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GPS MEASUREMENT OF RELATIVE MOTION OF THE COCOS AND CARIBBEAN PLATES AND STRAIN ACCUMULATION ACROSS THE MIDDLE AMERICA TRENCH

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Abstract. Global Positioning System (GPS) measurements in 1988 and 1991 on Cocos Island (Cocos plate), San Andres Island (Caribbean plate), and Liberia (Caribbean plate, mainland Costa Rica) provide an estimate of relative motion between the Cocos and Caribbean plates. The data for Cocos and San Andres Islands, both located more than 400 km from the Middle America Trench, define a velocity that is equivalent within two standard errors (7 mm/yr rate, 5 degrees azimuth) to the NUVEL-1 plate motion model. The data for Liberia, 120 km from the trench, define a velocity that is similar in azimuth but substantially different in rate from NUVEL-1. The discrepancy can be explained with a simple model of elastic strain accumulation with a subduction zone that is locked to a relatively shallow (20±5 km) depth.

Introduction

Global plate motion models such as NUVEL-1 [DeMets et al., 1990] predict relative plate motion in subduction zones based primarily on closure constraints from the global plate circuit. Subduction zones provide no direct rate data to constrain plate motion models, while the directional constraint provided by trench earthquake slip vectors is relatively weak. Slip vector azimuths can exhibit a high degree of scatter, and may be systematically biased due to refraction of seismic waves by the cold slab or tectonic consequences of oblique convergence [DeMets et al., 1990]. It is therefore useful to test the predictions of global models for subduction zones with space geodetic measurements. Complicating factors include precision requirements, the great distances necessary to span the deforming zone, and the paucity of suitable geodetic sites on the subducting plate. Also, elastic strain accumulation and release during the earthquake cycle and permanent crustal deformation many hundreds of kilometers from the trench complicate interpretation of geodetic results.

The CASA (Central and South America) experiments investigate these and related questions with GPS geodetic measurements involving the Cocos, Nazca, Caribbean and South American plates [Kellogg and Dixon, 1990]. I report here results quantifying convergence between the Cocos and Caribbean plates and documenting elastic strain accumulation within several hundred km of the Middle America Trench.

Data Analysis and Results

Major CASA GPS campaigns were conducted in 1988 and 1991. Each campaign included the establishment of a global tracking network for satellite orbit and reference frame definition [Kornreich Wolf et al., 1990; Kellogg and Dixon, 1990]. In the absence of such networks, baseline-length dependent errors can be significant [Larson et al., 1991], obscuring the geologic signals we seek to measure given the long distances, nearly 1000 km in the case of the Cocos-San Andres baseline. Freymueller et al. [1993] report results from these experiments using the "fiducial approach" in which a subset of the tracking sites is fixed to predetermined values. One disadvantage of this approach is that systematic errors in locations of the fiducial sites propagate into satellite orbit and site position estimates, leading to systematic errors in the site velocities of interest. This study uses the "no-fiducial" approach [Herring et al., 1991; Blewitt et al., 1992; Heflin et al., 1992] with the positions of all sites estimated, avoiding systematic error from fiducial site mislocation. Estimated positions are subsequently translated, rotated and scaled into a stable reference frame (in this case the International Terrestrial Reference Frame, ITRF-90) for comparison of data acquired at different epochs. Despite these differences, the results reported here and by Freymueller et al. [1993] are very similar and overlap within uncertainties (quoted here at twice the standard error).

Data were analyzed using the GIPSY software [Blewitt, 1989; Lichten, 1990] following analytical conditions listed in Dixon et al. [1993] except that polar motion was estimated and the no fiducial approach was used. Velocities and errors are based on weighted least squares fits through position data, with weights from formal errors scaled by day to day scatter. Results are summarized in Table 1 and Figures 1 and 2.

Discussion

The velocity of San Andres Island (Caribbean plate) with respect to Cocos Island (Cocos plate) is 88±7 mm/yr at an azimuth of 202±11°, identical within errors to the NUVEL-1 prediction. Since both sites are well away from the near-trench deforming zone, we conclude that the NUVEL-1 model, despite lack of strong data constraints in subduction zones and despite being an average over several million years, is an accurate representation of the far field motion across this subduction zone even for much shorter time scales. While additional GPS measurements here are important for investigating possible biases in the data or model at the level of a few per cent, the general agreement between GPS and NUVEL-1 velocities is an important result.

