

Seismic cycle and plate margin deformation in Costa Rica: GPS observations from 1994 to 1997

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Abstract. Global Positioning System (GPS) observations in Costa Rica from 1994 to 1997 reveal a complex pattern of motion consistent with the superposition of seismic cycle and secular plate margin deformation. In the south, velocity vectors are consistent with motion of the Panama Block plus postseismic deformation following the 1991 Limon earthquake and interseismic strain due to partial locking of the Middle America Trench (MAT) thrust. In the northwest, sites west of the volcanic arc are moving to the NW as a forearc sliver. Superimposed on this sliver motion are vertical and horizontal interseismic deformations from the adjacent Nicoya segment of the MAT. We apply two different inverse methods to understand the source of the seismic strain in NW Costa Rica. We compare fault-locking models derived using a singular value decomposition inversion with that of a simulated annealing global optimization approach. Both methods yield similar models for partial locking of the thrust interface beneath the Nicoya Peninsula. Our results define an area of nearly fully locked fault beneath the outer coast of the southern portion of the peninsula, with somewhat lower coupling beneath the northern half and with low coupling elsewhere. These initial results show the promise for detailed imaging of the locked portion of a thrust interface responsible for future large subduction zone earthquakes.

1. Introduction

Costa Rica lies in a complicated tectonic setting featuring fast subduction, deformation of the Caribbean Plate margin, recent large earthquakes (Figure 1), and the unusual location of the Nicoya Peninsula, which lies near the Middle America Trench (MAT) directly above the seismogenic zone of the subduction underthrust [Mann *et al.*, 1990]. Off the southwest coast of Costa Rica the Cocos plate subducts along the MAT at a convergence rate of 86–92 mm/yr [DeMets *et al.*, 1994]. Along its southeast Caribbean coast lie the thrust faults of the North Panama Deformed Belt (NPDB), recently the location of the 1991 M_w 7.6 Limon earthquake [Plafker and Ward, 1992]. The NPDB becomes a shear zone that cuts inland across central Costa Rica and forms the northern boundary of the Panama Block [Protti and Schwartz, 1994]. Off the northwest Pacific coast, immediately NW of the Nicoya Peninsula, the 1992 M_w 7.6 Nicaragua tsunamigenic earthquake ruptured the upper portion of the subduction thrust [Kanamori and Kikuchi, 1993; Piatanesi *et al.*, 1996; Ihmle, 1996]. In 1990 a M_w 7.0 thrust event occurred directly SE of the Nicoya Peninsula [Protti *et al.*, 1995a]. This contrasts with the Nicoya segment, which lies between these two recent earthquakes and is currently seismically quiescent but has been the location of earthquakes with $M > 7.5$ as recently as 1950. The Nicoya Peninsula's unusual topography and long-term measured uplift and subsidence pattern are consistent with strong seismic coupling beneath it

and the repeated large earthquakes that rupture the length of the peninsula [Marshall and Anderson, 1995].

The Costa Rica (CORI) Global Positioning System (GPS) project was initiated in 1991 to address questions of seismic cycle deformation and plate margin deformation. It built upon measurements of coseismic displacements of the Limon earthquake in 1991 over a sparse GPS network [Lundgren *et al.*, 1993] with a specific goal of targeting the Nicoya segment, both because of its maturity in the earthquake cycle and because of the proximity of the Nicoya Peninsula to the trench, allowing much higher resolution of the distribution of slip over the seismogenic portion of the subduction thrust.

We present GPS solutions from the CORI network from 1994 to 1997. We find a spatiotemporal pattern of deformation that is consistent with the expected secular plate margin motions and a superimposed pattern of earthquake cycle deformation. In particular, we invert for elastic deformation due to slip on the thrust interface of the MAT off northwest Costa Rica. We find that a combination of trench parallel motion of the forearc and interseismic strain due to heterogeneous partial locking beneath the Nicoya Peninsula are required to model the GPS-derived velocities.

2. GPS Analysis

We measured site positions by analyzing data from dual-frequency GPS receivers. Observations were carried out from 3 to 5 days for most sites (some up to 2 weeks), with all sites measured in February 1994 and 1996. Twelve sites in NW Costa Rica were measured a third time in April 1997. Data from 1994 and 1996 were collected with TurboRogue receivers using Dorn-Margolin choke-ring antennas. Data from the 1997 survey were split between TurboRogues and Trimble 4000SSI receivers, with both types using choke-ring antennas to minimize systematic errors due to heterogeneous receivers and antennas.

We analyzed the GPS data using the GIPSY/OASIS II software [Lichten and Border, 1987; Webb and Zumberge,

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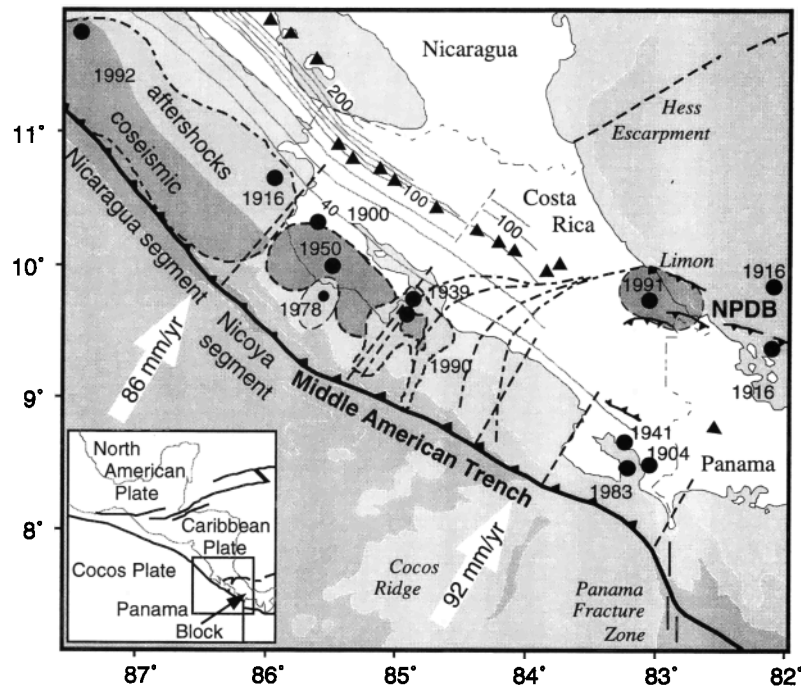


Figure 1. Tectonic map of Costa Rica. Solid circles, locations of $M > 7$ earthquakes of this century and their year; solid triangles, active volcanoes; shading shows the water depth and continuous lines the depth to the seismogenic slab in kilometers [Protti *et al.*, 1995b], NPDB, North Panama Deformed Belt; dashed lines perpendicular to the Middle American Trench delineate thrust segments; and dashed lines from the city of Limon across central Costa Rica represent the transcurrent northern boundary zone of the Panama Block.

