**Electronic supplement for "Forearc motion and deformation between El Salvador and Nicaragua: GPS, seismic, structural, and paleomagnetic observations"**

by D. Alvarado et al., Lithosphere, April, 2010.

## GPS data

This supplementary document describes the GPS data and methods we used to determine GPS station velocities for our tectonic analysis. The 35 GPS station velocities used in this study are derived from continuous measurements at one station in El Salvador (SSIA) and one station in Nicaragua (MANA), and campaign measurements at 13 stations in El Salvador, seven stations in southern Honduras, and 13 stations in Nicaragua. All 35 sites are located at the western end of the Caribbean plate (Fig. 1), directly onshore from the Middle America subduction zone.

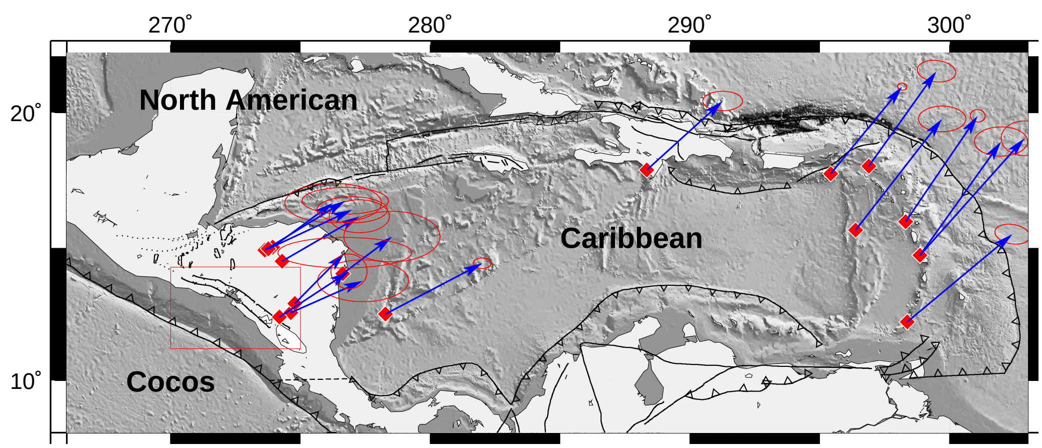


Figure 1: Motions relative to ITRF2005 of all seventeen GPS sites used to determine a best-fitting angular velocity for Caribbean plate motion relative to ITRF2005. Area outlined in red is shown in Fig. 2.

Measurements at the Salvadoran campaign sites extend from 2004 to mid-2008 (Fig. 2 and Table 1) and consist of three to five annual occupations per site. Each station occupation lasted 7 to 17 days, thereby providing a strong basis for estimating the station coordinates. All of the Salvadoran campaign measurements were made with Trimble 5700 GPS receivers and Zephyr geodetic antennas mounted on precisely leveled, 0.55-meter-high spike mounts. Our use of identical spike mounts and antennas for the Salvadoran sites eliminates differences between antenna types and incorrect antenna heights as a source of spurious antenna phase center offsets. Data from the only continuously operating site, SSIA in central El Salvador, span a 7.7-year-long period beginning in mid-2000 and constitute the best determined velocity in the study area.

Measurements at six of the seven Honduran stations consisted of three several-day-long occupations between late 2003 and mid 2007 (Table 1 and Fig. 2). One Honduran station, SLOR, operated continuously for two years beginning in mid-2000 before it was abandoned. We reoccupied the geodetic mark at this site for a week in each of 2006 and 2007. These seven stations are part of a larger, 33-station Honduran GPS network that is described and used by *Rodriguez et al.* [2009] to better understand deformation in the interior of northern Central America. We refer readers to *Rodriguez et al.* [2009] for a more complete description of the Honduran GPS data.

Measurements at the 14 Nicaraguan stations began as early as mid-1999 and span 2-3 years at most sites. Details of these measurements and corrections made to the station coordinate time series for offsets that occurred during the Jan. 13, 2001 El Salvador earthquake are given by *Turner et al.* [2007].