In contrast the velocity of Liberia on the west coast of Costa Rica relative to Cocos Island differs significantly from the NUVEL-1 prediction. While the vector azimuth agrees at the two standard error level, the GPS rate (70±5 mm/yr) is significantly less than the NUVEL-1 rate (85±6 mm/yr at Liberia). There are four plausible explanations for the discrepancy: 1. the GPS result is affected by systematic error;

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TABLE 1: Velocities Relative to Cocos Island[1]

	Liberia	Albrook	San Andres	NUVEL
Rate (mm/yr)	70±5	75±8	88±7	89±6
Azimuth (°East of North)	209±8	203±10	202±11	203±3

[1] NUVEL-1 vector (Caribbean-Cocos) at San Andres, from DeMets et al. [1990] with 4% rate decrease for recent adjustment to paleomagnetic time scale [DeMets, personal communication]. Uncertainties are twice standard error.

2. there is crustal shortening and permanent deformation inland (northeast) of Liberia; 3; the GPS result is affected by coseismic offsets; 4. elastic strain is accumulating near the trench, to be released later in an earthquake.

I reject (for now) the first explanation, for several reasons. First, the analytical approach used is designed to eliminate the largest known source of systematic error, namely the systematic error associated with fiducial site mislocation. Second, the result for the San Andres site is plausible in the context of other information such as the NUVEL-1 model, suggesting that systematic errors are not dominating our solutions. Third, the "no fiducial" technique gives a general indication of data quality from differences between "known" tracking site coordinates defined by a given reference frame and estimated coordinates for these sites based on the GPS data. These differences (for 7 global sites in 1988 and 12 in 1991) are typically less than 30 millimeters, too small to affect site velocity estimates in the CASA region by more than a few mm/yr. Fourth, Freymueller et al. (1993) report a result for the Cocos-Liberia baseline that is identical within errors to the result reported here. Their result is based on three experiments (1988, 1990, 1991) analyzed using the fiducial approach (we were unable to process the 1990 data with the no fiducial approach because of the limited tracking network for that period). Without additional observations we cannot eliminate the possibility of a blunder or other local effect specific to Liberia, but available evidence suggests that the velocity estimate reported here is realistic.

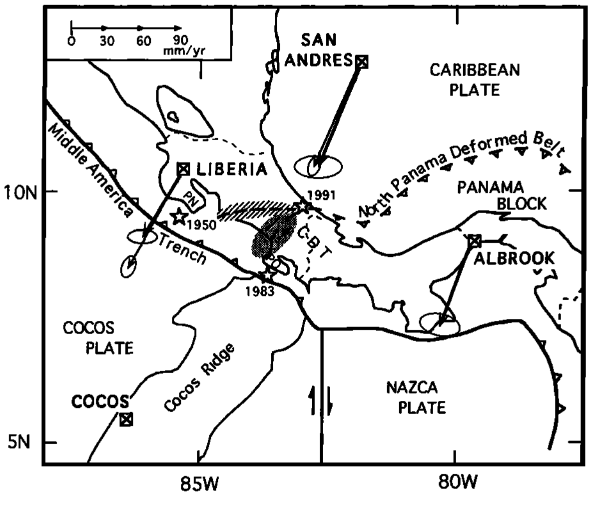

Fig. 1. Sketch map with plate or block boundaries, predicted motion (NUVEL-1, light lines, arrow) and observed motion (GPS, bold lines, arrow) of selected sites (squares with crosses) including San Andres and Liberia (Caribbean plate) relative to Cocos (Cocos plate). Ellipses at 2 standard errors. Stars are M_S>7.0 well located earthquakes (1950, M_S=7.7; 1983, M_S=7.2; 1991, M_S=7.6). CDT is Cordillera de Talamanca, PN is Peninsula de Nicoya, PO is Peninsula de Osa. Shaded area (west end, Panama block) is diffuse shear zone postulated by Goes et al. [1993] to mark boundary of Panama block; lined area is corresponding location from Jacob et al. [1991]. Modified from Goes et al. [1993].