1995; Zumberge *et al.*, 1997]. We used the precise orbits and clocks provided by the Jet Propulsion Laboratory, employing a reference-frame-free strategy [Heflin *et al.*, 1992] and correcting for carrier phase ambiguities [Blewitt, 1989]. Each of these daily network solutions were then transformed into the ITRF94 reference frame [Zumberge *et al.*, 1997]. All the daily solutions were combined to derive site positions and velocities using a weighted least squares inversion that is part of the GIPSY/OASIS II software. For each station, outlying daily solutions were removed (usually due to a short occupation interval on the first or last UTC day or due to noisy data). The affected daily network solution was then reanalyzed, and the site velocities were recombined. For the final set of combined solutions the reduced chi-square value was 13.49, suggesting that the calculated formal errors are too low. The data covariances were scaled by 13.49 to lower the reduced chi-square to 1, which is equivalent to scaling the solution errors by 3.67.

The final rates and their scaled one sigma errors are given in Table 1. Horizontal rate uncertainties are generally one to several millimeters per year, while vertical rate uncertainties are from 5 to >10 mm/yr and are similar in magnitude to campaign measurements found over a similar time period in Alaska (J. Freymueller *et al.*, Spatial variations in present-day deformation, Kenai Peninsula, Alaska, and their implications, submitted to *Journal of Geophysical Research*, 1999, hereafter referred to as Freymueller *et al.*, submitted manuscript, 1999). Several representative station time series are plotted (in ITRF94 reference frame) to give a feel for the velocity solutions (Figure 2). The examples shown are for sites in the Nicoya region, although sites in other parts of Costa Rica give similar solutions but without any data in 1997.

To convert horizontal velocities relative to a fixed Caribbean plate (Figure 3a), we used a model for the rotation of the Caribbean plate relative to ITRF94 [Dixon *et al.*, 1998]. This model is based on GPS solutions for two sites assumed to be on the stable Caribbean plate (SANA, San Andreas Island, and ROJO, Dominican Republic). The site ACOS is the site within the Costa Rica network that is most likely to lie on stable Caribbean lithosphere (or at least have the least amount of motion relative to that plate). We found it to have a very small motion directed away from the Middle America Trench, suggesting that the model of Dixon *et al.* [1998] provides a reasonable fit to this part of the Caribbean plate.

The horizontal velocities show distinct patterns of motion relative to the Caribbean plate. Across the Nicoya Peninsula, directly outboard of site ACOS, sites on the outer central Pacific coast side of the peninsula have high velocities toward the NE away from the MAT which decrease toward ACOS. This is the pattern expected for interseismic strain due to a locked fault (Figure 4). However, sites at the northern end of the Nicoya Peninsula show a counterclockwise rotation of the motion vectors to the NW. Significant NW motion of a sliver plate lying between the MAT and the volcanic arc along the Nicaragua Depression extending from northern Costa Rica into El Salvador has long been recognized from earthquake focal mechanisms [White, 1991]. This forearc sliver has been predicted to move at 15-20 mm/yr with respect to the Caribbean plate, based on the motion of the Caribbean and Cocos plates and their relative obliquity of convergence [DeMets *et al.*, 1996] and is similar to the 8-13 mm/yr motion predicted by numerical modeling of the plate margin (P. Lundgren and R. Russo; manuscript in preparation, 1999). Such a secular rate of plate sliver motion would only partially

Table 1. GPS Site Locations and Their Calculated Rates and Standard Deviations Relative to the Caribbean Plate

Site ID	Latitude	Longitude	North, mm/yr	North Error	East, mm/yr	East Error	Vertical, mm/yr	Vertical Error
ACOS	10.54	275.39	3.99	0.83	2.77	1.39	4.13	4.20
AGUJ	9.72	275.37	8.39	1.89	-2.09	2.98	-15.96	9.76
BALL	10.38	274.55	11.08	1.36	-2.77	1.87	-1.41	6.77
BRAT	9.55	277.10	8.23	1.97	13.95	3.15	-27.18	10.01
CABU	10.13	275.22	7.52	0.97	1.25	1.44	0.41	4.82
CAMP	8.63	277.16	7.31	1.91	12.00	3.34	-23.12	9.46
CARA	8.44	276.53	25.33	2.75	19.27	5.50	-8.19	14.62
CRUZ	11.05	274.36	7.76	1.60	-5.89	2.16	-0.29	7.75
ETCG	9.99	275.89	8.08	1.52	7.53	2.92	0.63	8.03
GRAN	10.56	274.34	9.96	1.31	-2.30	1.76	-3.43	6.39
GUAR	10.14	274.55	16.46	1.30	7.13	2.03	8.76	6.63
JICA	9.97	274.86	9.22	1.01	6.88	1.47	-1.18	5.02
LIBE	10.65	274.57	14.08	1.29	-3.43	1.91	1.17	6.58
LIMO	9.96	276.97	-0.52	1.62	8.09	2.38	-28.61	8.02
MANZ	9.61	277.32	9.61	3.13	9.63	5.71	-5.07	15.83
MATA	10.35	274.18	9.00	1.46	-1.03	2.26	-10.01	7.62
PAQU	9.83	275.04	9.83	1.12	5.20	1.85	7.38	5.96
SAMA	9.88	274.45	22.85	0.98	6.95	1.54	-27.51	5.21
SJOS	10.36	275.05	5.19	2.12	-4.87	3.81	7.29	10.94
SJUA	10.06	274.24	11.33	1.42	8.56	1.99	-9.26	6.88
TIGR	9.04	276.70	25.52	3.34	23.97	4.45	-16.62	17.62
VUEL	9.62	276.14	15.32	2.06	9.46	3.71	31.45	10.31
ZUMA	9.65	274.91	7.67	2.16	-0.76	3.39	-24.05	10.68

explain the observed horizontal motions. In addition, interseismic strain due to strong coupling of the Nicoya segment of the MAT and continued postseismic deformation from the September 1992 M_w 7.6 Nicaragua earthquake must also be considered as possible sources of deformation in NW Costa Rica. We will explore these more fully in the section 3.

In contrast to NW Costa Rica, the southern half of the country has horizontal motions that move to the ENE relative to the stable Caribbean plate (Figure 3a). This is the sense of motion expected for a separate Panama Block, consistent both with the seismicity of the NPDB [Wolters, 1986; Vergara Munoz, 1988], and with the GPS results measured in Panama as part of the Central and South America (CASA) project [Trenkamp et al., 1997].

Vertical motions (Figure 3b) are also found to be significant. In NW Costa Rica where we have three sets of measurements (Figure 3b), several sites on the coast of the Nicoya Peninsula have subsidence rates in excess of 10 mm/yr, transitioning to much smaller vertical rates inland. Generally, vertical GPS solutions have much larger uncertainties than do the horizontal component solutions, caused in large part by atmospheric effects, as well as other possible sources such as misread antenna heights, that most strongly affect the vertical component. Most plate tectonic motions are predominantly horizontal, and large vertical signals are mostly associated

with coseismic or postseismic deformation (e.g., Freymueller et al., submitted manuscript, 1999). In the case of subduction zones the coasts along most of these lie >100 km from the trench, resulting in limited vertical interseismic deformation. However, the Nicoya Peninsula extends into the region in which we might expect to find significant interseismic subsidence. Therefore, despite the large errors that exist in the vertical rates for Costa Rica, we have decided to include the vertical signal in our analysis of the Nicoya interseismic deformation and the inversion for the locked portions of the underlying subduction thrust interface. This is motivated by the large constraint that the vertical component has on defining the downdip extent of locking that cannot be matched by the corresponding changes in velocity of the horizontal component. This will be examined further in section 3.

