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Tectonic inversion in the Caribbean-South American plate boundary: GPS geodesy, seismology, and tectonics of the M_w 6.7 22 April 1997 Tobago earthquake

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Key Points:

- The 22 April 1997 M_w 6.7 Tobago earthquake inverted a low-angle thrust fault
- Seismology, GPS, and modeling resolve coseismic slip, fault geometry, and moment
- Coseismic slip subsided Tobago and moved it NNE

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Abstract On 22 April 1997 the largest earthquake recorded in the Trinidad-Tobago segment of the Caribbean-South American plate boundary zone (M_w 6.7) ruptured a shallow (~9 km), ENE striking (~250° azimuth), shallowly dipping (~28°) dextral-normal fault ~10 km south of Tobago. In this study, we describe this earthquake and related foreshock and aftershock seismicity, derive coseismic offsets using GPS data, and model the fault plane and magnitude of slip for this earthquake. Coseismic slip estimated at our episodic GPS sites indicates movement of Tobago 135 ± 6 to 68 ± 6 mm NNE and subsidence of 7 ± 9 to 0 mm. This earthquake was anomalous and is of interest because (1) its large component of normal slip and ENE strike are unexpected given the active E-W dextral shearing across the Caribbean-South American plate boundary zone, (2) it ruptured a normal fault plane with a low (~28°) dip angle, and (3) it reactivated and inverted the preexisting Tobago terrrane-South America ocean-continent (thrust) boundary that formed during early Tertiary oblique plate convergence.

1. Introduction

The Caribbean-South American plate boundary zone developed progressively through a multistage history that involved the following: (1) Mesozoic rifting of Pangaea that formed a north facing passive margin along northern South America; (2) Miocene oblique Caribbean-South American collision that formed a fold-thrust orogen, eastward migrating foreland basins, and a metamorphic hinterland that includes exotic accreted lithospheres (i.e., terranes); and (3) the current phase of ~ E-W trending transform tectonics [*Weber et al.*, 2001a; *Pérez et al.*, 2001]. This complex geologic history has only recently come into focus [e.g., *Mann and Escalona*, 2011, and citations therein]. One major breakthrough occurred when GPS data first and clearly showed that the oblique Caribbean-South American collision that assembled the Caribbean orogen along the southern rim of the Caribbean Plate is no longer ongoing [*Weber et al.*, 2001a; *Pérez et al.*, 2001]. The dynamic cause for the switch from oblique collision to transform motion is unknown, but according to geologic reconstructions, it probably occurred in the Pliocene or latest Miocene [*Pindell et al.*, 1998; *Giorgis et al.*, 2011]. There is now general consensus on the tectonic history outlined above, providing a conceptual framework in which questions related to tectonic inheritance (i.e., the connections between neotectonics and preexisting structures) and earthquake hazards may now begin to be addressed.

The Caribbean-South American plate boundary is currently a major dextral transform shear zone. Major strike-slip (transform) faults that right step across linking pull-apart basins (i.e., the Gulf of Cariaco and Gulf of Paria) (Figure 1) [*Schubert*, 1985; *Flinch et al.*, 1999; *Babb and Mann*, 1999; *Weber et al.*, 2001a, 2011] accommodate this dextral shear. The Caribbean Plate currently moves at ~20 mm/yr approximately eastward relative to South America [*Weber et al.*, 2001a; *DeMets et al.*, 2010]. Large strike-slip earthquakes, both historic and modern, are common in the eastern Venezuelan segment of the active plate boundary zone and are concentrated on the El Pilar Fault (Figures 1 and 2) [*Deng and Sykes*, 1995; *Mendoza*, 2000; *Weber et al.*, 2001a; *Jouanne et al.*, 2011]. Slip vectors from large strike-slip events on the El Pilar Fault corroborate the GPS finding of approximately east-west relative plate motion [*Weber et al.*, 2001a, Figure 2]. In Trinidad and Tobago there

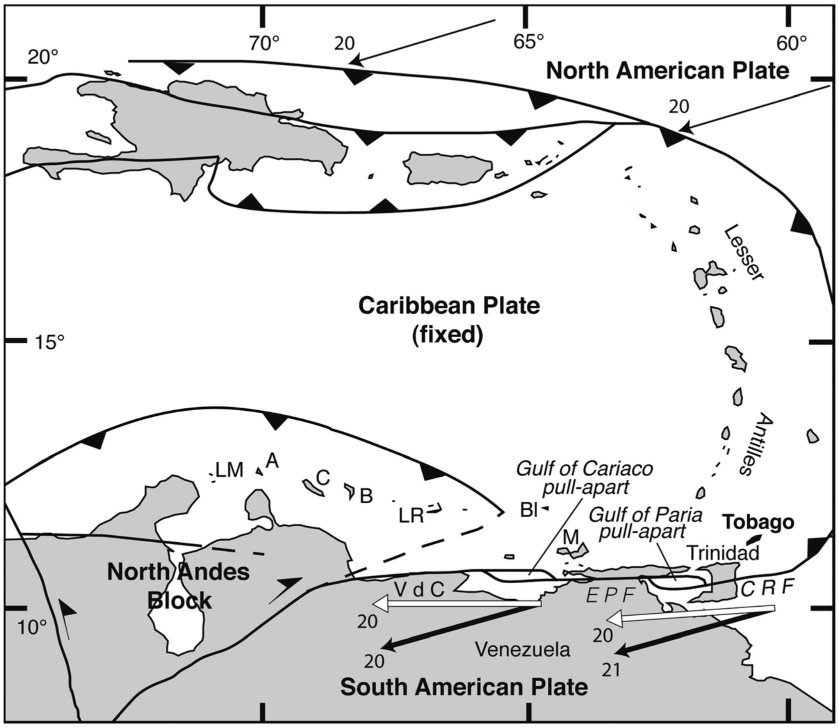

Figure 1. Regional structural geology and plate tectonic setting of the Tobago study area. The Caribbean Plate currently moves ~20 mm/yr eastward relative to South America [*Weber et al*., 2001a; *DeMets et al*., 2010] along the right-stepping El Pilar (EPF) and Central Range (CRF) strike-slip faults and across associated Gulf of Paria and Gulf of Cariaco pull-apart basins. The Lesser Antilles is a modern arc developing as the Caribbean Plate overrides and subducts Atlantic lithosphere of the North and South American plates. Shown are MORVEL predictions in a fixed-Caribbean reference frame [*DeMets et al*., 2010] for Caribbean-South American (thick black arrows) and Caribbean-North American (thin black arrows) relative plate motion vectors (mm/yr). A regional Caribbean-South American plate motion model from *Weber et al*. [2001a] predicts relative plate motion (white arrows; mm/yr) vectors that are approximately parallel to the E-W azimuth of the El Pilar transform fault. Older oceanic fore-arc and arc crust and lithosphere obducted over and accreted to South American continent crops out mainly as a series of submerged islands including Tobago, Margarita (M), Blanquilla (Bl), Los Roques (LR), Bonaire (B), Curacao (C), Aruba (A), and Los Monjes (LM); the Villa de Cura nappe (VdC) is its largest "trapped" on-land exposure.

are no clear historic or instrumental records of large approximately E-W striking, subvertical, strike-slip faulting events, indicating that the major strike-slip faults in this segment of the plate boundary (e.g., the Central Range Fault) are either locked with long repeat times, releasing stored motion during slow slip events, or creeping (Figures 1 and 2) [e.g., *Speed et al*., 1991; *Russo et al*., 1993; *Weber et al*., 2001a; *Prentice et al*., 2010; *Weber et al*., 2011].

