approach, the coordinates of three tracking sites are constrained to the coordinates determined from very long baseline interferometry

(VLBI). In addition, data were used from as many other tracking sites as possible. The positions of these additional sites were not constrained, but their use significantly improves the estimates of the orbit corrections [e.g., Freymueller and Kellogg, 1990; Kornreich Wolf et al., 1990]. This approach makes the solutions sensitive to errors in the coordinates of the constrained stations; any such errors will bias the estimates for the baselines of interest in the CASA region. Also, the distribution of tracking sites around the world can change the estimates for the baselines of interest by an amount comparable to their uncertainties [Freymueller and Kellogg, 1990]. We attempt to estimate the magnitude of these effects, and add it to the formal uncertainties. By doing so, the uncertainties on our plate motion estimates will better reflect the true uncertainties in the GPS solutions.

#### Consideration of Potential Systematic Errors

The tracking sites used in each experiment were different, as a different set of sites were operating at the times of each CASA experiment (Figure A1). In particular, the 1990 tracking network spanned less of the globe than the others, so additional uncertainty is included in the baseline estimates from 1990 [Freymueller, 1991]. All of the available tracking sites were used in each solution, and three of the following sites were constrained: Owens Valley (California), Fort Davis (Texas), Richmond (Florida) and Westford (Massachusetts). The coordinates used for these stations are taken from the Goddard Space Flight Center VLBI model GLB223 (C. Ma, published as Table 1 by Larson et al. [1991]), in which North America is constrained to move according to the AM0-2 absolute plate motion model of Minster and Jordan [1978]. A small geocenter offset to the GLB223 coordinates is applied to provide a geocentric reference frame. Further detail is given by Freymueller [1991].

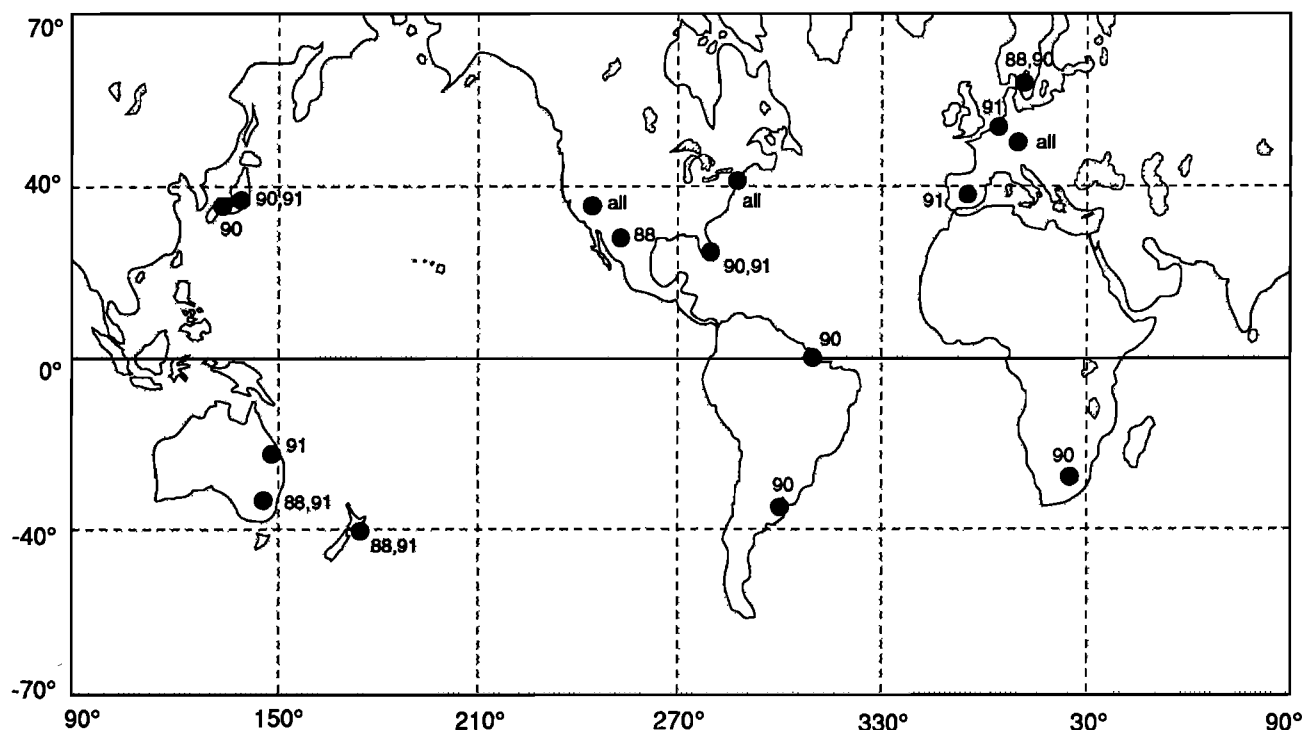


Fig. A1. Tracking networks used in the three campaigns. The years in which each site was used are indicated by numbers next to each site.