In southeastern Costa Rica the large vertical subsidence is most likely associated with postseismic deformation after the 1991 earthquake. Subsidence is also found for sites closer to the Pacific coast of SE Costa Rica (AGUJ, CAMP, CARA, TIGR). These are suggestive of interseismic deformation due to locking of the MAT thrust. However, the sparseness of these sites, their large vertical uncertainties, and the lack of a clear corresponding pattern in their horizontal velocities (i.e., greater NE motion at the Pacific coast compared to sites inland) preclude a definitive interpretation at this time.

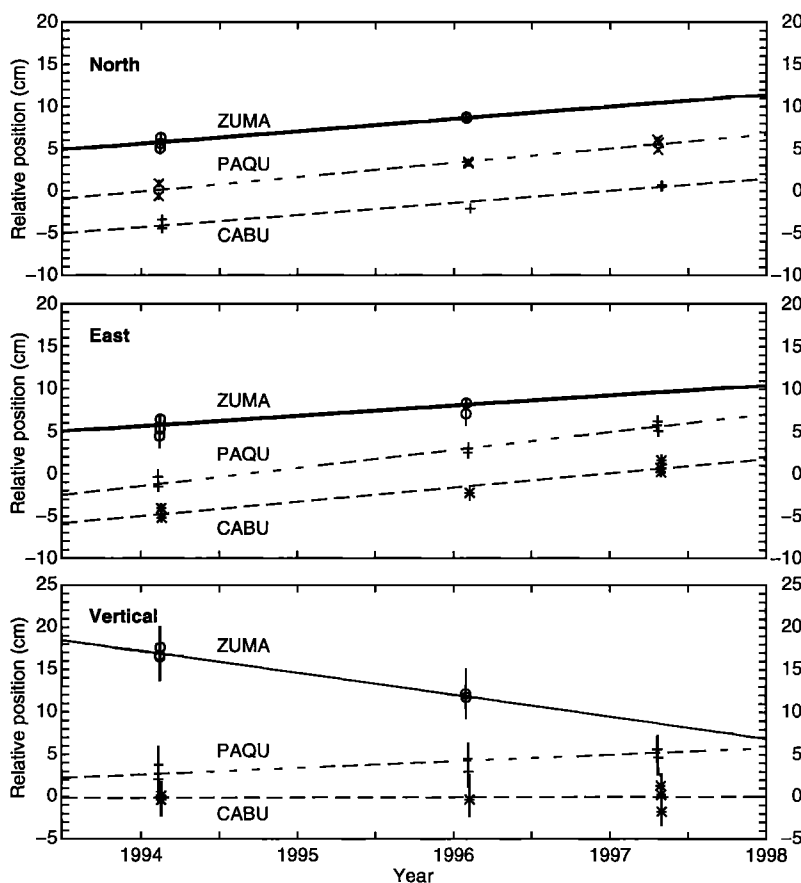


Figure 2. GPS time series for sites in the Nicoya region of NW Costa Rica. Each point represents a single day position with the scaled formal error given by the vertical line (scale factor 3.67). Solutions for different sites have been offset, tick marks are at 1-cm intervals. Station codes correspond to sites shown in Figure 3a.

3. Seismic Cycle Deformation in the Nicoya Region

The crustal motions in northwest Costa Rica are likely due to the superposition of three main deformations: secular sliver motion of the forearc; postseismic motions continuing after the 1992 Nicaragua earthquake; and interseismic strain along the rest of the MAT, in particular, along the seismogenic zone beneath the Nicoya segment. The large subsidence along the Nicoya coast transitioning to uplift farther inland appears to fit a simple dislocation model (Figure 4) for interseismic strain of a partially locked subduction thrust [Savage, 1983; Okada, 1985; Dixon, 1993]. The concept of interseismic deformation at a subduction zone is that the converging oceanic plate (Cocos in this case) subducts at a constant rate. Between earthquakes (interseismic period), the fault is locked, and the overriding plate deforms as the subducting plate drags it down and compresses it toward its interior.

In contrast to most other land areas adjacent to subduction zones, the Nicoya Peninsula lies especially close (within 55-60 km) to its trench. Therefore, while most other coastal areas adjacent to trenches lie at or inland from the hinge line (crossover from interseismic subsidence to uplift), Nicoya juts out well into the much larger amplitude subsidence region. In addition, horizontal velocities of coastal Nicoya sites with respect to ACOS in northern Costa Rica are significant, in keeping with an interseismic source for the observed deformation. An important feature of the Nicoya Peninsula

geometry is its potential for discriminating between models of seismogenic coupling. The data in the central Nicoya Peninsula have relatively large subsidence compared to their horizontal motion toward the plate interior, suggesting that the locked portion does not extend close to the trench (Figure 4). However, there is considerable spatial structure to the horizontal motions that is not easily fit with a simple cross-section model.

To solve for the subduction related seismic deformation in the Nicoya Peninsula region, we apply two different numerical inversion algorithms. Each method seeks to solve for a distribution of subfaults with varying slip to best match the GPS observed deformation. Hopefully, insight can be gained by examining where the fault slip models are similar and where they differ. As we will show, both methods give similar solutions and suggest that within the limitations of our GPS solutions and the spatial distribution of sites and within the intrinsic limitations for surface geodetic measurements to discriminate deformation sources with increasing distance (e.g., depth) from the source, the solutions provide reasonable constraints on the interseismic coupling of the Nicoya subduction segment.

4. Simulated Annealing

First, we apply a simulated annealing algorithm [Kirkpatrick *et al.*, 1983], an iterative global minimization approach that uses rectangular elastic half-space Greens

