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## Tectonic Development of Panama, Costa Rica, and the Colombian Andes: Constraints from Global Positioning System Geodetic Studies and Gravity

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# *Tectonic development of Panama, Costa Rica, and the Colombian Andes: Constraints from Global Positioning System geodetic studies and gravity*

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## ABSTRACT

Global Positioning System (GPS) measurements suggest the existence of a rigid Panama–Costa Rica microplate that is moving northward relative to the stable Caribbean plate. Northward motion of Central America relative to the Caribbean plate is independently suggested by the April 1991 Costa Rica earthquake, active folding in the North Panama deformed belt, and a south-dipping Wadati-Benioff zone beneath Panama. Panama may also be continuing to collide eastward with the northern Andes. Rapid subduction is occurring at the Middle America (72 mm/yr), Ecuador (70 mm/yr), and Colombia (50 mm/yr) trenches. The northern Andes are moving northeastward relative to stable South America. Preliminary GPS results also suggest Caribbean–North Andean convergence and an independent North Nazca plate.

About 6 Ma the Panama-Choco island arc collided with the northwestern margin of South America, eventually forming a land bridge between the Americas; closed the Pacific-Caribbean seaway, changing ocean circulation patterns and perhaps the world's climate; folded the East Panama deformed belt; and uplifted the Eastern Cordillera of Colombia. An interpretation of the paleo-Romeral suture in southern Colombia as a low-angle fault dipping to the west into the lower crust under the Cordillera Occidental is compatible with seismic velocity and gravity data. During the Late Cretaceous the Western Cordillera oceanic terrane was obducted eastward on the fault system over continental crust.

## INTRODUCTION

The tectonic development of southern Central America and the northern Andes has been the subject of a number of studies (e.g., Case et al., 1971; Jordan, 1975; Toussaint, 1978; Duque-Caro, 1979; Case and Holcombe, 1980; Pennington, 1981; Wadge and Burke, 1983; Dengo, 1985; Escalante, 1990;

Mann and Corrigan, 1990; Silver et al., 1990). Particularly controversial questions are the timing and geometry of the accretion of the Western Cordillera of Colombia and Ecuador, the location of the Panama arc–South America suture, and present-day plate boundaries and relative motions. The rela-

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tive velocity of the Caribbean plate with respect to the Cocos, Nazca, and South American plates is poorly constrained because the Caribbean plate has no spreading ridges on its western, southern, and eastern boundaries. The only direct rate information available for the Caribbean plate is from magnetic lineations produced by the small spreading center within the Cayman Trough (Rosencrantz and Sclater, 1986).

Caribbean–Nazca–South America triple junctions have been shown as far east as Colombia's Eastern Cordillera (Dewey, 1972), as far west as the Panama fracture zone (Shagam, 1975), and as far south as Ecuador's Gulf of Guayaquil (Aggarwal, 1983). Deformation of Panama by distributed slip on a number of left-lateral strike-slip faults has been suggested by Mann and Corrigan (1990), based on field mapping and on air photo and satellite image analysis. Silver et al. (1990) explained the kinematics of Panama with a flexural beam model. Their model assumed an original east trend to the isthmus and an eastward movement relative to the South American plate. Jordan (1975) and Wadge and Burke (1983) noted the diffuse seismicity in Panama and northwestern South America (Fig. 1) and interpreted the seismic zone as a diffuse plate boundary accommodating deformation over a broad area. Pennington (1981) and Adamek et al. (1988) explained the tectonics as the interaction of three large plates and one to three microplates. Kellogg et al. (1985, 1989) have interpreted the tectonics in the region by two additional blocks or microplates, Panama and the North Andes (Fig. 2). In this chapter we use geologic, gravity, seismic, and Global Positioning System (GPS) geodetic data to derive a tectonic model for the North Andes and southern Central America.

One of the most controversial problems in Caribbean tectonics is the location of the current Caribbean–South American plate boundary. Seismologists noted that most of the historical seismicity was located along the Bocono fault in the Venezuela Andes and put the Caribbean–South American plate boundary there (e.g., Dewey, 1972; Aggarwal, 1983). However, multichannel seismic reflection profiles across the South Caribbean deformed belt show that Caribbean acoustic basement has underthrust the deformed belt, and folding of the youngest sediments suggests that the deformation is active (Edgar et al., 1971; Silver et al., 1975; Lu and McMillen, 1982; Lehner et al., 1983; Ladd et al., 1984). Furthermore, Dewey (1972) and Pennington (1981) recognized a zone of earthquakes dipping about 20 degrees to the southeast under the Santa Marta massif and Sierra de Perija and terminating 200 km below the Maracaibo Basin. Kellogg and Bonini (1982) and Toto and Kellogg (1992) interpreted these earthquakes as a Benioff zone produced by slow amagmatic subduction of Caribbean lithosphere. A convergence rate of  $1.9 \pm 0.3$  cm/yr was estimated from the 390-km length of the seismic zone, assuming a thermal equilibration time of 10 m.y. A similar rate of  $1.7 \pm 0.7$  cm/yr was calculated from velocity vector closure between the North Andean block and the Caribbean and South American plates (Fig. 2; Kellogg et al., 1985; Kellogg and

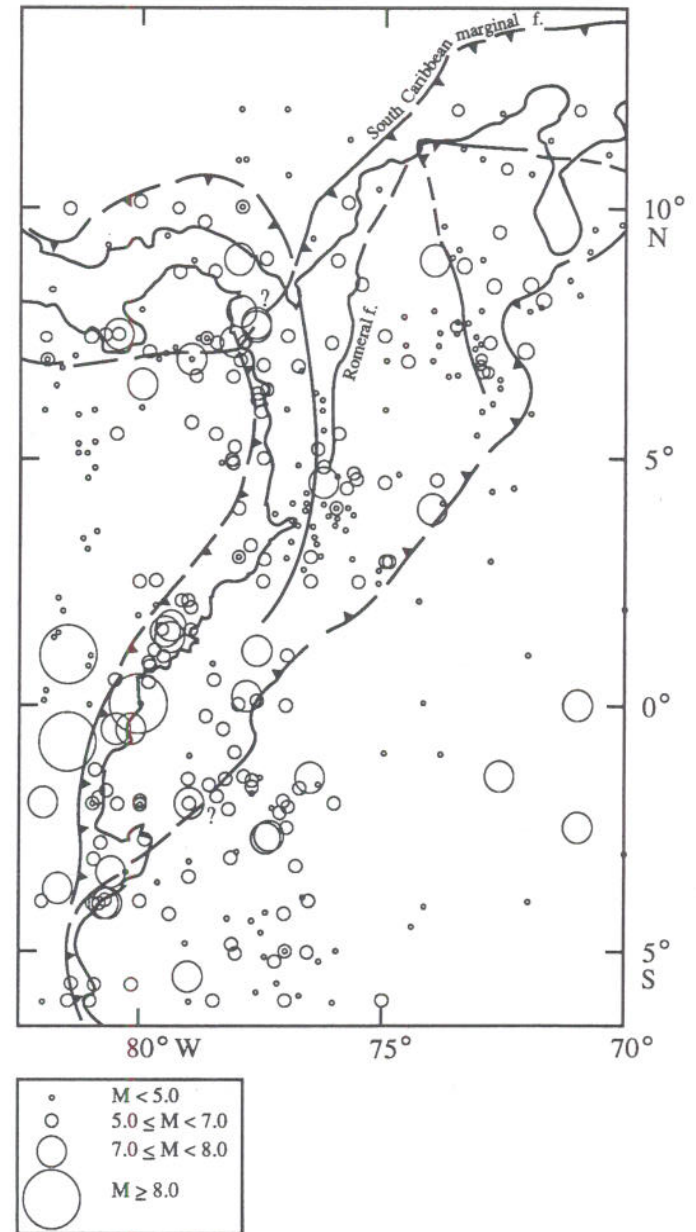


Figure 1. Earthquake epicenters for northwestern South America from the NOAA-EDIS Earthquake Data File. Most of the earthquakes are from the period 1962 to 1981.

Bonini, 1985). This predicted rate is about twice as fast as the 1.0 cm/yr right-lateral displacement on the seismically active Bocono fault.