On 22 April 1997 a M_w 6.7 earthquake, the largest recorded event along the Trinidad-Tobago segment of the plate boundary zone, ruptured a shallow (~9 km), ENE striking (~250° azimuth), shallowly dipping (~28°) dextral-normal fault ~10 km south of Tobago. It is noteworthy that this large earthquake did not rupture an approximately E-W striking, subvertical, dextral strike-slip fault nor any subsidiary fault related to active E-W dextral plate boundary shear (i.e., *R* or *R'* shear, NW striking normal fault, or NE striking thrust [*Tchalenko*, 1970]).

Here we present an interdisciplinary study that explores connections between the kinematics of this large earthquake and the tectonic setting and geology of Trinidad and Tobago. We first describe the seismology of the 22 April 1997 earthquake using data from a local network and global databases. We then estimate coseismic displacements at two episodic GPS stations located on Tobago and model the magnitude of slip and fault parameters for the earthquake. We discuss the similarities and differences between our geodetically derived fault dip, slip magnitude, and moment release and those determined independently through the inversion of seismic data that we obtained from the following: (1) the U.S. Geological Survey's National Earthquake Information Center (NEIC), (2) the International Seismological Centre (ISC), (3) the global centroid

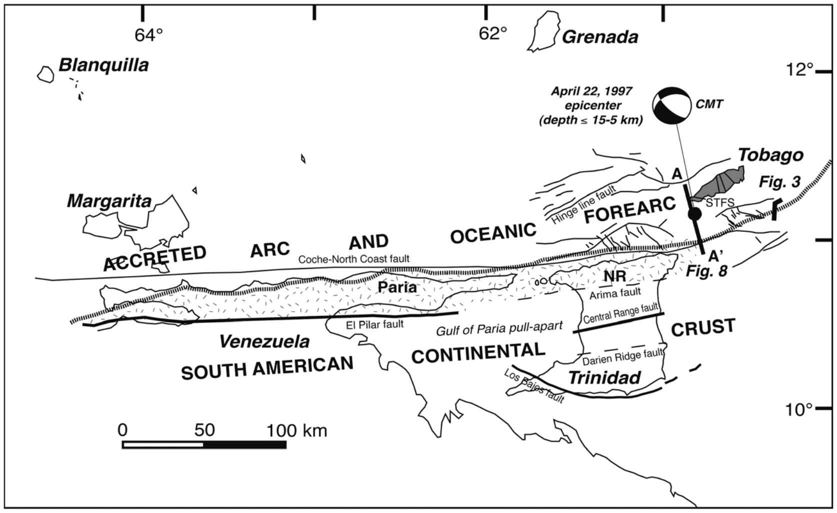

Figure 2. Principal active and fossil faults and tectonic and geologic elements around the Tobago study area. Principal active strike-slip faults in eastern Caribbean-South American plate boundary zone are as follows: El Pilar, Central Range, and Los Bajos, faults, and those (not shown) in Gulf of Paria pull-apart. The Darien Ridge fault may or may not be active. Faults in Trinidad-Tobago offshore and on-land Tobago are from *Snoke et al*. [2001b]. STFS = Southern Tobago Fault System. Stippled pattern marks mountainous Northern Range (NR)-Paria coastal metamorphic belt [*Frey et al*., 1988; *Foland et al*., 1992; *Weber et al*., 2001b; *Teyssier et al*., 2002]. The accreted arc-oceanic fore-arc (Tobago terrane)-continental South America boundary (heavy hatchured pattern), after *Speed and Smith-Horowitz* [1998] and *Snoke et al*. [2001b], was reactivated during the 22 April 1997 Tobago earthquake, for which CMT focal mechanism and CMT and NEIC epicenter and focal depth range are shown.

moment tensor (GCMT) catalogue [e.g. *Dziewonski et al*., 1981; *Ekström et al*., 2012], and (4) from the local seismic network at the University of the West Indies, Seismic Research Centre (SRC; previously the Seismic Research Unit; sometimes referred to in the international seismological community as TRN). Finally, we interpret the meaning and significance (i.e., the geodynamics) of this earthquake in the context of the tectonic history of the Caribbean-South American plate boundary zone.

2. Trinidad and Tobago's Geologic, Paleotectonic, and Neotectonic Setting

As outlined above, the principal tectonic elements in the Caribbean-South American plate boundary zone were formed and assembled during Mesozic rifting, Miocene oblique convergence and terrane accretion, and Pliocene to Recent transform tectonics (Figure 2) [e.g., *Robertson and Burke*, 1989; *Speed et al*., 1991; *Algar and Pindell*, 1993; *Mann and Escalona*, 2011]. Eastward migration of the locus of early Tertiary oblique convergence is recorded by a series of foredeep basins that developed on the down-flexed South American continental lithosphere and become progressively younger eastward along the plate boundary [*Speed*, 1985; *Pindell et al*., 1998]. The Aruba-Curacao-Bonaire belt, the Villa de Cura-Margarita belt, and the Tobago terrane represent the main exposures of arc and fore-arc lithosphere(s) that were obducted and accreted in the early Tertiary (Figures 1 and 2) [*Beets et al*., 1984; *Maresch*, 1974; *Smith et al*., 1999; *Snoke et al*., 2001a]. From late Paleogene to early Neogene, dextral oblique arc-continent collision smeared out this arc and fore-arc material along the leading edge of the Caribbean Plate and accreted it to the northern edge of South America [e.g., *Pindell et al*., 1998]. Fore-arc material that was deeply subducted prior to accretion now makes up the high-pressure rocks that have been exhumed to the surface in the coastal hinterland metamorphic belt [*Sisson et al*., 1997; *Avé Lallemant*, 1997; *Smith et al*., 1999]. Along the southern edge of the Tobago terrane, oceanic fore-arc and arc basement rocks are exposed at the surface, but the bulk of the rocks in this terrane is buried by Pliocene and younger sediments and covered by the Caribbean Sea [*Robertson and Burke*, 1989; *Speed and Smith-Horowitz*, 1998; *Snoke et al*., 2001a].