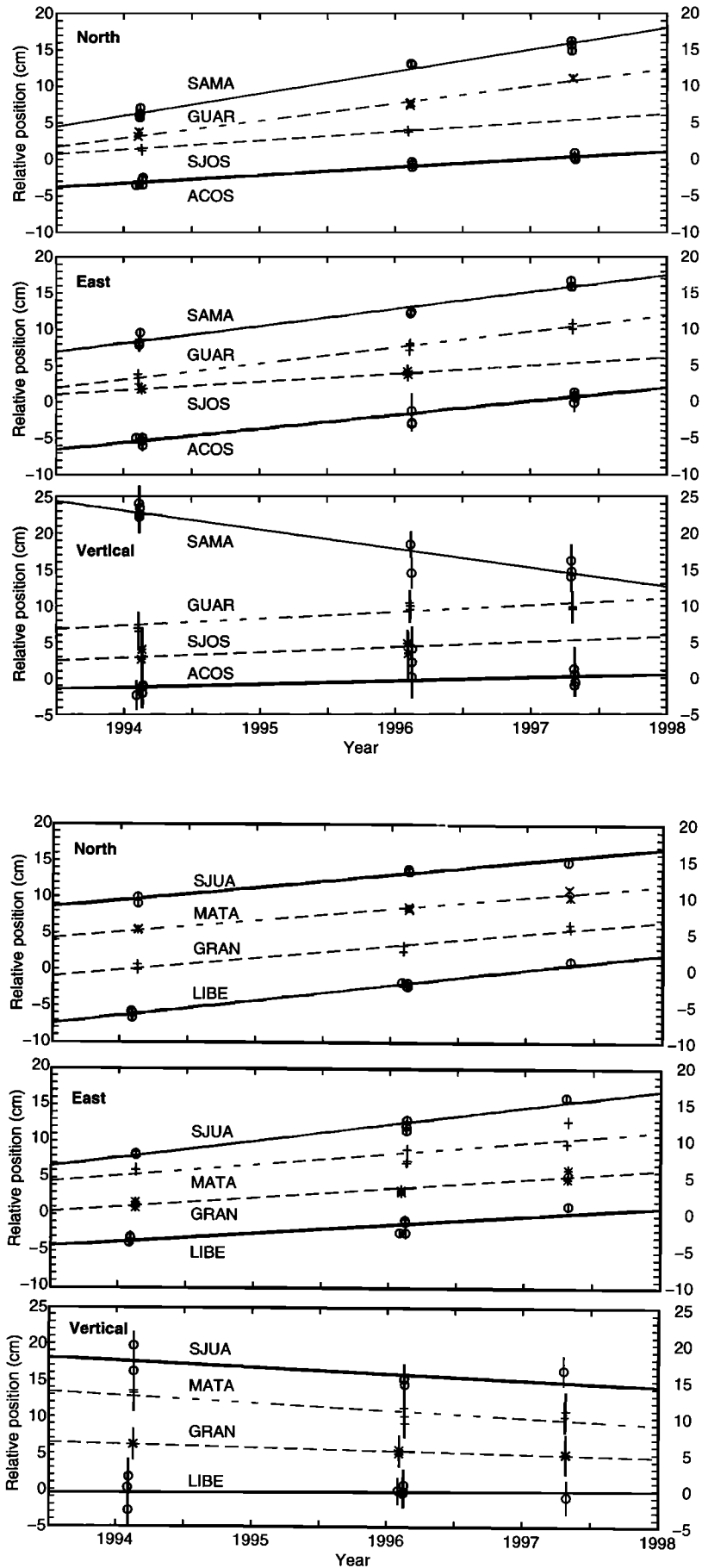


Figure 2. (continued)

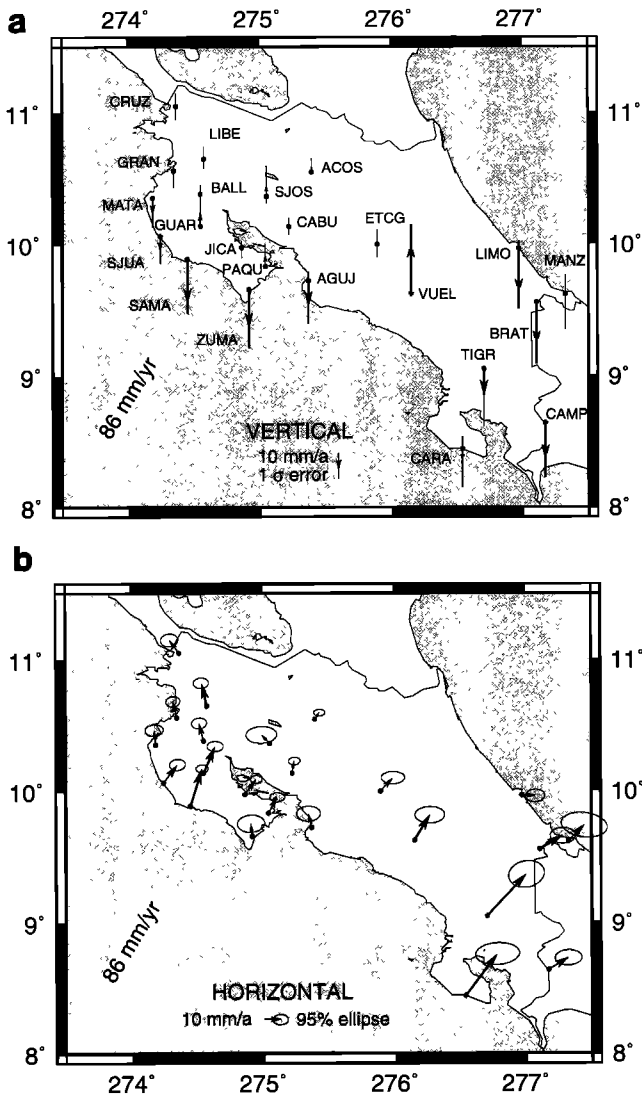


Figure 3. GPS solutions. (a) Vertical rates with station codes labeled. (b) Horizontal velocities with respect to the fixed Caribbean plate model of Dixon *et al.* [1998].

functions [Okada, 1985], to solve for multiple dislocations in an elastic half-space. The algorithm we use is based on that of *Ihmlé* [1996] as applied to seismic data and more recently applied to GPS data for the distribution of coseismic slip [Ihmlé and Ruegg, 1997]. The simulated annealing algorithm in our application to GPS site vectors solves for the slip of individual subfaults. For this study the fault location and geometry is specified, and the parameters we solve for are the dip-slip and strike-slip components of locking. In general, additional parameters can be solved for by simply adding them to the parameter space.

The simulated annealing algorithm is a quasi Monte Carlo approach that iterates to a solution by choosing an evenly distributed random value (0:1) for the slip on a specific parameter (subfault slip) over a specified range of that parameter. For a given iteration the algorithm loops over the parameter space, changing each parameter one at a time. Each solution is tested, with solutions that reduce the total cost retained, along with occasional solutions that cause an

increase in the total cost as determined by a Boltzman probability function criteria according to $r < \exp(-d_c/T)$, where r is a random number in the interval (0:1), d_c is the difference between the new and old total costs, and T is the "temperature." At high T the solution readily accepts new solutions that cause an increase in the cost, allowing the inversion to search for a global minimum. At lower T , only solutions that actually lower the cost are kept, and the solution approaches that local minimum. If the starting T is high enough, and lowered slowly enough, then this local minimum should be a global one. The initial value of T is determined from an initial selection of a large number of solutions based on the maximum difference (d_c) in these solutions. The temperature is lowered according to $T = T \exp(-\lambda T/\sigma_x)$, where λ is the cooling speed (set at 0.5 in this study) and σ_x is the standard deviation in the costs of the previous iterations.

At each change of model parameter, cost functions are computed. These are quite flexible and are generally of the form $\text{cost}_x = \sum (x_{\text{obs}} - x_{\text{mod}})^2 / \sigma^2$, where cost_x is the cost of parameter x based on the sum of the squared errors divided by the observed sigmas (σ). Costs can be computed for the data fit, for an a priori estimate of the total moment (in the case of an earthquake), and for slip heterogeneity: smoothing can be imposed based on minimizing the gradient between adjacent subfault slip. For purely geodetic data, such smoothing is unnecessary since the solutions tend to smooth naturally, and for interseismic deformation we do not constrain the total moment. The only cost we impose in this study is for the model and data misfit. We restrict the solution space to not allow the rate of normal slip to exceed the plate convergence rate.

The fault parameters we used are given in Table 2 and consist of an 8x7 mosaic of fault patches, each 30 km long and 20 km wide, forming a 240 x 140 km fault. For the west coast of Costa Rica the marine seismic study of *Ye et al.* [1996] allows us to define the strike, dip, and depth of the thrust interface. The thrust interface dips shallowly toward the coast, increasing to a dip angle of 10° at the central Nicoya coast. From the coast inland the dip is increased to reach a depth of 40 km beneath the axis of the Gulf of Nicoya, based on the depth to seismicity at the top of the subducting slab (M. Protti, personal communication, 1998). The fault model used in this study starts 20 km down dip from the trench.