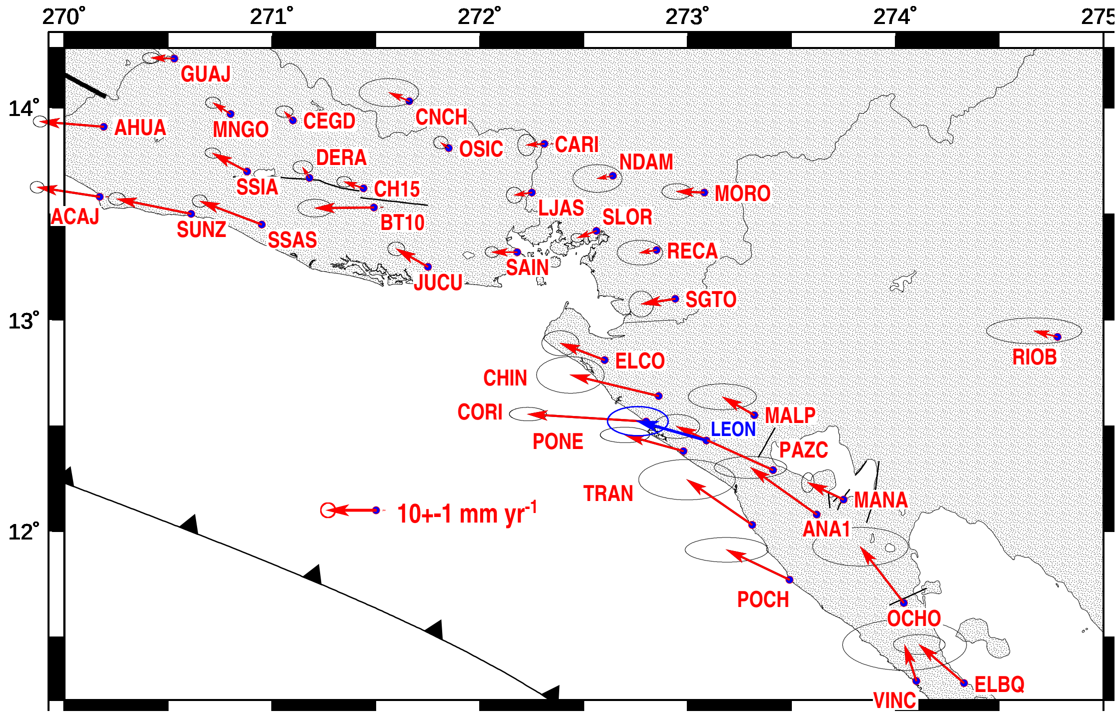


Figure 2: Locations, names, and velocities for GPS stations from El Salvador, southern Honduras, and Nicaragua used for the analysis. Motion of the Caribbean plate is removed from each station's motion, as described in the text.

### GPS data processing procedures

All of the continuous and campaign GPS data used in this study were analyzed with GIPSY-OASIS II software (release 4.02) from the Jet Propulsion Laboratory (JPL). Daily data from the individual GPS sites were analyzed via a standard precise point-positioning [*Zumberge et al.* 1997] followed by resolution of phase ambiguities using AMBIZAP software [*Blewitt* 2008]. The daily site coordinates were estimated initially in a no-fiducial reference frame [*Heflin et al.* 1992] with fiducial-free satellite products from JPL. The satellite products consist of the non-fiducial (*e.g.* *_nf.eci, *_nf.tdpc, etc...) files that were produced by JPL up until August 15, 2009 and do not include the newer generation orbits from JPL that have been generated since early 2009 for use with release 5.0 of GIPSY. The daily no-fiducial station locations are transformed to ITRF2005 [*Altamimi et al.* 2007] using daily seven-parameter Helmert transformations from JPL.