#### CRUSTAL MOTIONS MEASURED WITH THE GLOBAL POSITIONING SYSTEM

The Central and South America (CASA) Global Positioning System (GPS) project was inaugurated in 1988 to study plate motions and crustal deformation in Central America and

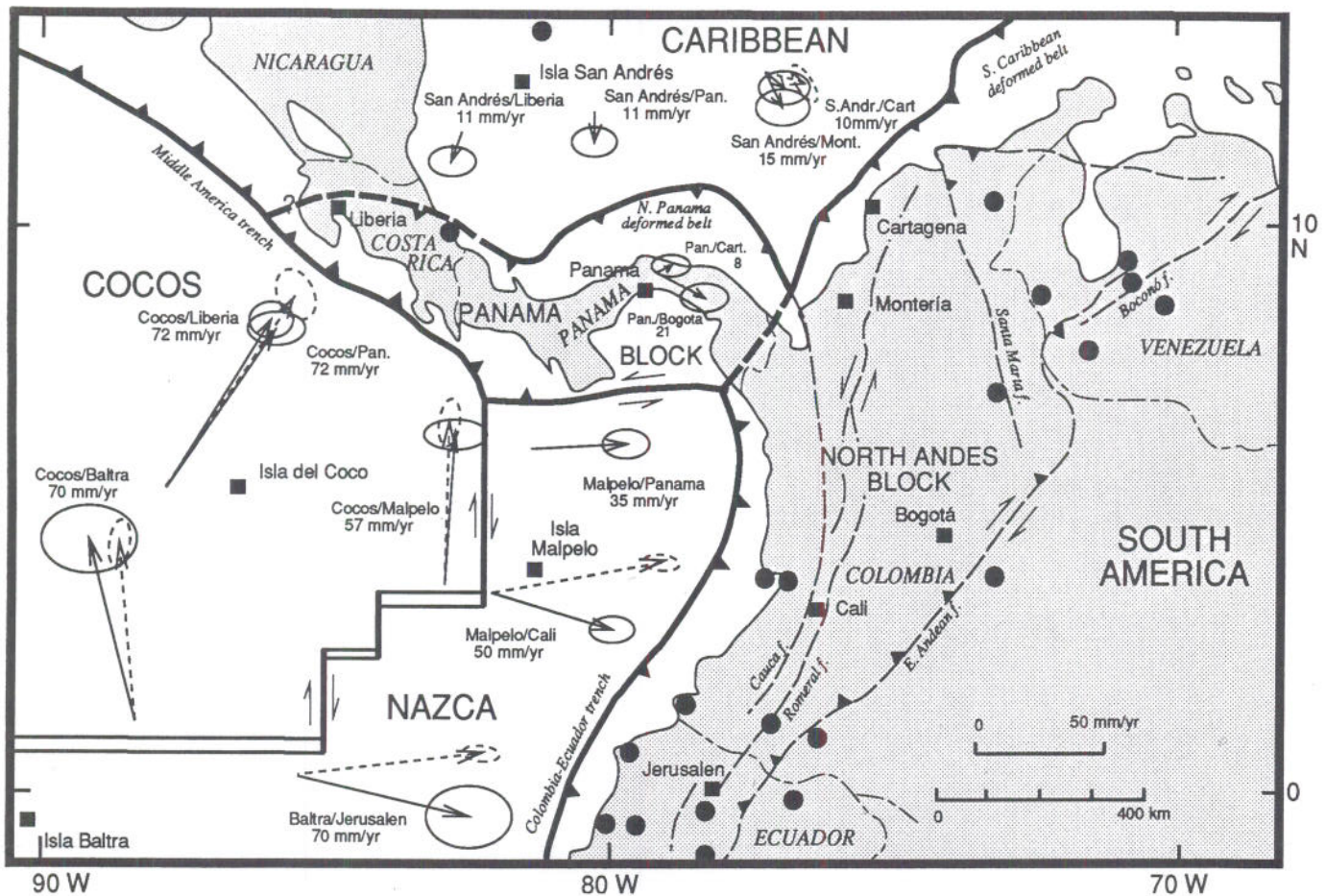


Figure 2. Observed GPS (solid lines) and model NUVEL-1 (dashed lines) baseline rates of change, with their 95% confidence ellipses, between the sites indicated by solid squares. The solid circles indicate the remaining sites in the CASA network.

northern South America. GPS is a satellite-based positioning system allowing centimeter-level geodesy to be performed with low-cost portable receivers. Centimeter-level precision has been demonstrated on baselines up to 2,000 km in length (e.g., Beutler et al., 1987; Blewitt, 1989; Tralli and Dixon, 1988; Dong and Bock, 1989). Repeated geodetic measurements with GPS provide direct measurements of displacements due to active plate motions and intraplate deformation, which can provide important constraints on regional kinematic plate motions and on the active tectonics of the deforming zones of the convergent margins. Dynamic problems such as the relation between the earthquake cycle and large-scale plate motions or intraplate deformation at convergent margins can be addressed once a sufficiently long-term span of data has been collected.

The CASA network currently consists of 30 primary sites in five countries (Fig. 2), most of which have now been occupied at least twice (Kellogg et al., 1989; Kellogg and Dixon, 1990). Preliminary computed baseline vector changes in mm/yr are shown with their 95% confidence ellipses in Figure

2 (Vega and Kellogg, 1992). The measurements cover a three-year period, 1988 to 1991. Freymueller et al. (1993) presented results from four sites that were occupied in all three campaigns (Isla Baltra and Jerusalen, Ecuador; Isla del Coco and Liberia, Costa Rica) and two sites (Isla San Andrés and Cartagena, Colombia) that were occupied in 1988 and 1991. This chapter presents results with 10 additional station days of data from Baltra and Jerusalen and six additional station days of data from Isla San Andrés and Cartagena. We also present new results based on 103 station days of data for five additional sites that were occupied in 1988 and 1991 (Panama City, Panama; Monteria, Bogotá, Cali, and Isla Malpelo, Colombia).

Details of the GPS data analysis are given in Freymueller (1991). Data from a global tracking network were used to estimate corrections to the GPS satellite orbits. The coordinates of three tracking sites were constrained to the coordinates determined from Very Long Baseline Interferometry (VLBI). The 95% confidence ellipses for baselines that were occupied three times (Fig. 2) are based on the formal uncertainties and esti-

mates of other substantial systematic errors such as fiducial, global, and local network effects. For example, the 585-km baseline from Isla del Coco to Liberia, Costa Rica, was occupied in 1988, 1990, and 1991. The baseline solutions as a function of time (Figs. 2 and 3) give a shortening rate of 72 mm/yr,  $40 \pm 9.4$  mm/yr in the east and  $59 \pm 6.5$  mm/yr in the north, at the 95% confidence level. For baselines that were occupied in only two campaigns, 1988 and 1991, the displacement rate is the difference between the two solutions divided by the time elapsed between the experiments (3.05 years). The uncertainties in the rates for these baselines are based on the mean formal precision of each experiment's solution.

### Isla del Coco–Liberia baseline

The 585-km Isla del Coco–Liberia baseline crosses the Middle America trench. Relatively rapid subduction occurs at the Middle America trench, with the Cocos plate being subducted beneath the Caribbean and North American plates. DeMets and others (1990) predicted a subduction rate of 91 mm/yr, nearly normal to the trench. The submarine Cocos Ridge is being subducted under southern Costa Rica (Fig. 4; Kolarsky et al., this volume). North of the ridge, the geometry of the subducted slab changes, and Burbach et al. (1984) suggest that the slab may have been torn as a result of the effects of the attempted subduction of the buoyant Cocos Ridge. Subduction may be slowing or stopping in the Costa Rica segment of the subduction zone (van Andel et al., 1971; Pennington, 1981; Burbach et al., 1984). In March and April 1990, a series of five subduction zone earthquakes, the largest being  $M_s \sim 6.9$ , and three others being larger than  $M_s \sim 6.0$ , ruptured the trench from southern Nicaragua south to Panama. The first and largest event occurred just south of the tip of Nicoya Peninsula, approximately on a line between Liberia and Isla del Coco (Fig. 4).

The 72 mm/yr computed displacement rate for the Isla del Coco–Liberia baseline is based on a linear fit of the GPS solutions as a function of time (Fig. 3). The reduced chi-squared statistic for the linear fit was 1.29, indicating that the scatter of the data about the best fit line is consistent with the given

uncertainties. The observed rate is only 79% of the 91 mm/yr Cocos–Caribbean convergence predicted by the NUVEL-1 plate motion model (DeMets et al., 1990). The discrepancy may be partly explained by the 11 mm/yr convergence rate measured between Liberia, Costa Rica, and Isla San Andrés, Colombia, located on the stable Caribbean plate (Fig. 2).

### Isla San Andres–Liberia and Isla San Andres–Panama City baselines

Similar convergence rates were measured for the Isla San Andres–Liberia and the Isla San Andres–Panama City baselines (11 mm/yr; Fig. 2). No significant deformation was measured between Liberia, Costa Rica, and Panama City, Panama.