The accreted oceanic fore-arc-arc composite (Tobago) terrane is bounded to the south by the topographically high Cordillera de la Costa-Paria-Northern Range coastal hinterland metamorphic belt (Figure 2). In Trinidad and eastern Venezuela, this mountainous belt is made up primarily of South American passive margin deposits that were metamorphosed under greenschist facies conditions and underwent intense mid-Miocene ductile

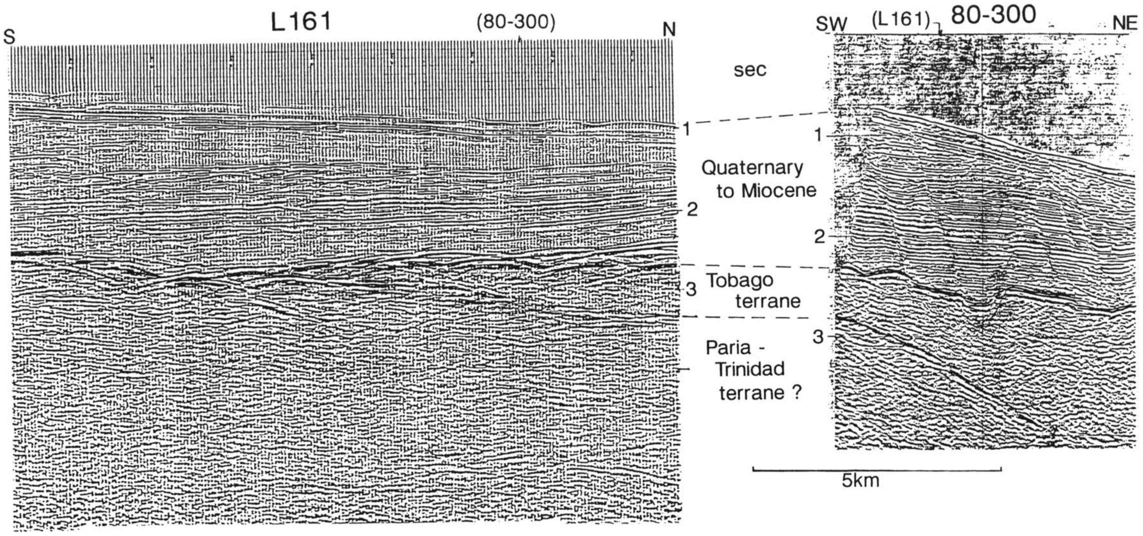

Figure 3. Seismic section taken with permission (www.tandfonline.com) from *Speed and Smith-Horowitz* [1998] and located in Figure 2. Low-angle fault (formerly thrust) boundary beneath the Tobago terrane was reactivated and inverted during the April 1997 earthquake sequence. Trinidad-Paria terrane is made up of deformed and metamorphosed continental South America lithosphere. Note that both tectonostratigraphic units are covered by Quaternary to Miocene sediments and sedimentary rocks that are normal faulted and show clear evidence for recent, mild approximately N-S extension.

deformation and were then exhumed largely in the Pliocene [*Foland et al*., 1992; *Frey et al*., 1988; *Avé Lallemant*, 1997; *Algar et al*., 1998; *Weber et al*., 2001b; *Teyssier et al*., 2002; *Denison et al*., 2009].

The accreted oceanic fore-arc-arc belt has a peculiar geomorphic expression; it occurs in a topographic low north of the mountainous coastal metamorphic belt. Except for a few segments that were trapped structurally high and on top of the South American continent, like the Villa de Cura nappe, the accreted oceanic fore-arc-arc terrane is now exposed in islands and island chains, like the Aruba-Curacao-Bonaire chain and Margarita, Blanquilla, and Tobago (Figures 1 and 2).

The boundary between the Tobago terrane and the coastal hinterland metamorphic belt has likely had a long, polyphase history. This has led to the diverse range of views on its geometry and kinematics presented in the geological literature. *Speed and Smith-Horowitz* [1998] present a relatively comprehensive analysis of this boundary as part of their synthesis and study of the Tobago terrane. Their interpretation is that the boundary is a shallowly (12°) north dipping thrust that puts Tobago terrane rocks over the top of coastal hinterland metasedimentary rocks and that it closely follows the trend of the more steeply dipping Coche-North Coast Fault (Figure 2). This view is based on the examination and interpretation of scattered well data, magnetic surveys, and 2-D reflection seismic lines (i.e., time sections) (Figure 3). We note that *Speed and Smith-Horowitz*'s [1998] dip angle estimate was apparently not based on rigorous depth-time conversions and is open to refinement. *Russo and Speed* [1992] also emphasized the low-angle thrust nature of this boundary in their broadscale tectonic wedging model. *Algar and Pindell* [1993] summarized evidence for long-term down-to-the-north normal slip across the boundary zone. The sharp basement relief between the high Northern Range and low sedimentary basins immediately offshore between Trinidad and Tobago, together with the distinctive structural style north of the boundary, a field of horsts and grabens with Pliocence-Quaternary fill, formed the basis for this interpretation. *Robertson and Burke* [1989] mapped the boundary using an extensive set of industry well and 2-D seismic data. Although they also recognized the disparate basement rock types across it, which were emphasized in the *Speed and Smith-Horowitz* [1998] study, their work focused on the E-W to NE striking, steeply (60–90°) dipping, possible map view right-lateral strike-slip characteristics of the Coche-North Coast Fault portion of the boundary zone (Figure 2). *Speed et al*. [1991] critiqued and criticized some of *Robertson and Burke*'s [1989] arguments for promoting a solely right-lateral strike-slip origin for the faults in this zone.

The Southern Tobago Fault System (STFS) is a major surface expression of the geologically young submarine extension in the Tobago terrane described above (i.e., the horst and grabens mapped by *Robertson and Burke*

[1989]) (Figure 2). The STFS was first identified and named by *Morgan et al*. [1988] in their study of an earthquake swarm that occurred on it in 1982. The seismological data, together with borehole and seismic reflection data that *Morgan et al*. [1988] reviewed, were interpreted to indicate neotectonic activation of a buried E-W striking, steeply dipping (71°N) fault “system.” The local network derived, main shock focal mechanism solution indicated right-lateral strike slip but was not well constrained. On the other hand, Tobago’s geology clearly records significant longer-term, down-to-the-south, normal slip across this fault. Tobago’s Albian metaigneous basement rocks are dropped significantly below the Pleistocene carbonate rocks that cover the southern Tobago lowlands, relative to their exposed and higher position north of the STFS [*Snoke et al*., 2001b]. Kinematic fault data collected on faults that offset Pliocene to Pleistocene units at eight localities in southern Tobago also consistently indicate that N-S stretching on E-W striking normal faults occurred across much of southern Tobago over geologically long timescales [*Ringerwole et al*., 2011]. In this paper, we study the 22 April 1997 M_w 6.7 Tobago earthquake, foreshock, and aftershock seismicity and relate them to reactivation of the fossil Tobago terrane-coastal metamorphic hinterland terrane thrust boundary as a dextral oblique-slip normal fault.