### GPS coordinate time series and station velocities

Fig. 3 shows the coordinate time series for the Honduran and Salvadoran sites included in this analysis. The repeatabilities in the daily station coordinates are typically 2-3 mm and 3-5 mm for the north and east components, respectively, after post-processing to estimate and remove common-mode noise from the station coordinates [*Marquez-Azua and DeMets* 2003]. A weighted linear regression of each stations's coordinate time series was used to determine its velocity relative to ITRF2005 (Table 1). Corrections, if any, for the coseismic offsets due to nearby earthquakes were estimated and removed from the continuous station time series or were predicted and removed

Table 1: GPS station information: El Salvador and southern Honduras

| Site name | Coordinates Lat. (N) | Long. (E) | Time Yrs | Station days 2003 | 2004 | 2005 | 2006 | 2007 | 2008 | Velocity† North | East |
|---|---|---|---|---|---|---|---|---|---|---|---|
| ACAJ | 13.5751 | -89.8333 | 3.9 | - | 7 | 7 | 10 | 7 | 7 | 6.6±0.7 | -0.9±0.9 |
| AHUA | 13.9087 | -89.8081 | 3.9 | - | 11 | 7 | 7 | 7 | 7 | 5.7±0.6 | -1.3±0.9 |
| BT10 | 13.5290 | -88.5071 | 1.9 | - | - | - | 15 | 16 | 17 | 5.0±1.1 | -0.1±2.4 |
| CARI | 13.8333 | -87.6891 | 3.0 | - | 3 | - | 6 | 4 | - | 5.2±1.4 | 8.3±1.1 |
| CEGD | 13.9395 | -88.9017 | 3.8 | - | 7 | 7 | 7 | 11 | 7 | 6.8±0.7 | 10.2±1.2 |
| CH15 | 13.6224 | -88.5612 | 4.1 | - | 8 | 6 | 6 | 15 | 7 | 6.5±0.6 | 8.1±1.0 |
| DERA | 13.6684 | -88.8227 | 3.7 | - | 7 | 7 | 7 | 10 | - | 7.2±0.8 | 10.8±1.3 |
| GUAJ | 14.2283 | -89.4687 | 3.9 | - | 9 | 7 | 8 | 7 | 7 | 4.9±0.6 | 7.0±1.1 |
| JUCU | 13.2529 | -88.2496 | 3.5 | - | 5 | 7 | 7 | 8 | 5 | 8.2±0.8 | 4.4±1.5 |
| LJAS | 13.5957 | -87.7470 | 3.0 | - | 7 | - | 5 | 7 | - | 4.9±1.0 | 8.5±1.0 |
| MNGO | 13.9651 | -89.1974 | 3.9 | - | 6 | 7 | 7 | 17 | 7 | 7.2±0.6 | 8.3±1.0 |
| MORO | 13.5989 | -86.9246 | 3.0 | - | 3 | - | 4 | 4 | - | 6.0±1.0 | 6.4±2.0 |
| NDAM | 13.6777 | -87.3568 | 2.8 | - | 6 | - | 3 | 4 | - | 5.0±1.9 | 8.9±3.4 |
| OSIC | 13.8139 | -88.1457 | 4.2 | - | 8 | 7 | 7 | 8 | 7 | 6.4±0.8 | 10.4±0.9 |
| RECA | 13.3322 | -87.1548 | 3.0 | - | 6 | - | 10 | 3 | - | 5.1±1.7 | 8.8±3.1 |
| SAIN | 13.3248 | -87.8153 | 4.0 | - | 15 | 7 | 14 | 17 | 7 | 5.5±0.6 | 6.9±0.9 |
| SGTO | 13.0995 | -87.0626 | 3.0 | - | 3 | - | 5 | 4 | - | 4.6±1.7 | 5.4±1.7 |
| SLOR | 13.4239 | -87.4365 | 6.8 | - | - | - | 5 | 4 | - | 4.1±0.5 | 8.3±0.8 |
| SSAS | 13.4463 | -89.0519 | 3.7 | - | 7 | 8 | 10 | 8 | 7 | 9.8±0.7 | -0.7±1.0 |
| SSIA | 13.6971 | -89.1166 | 7.7 | 263 | 36 | 216 | 163 | 248 | 145 | 8.7±0.5 | 4.9±1.0 |
| SUNZ | 13.5021 | -89.3904 | 3.9 | - | 8 | 8 | 7 | 7 | 7 | 7.9±0.7 | -3.3±1.1 |

†Velocities are relative to ITRF05 and are specified in units of millimeters per year. Uncertainties are standard errors. Time specifies the interval in years spanned by the observations. Information about station histories before Y2003 is given by DeMets *et al.* (2007).

from the time series of some campaign sites, as described in the following section. Uncertainties in the station velocities were determined using an empirically based error model that accounts for different noise components in the time series (white noise, flicker noise, and random monument walk) [*Mao et al.* 1999].