Earthquake focal mechanisms and seismicity suggest a poorly defined Wadati-Benioff zone dipping about  $50^\circ$  to the southwest beneath the Panama fold belt (Wolters, 1986; Adamek et al., 1988). The April 1991 Costa Rica earthquake ( $M_s \sim 7.4$ ) on the Caribbean coast of Costa Rica was a thrust event on a plane dipping  $17^\circ$  to  $30^\circ$  to the southwest (Fig. 4; Guendel et al., 1991; Goes et al., 1993; Tajima, this volume). It occurred on one of a system of thrust faults that make up the northern extension of the North Panama fold belt. The earthquake produced as much as 157 cm of uplift along the coast, measured by uplift of coral reefs and other shoreline features (Plafker and Ward, 1992) and by repeated geodetic leveling (De Obaldia et al., 1991). Vertical coseismic displacements of a similar magnitude also have been measured using GPS satellite geodesy (Lundgren et al., 1993). The center of uplift due to the earthquake was located near the Limon GPS site, and over 2 m of horizontal coseismic displacement was observed for this site (Lundgren et al., 1993).

Bowin (1976), Case et al. (1984), Kellogg et al. (1985), and Adamek et al. (1988) predicted a Panama block or microplate to help explain the regional tectonics. The GPS results are consistent with this model if the microplate includes most of Panama and Costa Rica. Northward motion of Central America relative to the stable Caribbean plate is independently suggested by the April 1991 Costa Rica earthquake (Fig. 4), a south-dipping Wadati-Benioff zone beneath Panama (Wolters,

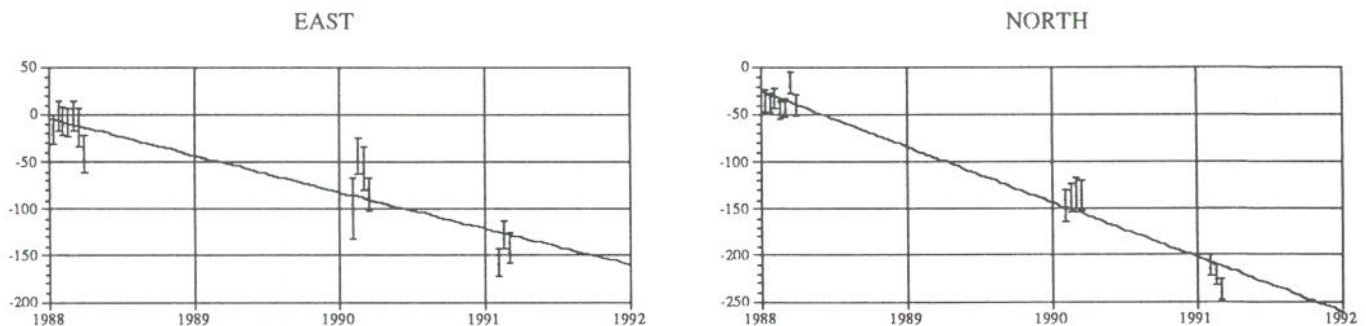


Figure 3. GPS baseline solutions (mm/yr) as a function of time for the 585-km Cocos–Liberia baseline. The horizontal separation of solutions for each experiment has been exaggerated to show the individual solutions.

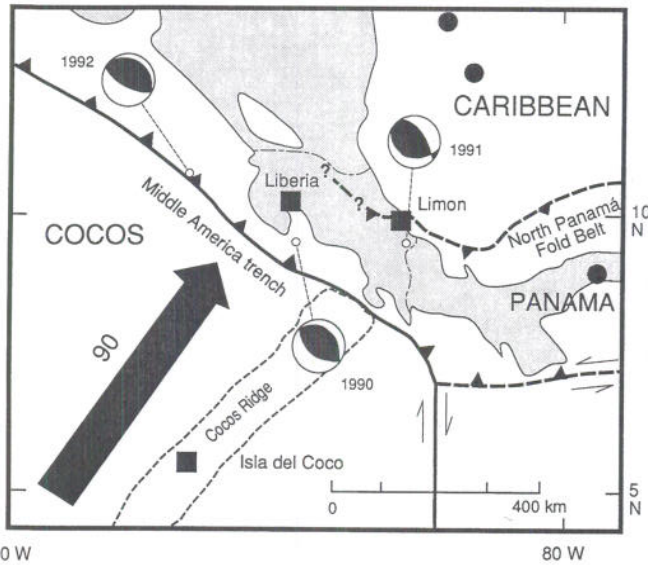


Figure 4. The Costa Rica subduction system (Freymueller and others, 1993). Focal mechanisms are shown for the 1990 ( $M \sim 6.9$ ; Harvard CMT solution), 1991 ( $M \sim 7.4$ ; Plafker and Ward, 1992), and 1992 ( $M \sim 7.0$ ; Harvard CMT solution) earthquakes. Solid squares and solid circles as in Figure 2.

1986; Adamek et al., 1988), and active folding in the North Panama deformed belt (e.g., Silver et al., this volume). A SeaMARC II survey of the North Panama fold belt shows that it consists of four nearly straight segments (Silver et al., 1990, this volume). The Central Panama segment is the longest and maintains a nearly constant orientation of  $075^\circ$ . Silver et al. (1990, this volume) showed that this orientation is consistent with a model of bending of the Isthmus of Panama as a result of the collision with South America. Previous workers have proposed that the northwestern boundary of the Panama microplate passed through the middle of Costa Rica (e.g., Kellogg et al., 1989; Fan et al., 1993). The lack of motion observed between Liberia and Panama City, however, suggests that the northwestern boundary of the Panama–Costa Rica microplate must be north of Liberia and may be the Santa Elena suture along the Nicaragua–Costa Rica border (Case and Dengo, 1982; Escalante, 1990). Alternatively, the Liberia observations can be explained by elastic strain accumulation with a locked subduction zone (Dixon, 1993).

#### *Isla Malpelo–Panama City baseline*

Malpelo Island was displaced 35 mm/yr eastward relative to Panama City (Fig. 2). The vector azimuth is consistent with left-lateral strike-slip movement south of Panama predicted from plate vector closure by Jordan (1975) and from the seismicity by Adamek et al. (1988). The observed vector azimuth is also consistent with oblique convergence at the Panama fracture zone complex southwest of Panama observed in seismic reflection profiles and SeaMARC II imagery by Moore and

Sender (this volume). The observed motion does not, however, support active northward spreading in the northern part of the Nazca plate as proposed by de Boer and others (1988).

#### *Panama City–Cartagena–Bogota baselines*

CASA GPS measurements at Panama City, Panama, and Cartagena and Bogota, Colombia, suggest ongoing collision between the Panama–Costa Rica microplate and the North Andes at about 8 to 21 mm/yr (Fig. 2). The Panama–Colombia border area is one of the most seismically active areas in northwestern South America (Fig. 1; Bermudez, 1985). More than 64 earthquakes of magnitude 5.0 or larger occurred in the area between 1963 and 1981. A shallow earthquake on January 20, 1904, measured 7.9 on the Richter scale. The seismic zone coincides with an active Quaternary fault zone identified from aerial photographs (W. Page, Woodward-Clyde, personal communication, 1984) and may mark a Panama–Nazca–North Andes triple junction (Fig. 2). A number of focal mechanisms from the seismically active Panama–Colombia border area indicate east-west compression (e.g., Pennington, 1981; Kolarsky and Mann, this volume). Focal mechanisms for two large October 1992 earthquakes in northwestern Colombia ( $M_s = 6.6$  and 7.2) are consistent with northwest-southeast compression.

#### *Isla San Andres–Cartagena and Isla San Andres–Monteria baselines*

Repeat GPS measurements in 1988 and 1991 at Isla San Andrés, Cartagena, and Monteria, Colombia, show 10 and 15 mm/yr of convergence in a northwest-southeast direction. These preliminary results are in agreement with predictions of 17 to 19 mm/yr of northwest-southeast convergence at the South Caribbean deformed belt by Kellogg and Bonini (1982) and Kellogg et al. (1985). Thus, although the Caribbean–South American plate boundary may be a broad zone of deformation, most of the deformation is occurring at the South Caribbean deformed belt.

#### *Isla Baltra–Jerusalen baseline*

Nazca–North Andes convergence was measured by the 1,323-km baseline from Baltra to Jerusalen, Ecuador, and the 585-km baseline from Malpelo Island to Cali, Colombia. Active subduction of Nazca oceanic lithosphere at the Colombia trench is indicated by a Benioff zone dipping  $30^\circ$  to the east (Galvis, 1980; Pennington, 1981) and by andesitic volcanism in the Central Cordillera. The observed convergence rate of 70 mm/yr between the Baltra and Jerusalen sites is based on a linear fit of the 1988, 1990, and 1991 GPS solutions as a function of time, with a reduced chi-squared statistic of 0.44. The observed displacement rate is in general agreement with the NUVEL-1 model.