3. The 1997 M_w 6.7 Tobago Earthquake

3.1. Earthquake Sequence

There are no historical accounts of damaging earthquakes affecting Tobago, and only two explicit references to Tobago in historic earthquake felt reports [*Robson*, 1964]. During the instrumental era, which began locally in 1952, earthquake activity in the vicinity of Tobago has been generally at a low level with, on average, less than one earthquake of magnitude $\leq$3.5 located in the area every month and less than one of magnitude $\geq$3.5 and $\leq$4.5 per year. However, superimposed on this low-level background seismic activity is the occurrence of damaging earthquake sequences. There have been three such sequences since recording began in 1952. The two sequences prior to the 1997 sequence that we study here occurred in 1958 and 1982 [*Morgan et al*., 1988; *Latchman*, 1998; *Latchman*, 2009].

The 1958 seismic activity was similar to the 1997 earthquake sequence in that the two largest events were also located west and south of Tobago. Unfortunately, that activity occurred when the local seismic network was in its initial stages of development, and as a result, only seven located earthquakes make up the data set for this sequence *Latchman* [1998, 2009]. Therefore, no focal mechanisms are available for the 1958 main shock(s) nor is it possible to construct any using local network data.

Morgan et al. [1988] investigated the seismology and geologic setting of the 1982 southwest Tobago earthquake sequence, which revealed by epicentral alignment the previously unknown N76°W striking STFS. The main shock in this sequence was a m_b 5.2 event that occurred on 20 September 1982 and caused minor damage in southwest Tobago. *Latchman* [1998, 2009] provide additional analyses and details related to the 1982 sequence.

The 22 April 1997 M_w 6.7 Tobago earthquake was the main shock of a seismic sequence of $>$300 located events (Figure 4). High-level seismic activity ($>$200 events) occurred during the month of April, with seismicity decaying to background levels by the end of 1997 (Figure 4) [*Latchman and Shepherd*, 2003; *Latchman*, 2009]. The April 1997 Tobago seismic series consisted of two subsequences. On 2 April the first subsequence began with a magnitude M_t 5.6 (SRC; see below) main shock west of Tobago (Figure 4). That sequence ran its course over a 2 day period, with most of the earthquakes in the area west of Tobago occurring during that time. The NEIC focal mechanism for this main shock indicates either sinistral strike slip on a subvertical (Dip = 89°) N273°E striking fault plane or dextral strike slip on a subvertical (Dip = 72°) N003°E striking fault.

On 4 April 1997 foreshock activity began in the area south of Tobago that would build to the main shock on 22 April 1997 [*Latchman*, 2009]. The NEIC was able to discriminate, from broadband instrument recordings, that the main shock signature is composed of two events 3 s apart. The main shock together with its aftershock distribution (Figure 4c) demonstrates dextral-normal slip on a low-angle ENE-SSW striking fault plane.

The first subsequence was markedly different in depth, geometry, and kinematics from that of the second subsequence on 22 April 1997 that produced the M_w 6.7 main shock. In general, events in the early subsequence

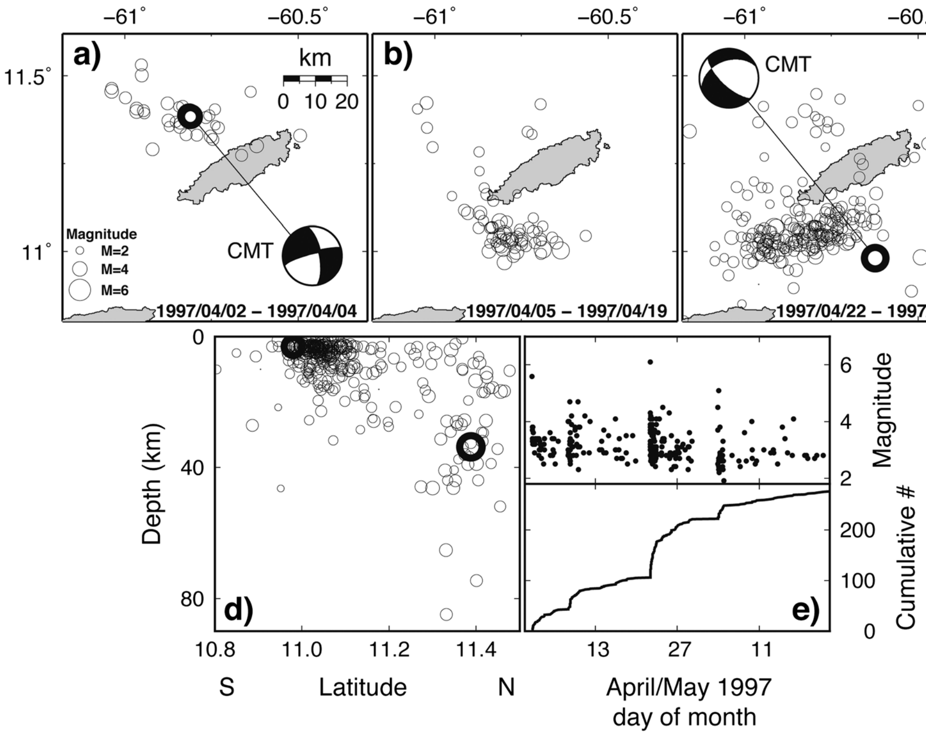

Figure 4. Events in April 1997 Tobago earthquake swarms: (a, b) prior to and (c) including the 22 April 1997 M 6.7 Tobago earthquake and its aftershocks. Epicentral locations and magnitude are determined by the University of the West Indies Seismic Research Centre (UWI-SRC) network. Scale is given for foreshocks and aftershocks; the two subsequence main shocks, for which CMT focal mechanisms are shown, are shown in bold. (d) N-S cross section showing all events in the swarm; the two subsequence main shocks are shown in bold. (e) Time series showing the evolution of the earthquake swarm in terms of cumulative number of events and event magnitude. Sections 3.2 and 3.3 in the text describe the differences in the main shock magnitude determined by UWI-SRC (shown here) and teleseismically.

west of Tobago occurred at depths of 35–50 km (NEIC), whereas those in the south Tobago subsequence were at 5–15 km in depth (NEIC, SRC). Although these events occurred on different fault planes, the main shock may have been triggered by the 4 April 1997 M_t 5.6 earthquake.

3.2. Location

Location parameters of the 22 April 1997 earthquake south of Tobago earthquake are available from the agencies responsible for processing global seismicity—the NEIC, ISC, and GCMT—and from the regional seismic monitoring agency, SRC—recognized as authoritative for the eastern Caribbean by those agencies. Following are the time, location, depth, and magnitude hypocentral parameters determined by those four agencies: ISC 09:31:28.85, 11.162°, 61.091°, 47.1 km, 5.8 m_b; NEIC 09:31:23.2, 11.11°, 60.89°, 5 km, 6.7 M_w; GCMT 09:31:32.7, 11.28°, 61.05°, 15 km, 6.7 M_w; and SRC 09:31:21.64, 11.00°, 60.73°, 2 km, 6.1 M_t. Differences between these determinations represent to some extent the uncertainty involved in locating earthquakes in this region due to local and global differences in velocity models and seismic phases used in the inversions (see below).