4.1. Model Resolution

As a first step, we test the resolving power of the Nicoya site distribution and the assumed fault geometry by generating a synthetic model for a checkerboard pattern of slip for the fault model given in Table 2 (Figure 5a). We solve for both dip-slip and strike-slip fault motion (Figures 5b and 5c). To understand the model uncertainty, we run the simulated annealing inversion a number of times, each time using a Gaussian random number generator to vary the inverted simulated GPS data according to each data component's uncertainty. The standard deviation for each fault patch solution is then computed after N runs (Figures 5d and 5e). We find that the most reliable portions of the modeled fault plane are those directly beneath the stations. The solution we find demonstrates that the optimization does a reasonable job beneath the GPS sites but does poorly toward the trench and toward greater depth. Keep in mind that the modeled fault has

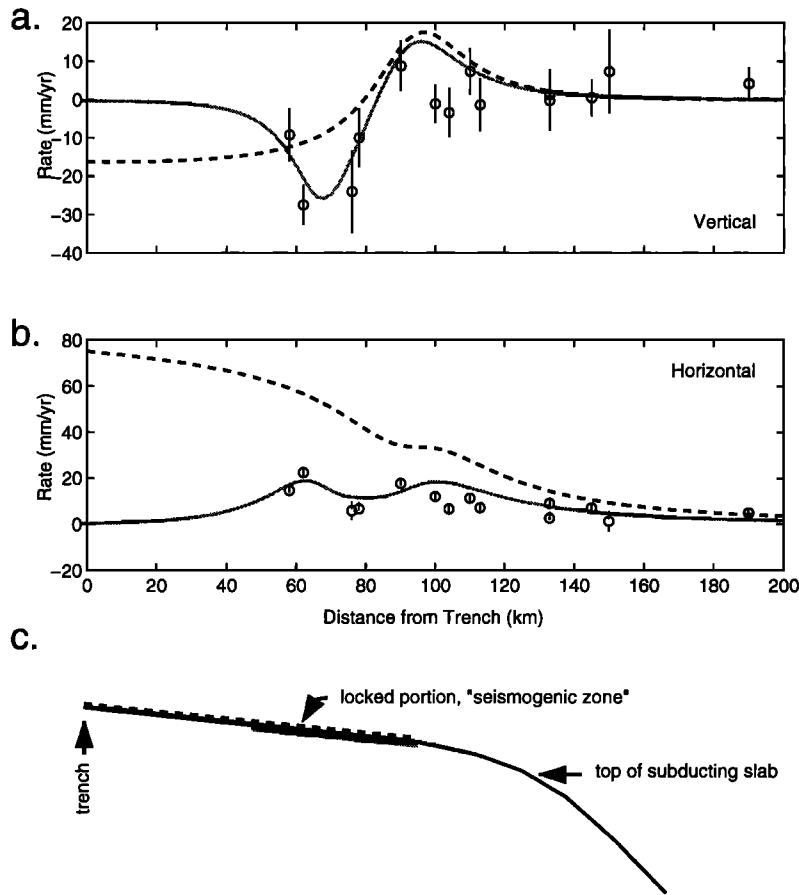


Figure 4. Theoretical dislocation models after *Okada* [1985]. (a) Vertical deformation as a function of distance perpendicular to the trench. Dashed curve is for a fully locked thrust from the trench for a distance of 95 km downdip, shown as the dashed portion of the thrust in Figure 4c. Solid shaded curve is for a short (25 km) locked segment from 70 to 95 km downdip (solid shaded segment in panel Figure 4c). (b) Horizontal surface motions expected for each of the models shown in Figure 4c relative to the plate interior. In Figures 4a and 4b the vertical and trench perpendicular components of the GPS velocities for the sites in the Nicoya region are plotted with their 1 sigma errors. The shaded curve shows that for a short locked segment a reasonable fit to the first-order deformation pattern is obtained: a large-amplitude vertical subsidence at the Nicoya coast with a relatively low horizontal motion in comparison.

precisely the same geometry as that which generated the input "data." Other tests in which the fault model was composed of a larger checkerboard were much better resolved. The smaller the fault patch size the more slip is smoothed into neighboring patches. Fault patches located farther from the GPS sites can

have relatively large slip that produces a small improvement in the vertical or horizontal fit to a distant site but without the constraint on amplitude and position that a data point local to that patch would provide. This, of course, is a well-known limitation in geodesy that resolution degrades with distance. On the other hand, locking the entire fault updip (toward the trench) from the coastal sites would produce an unacceptable fit to the data (Figure 4).

Table 2. Top, Center Location of Each Row of Fault Model

Row	Latitude	Longitude	Depth, km	Dip, deg
1	9.709	-85.871	6.0	8
2	9.851	-85.762	8.8	10
3	9.993	-85.654	12.3	15
4	10.136	-85.545	17.4	25
5	10.278	-85.437	25.9	35
6	10.420	-85.329	37.4	40
7	10.562	-85.220	50.2	45

Each row has a total length of 240 km (eight 30 km long patches) with the total width 140 km (seven rows, each 20 km wide).

4.2. Modeling the CORI Data

Early in the analysis it became apparent that there was consistently a residual strike-parallel component of motion (toward the NW) of sites along the interior forearc that was not accounted for by any reasonable models. Since the dislocation model only fits motion associated with fault strain, any secular plate motions would not be expected to be fit by such a model. Therefore we have removed the SJOS strike-parallel component (7 mm/yr) from all the modeled vectors in NW Costa Rica except ACOS, which lies beyond the volcanic arc and is less affected by forearc sliver motion. To allow for