On the east side of the North Andes, right-lateral movement is taking place on the Bocono fault zone (Figs. 2 and 5). From the short-term seismicity Aggarwal (1983) deduced a seismic-slip rate of  $1 \pm 0.2$  cm/yr. Using a measured 100-m

right-lateral offset of glacial moraines, Schubert (1980) estimated a similar average rate of strike slip motion on the fault, 0.8 cm/yr for the last 12,000 years. If the predicted northward motion of the North Andes block relative to South America is added to the displacement rate, the NUVEL-1 model would lie within the 95% confidence ellipse of the GPS estimate (Frey-mueller et al., 1993).

### *Isla Malpelo–Cali baseline*

A much slower convergence rate at the Colombia trench (50 mm/yr) was measured between Malpelo Island and Cali from 1988 to 1991. The difference between the Ecuador and Colombia trench convergence rates may be related to east-west-trending left-lateral strike-slip motion in the northern part of the Nazca plate (Wolters, 1986; Adamek et al., 1988), although the east-west uncertainty in the measurements is rather large ( $\pm 14$  mm/yr at the 95% confidence level).

### *Future measurements*

The GPS results for Liberia, Isla del Coco, Isla Baltra, and Jerusalem are based on measurements in 1988, 1990, and 1991. The scatter of the data about the best-fit displacement rate is consistent with the given uncertainties. All other GPS

results discussed in this chapter are based on measurements in 1988 and 1991, and there are potential systematic errors. 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 vector from GPS is comparable to the uncertainty for the same vector in the NUVEL-1 model; with future occupations, GPS can be expected to determine relative plate motions with a precision comparable to or better than that of the NUVEL-1 plate motion model (Frey-mueller et al., 1993). Past plate motion determinations and plate margin geometries must be constrained by other methods, however. The gravity field (Fig. 5; Stallings et al., Appendix, this volume), for example, can help to constrain the geometry of paleo-plate margins.

## GRAVITY

### *Density model of the North Panama fold (deformed) belt*

The northern margins of Panama and Colombia consist of extensive fold belts (Case, 1974; Bowin, 1976) that are part of a deformed zone extending from Costa Rica to eastern Venezuela (Fig. 6). As much as 10 km of Tertiary turbidites, carbonates, and fluvial and lacustrine sediments have been preserved in the deformed belt in northern Colombia (Duque-

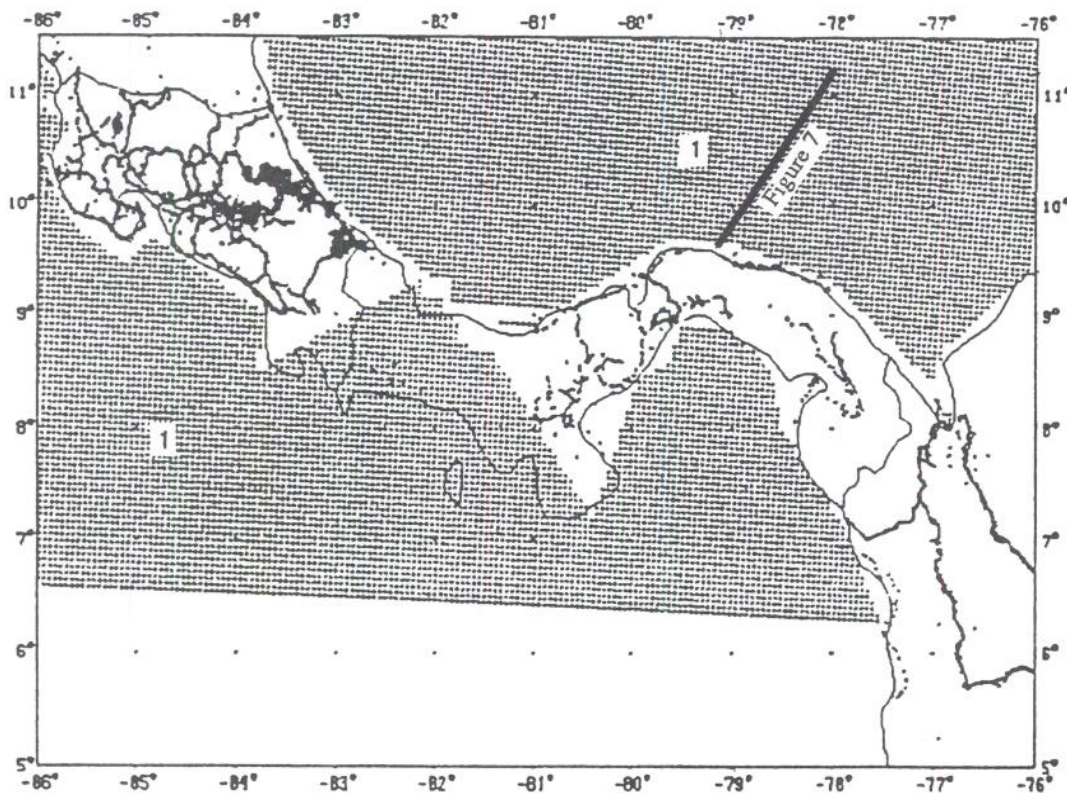


Figure 5. Data source location map for gravity anomaly map of southern Central America (Stallings et al., Appendix, this volume). 1: National Geophysical Data Center (1990). Figure 7: Profile of the North Panama fold belt.