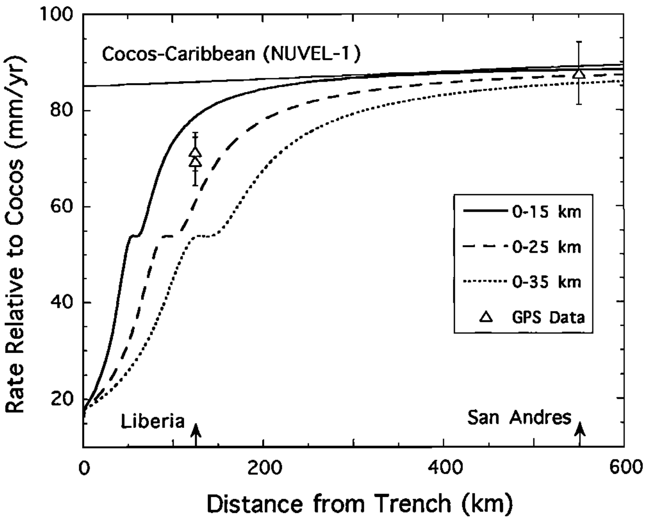

Fig. 2. GPS rates and errors (2σ) for sites Liberia and San Andres (Caribbean plate) relative to Cocos (Cocos plate). Two data points at Liberia are same data analyzed with fiducial [Freymueller et al., 1993] and no fiducial (this study) approaches. Curves show predicted velocity for elastic half space model of strain accumulation above locked subduction zone [Savage, 1983] dipping at 15° for three locking depths (surface to 15, 25 and 35 km). Kinks show surface location above transition from locked behavior to aseismic slip.

Significant crustal shortening northeast of Liberia can be eliminated on geologic grounds. The discrepancy (15 mm/yr), if accommodated by crustal shortening over geologic time, would result in an active fold and thrust belt with significant topographic elevation, which is not observed. While such deformation is clearly going on north of Panama offshore along the North Panama Deformed Belt (discussed below) and in southeastern Costa Rica in the Cordillera de Talamanca (Figure 1), it does not appear to be occurring in the "back arc" region behind Liberia. Small amounts (a few mm/yr or less) of such deformation cannot be precluded, but the explanation for the majority of the discrepancy must be sought elsewhere.

The only significant earthquake between the GPS measurements was a M_S=7.0 earthquake in 1990, a shallow, thrusting subduction zone event located near the trench about 100 km south of Liberia (M. Protti, personal communication). Elastic dislocation models (Freymueller et al., 1993) suggest ~20 mm of southward motion at Liberia, too small and in the wrong direction to explain the discrepancy.

Elastic strain accumulation is a plausible mechanism. Strain accumulation models in many subduction zones satisfy a variety of geologic, seismic and geodetic data. Locking at the thrust interface between subducting and overriding plates is assumed to occur in the high strength brittle upper crust, transferring strain (and stress) to the overriding plate, to be released at some future time in an earthquake. I have tested this hypothesis with simple forward models, comparing GPS-based velocities to the dislocation model for strain accumulation of Savage [1983]. The locked condition is simulated by adding a supplementary solution (normal slip at the plate rate) to steady state subduction on the locked portion of the thrust zone, which everywhere else slips aseismically at the full plate rate. Surface velocities for normal slip in an elastic half space were obtained following Savage [1980, Equation 115]. Input parameters for the model are the far field convergence rate, from NUVEL-1, the depth limit of the locked zone, varied between 15 and 35 km, and the dip of the locked zone. From the trench inland several tens of km, seismic reflection indicates very shallow (5°-10°) dips for the decollement separating subducting and overriding plates [Shipley et al., 1982]. Within 40-50 km of the trench, seismicity begins to define the plate interface, and shows that dips steepen to ~10°-25°. This dip is maintained to depths of 50-60 km, then steepens further to ~60° [Burbach et al., 1984]. The intermediate portion of the plate interface is of interest here, consequently a dip angle of 15° is employed.

Model results are shown in Figure 2. The GPS data can be explained by elastic strain accumulation with the thrust interface between the plates locked to shallow (<25 km) depths. We can test the plausibility of this model not only by its ability to fit the sparse GPS data, but by the extent to which the modeled depth of the locked zone is consistent with other data, e.g., earthquake depths. If we consider only thrusting earthquakes that rupture the interface between subducting and overriding plates and not deeper events within the slab, then the maximum earthquake depth should correspond to the base of the locked zone in the model. Typical seismogenic depths for large (M_S>7.0) interplate thrusting earthquakes along the Middle America Trench are less than 25 km [Singh and Mortera, 1991; Burbach et al., 1984] in good agreement with the model. A complicating factor for Costa Rica is that shallow interplate thrust earthquakes are rare; the 25 km depth cutoff is better defined on the basis of earthquakes to the north near Nicaragua and southern Mexico [Singh and Mortera, 1991; Burbach et al., 1984]. While shallow thrusting earthquakes have occurred on the Costa Rica segment of the trench in the past, most recently in 1950 (M_S=7.7; Figure 1), the depths of these events are poorly constrained. Smaller thrust earthquakes occurred in 1990 just south of the Nicoya region (M_S=7.0, depth 20 km) and in 1983 off the Osa Peninsula (M_S=7.2, depth 24 km) [Jacob et al. 1991] (Figure 1). In summary, available seismic data suggest that large interplate thrusting earthquakes in this part of the trench nucleate above 25 km, in agreement with the strain model.