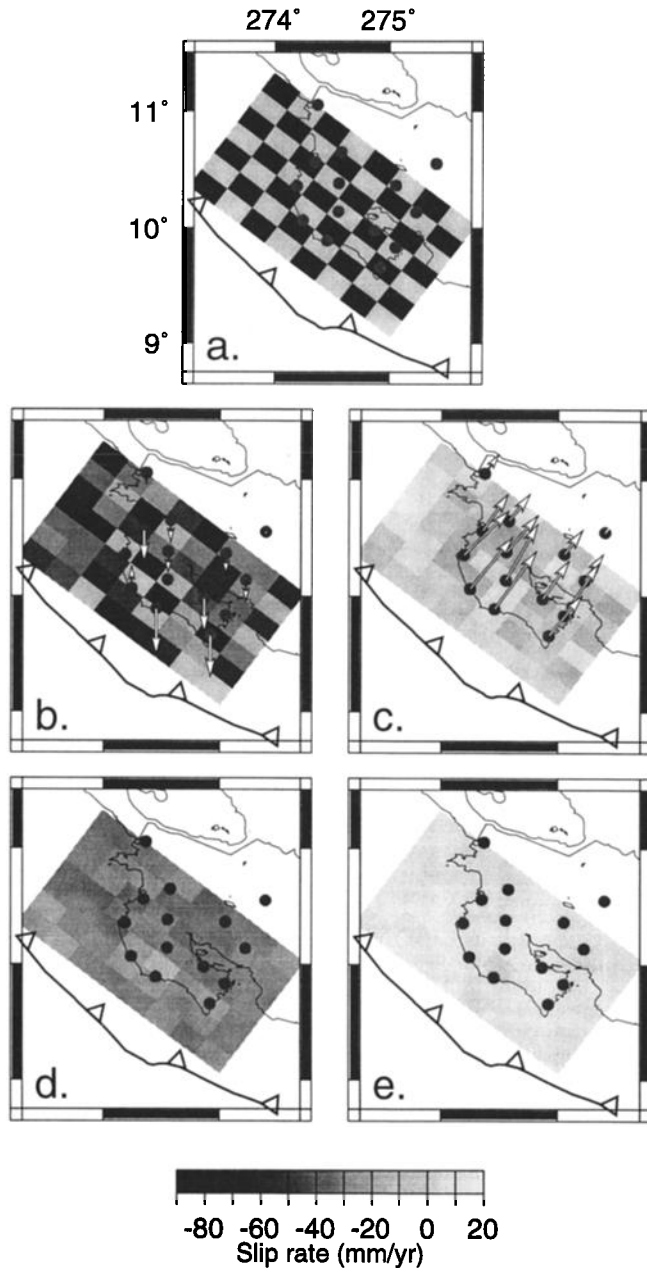


Figure 5. Sensitivity test of the simulated annealing inversion. (a) Input checkerboard pattern of slip on the thrust fault, solid patches corresponding to a rate of 83 mm/yr of normal slip, shaded patches with 0 slip. (b) Dip-slip component of the inverted slip. Arrows show the vertical simulated data (solid) with the solved for vectors shown as open. (c) Strike-slip component of the inverted fault slip. Arrows show the simulated data (solid) and solved for horizontal vectors (open). (d) Standard deviation in the inverted dip-slip component. (e) Standard deviation for the strike-slip component.

uncertainties in this forearc sliver component, as well as the uncertainty (1-2 mm/yr) in the *Dixon et al.* [1998] Caribbean plate Euler pole relative to the ITRF94, we have added a 3 mm/yr uncertainty to the horizontal GPS vector velocity uncertainties used by both the simulated annealing and singular value decomposition (SVD) inversions.

The best fitting model consists of interseismic deformation from partially locked patches beneath the Nicoya Peninsula

(Plate 1). As with the checkerboard test (Figure 5), to estimate the uncertainties in the fault model, we make a number of runs (20 in this case) where the data at each iteration consist of the original data plus randomly generated deviations from the original values (Δx , Δy , Δz) that are computed as a normalized (Gaussian) distribution with a standard deviation equal to that of the original data. From these solutions we calculate the standard deviation of each subfault slip component (Plates 1c and 1d). The greatest uncertainties generally lie toward the outer side edges of the fault model farthest from the GPS sites, as we found for the test example. A greater amount of uncertainty also lies beneath the inner coast of the Nicoya Peninsula. The fault patches that show the least variation are those directly beneath the SE outer coast of the peninsula, where the high subsidence rates and shallow depth to the fault put the tightest constraints on the solution, and on the fault patches toward the central downdip edge of the fault where the solution is required to be near zero.

The areas of greatest coupling (most negative dip-slip motion) lie predominantly beneath the outer Nicoya Peninsula, with two other areas located on either end of the modeled fault and farther downdip. These latter fault patches are less reliable as demonstrated by their much higher standard deviations (Plate 1c).

5. Singular Value Decomposition

The second technique we use is the singular value decomposition (SVD), a widely used method for underconstrained inverse problems [Lanczos, 1961; Menke, 1984]. We use the computer program of *Larsen* [1991] that follows the approach of *Harris and Segall* [1987]. For this study we have modified the *Larsen* [1991] SVD inversion software to compute the elastic deformation due to slip on individual fault patches using the equations of *Okada* [1985], the same used in the simulated annealing inversion.

In applying the SVD approach it is possible to restrict the parameter space by keeping only the k largest singular values [e.g., *Press et al.*, 1986]. The fit to the data and the variance of the model depend on the number of k retained. Few k result in lower model variance (i.e., smoother fault slip) at the expense of a poorer fit to the data. For high-resolution fault models the *Larsen* [1991] algorithm can avoid oscillatory patterns in the slip distribution by applying smoothing constraints over the model null space by considering quasi-data [Snay, 1989].

We apply the SVD inversion using the same fault geometry used for the simulated annealing inversion (Table 2). This particular solution (Plate 2) was computed for $k = 30$, although models with $k < 5$ produced very similar slip distributions, particularly for the dip-slip component beneath the central Nicoya coast. Thus the model vectors match the data fairly well at the expense of greater slip heterogeneity. This is most visible in the strike-slip solution where the solution is close to zero in general. However, even at very low k values, the central area of the dip-slip solution was robust, with the smaller singular values (higher k) refining the fit, especially for sites at the margins of the GPS network. In general, the SVD solutions are most sensitive to areas on the fault nearest the data. This is not surprising given the subfault dimensions with respect to the GPS site spacing and the spatial geometry of sites nearest the trench where the fault plane lies nearly horizontal beneath them at a shallow depth of 10-15 km.

Not surprisingly, the dip-slip component is more pronounced. It defines an area roughly coincident with the