There are five main seismic velocity models used by the SRC for eastern Caribbean earthquakes. These models were derived from various studies in the region (e.g., PERAGG for northern Venezuela and Trinidad events [*Pérez and Aggarwal*, 1981] and WINDWARD [*Boynton et al*., 1979] for events occurring within 11°–14°N). SRC solutions are considered to be accurate to about ±5 km in epicentral location and ±10 km in depth [*Bulletin of the Seismic Research Unit*, 1988]. It has been observed from low-magnitude events with highly localized felt areas that SRC solutions fit well with the macroseismic observations. Damage in southern Tobago caused by the 22 April 1997 earthquake is more consistent with the SRC location than with those of the other agencies [*Latchman*, 2009] (Figure 4).

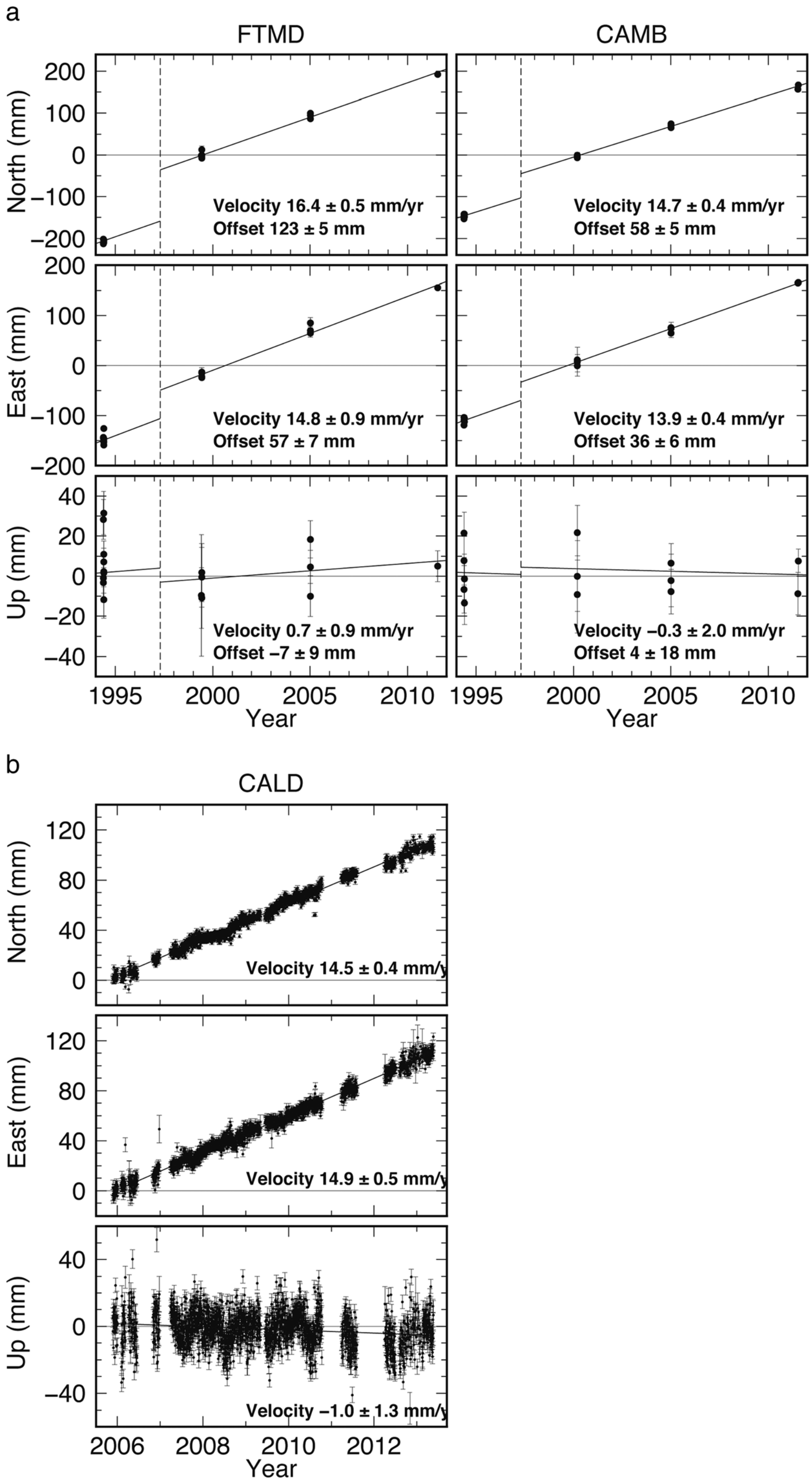

Figure 5. (a) GPS-derived north, east, and up coordinate (dots with error bars) time series for campaign sites 3252, Fort Campbleton (CAMB), in northern Tobago, and 3225, Fort Milford (FTMD), in southern Tobago (see Figure 6), measured before and after the 22 April 1997 Tobago earthquake. Time series are in the ITRF2008 reference frame. Estimated coseismic displacements are labeled as “offset.” All parameters derived used methods described in text. Note that the southern campaign site (FTMD), which is closest to the epicenter, experienced the largest coseismic displacements. (b) Time series for continuous GPS site CALD in central Tobago (11.20°, −60.73°; see Figure 6), also given in ITRF2008. Note that CALD’s east and north interseismic velocity components are very similar to those (labeled as “velocity”) that we estimated for episodic sites CAMB and FTMD.

Table 1. GPS-Determined Coseismic Offsets

Site ID	Site Number	Site Name	Latitude	Longitude	Offset *N* (mm)	Offset *E* (mm)	Offset *U* (mm)
FTMD	3225	Fort Milford	11.15	−60.84	123 ± 5	57 ± 7	−7 ± 9
CAMB	3252	Fort Campbleton	11.32	−60.56	58 ± 5	36 ± 6	4 ± 18

3.3. Magnitude

The teleseismic hypocentral solutions described above (section 3.2) give both moment magnitude (M_w) and body wave magnitude (m_b) estimates. The SRC uses a duration magnitude, M_t, which was derived to be consistent with body wave magnitude, m_b [*Shepherd and Aspinall*, 1983]. It is defined as $M_t = -0.705 + 2.073 \log_{10} \tau + 0.0018R$ where τ is signal duration in seconds and R is hypocentral distance in kilometers. The local SRC magnitude, M_t, of 6.1 is larger than the m_b value found by the ISC ($m_b = 5.8$).

3.4. Focal Plane Solution

Focal mechanisms are available from the NEIC and GCMT for this event. Both determinations give essentially the same result (NEIC NP1: Strike = 223, Dip = 17, Slip = −166; NEIC NP2: Strike = 119, Dip = 86, Slip = −73; CMT NP1: Strike = 250, Dip = 41, Slip = −146; and CMT NP2: Strike = 133, Dip = 69, Slip = −54), with normal (and subsidiary dextral) slip on a shallowly dipping, ENE striking fault plane (NP1) and normal (and subsidiary sinistral) slip on a steeply dipping, ESE striking auxiliary plane (NP2) (Figure 4). Differences in strike, dip, and slip values between the two solutions are of order ±20°.