The Panama Block

The Panama block is defined mainly on the basis of the Northern Panama Deformed Belt (NPDB), a series of active shallow folds and thrust faults in the Caribbean basin offshore northern Panama (Silver et al., 1990; Figure 1). GPS data for a single site in Panama (Albrook; Figure 1) show that motion of the Panama block relative to the Cocos plate is similar in direction to the Caribbean plate but slower, probably due to compression across the NPDB (~13±10 mm/yr NNE-SSW based on the difference between the Albrook and San Andres velocity vectors). The April 1991 M_S=7.6 Costa Rica earthquake occurred on a shallow southwest dipping thrust fault associated with the onshore extension of the NPDB in Costa Rica (Figure 1) [Plafker and Ward, 1992]. Could deformation in this belt extend west, affecting the Liberia site?

Aftershocks for the 1991 event define a diffuse zone with left-lateral strike slip mechanisms trending southwest from the main shock [Dziewonski et al., 1992] and there is geological evidence for a complex zone of strike slip faulting near the termination of the rupture zone along its northwest edge [Ponce and Case, 1987]. These data led Goes et al. [1993] to suggest that the western boundary of the Panama Block is configured as shown in Figure 1. Jacob et al. [1991] suggest that this boundary trends more westerly (Figure 1) through the Valle Central of Costa Rica, on the basis of left lateral strike slip focal mechanisms for three earthquakes (M~7.0, 1924; M=6.0, 1983; M=5.9, 1991). In either case, Liberia is located considerably north of the postulated boundary (Figure 1). Thus deformation of the North Panama Deformed Belt and motion of the Panama block should not affect our interpretation of the Liberia GPS data.

Seismic Hazard

The results of this study suggest that at least one segment of the subduction interface between the Cocos and Caribbean plates is currently locked and accumulating elastic strain. The Nicoya segment of the Middle America Trench has broken repeatedly with large (M>7.0) earthquakes, including events in 1827, 1853, 1863, 1900 (M_S~7.2), 1916 (M_S~7.4), 1939 (M_S=7.3) and 1950 (M_S=7.7) [Nishenko, 1991]. All of these events are believed to be shallow (<25 km) interplate thrusting earthquakes. While the last major earthquake that fully ruptured this segment of the trench was in 1950, more recent events, including two M_S=7.0 events in 1978 and a M_S=7.0 event in 1990, have also occurred near the Nicoya region [Jacob et al., 1991]. Nishenko [1991] gives the recurrence interval for M_S≥7.0 events as 22±2 years, and lists this part of the Middle America Trench as a seismic gap with a 64% chance of rupturing in the period 1991-2001. The 1990 event was just south of the Nicoya segment.

Kagan and Jackson [1991] suggest that large subduction zone earthquakes cluster in time rather than exhibit periodic behavior. Ward [1991] suggests that both characteristic (single fault segment) and non-characteristic (multiple fault segment) ruptures could occur in the Middle America Trench depending on segment interaction. Thus while evidence of strain accumulation presented here confirms the obvious seismic hazard, by itself this is unlikely to lead to an accurate forecast of either the size or timing of a future earthquake.

McNally and Minster [1981] noted that seismic slip from regular trench earthquakes of the last century is much less than the total slip required by global plate motion models. The data presented here constrain possible explanations for this deficit. First, the GPS results rule out systematic errors in the plate motion models. Second, if the deficit is caused by some fraction of plate motion being accommodated aseismically, then it is more difficult to reconcile the depth data for shallow thrusting earthquakes in the region with the locking depth required by the GPS data, at least with the simple strain accumulation models presented here. While models can be generated that match the sparse GPS data and allow some aseismic slip (in Figure 2, these models would have a velocity step at the trench) the required depth limit for partial locking to match the GPS data is deeper than 25 km, i.e., deeper than observed interplate seismicity. Alternately, aseismic slip is not the explanation for the slip deficit, implying that strain may accumulate through several seismic cycles, and characteristic earthquakes of the historical record have not succeeded in releasing this accumulated long term strain. If correct, this explanation requires that the slip deficit will be made up in the future by earthquakes larger than characteristic events of the past. Stein et al. (1986) suggested a similar explanation for the great 1960 Chile earthquake, since seismic slip in that event was significantly larger than that implied by simple multiplication of recurrence interval by plate rate.

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