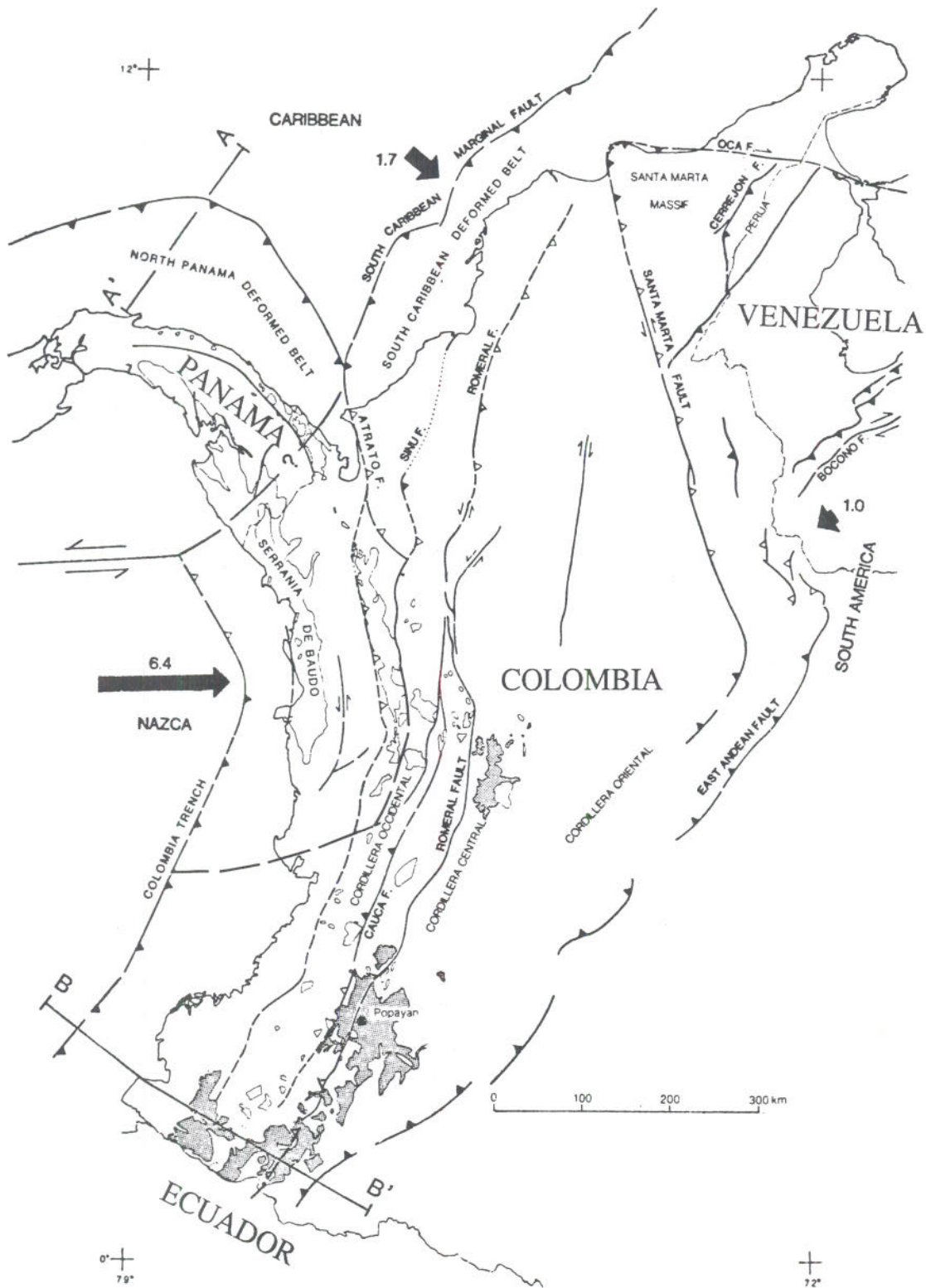


Figure 6. Tectonic map of northwestern South America. Enclosed areas are exposed Tertiary igneous rocks; stippled areas are the youngest andesites and dacites (Tertiary-Quaternary). Dark bars: active overthrusts. Open bars: inactive or uncertain. Left-lateral slip shown for the northern Romeral fault zone is based on the results of a 17-month microearthquake seismic study (Hutchings et al., 1981). Present-day plate motions (bold arrows) relative to the northern Andes showing average slip rates (cm/yr) during the last 5 to 10 m.y. are after Minster and Jordan (1978). A-A': Profile of North Panama fold belt (Figure 7). B-B': Profile of the Andean margin in southern Colombia (Figures 8 and 9).



Caro, 1979). The North Panama fold belt is bounded on the south by uplifted oceanic basalts, andesites, silicic intrusives, and scattered Tertiary and Quaternary volcanic deposits of eastern Panama (Terry, 1956; Case, 1974).

Seismic refraction measurements near the North Panama fold belt indicate that the Colombian basin crust is oceanic, although its 15-km thickness is greater than typical oceanic crust (Ewing et al., 1960; Houtz and Ludwig, 1977). A multichannel seismic survey shows undeformed Caribbean acoustic basement dipping landward beneath folded sediments of the deformed belt (Lu and McMillen, 1982). Lu and McMillen (1982) pointed out the similarities of the deformed belt with active margins elsewhere and noted that the youngest sediments were involved in the folding.

A two-dimensional density model (Fig. 7; Ogujiofor, 1985) was constructed along multichannel seismic profile CT1-21 of the North Panama fold belt (Lu and McMillen, 1982). Densities were derived from refraction interval velocities (Ewing et al., 1960; Houtz and Ludwig, 1977) using the empirical velocity-density relationships of Nafe and Drake (1957) and Gardner et al. (1974).

The observed gravity field is similar to those of other active accretionary wedges with a forearc basin and landward-dipping oceanic crust beneath the arc (Bowin, 1976; Briceño-Guarupe, 1978). Arcward (south) of the basin, crustal rocks have high densities suggestive of oceanic crustal basement. Mechanically, the arc could therefore be expected to act as a very rigid backstop relative to the weak accretionary wedge.

From the cross-sectional area and geometry of the accretionary prism as shown in Figure 7, an order of magnitude esti-

mate can be made for the age of the prism. We assume that the thickness of sediments on the underthrusting Caribbean plate is constant (1.9 km), the Panama-Caribbean convergence vector is constant (11 mm/yr approximately north/south; Fig. 2), and the contribution of river sediment to the prism is 1,000 metric tons/yr/km<sup>2</sup> of area drained (Milliman and Meade, 1983). If we assume that all of the sediments on the underthrusting Caribbean plate are accreted to the prism, we calculate the river sediment input as 24% of the total and the age of the prism as approximately 18 Ma. Total Panama-Caribbean convergence would be on the order of 200 km. Seismic stratigraphic analysis of the southern Colombian basin (Bowland, 1984) independently suggests that the North Panama fold belt has been active since middle Miocene time (11 to 17 Ma).

#### *Geological and gravity cross sections of the Andean margin in southern Colombia*

The Cordillera Occidental (West Andes or Western Cordillera) of Colombia (Fig. 6) is part of the Basic Igneous Complex, one of the world's largest ophiolitic complexes, which extends from Costa Rica through Panama and Colombia to Ecuador. The Western Cordillera consists of Cretaceous marine strata, ultramafic rocks, tholeiitic basalts, calc-alkaline mafic andesites, andesites, and Tertiary quartz diorite intrusives (Case et al., 1973; Galvis, 1980; Arango and Ponce, 1982; Bourgois et al., 1982; Grosser, 1989). In the Central and Eastern Cordilleras of southern Colombia, Quaternary andesitic volcanic deposits cover Precambrian migmatites and Paleozoic metamorphic rocks of greenschist to amphibolite grade (Arango and Ponce, 1982).

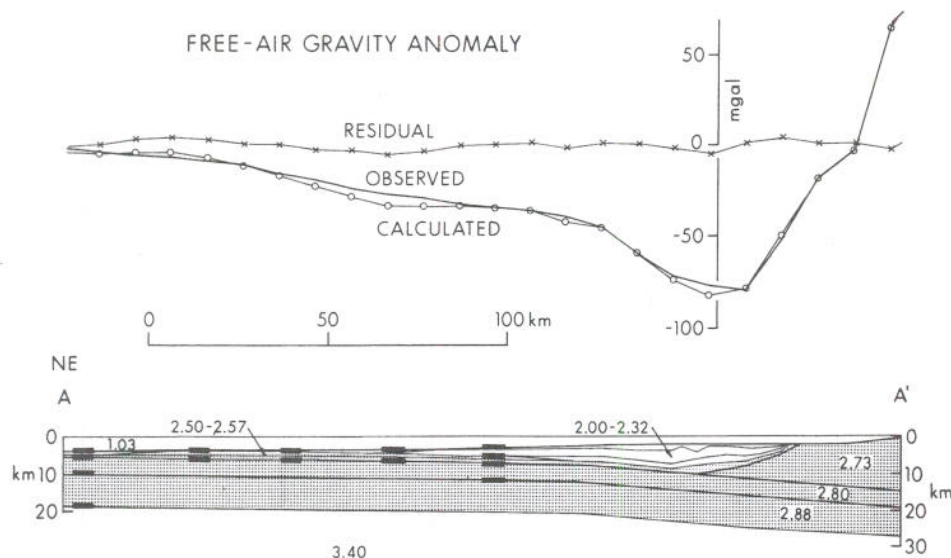


Figure 7. Section of North Panama fold belt showing observed free-air gravity anomalies (Kellogg et al., 1991), two-dimensional density model, and calculated and residual anomalies. Pattern: oceanic crustal basement, 2.73 to 2.88 g/cm<sup>3</sup>; dense sediments, 2.50 to 2.57 g/cm<sup>3</sup>. The bars indicate approximate locations of seismic refraction velocity discontinuities (Ewing and others, 1960; Houtz and Ludwig, 1977): 2.50 to 2.57 g/cm<sup>3</sup> (1.9 to 3.8 km/s), 2.80 g/cm<sup>3</sup> (4.6 to 6.1 km/s), 2.88 g/cm<sup>3</sup> (7.0 km/s), 3.40 g/cm<sup>3</sup> (8.2 km/s). For location, see Figs. 5 and 6 (A-A').

To explain the pronounced gravity and seismic velocity gradients across the Romeral fault system, Case et al. (1971, 1973) interpreted the fault as separating dense, high-velocity oceanic crust to the west from lighter, lower-velocity continental crust to the east. Meissner et al. (1976) reached a similar conclusion based on deep seismic refraction results from the Nariño Project. If the paleo-Romeral zone marks a Cretaceous trench, however, why is the fault system as close as 15 km to the Cretaceous batholiths? Bourgois and others (1982) concluded from a structural field study (4°N) that the Cretaceous ophiolitic suite of the Western Cordillera was emplaced by thrusting to the southeast.