4. Geodetic Methods and Observations

We made repeat episodic GPS observations at two sites in Tobago: in southern Tobago at Fort Milford (FTMD, 3225) and in northern Tobago at Fort Campbleton (CAMB, 3252), for 5–9 days in May–June 1994, 3 days in June 1999, 4 days in March 2000, and 2 days in July 2011 (Figure 5). We processed the GPS data using the GNSS Inferred Positioning System-Orbit Analysis Simulation Software II (GIPSY-OASIS II) version 6.1.2 [*Zumberge et al.*, 1997] and final satellite ephemeris and clock files developed and produced at the Jet Propulsion Lab, respectively, and absolute antenna phase centers from the International Global Navigation Satellite Systems Service. Ambiguity resolution was performed using the Ambizap code of *Blewitt* [2008].

We derived daily point positions in International Terrestrial Reference Frame (ITRF) 2008 [*Altamimi et al.*, 2011] that are precise to plus-or-minus a few millimeters. We then used these position time series to calculate interseismic site velocities using data after the 1997 Tobago earthquake (i.e., 1999–2011), with velocity uncertainties calculated following *Geirsson et al.* [2006]. To estimate the horizontal and vertical coseismic offsets, we assumed that the interseismic velocities were the same before and after the 1997 earthquake and calculated the difference in positions before and after the earthquake (Figure 5 and Table 1). Our offset uncertainty estimates account both for uncertainty in the interseismic velocity estimates and the daily position scatter in the data. Similar studies that use continuous GPS (cGPS) data have shown that postseismic slip (afterslip) can also be significant and persistent, albeit generally with magnitudes about 10 times smaller than those of the associated coseismic slip [*Hsu et al.*, 2006, 2009]. Because we use episodic GPS data widely spaced in time (i.e., ~3 years before and ~2 years after) around the earthquake, we are unable to quantify any possible postseismic slip.

In southern Tobago at site FTMD, ~10–15 km north of the earthquake epicenter, we estimate a northward displacement of 123 ± 5 mm, an eastward displacement of 57 ± 7 mm, and a vertical displacement of −7 ± 9 mm (Figure 5a). At our northern site CAMB, ~35–40 km northeast of the epicenter, we estimate a northward displacement of 58 ± 5 mm and eastward displacement of 36 ± 6 mm. The vertical displacement is highly uncertain at 4 ± 18 mm (Figure 5a). That site FTMD indicates significantly larger coseismic displacements than site CAMB is in good agreement with it being closer to the epicenter of the 22 April 1997 earthquake.

5. Elastic Dislocation Modeling and Methods

To investigate the kinematics and fault geometry of the 22 April 1997 earthquake, we modeled our estimated coseismic displacements with a rectangular, uniform-slip dislocation model in an elastic half-space following *Okada* [1985]. We ran forward models to fit the three observations (Δ_n, Δ_e, and Δ_v) at the two GPS stations (CAMB and FTMD) (Table 1). Both horizontal and vertical displacements were modeled and matched (Table 1

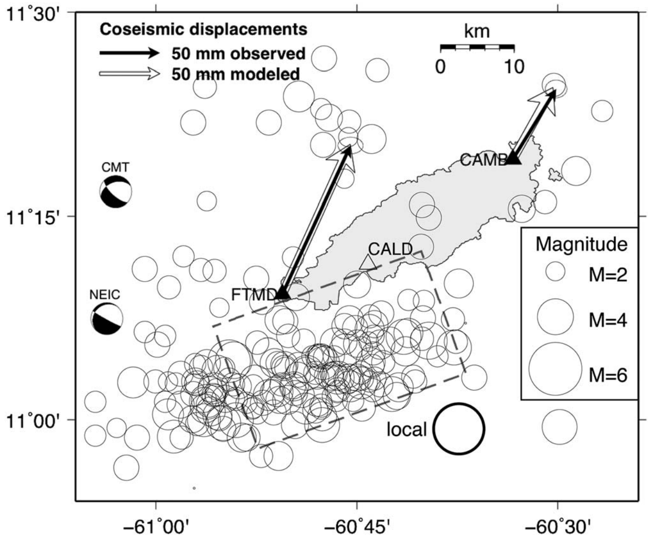

Figure 6. Observed (black arrows) and best fit elastic dislocation forward model-derived (white arrows) coseismic displacements, derived using methods described in text, for sites 3252, Fort Campbleton (CAMB), and 3225, Fort Milford (FTMD), for 22 April 1997 Tobago earthquake. Fixed model parameters include fault length, width, and strike (model fault plane shown); model-derived best fit parameters include fault slip, dip, and rake. NEIC, CMT, and local (UWI-SRC) epicenter locations are also shown. NEIC and CMT focal mechanisms (magnitudes not to scale) are shown in correct epicentral positions. UWI-SRC aftershocks are shown for the period 22 April to 24 December 1997. Location of cGPS site CALD (open triangle) is also shown.

and Figure 6). The limited spatial coverage of the observations and offshore location of the earthquake results in a wide range of possible solutions that fit the observed geodetic data. We performed a grid search through the parameter space (Table 2) and calculated the χ^2 value for each forward model. For each parameter, we searched through 15 evenly spaced values. We fixed the length, width, and strike of the fault and varied the location of the fault center (latitude, longitude, and depth), dip, rake, and amount of slip. We chose to fix the dimensions of the fault because they should approximately correspond to and can thus be directly and empirically estimated from the distribution of aftershocks (Figure 4c) [*Latchman*, 1998; *Latchman and Shepherd*, 2003]. In this case we fixed the fault dimensions to 30 km long by 20 km wide (down-dip), which represents the area around the aftershocks (Figures 4c and 6). We fixed the fault strike using the GCMT value of 250°, which is also in agreement with the observed aftershock distribution, although a significant number of aftershocks plot WSW of the best fit fault plane (Figure 6).

6. Results

Our empirically derived coseismic displacements qualitatively match physical expectations based on the reported focal mechanisms for the 22 April 1997 M_w 6.7 earthquake. Our calculated offsets are largest in southern Tobago at site FTMD, closest to the earthquake epicenter, and decrease to the north at site CAMB (Figure 6). In addition, both sites moved mainly to the north during this ENE striking, predominantly low angle normal faulting event. From our elastic modeling, using a few fixed constraints, we derived reasonable values for our adjustable parameters and a very close match to our GPS-derived calculated coseismic displacements (Figure 6).