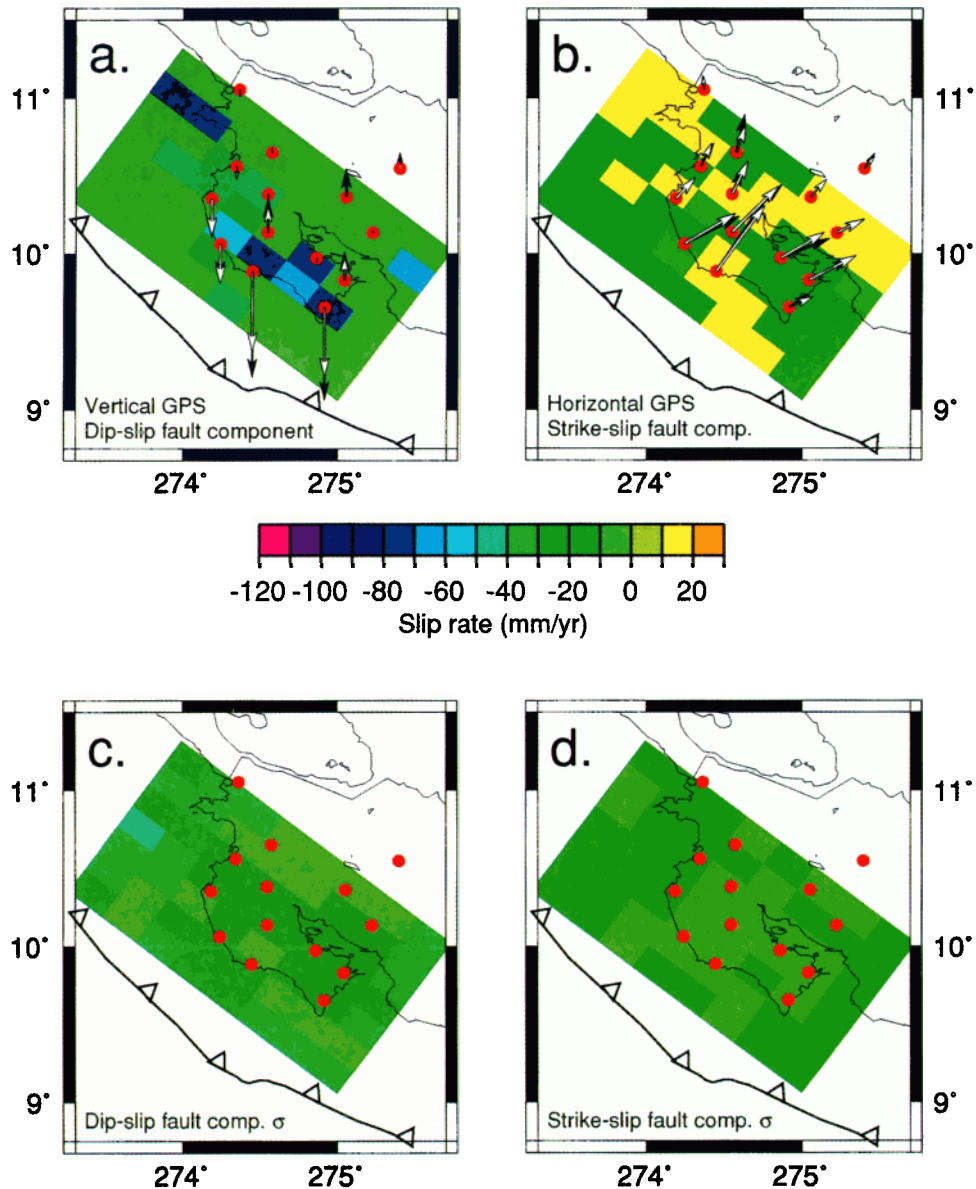


Plate 1. Simulated annealing inversion of the GPS solutions for NW Costa Rica. (a) Dip-slip component of the fault slip. Arrows show the observed (black) and inverted (white) vertical components. (b) Strike-slip component of the fault slip. Arrows show horizontal observed (black) and inverted (white) vectors. (c) Standard deviation in the dip-slip component. (d) Standard deviation in the strike-slip component.

Nicoya Peninsula, generally at 25-75% coupling, but with two strongly coupled patches beneath the central outer coast of the peninsula (Plate 2a).

6. Simulated Annealing Versus SVD Models

We applied two different inverse methods that resulted in similar models. Both of these models solved for the deformation due to a dislocation buried in an elastic half-space [Okada, 1985]. In this regard the models are directly comparable, but the presence of significant crustal structural heterogeneity would be expected to modify our results. To this end, more sophisticated modeling would be required (e.g., finite element or other numerical modeling techniques) and is beyond the scope of this paper.

The models derived with the SVD and simulated annealing inversions all had several features in common. What is

modeled as either strike-slip or normal fault motion on the fault plane represents the deformation resulting from partially locked patches on the subduction thrust interface (i.e., Savage, 1983). Therefore, for a patch with a dip-slip motion computed as -86 mm/yr (normal motion) this is equivalent to 100% locking on that patch for a convergence rate of 86 mm/yr. Positive strike-slip motion is right-lateral (RL) in this model. Negative, left-lateral (LL), values correspond to locked patches moving toward the NW with the slightly oblique motion of the Cocos plate, while RL motion would represent creep of the over riding plate toward the SE. For the representative model (Plates 1b and 2b) the strike-slip component is fairly heterogeneous, with one area of RL motion found beneath the SE end of the Nicoya Peninsula, while LL patches are more randomly scattered. Since we have already removed the 7 mm/yr sliver motion, we are assuming slip partitioning due to

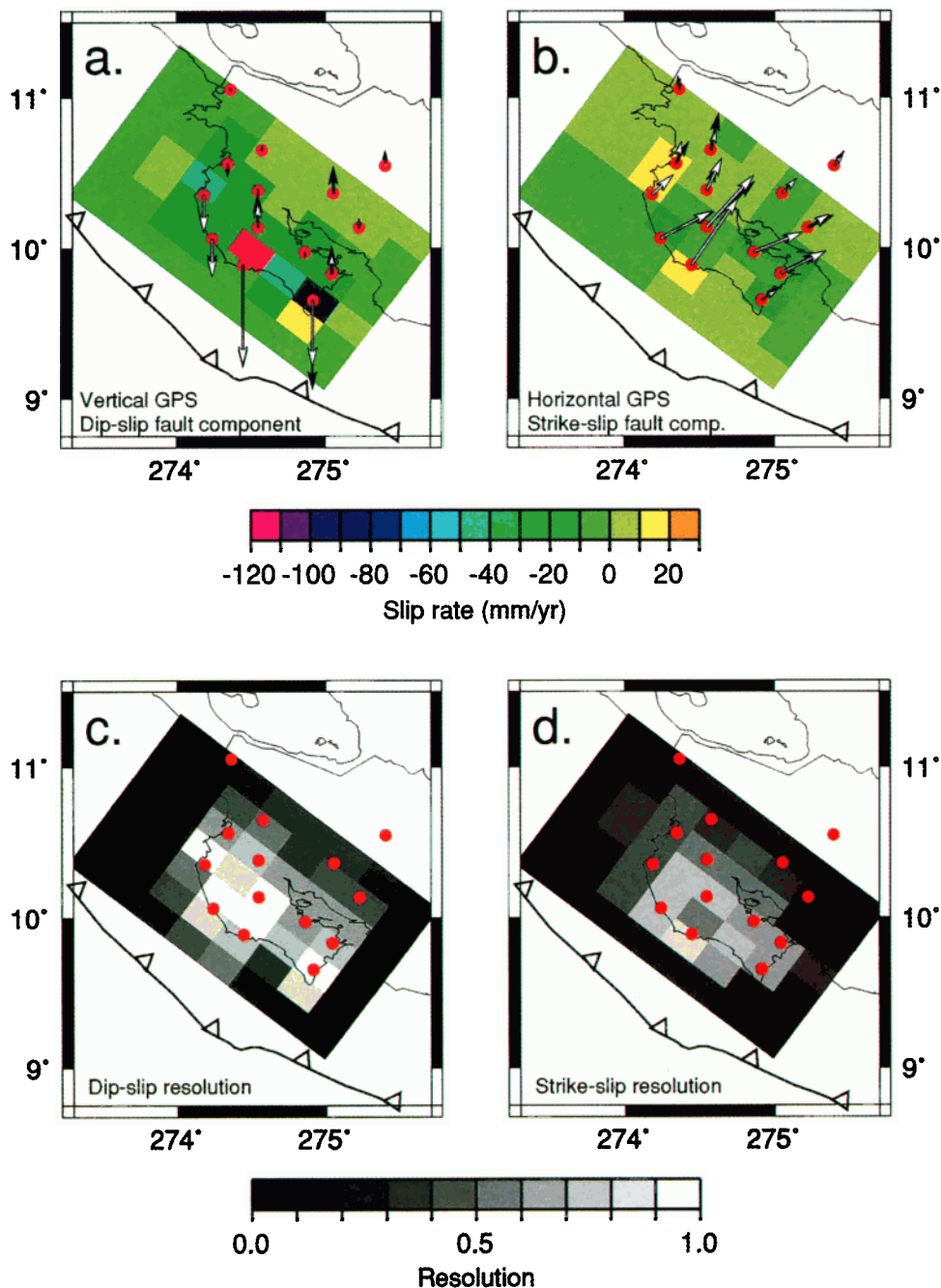


Plate 2. Interseismic model derived using the SVD algorithm. (a) Dip-slip component of the inverted fault slip. Arrows show the vertical component of the observed and inverted velocities (same convention as in Plate 1). (b) Strike-slip component of the inverted fault slip. Arrows show the horizontal observed and inverted site velocities. (c) and (d) The standard deviations in the dip-slip and strike-slip fault components, respectively.

oblique subduction. As a long-term kinematic model, slip partitioning can provide only a partial explanation where crustal deformation on short timescales is dependent on the coupling across the subduction and interior strike-slip fault zones. Models in which the LL trench parallel component for site SJOS was not removed had a strong LL patch beneath the entire Nicoya Peninsula, consistent with the oblique subduction and coupling of the thrust fault.