To model the paleosuture geometry, Kellogg et al. (1985) constructed a schematic geologic cross section (Fig. 8) from the surface geology (Arango and Ponce, 1982; Ingeominas, 1988). The oceanic-continent suture zone is referred to in this chapter as the paleo-Romeral or Dolores suture zone. The trace of the suture zone was drawn between outcropping oceanic and continental rocks within the Central Cordillera of Colombia (Fig. 6; Arango and Ponce, 1982; Ingeominas, 1988). This is about 30 km east of where Case et al. (1973) placed the suture. Subsurface structure was partly constrained by seismic refraction data (Meissner et al., 1976). A density model (Fig. 9) was then constructed from the geologic cross section and the seismic velocities. The nonuniqueness problem of density models was thus minimized by seismic constraints and the requirement that the model make geological and structural sense. The thickness of sediments in the trench (Colombia fault), shown as 5 or 6 km in Figure 8, is actually no more than 3 km (Westbrook et al., this volume). Oceanic crust is all shown as metaophiolite in this schematic cross section (Fig. 8). The descending oceanic crust can transform to eclogite at 30-km depth, resulting in a local density excess. Grow and Bowin (1975) estimated the regional gravity contribution due to the descending lithosphere at the Chile margin as over 160 mGals at the shore line, decreasing gradually to the east. However, the steep gravity gradients associated with the Western Cordillera gravity high, both parallel to and perpendicular to the margin (Kellogg et al., 1991), indicate that the density anomaly has a crustal origin not associated with the descending lithosphere. Because the regional gravity contribution of the descending lithosphere does not significantly affect the Andean crustal density interpretation, it has been ignored in the density model (Fig. 9). Terrain corrections were not attempted because of inadequate topographic map coverage, but Case et al. (1973) estimated them as up to 15 mGals. Terrain corrections should not significantly affect our interpretation of the 275-mGal anomaly associated with the ocean-continent suture zone.

The crustal thickness model derived from the gravity data by Case et al. (1973) was supported by the deep seismic refraction data from the Nariño Project (Meissner et al., 1976). The crust is as thick as 45 km under the altiplano and as thin as 28 km beneath the Western Andes (Figs. 8 and 9). However, our

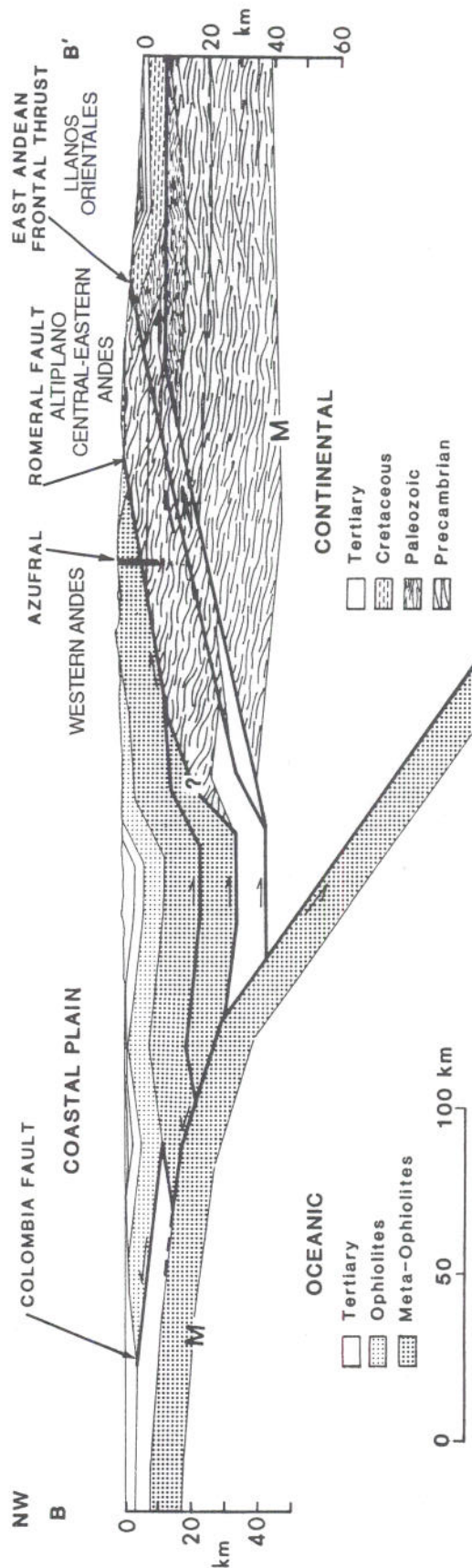


Figure 8. Geologic cross section of the Andean margin in southern Colombia. The vertical bar is a schematic feeder conduit for Azufral volcano. M: Moho boundary. No vertical exaggeration. For location see Figure 6 (B-B').

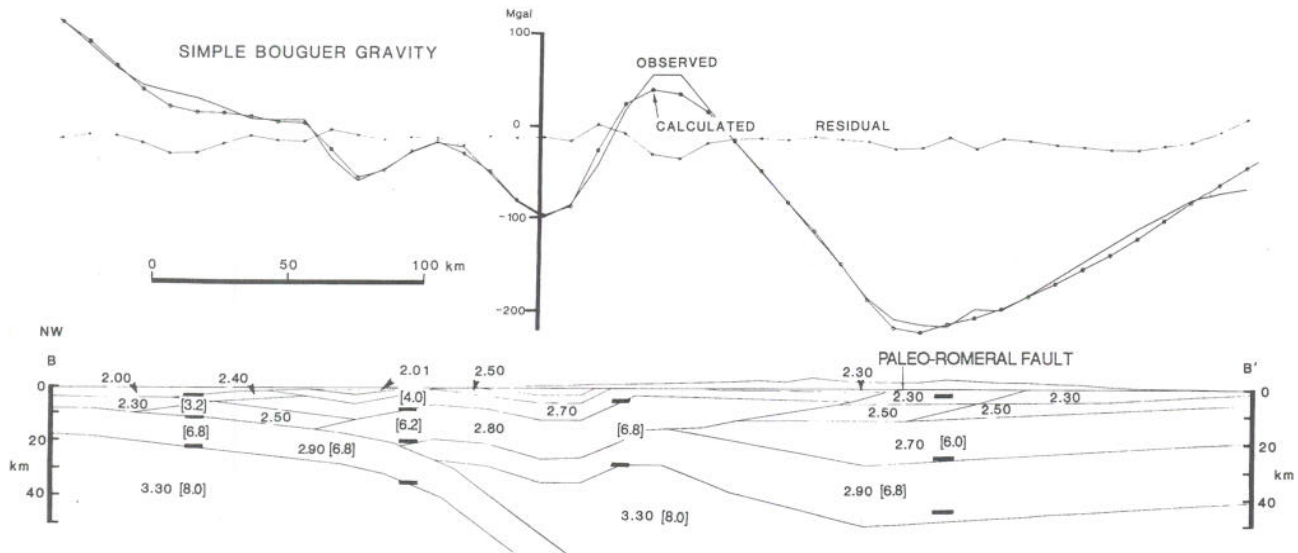


Figure 9. Section of the Andean margin in southern Colombia showing the observed Bouguer gravity anomalies (Kellogg et al., 1991), two-dimensional sea-level density model ( $\text{g}/\text{cm}^3$ ), and calculated and residual anomalies. Bars indicate approximate locations of seismic velocity discontinuities from Project Nariño refraction studies (Meissner and others, 1976) with the velocities (km/s) in brackets. No vertical exaggeration. Same location as Figure 8.

model differs from that of Case et al. (1973) in the shallow structure of the suture zone. The difference is primarily caused by our relocation of the surface trace of the paleo-Romeral suture zone based on geologic mapping by Arango and Ponce (1982) and Ingeominas (1988). The observed geology, gravity, and seismic velocities are compatible with a low-angle (approximately  $12^\circ$ ) northwest dip on the paleo-Romeral fault (Figs. 8 and 9). Our model supports the conclusion of Tousseint (1978) and of Bourgois and others (1982) that during the Cretaceous period the Western Cordillera oceanic terrane was obducted eastward over continental crust. Ophiolite slabs dipping into the lower crust and upper mantle (Coleman, 1971) are also suggested by geophysical studies of the Troodos massif of Cyprus (Gass and Masson-Smith, 1963), the Eastern Papua New Guinea belt (Milsom, 1973; Finlayson et al., 1977), and the New Caledonia ultramafic complex (Collot et al., 1987). Our geologic cross section (Fig. 8) suggests at least 70 km of horizontal shortening on the paleo-Romeral fault. Such convergence might help explain the proximity of the suture and the Cretaceous batholiths.

Paleozoic and Precambrian crystalline rocks and Cretaceous units overthrust Tertiary sediments on the East Andean frontal thrust fault (Arango and Ponce, 1982), but there is no large gravity anomaly associated with the fault zone. The densities of the metamorphic units may have been reduced by fracturing, or the East Andean décollement may be shallower than we have proposed.

## DISCUSSION

### *Present plate motions*

Observed GPS Isla San Andres–Panama City baseline rates of change (Fig. 10) support Panama–Caribbean convergence proposed by Adamek et al. (1988) and Silver et al. (1990). The measured convergence rate (11 mm/yr) is not significantly different at the 95% confidence level from the 7 mm/yr proposed by Silver et al. (1990). The lack of significant movement between Panama City, Panama, and Liberia, Costa Rica, agrees with the rigid Panama microplate model proposed by Adamek et al. (1988) if the microplate includes most of Costa Rica (Fig. 2) but does not support the active Panama bending model (Silver et al., 1990) or the left-shear model (Mann and Corrigan, 1990). However, this preliminary conclusion is only based on observations at two sites in Central America, and the geology of the isthmus and North Panama fold belt suggest that both bending and left-shear were important deformation mechanisms in the past. Alternatively, the Liberia observations can be explained with elastic strain accumulation with a locked subduction zone (Dixon, 1993).