Table 2. Fault Parameter Estimates From Elastic Dislocation Modeling Grid Search

	Range Tested			
Parameter	Minimum Value	Maximum Value	Best Fit Value	Acceptable Range
Length (km)	30			Fixed
Width (km)	20			Fixed
Strike (deg)	250			Fixed
Latitude[a] (deg)	10.8	11.3	11.09	10.95 to 11.13
Longitude[a] (deg)	−61.4	−60.6	−60.77	−61.00 to −60.70
Depth[a] (km)	4	25	8.5	7 to 18
Dip (km)	15	50	27.5	15 to 50
Rake (deg)	−170	−100	−125	−120 to −145
Slip (m)	0.1	2.2	1.0	0.7 to 2.2

[a] Latitude, longitude, and depth refer to the center point of the fault.

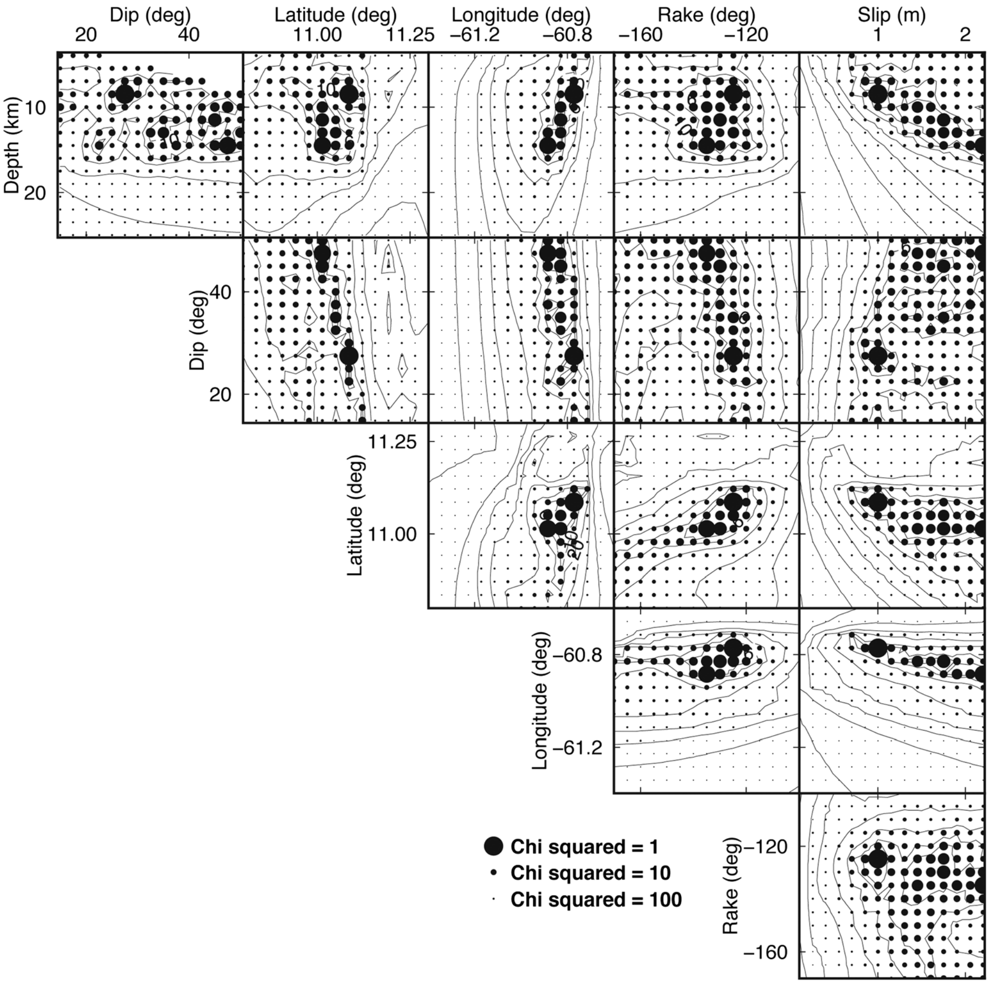

Figure 7. Cross-correlation plots for fault parameters solved for with the forward elastic models. The plots show the best fit solutions and sensitivity.

Our elastic modeling gives good constraints on some fault parameters, while others are more poorly determined, yet in close agreement with the seismically derived focal mechanism parameters (Figure 7). The centroid location of the fault is tightly constrained and correlates fairly well with aftershock locations (Figures 4 and 7). The depth to the center of the rectangular fault is constrained between 8 and 15 km and correlates somewhat with longitude and slip, such that more westerly locations and higher slip magnitudes require greater depth. However, the dip is less tightly constrained as our best fit model ($\chi^2 = 0.95$) gives a dip of 27.5°, and the second best model ($\chi^2 = 1.26$) gives a dip of 47.5° (Figure 7). The dip correlates somewhat with latitude, such that the farther south the fault plane lies, the steeper the dip. The estimated GCMT dip is 41° and the NEIC dip is 17°, both of which are within the range of our estimates. The locally estimated epicenter lies to the southeast of our best fit plane (Figure 6). If the center of our model plane was farther south, it would imply a steeper fault dip based on the parameter correlations (Figure 7). The magnitude of slip shows the expected correlation with the centroid depth, such that a higher slip necessitates a deeper epicenter. Because we fixed the fault dimensions, the resulting moment scales directly with the slip magnitude. Our best fit slip value is 1.0 m, with an acceptable range of 0.7–2.2 m. Assuming a standard shear modulus of 30 GPa [e.g., *Masters and Shearer*, 1995], we obtain a moment in the range of 1.5×10^{19} to 4.0×10^{19} Nm, with a best fit value of 1.8×10^{19} Nm, similar to the U.S. Geological Survey moment estimate of 1.13×10^{19} Nm.

7. Discussion

The accretion of arc and fore-arc terranes to continents is a fundamental process in tectonics. Accreted terrane boundaries are inherent weaknesses in the lithosphere that can be reactivated as relative plate

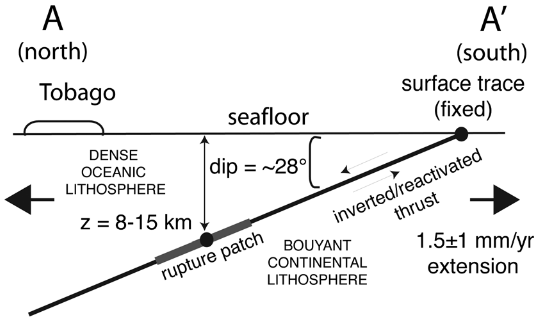

Figure 8. Diagram showing best fit constraints on the geometry of the interpreted reactivated low-angle Tobago terrane (formerly thrust) boundary, as mapped by *Speed and Smith-Horowitz* [1998], and observed seismologically. See Figure 2 (heavy hatchured line) for a map view of this reactivated terrane boundary. The geology shown is greatly simplified and is schematic with all Quaternary-Miocene cover rocks removed.

motions change. As described above, the Caribbean-South America plate boundary is no exception. The Tobago terrane was accreted onto the northern edge of the South American continent during Miocene time, and the suture zone is directly beneath and south of Tobago island. It is striking that the fault plane that ruptured during 22 April 1997 M_w 6.7 earthquake coincides with the Tobago terrane-South American continent thrust boundary mapped by *Speed and Smith-Horowitz* [1998] (Figures 2, 3, and 8). Caribbean fore-arc oceanic lithosphere of the Tobago terrane was initially obducted over or wedged into (i.e., thrust over or into) the subgreenschist-greenschist grade metasedimentary rocks, formerly South American passive margin deposits, of the coastal metamorphic belt [*Russo and Speed*, 1992; *Speed and Smith-Horowitz*, 1998; *Avé Lallemant*, 1997] along this boundary during early Tertiary oblique convergence. We interpret the 22 April 1997 event as a reactivation and inversion of this terrane boundary, which must have initially had a low dip angle and thrust (reverse) sense of displacement (Figure 8).