TABLE A1. Error Budget for Considered Systematic Errors for Two Sample Baselines in the CASA Region

Error Source	East	North	Vertical
<i>Isla Baltra/Jerusalen (1323 km)</i>			
1988 Fiducial error	24	20	10
1990 Fiducial error	31	17	18
1990 Tracking net difference	20	20	20
1990 Local net difference	10	10	10
1991 Fiducial error	31	17	18
<i>Isla del Coco/Liberia (585 km)</i>			
1988 Fiducial error	14	8	10
1990 Fiducial error	10	10	18
1990 Tracking net difference	10	10	10
1990 Local net difference	5	5	5
1991 Fiducial error	10	10	18

These numbers are an estimate of the potential magnitude of the systematic error in the baseline due to each systematic error source. These errors are added in quadrature to the formal uncertainties to give a truer estimate of the baseline accuracy.

TABLE A2. GPS Baseline Precision for the Baselines Used in the Study

Baseline	Length	Formal	Repeatability	Consider
<i>1988</i>				
Isla Baltra / Jerusalen	1323	20/14	36/14	24/20
Isla Baltra / Isla del Coco	754	14/11	54/16	16/10
Isla del Coco / Liberia	585	8/7	11/8	14/8
Isla San Andrés / Cartagena	710	9/8	11/8	14/8
<i>1990</i>				
Isla Baltra / Jerusalen	1323	24/12	24/20	38/28
Isla Baltra / Isla del Coco	754	20/7	23/7	25/21
Isla del Coco / Liberia	585	14/5	23/4	15/15
<i>1991</i>				
Isla Baltra / Jerusalen	1323	19/12	28/17	31/17
Isla Baltra / Isla del Coco	754	17/7	17/22	20/15
Isla del Coco / Liberia	585	12/4	15/12	10/10
Isla San Andrés / Cartagena	710	14/6	14/4	20/15

Given are the baseline length in kilometers, the mean formal uncertainty ("formal") for the baseline and the observed rms repeatability ("repeatability") for each campaign, and the added uncertainty to account for possible systematic effects ("consider"). All uncertainties are given in millimeters for East/North components.

An error budget for two sample baselines used is given in Table A1, including estimates of the magnitudes of the systematic changes in the baseline estimates due to errors in the coordinates of the constrained sites, and differences in the tracking networks and the local CASA network in 1990. The latter effect is included because the 1990 local network was also very sparse, consisting of a small number of stations widely separated. A test using 1988 data indicated that there were small changes to the estimates of the longest baselines when such a sparse network was used. It is not clear whether the changes are systematic, but to be conservative we have assumed that they are. In effect, the consideration of these potential systematic errors deweights the 1990 solutions relative to the others.

#### Observed Precision of the GPS Baseline Estimates

In general, the precision and accuracy of GPS baseline solutions degrade with baseline length because the effects of satellite orbital errors become more important as the station separation increases. There is also a component of precision which is independent of baseline length. In the 1988 experiment, the precision of our GPS solutions was approximately (5-6 mm) + (1-3) parts in  $10^8$  for the horizontal baseline components for baselines up to 750 km in length. Ambiguity resolution was less successful in the 1990 and 1991 solutions, but there were more satellites available (7 in 1988, 12 in 1990, 16 in 1991). As a result, it is not simple to compare baseline precision in the three experiments, as there are different constant and length-dependent terms for each experiment. In general, for the baselines used here, the highest precision was obtained in 1988, followed in order by 1991 and 1990 (Table A2). The precision of the solutions for the baseline vertical component varies from 10 to 60 mm in 1988, and 20 to 40 mm in 1990 and 1991. While it is not independent of baseline length, there is no simple relation with length.

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J. T. Freymueller, Department of Geophysics, Stanford University, Stanford, CA 94305.

J. N. Kellogg and V. Vega, Department of Geological Sciences, University of South Carolina, Columbia, SC 29208.

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