The measured Panama City–Isla Malpelo velocity vector (Figs. 2 and 10) indicates left-lateral strike-slip movement on a transform fault south of Panama, as suggested by Jordan (1975). The small magnitude of the vector (35 mm/yr) and the slower convergence at the Colombia trench (50 mm/yr, Malpelo–Cali,

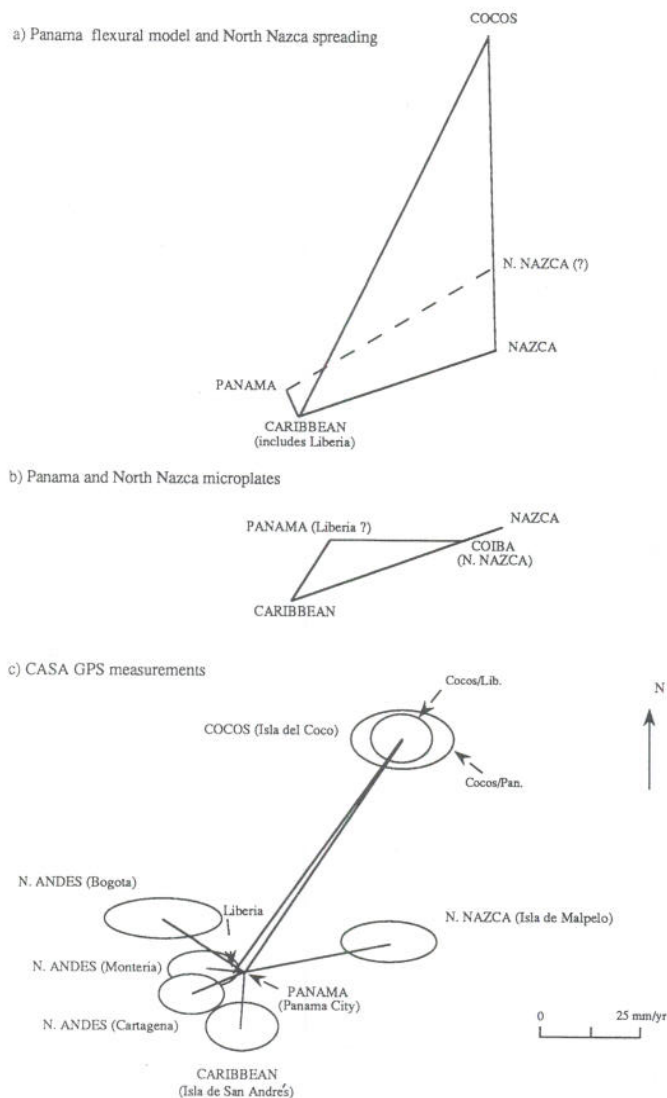


Figure 10. a, Velocity vector diagram for Panama flexural model and North Nazca spreading, after Silver et al. (1990) and de Boer et al. (1988). b, Velocity vector diagram for rigid Panama and North Nazca microplates, after Adamek et al. (1988). c, Observed GPS baseline rates of change, with their 95% confidence ellipses. Baseline change rates are shown as velocity vectors relative to Panama City. Vector is also shown for Isla del Coco-Liberia, Costa Rica.

Fig. 2) than at the Ecuador trench (70 mm/yr, Baltra-Jerusalem, Fig. 2) supports the existence of a separate North Nazca plate, similar to those proposed by Wolters (1986) and Adamek et al. (1988) but extending south of Isla Malpelo. The GPS observations do not indicate significant active northward spreading in the northern part of the Nazca plate as proposed by de Boer et al. (1988, Fig. 10; Silver et al., 1990).

GPS measurements also suggest that the Panama-Costa Rica microplate is continuing to collide eastward with the

northern Andes. Rapid subduction is occurring at the Middle America and the Colombia-Ecuador trenches. The northern Andes are moving northeast relative to stable South America. Preliminary GPS results also suggest Caribbean-North Andean convergence, with most of the deformation occurring at the South Caribbean deformed belt.

### *Miocene collision of Panama arc and South America*

The Panama-Choco arc terrane (Figs. 6 and 11) can be recognized in the Western Cordillera by positive gravity anomalies that are continuous over the Serrania de San Blas-Darien in Panama (Case et al., 1971; Case, 1974; Kellogg et al., 1991; Stallings and others, Appendix, this volume); exotic Paleocene planktonic foraminifera, which resemble the Paleocene fauna of northern Central America in Guatemala and Mexico (Duque-Caro, 1990); and Eocene-Oligocene age (34 to 47 Ma) calc-alkaline mafic andesites and andesites (Grosser, 1989). The suture zone separating the Panama-Choco arc from South America passes southeastward along the Atrato fault, through the Western Cordillera of Colombia, then turns southwestward along the Garapatas or Isthmina fault zone to meet the Colombia trench (Figs. 6 and 11).

About 6 to 12 Ma the Panama-Choco island arc arrived on the Caribbean plate at the northwestern margin of South America (Fig. 11; Keigwin, 1982; Keller et al., 1989; Duque-Caro, 1990). The arc-continent collision eventually formed a land bridge between the Americas, allowing the migration of mammals; closed the Pacific-Caribbean seaway, drastically changing ocean circulation patterns and perhaps the world's climate, folded the East Panama deformed belt (Kolarsky and Mann, this volume); and uplifted the Eastern Cordillera of Colombia. The correlation between the Panama arc-South America collision and the uplift of the Eastern Cordillera is based on the geometry (the maximum shortening is east-southeast of the suture zone) and the Late Miocene-Pliocene timing of the uplift (Dengo and Covey, 1993). Estimates of shortening in the Eastern Cordillera based on balanced cross sections range from 100 to 150 km (Colletta et al., 1990; Dengo and Covey, 1993). Over a 12-m.y. period this would imply an average shortening rate of 8 to 13 mm/yr. Measurements over a three-year period with GPS satellite geodesy suggest ongoing collision at a rate of 10 to 20 mm/yr between Panama City and Bogota, Colombia.

The proposed Panama-Choco allochthonous arc also helps explain the occurrence of westward coarsening of quartzose turbidites of Late Cretaceous age in the Western Cordillera (Calle and Salinas, 1986; Duque-Caro, 1990). The observed westward coarsening is not in agreement with the eastern continental lands, the Central Cordillera, as the quartz source for these Cretaceous basins, the explanation that has previously been generally accepted.

### Late Cretaceous accretion of Western Cordillera oceanic terrane

During Late Cretaceous time, the suture zone between oceanic and continental crust was 250 km east of the present trench at the paleo-Romerol fault (Fig. 12). The geologic and gravity model in Figures 8 and 9 support the conclusion of Toussaint (1978), and Bourgois et al. (1982) that the Western Cordillera oceanic terrane was obducted eastward over continental crust. The trace of the suture zone in Figure 12 was drawn between outcropping oceanic and continental rocks within the Central Cordillera of Colombia (Arango and Ponce, 1982; Ingeominas, 1988) and thus represents schematically the position of the terrane boundaries at the end of obduction. The Western Cordillera (West Andean) oceanic terrane may have been derived from the Caribbean plate and been continuous with the Aves Ridge terrane (Fig. 12; Pindell and Barrett, 1990). The Western Cordillera terrane was an island arc south

in Ecuador and an immature oceanic island arc (e.g., Barrero, 1977; McCourt et al., 1984) or ocean crust (Bourgois et al., 1982) north in Colombia. The Aves Ridge terrane was subsequently transported eastward to its present location east of the Venezuelan Basin by Tertiary Caribbean plate motion. The andesitic arc rocks recognized by Barrero (1977) and Grosser (1989) in the northwest flank of the Western Cordillera are part of the Panama-Choco arc accreted during the last 6 to 12 m.y.

### SUMMARY

We propose the following simplified sequence of events for the accretionary development of southern Central America and the northern Andes:

1. During Late Cretaceous time the Western Cordillera oceanic terrane was obducted eastward on the paleo-Romerol suture zone over South American continental crust.
2. The accretion of the Sinu-San Jacinto sedimentary wedge (South Caribbean deformed belt) commenced in the Eocene epoch (Duque-Caro, 1979; Toto and Kellogg, 1992) contemporaneous with a major change in Caribbean plate motion.
3. In late Oligocene time uplift of the Central Cordillera of Colombia (unpublished apatite fission-track ages), the Santa Marta massif, and the Sierra de Perijá (Kellogg, 1984) began.