Following *Argus* [2007], we adopt Earth's center-of-mass as the appropriate origin for geodetically described plate motions. *Argus* [2007] estimates that Earth's center-of-mass moves relative to the ITRF2005 geocenter at respective rates of 0.3 mm yr$^{-1}$, 0.0 mm yr$^{-1}$, and 1.2 mm yr$^{-1}$ in the X, Y, and Z directions. We therefore removed these motions from the Cartesian components of all the GPS station velocities used in our study, including the velocities of 17 sites whose motions we use to define the Caribbean plate reference frame relative to which all stations motions are described in our analysis. The residual station velocities shown in Fig. 2 and in figures in the related manuscript are corrected for this motion.

**Influence of regional earthquakes on GPS site velocity estimates**

Given our goal of quantifying steady interseismic deformation in our study area, we corrected our GPS coordinate time series for any offsets due to earthquakes close enough to our study area to induce measurable deformation at any of our GPS stations. Below, we describe these corrections.

The only notable earthquakes that occurred near El Salvador and southern Honduras since GPS stations in these two countries began operating in late 2000 were the $M_w$ = 7.7, Jan. 13, 2001 normal faulting earthquake within the Cocos plate beneath central El Salvador and the $M_w$ = 6.6, Feb. 13, 2001 strike-slip earthquake within the volcanic arc of central El Salvador [*Martinez-Diaz et al.* 2004]. Only two GPS stations in El Salvador and Honduras, SLOR and SSIA, were