For both inversions the areas of greatest locking are generally located beneath the outer coast of the Nicoya

Peninsula. Partly, this reflects the limited distribution of our GPS sites, but certain features such as the high coupling beneath the SE outer coast of the peninsula and, conversely, the requirement of little coupling beneath the inner coast of the peninsula are features evident in the GPS data. The GPS vertical signal is especially critical in these solutions. The much greater uncertainty in the vertical GPS means that the details of the locking pattern, particularly its downdip extent, are strongly dependent on sites located in the transition from subsidence along the outer coast to uplift toward the interior.

The large amplitude of the vertical signal on the outer coast relative to the magnitude of the horizontal vectors restricts the amount of locking allowed toward the trench.

Comparing and contrasting these two models suggests that we are beginning to get an understanding of the seismic coupling heterogeneity beneath the Nicoya Peninsula. A greater density of sites within the Nicoya Peninsula would help improve the resolution of the slip heterogeneity.

7. Discussion and Conclusions

Preliminary GPS results from Costa Rica show a varied signal that is the summation of several sources due to fundamentally different processes operating on differing timescales. Future measurements across the entire network will allow us to extend the modeling of the MAT farther south, better constraining its seismic hazard, and will allow a quantitative assessment of postseismic effects following the 1991 Limon earthquake beneath the entire southern half of the country. The modeling results for the Nicoya region demonstrate the limitations of the current network. A greater number of sites, both along the strike of the MAT and in the density of sites in areas such as the Nicoya Peninsula and the number of measurement episodes, are needed to better define the properties of the seismogenic zone. Greater site density would provide important data strength and allow a higher resolution of the slip heterogeneity across the thrust interface.

Several limitations with the current data set deserve further comment. The first regards the vertical GPS solutions. As evident in GPS time series (Figure 2), several sites on the Nicoya peninsula show patterns of deformation that do not fit a perfectly straight line after three sets of occupations. These sites include ACOS, SAMA (possibly), SJUA, MATA, and to a lesser extent PAQU. In the case of ACOS the 1996 data appear higher than a line connecting 1994-1997 would predict, while for the subsiding sites such as SJUA, the apparently fast subsidence from 1994 to 1996 was nonexistent from 1996 to 1997. This pattern appears most evident along the coast and is possibly due to atmospheric conditions that were different in one of the campaigns, for example. Sites SAMA, SJUA, PAQU, and JICA had normal dry season conditions in 1997, whereas MATA, GRAN, GUAR, and BALL were occupied during a week of high humidity and scattered thunderstorms. This was particularly evident in the MATA and GRAN vertical data where there was a larger amount of scatter in the daily solutions than usual. In 1994 and 1996 the data were collected in the middle of the dry season.

A second limitation lies with the horizontal motions used to model the fault. The conversion to the Caribbean fixed reference frame and the removal of a trench parallel component both have their uncertainties. We have attempted to include these uncertainties in the modeling. The error in the forearc motion would mostly affect the strike-slip component of the fault model. The conversion of the horizontal vectors to a Caribbean frame fits well with the small trench perpendicular motion that is left at site ACOS.

Steady state plate margin deformation is apparent (Figure 3b) along the forearc sliver of NW Costa Rica at a rate around 7 mm/yr based on the component of arc-parallel motion that was not readily modeled as interseismic deformation. This is not a very satisfying way of arriving at an estimate of the forearc motion, but even with more data from sites distributed along

the entire forearc through Nicaragua, any estimation of this motion by geodesy will necessarily rely on separating out a component of seismic cycle slip, either due to a strike-slip component on the seismogenic interface or due to effects from adjacent segments with different amounts of coupling.

In southern Costa Rica we find E-NE motion of the Panama Block with respect to the Caribbean plate proper. However, here too there are significant seismic cycle contributions to the secular motions that hinder a unique solution. The southern half of Costa Rica features both interseismic strain from subduction beneath its Pacific coast and postseismic deformation following the 1991 Limon earthquake beneath its Caribbean coast. Sites along the SE Caribbean coast of Costa Rica have very low horizontal velocities relative to the stable Caribbean plate compared to sites farther inland. In contrast, these sites have large vertical rates suggesting either large interseismic strain from the thrusts of the NPDB or postseismic deformation continuing after the 1991 Limon earthquake. We are waiting to remeasure these sites in the future before discriminating between models. An interseismic signal should be steady state, whereas any postseismic signal should be time-dependent. One unresolved issue that arose from GPS measurements collected after the Limon earthquake in 1991 was the vertical discrepancy between the GPS measured uplift at LIMO (16 cm) by *Lundgren et al.* [1993] ~70 days after the earthquake, leveling data (23 cm) ~50 days after the earthquake [*DeObaldia et al.*, 1991], and the 60-80 cm of coastal uplift adjacent the LIMO site measured by *Plafker and Ward* [1992] ~2 weeks following the earthquake. Rapid postseismic afterslip such as that measured with GPS immediately following the 1995 Jalisco earthquake by *T. Melbourne et al.* (manuscript in preparation, 1999) suggests that a similar postseismic process may have been active following the 1991 Limon earthquake.

In NW Costa Rica the GPS observations fit a model of heterogeneous seismic coupling with individual fault patches beneath the central and southeast Nicoya Peninsula having the highest amount at >80% locked assuming a convergence rate of 86 mm/yr. The deformation pattern we find in NW Costa Rica has many similarities with recent observations from Sumatra [*Prawirodirdjo et al.*, 1997] and the central Andes [*Norabuena et al.*, 1998]. In those studies, only horizontal GPS motions were used to estimate dislocation model parameters, and the observed deformation patterns could be fit with a combination of interseismic strain partitioning between the trench and an interior fault system.

Despite the current solution set's limitations, particularly with regard to the vertical uncertainties, an important step can be made toward defining the slip distribution along the seismogenic zone (Plates 1 and 2). An important part of this is due to the significant vertical signal measurable with episodic GPS observations to which the dislocation models are particularly sensitive. In this regard the Nicoya Peninsula, by lying directly above the seismogenic zone (10-20 km beneath) in a location of fast convergence, is uniquely suited to defining the slip distribution across the subduction thrust interface. Additional measurements and densification of the network would allow greater resolution of this heterogeneity. Such a detailed map of seismic coupling when combined with a future large thrust earthquake will provide important insight into the relation between interseismic coupling and the nucleation of large subduction zone earthquakes and the slip potential for future earthquakes.

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