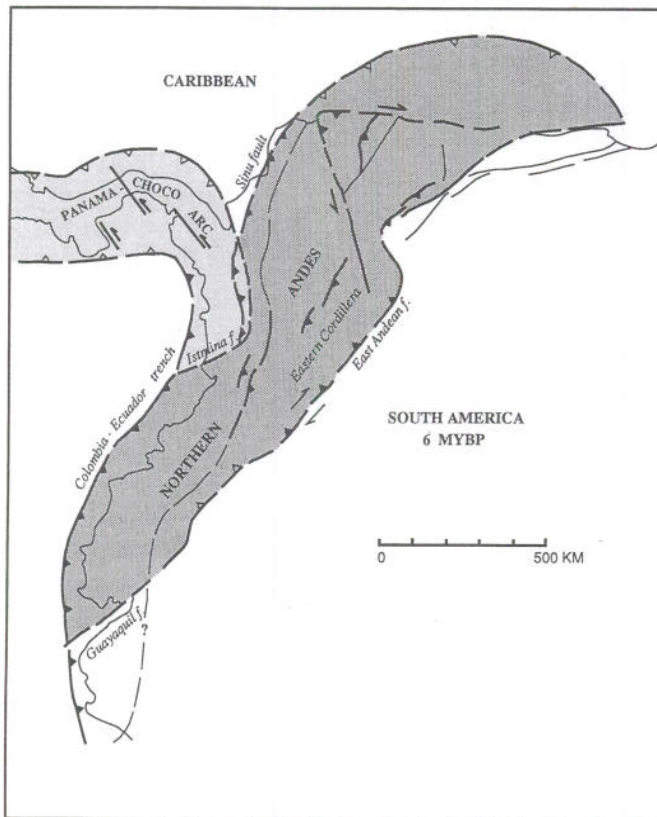


Figure 11. Schematic reconstruction of the northern Andean margin 6 Ma showing the Panama-Choco arc (light pattern) and the North Andean block or microplate (dark pattern). Plio-Pleistocene right-lateral strike-slip movement on the East Andean fault has been removed, but no attempt has been made to remove Plio-Pleistocene crustal shortening in the northern Andes. Open barbs on thrust zones: location uncertain. The present coastlines are shown for location.

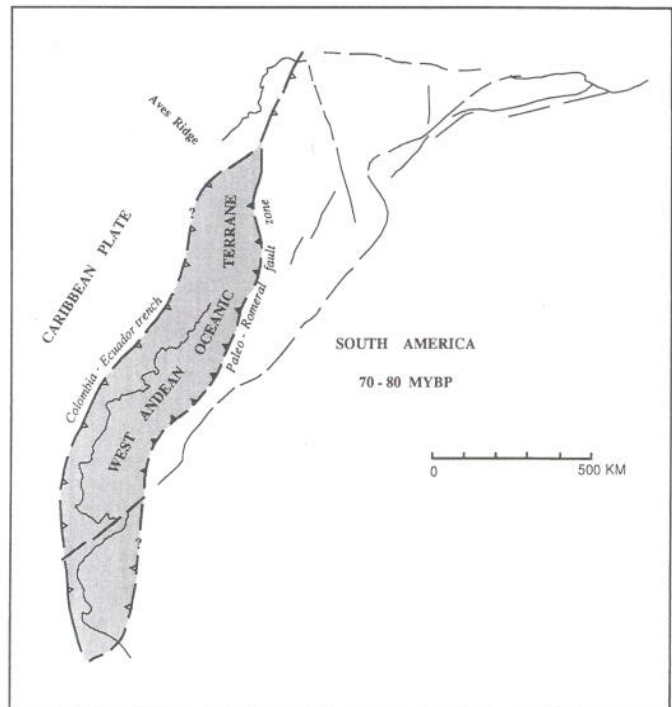


Figure 12. Schematic reconstruction of the northern Andean margin 70 to 80 Ma showing the positions of the Caribbean plate, the accreted West Andean oceanic terrane (dark pattern), the paleo-Romerol fault zone, and the Aves Ridge. Open barbs on thrust zones: location uncertain. The present coastlines and fault traces are shown for location.

4. The late Miocene-Pliocene collision of the Panama-Choco island arc with South America eventually formed a land bridge between the Americas, allowing the migration of mammals; closed the Pacific-Caribbean seaway, drastically changing ocean circulation patterns and perhaps the world's climate; folded the East Panama deformed belt; and uplifted the Eastern Cordillera of Colombia. The coastal range (Serranía de Baudo) was accreted to the continental margin.

5. GPS measurements suggest the existence of a rigid Panama-Costa Rica microplate that is moving northward relative to the stable Caribbean plate and continuing to collide eastward with the northern Andes. Measurements do not indicate active left-slip or bending of Panama. However, the geology of the isthmus and North Panama fold belt suggest that both left-slip and bending were important deformation mechanisms in the past. Rapid subduction is occurring at the Middle America and the Colombia-Ecuador trenches. The northern Andes are moving northeast relative to stable South America. Preliminary GPS results also suggest an independent North Nazca plate and Caribbean-North Andean convergence, with most of the deformation occurring in the South Caribbean deformed belt. We expect that additional occupations of the CASA GPS network will significantly improve the uncertainties in the GPS-derived plate motion rates and will help resolve details of active slip partitioning in southern Central America and the northern Andean margin.

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#### APPENDIX. GRAVITY ANOMALY MAP OF SOUTHERN CENTRAL AMERICA

*T. C. Stallings, Carlos L. V. Aiken, and James N. Kellogg*

The data used to construct the gravity anomaly map (Plate 1) were from several bases: (1) Aiken, C. L. V., University of Texas at Dallas, and Kellogg, J. N., University of South Carolina, Latin America gravity data base, 1992, (2) U.S. Geological Survey (Ponce, 1986), (3) Defense Mapping Agency/Gravity Library, St. Louis, 1990, and (4) Committee for Gravity Anomaly Map of North America (1987). All these data sets had principle facts except for (4), which consisted of a 6-km grid. In order to edit the data for the map the above order was used for prioritizing the preference of the station values if there were data value conflicts.

The offshore data consist exclusively of grid values from the Gravity Anomaly Map of North America, distributed by the National Geophysical Data Center (NGDC). Examining the station location map from the North American map, it can be seen that the offshore data are made up of some tracklines in the Caribbean, digitized contour maps over much of the area, and a grid of Seasat altimeter data for the remaining areas. This gridded data set was considered the most complete for the marine areas of the map, so part of the North American grid was extracted and used. The land areas of the new map (Plate 1) include data from Aiken and Kellogg that were used in the original North American map along with additional data from Aiken and Kellogg and new data from the Defense Mapping Agency and Ponce, 1986. The data coverage of Costa Rica, and to a lesser extent of Panama, is better than that used for previously published maps of the area. Part of the land coverage also includes the gridded North American data, because there were some areas in western Panama where the coverage from the grid was slightly superior. There are areas of very sparse gravity coverage in the map, especially along the Caribbean coasts of Nicaragua and western Panama.

The data were gridded at a 10-km interval and then contoured at 5-mGal intervals by the RADIANT COS/PC graphics software. Areas with very sparse data are left blank, and hachures are on the side of more negative gravity values. This marine free-air and land Bouguer anomaly map extends farther west and south than most published gravity maps of the area (e.g., Case et al., 1971; Bowin, 1976; Kellogg et al., 1991).

All the main tectonic elements discussed in the text (Fig. 2) have apparent gravity expressions. This is especially true for the marine free-air anomalies that reflect the bathymetry, and hence the first-order tectonics. For example, the trenches, which are great bathymetric lows, result in elongate gravity lows off the Pacific coasts of Nicaragua and Costa Rica and off the Colombian coast. The high Cocos Ridge, trending northeasterly perpendicular to the Middle America trench (Fig. 4), is associated with a gravity high. The Middle America trench is intersected by the north-trending Panama fracture zone, which is characterized by a series of parallel gravity highs and lows. To its east is a parallel gravity high over the Coiba Ridge. The gravity low north of Panama reflects the thick sedimentary wedge of the North Panama fold belt (Fig. 7).

On land, Bouguer gravity anomaly lows are associated with the volcanoes of northern Costa Rica. High Bouguer gravity anomalies reflect the uplift of oceanic crust in Panama (Case et al., 1971) and the continuation of the Panama-Choco arc (Fig. 11) into northwestern Colombia.

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