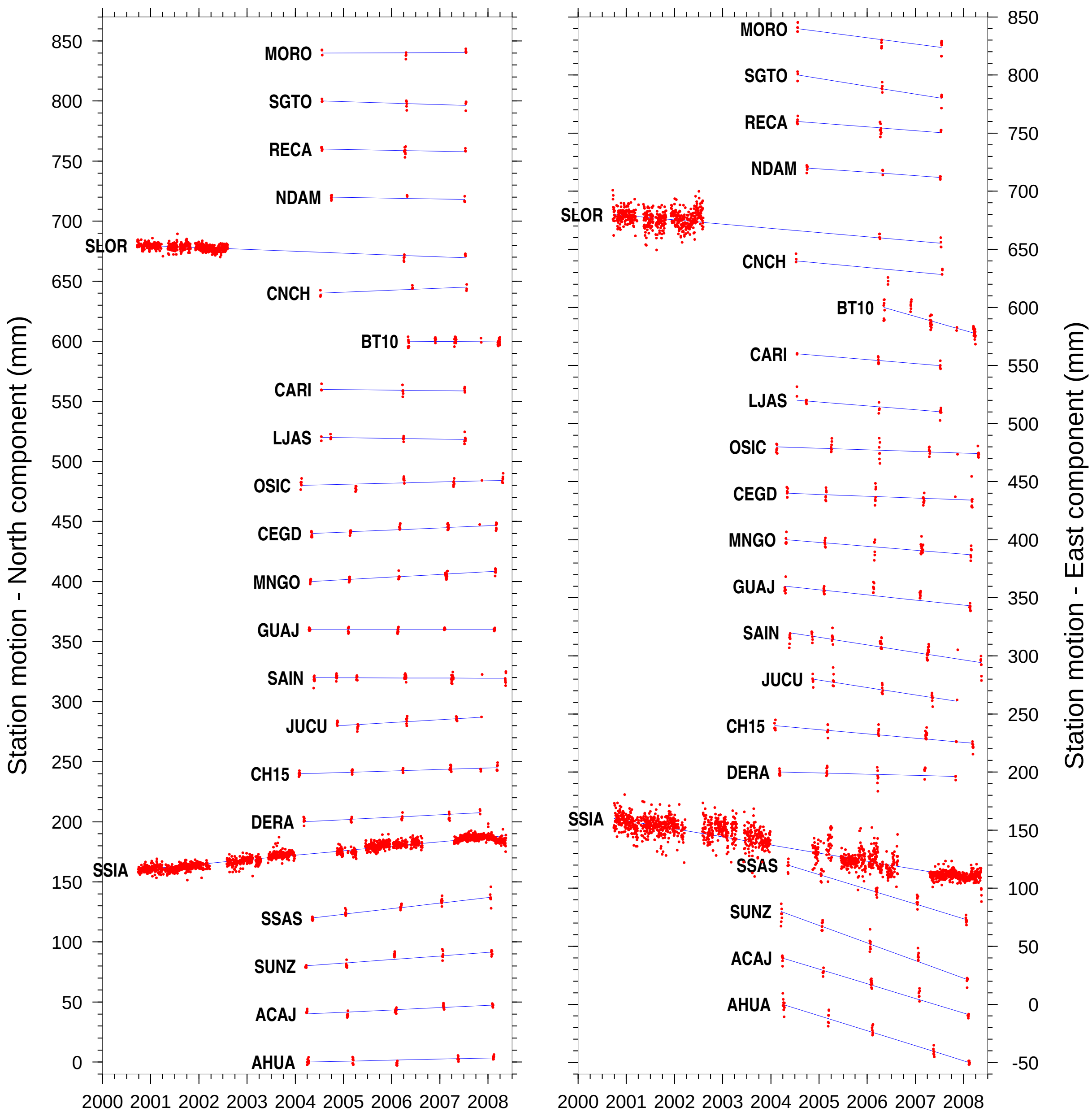


Figure 3: North (left panel) and east (right panel) displacements through mid-2008 of GPS stations from El Salvador and Honduras used in this study. Each circle shows the daily location determined for a site from 24 hours of measurements. Offsets from the $M_w$ = 7.7, Jan. 13, 2001 earthquake beneath El Salvador were estimated and removed from the time series for stations SLOR and SSIA, but are not shown. Common-mode noise has been estimated from the time series of continuous stations external to the study area and removed from the daily coordinates for all stations shown in the figure. Station time series are shown in a reference fram fixed to the Caribbean plate. Details of the station occupations are given in Table 1.

operating during those earthquakes. We therefore estimated and removed the coseismic offsets for both earthquakes from the time series. The continuous time series at both of these sites (Fig. 3) indicate that any postseismic transient motion from these 2001 earthquakes was no more than a few millimeters, too small to affect any of the results or conclusions that follow. We thus did not attempt to correct either of their coordinate time series for the postseismic effects of either earthquake. All the other Honduran and Salvadoran sites were first occupied in late 2003 or early 2004, too long after the earthquakes in 2001 to be affected by their small postseismic transients.

The $M_w$ = 7.7, Jan. 13, 2001 earthquake also caused coseismic offsets of up to 3 millimeters at locations in Nicaragua, where GPS sites were first occupied in 1999 or early 2000 [*Turner et al.* 2007]. Corrections for the coseismic motions were therefore estimated and applied to the Nicaraguan station time series prior to our determination of the station velocities. Our Nicaraguan station velocities are determined solely from measurements made through February of 2003 and are thus not influenced by the $M_w$=6.9 Oct. 9, 2004 earthquake off the coast of Nicaragua.

### Caribbean plate reference frame

For our tectonic analysis, all of the GPS station velocities described above were transformed from ITRF2005 to a reference frame tied to the Caribbean plate. To accomplish this, we analyzed code-phase GPS data from 17 GPS stations located on the Caribbean plate (Fig. 1), derived velocities for each site, and from them determined a best-fitting angular velocity for the Caribbean plate relative to ITRF2005 (37.8°N, 98.5°W, 0.262° $Myr^{-1}$). This angular velocity agrees closely with that determined by *DeMets et al.* [2007] for 15 Caribbean plate sites whose motions were specified in the older ITRF2000 frame. Propagation of the formal uncertainties in the Caribbean-ITRF2005 angular velocity into the velocity uncertainties for the GPS stations in Central America typically increases those uncertainties by only 0.2 mm $yr^{-1}$ or less, too small to matter for our analysis.

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