The approximately E-W dextral shear that is currently being accommodated along the Caribbean-South American plate boundary, however, is not consistent with the 250° strike and the relatively large (~2:1) ratio of normal dip slip to dextral strike slip (at site FTMD) observed for the 22 April 1997 event. *Weber et al.* [2011] showed that GPS sites in northern Trinidad move at nearly the full velocity of the Caribbean Plate (~20 mm/yr), relative to a fixed South American Plate, whereas sites in southern Trinidad move only a few mm/yr. This, and additional studies [*Prentice et al*., 2010; *Soto et al*., 2007], indicates that most of the plate motion between the Caribbean and South American Plates is taken up on the Central Range Fault in Trinidad and that Tobago lies within or near the edge of the stable Caribbean Plate as defined in *Weber et al*. [2001a] and *Weber et al*. [2011]. We next explore our new Tobago interseismic velocities in this context but using the newer MORVEL plate motion model [*DeMets et al*., 2010].

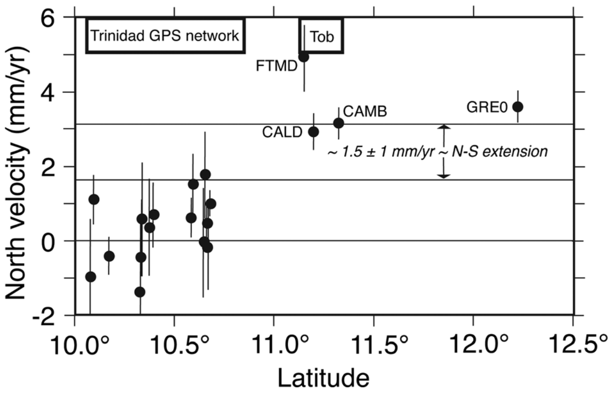

Figure 9. Velocity profile across the Trinidad/Tobago region showing north component of interseismic velocity in fixed South American Plate reference frame from our Trinidad and Tobago GPS network and from site GRE0 (Grenada) from the COCONet cGPS network [e.g. *Braun et al*., 2012]. All data were processed as described in Geodetic Methods and Observations section. Coseismic motions shown in Table 1 have been removed from episodic Tobago sites FTMD and CAMB. The Trinidad portion of our network is described in *Churches et al*. [2014]; COCONet cGPS data are available publically at http://coconet.unavco.org/.

Figure 5 shows the interseismic velocities that we estimate at CAMB (V_n 16.4, V_e 14.8) mm/yr and FTMD (V_n 14.7, V_e 13.9) mm/yr; these are close to the MORVEL plate motion model [*DeMets et al*., 2010] predicted rates of (V_n 13.7, V_e 13.8) mm/yr and (V_n 13.8, V_e 13.7) mm/yr, respectively. In addition, we obtained and processed data from one continuous GPS site in Tobago, CALD (11.20°, −60.73°), which is approximately midway between CAMB and FTMD, has been in operation since 2005, and is thus uncontaminated by coseismic or postseismic motions related to the 1997 earthquake swarm (Figure 5b). Site CALD shows interseismic motions relative to stable South America of $V_n = 7.8$ and $V_e = 22.8$ mm/yr, close to MORVEL's predicted steady state Caribbean plate motion of $V_n = 4.7 \pm 3.1$ mm/yr and V_e,$=19.6 \pm 3.2$ mm/yr (Figure 1).

Because the event produced motions distinct and different from those expected during active dextral shearing in the plate boundary, additional motions and forces were likely involved in driving the deformation. Our Trinidad and Tobago GPS network, which we have been building and improving since the 1990s, is now spatially and temporally mature enough that we detect ≥1.5 mm/yr of active approximately N-S extension between Trinidad and Tobago (Figure 9). We suggest that this small amount of extension, the preexisting Tobago terrane boundary, and gravitational forces resulting from the stacking of oceanic crust over continental crust acted together to drive the large component of normal dip slip that occurred during the 22 April event (Figure 8). After a critical amount of elastic strain accumulated, the Tobago terrane probably exploited the preexiting weak fault and quickly slid NNE. Assuming that extension rates are constant, similar earthquakes could recur about once every ~500 years. Another modern example of this geodynamic process may be found in the D'Entrecasteaux Islands, Papua New Guinea. Low-angle normal faults near the D'Entrecasteaux Islands are driven by extension in the Woodlark Basin that propagates westward into more buoyant continental lithosphere with a previously thrust-stacked Papuan ophiolite over its top [*Abers*, 1991; *Abers et al.*, 1997; *Baldwin et al.*, 2012].

Hippolyte and Mann [2011] documented similar but currently inactive normal faults in the western Lesser Antilles arc-fore arc (Aruba, Bonaire, and Curacao). Such normal faults, slipping over many earthquake cycles, might explain the peculiar sunken geomorphic expression of the accreted oceanic fore-arc-arc terrane along the entire plate boundary (Figures 1 and 2). Normal faulting, possibly with locally variable stretching directions, provides a viable tectonic mechanism for stretching, thinning, and subsiding the accreted oceanic fore-arc-arc lithosphere.

Shallowly dipping normal faults have received much attention in the tectonics literature, in part because of their importance in accommodating the large magnitude of horizontal stretching observed in the Basin and Range and in other high-strain continental rifts. One additional major controversy has centered on whether such faults form with primary low dip angles or form with high dip angles and are subsequently rotated to shallower dips [e.g., *Axen and Bartley*, 1997]. The 22 April 1997 event is a clear example of a nonrotated, low-angle (28°) normal fault that formed via reactivation of an earlier low-angle, terrane-bounding thrust; the Woodlark-D'Entrecasteaux case cited above may provide another possible example.

We conclude that the 22 April 1997 earthquake ruptured a segment of the fossil ocean-continent boundary between the Tobago terrane and continental South America that formed during early Tertiary oblique plate convergence (Figures 2 and 3). This event is thus anomalous and of interest because (1) its large normal slip component and ENE strike are unexpected given the current approximately E-W dextral shearing in the plate boundary; (2) it ruptured a normal fault plane with a low (~28°) dip angle; and (3) it reactivated and inverted a former terrane thrust boundary.

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