Active strike-slip faulting in El Salvador, Central America

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ABSTRACT

Several major earthquakes have affected El Salvador, Central America, during the Past 100 yr as a consequence of oblique subduction of the Cocos plate under the Caribbean plate, which is partitioned between trench-orthogonal compression and strike-slip deformation parallel to the volcanic arc. Focal mechanisms and the distribution of the most destructive earthquakes, together with geomorphologic evidence, suggest that this transcurrent component of motion may be accommodated by a major strike-slip fault (El Salvador fault zone). We present field geological, structural, and geomorphological data collected in central El Salvador that allow the constraint of the kinematics and the Quaternary activity of this major seismogenic strike-slip fault system. Data suggest that the El Salvador fault zone consists of at least two main ~E-W fault segments (San Vicente and Berlin segments), with associated secondary synthetic (WNW-ESE) and antithetic (NNW-SSE) Riedel shears and NW-SE tensional structures. The two main fault segments overlap in a dextral en echelon style with the formation of an intervening pull-apart basin. Our original geological and geomorphologic data suggest a late Pleistocene–Holocene slip rate of ~11 mm/yr along the Berlin segment, in contrast with low historical seismicity. The kinematics and rates of deformation suggested by our new data are consistent with models involving slip partitioning during oblique subduction, and support the notion that a trench-parallel component of motion between the Caribbean and Cocos plates is concentrated along E-W dextral strike-slip faults parallel to the volcanic arc.

Keywords: strike-slip faulting, active tectonics, El Salvador, seismic hazard.

INTRODUCTION

El Salvador, Central America, is a highly seismically active country, where at least 11 major earthquakes have caused more than 3000 casualties in the past 100 yr (e.g., Lopez et al., 2004; Martínez-Díaz et al., 2004). Seismic activity is associated with subduction of the oceanic Cocos plate under the Caribbean plate along the Middle America Trench at rates of 73–84 mm/yr (De Mets, 2001; Fig. 1A). Several studies suggest that the oblique convergence between the two plates is partitioned between trench-orthogonal compression and strike-slip deformation parallel to the volcanic arc, associated with northwestward transport of a forearc sliver relative to the Caribbean plate (Harlow and White, 1985; White, 1991; De Mets, 2001). The transcurrent component of motion is estimated to be ~14 mm/yr (Fig. 1A). Because of this kinematic setting, earthquakes are of two distinct types: subduction related and strike-slip related (e.g., Carr and Stoiber, 1977; White, 1991; White and Harlow, 1993; Dewey et al., 2004; Martínez-Díaz et al., 2004). The subduction events include the largest earthquakes in the area ($M_w > 7.0$), with focal depths >50 km. This seismic activity is characterized by reverse faulting focal solutions linked to plate convergence and normal-slip events related to the flexure of the subducting plate. On land, in contrast, strike-slip earthquakes dominate (Fig. 1B). These events are characterized by moderate magnitudes ($5.5 < M_w < 6.8$) and occur in the upper crust (<20 km). The shallow depth is responsible for the strong damage and destruction associated with these moderate-sized events.

On the basis of seismotectonic and morphotectonic observations, Martínez-Díaz et al. (2004) proposed the existence of an E-W–trending major transcurrent fault system (El Salvador fault zone) extending along the volcanic arc and representing the source of this strong seismicity (Fig. 1B). However, no field studies constraining the kinematics, current activity, and regional segmentation of this fault system have been reported. Our study fills this gap with new geological, structural, and geomorphic data concerning the El Salvador fault zone, southeast of San Salvador. These data have important implications for the evaluation of seismic hazard in the area and shed new light on the strain partitioning induced by the oblique plate convergence in Central America.

STRIKE-SLIP SEISMIC ACTIVITY IN EL SALVADOR

The major upper crustal seismic events that have occurred since 1912 in El Salvador are aligned parallel and located north of the volcanic arc (e.g., Carr and Stoiber, 1977; White, 1991; White and Harlow, 1993; Ambraseys et al., 2001; Dewey et al., 2004; Martínez-Díaz et al., 2004). Reliable focal mechanisms indicate strike-slip events with one of the planes oriented E-W (Fig. 1B). The distribution and kinematics of earthquakes suggest that they occurred on the El Salvador fault zone, north of the volcanic arc. On land, one of the strongest earthquakes occurred on February 13, 2001 ($M_w = 6.6$); the epicentral location, focal mechanism, and aftershock distribution strongly suggest that this earthquake was pro-

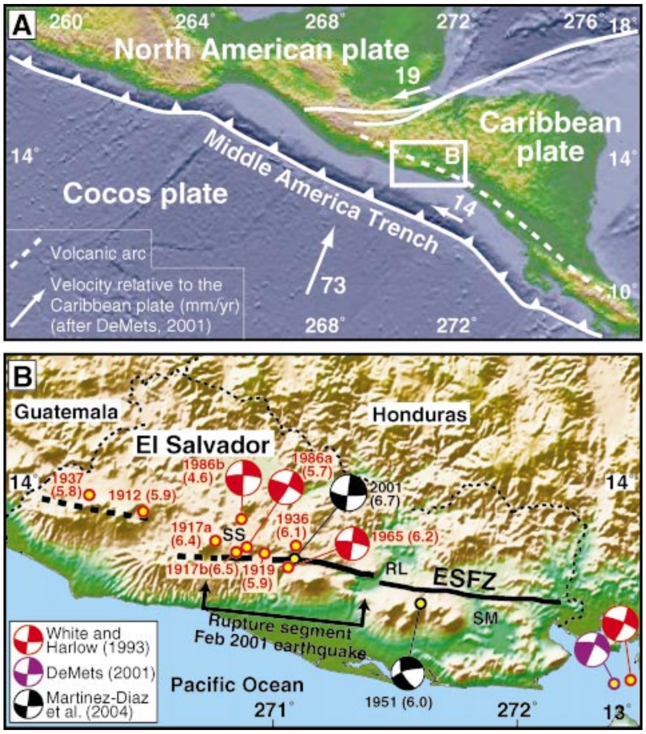

Figure 1. A: Geodynamic setting of Central America (after DeMets, 2001). B: Historical destructive earthquakes and focal mechanisms of crustal-depth earthquakes available for El Salvador area (numbers refer to year and magnitude of events). Thick black line indicates inferred trace of El Salvador fault zone (ESFZ; modified after Bosse et al., 1978; Martínez-Díaz et al., 2004); fault segment that ruptured during February 2001 earthquake is also reported (after Martínez-Díaz et al., 2004). RL—Rio Lempa; SM—San Miguel; SS—San Salvador.

duced by the rupture of a major segment of the El Salvador fault zone, extending between Rio Lempa and Lago Ilopango (Benito et al., 2004; Dewey et al., 2004; Martínez-Díaz et al., 2004). In particular, the fault plane of the main shock was constrained by best fitting aftershocks distribution to be oriented N94°E and to dip 70° to the south. At least six of the major destructive earthquakes ($M \geq 6$) along the volcanic arc seem to be related to slip along this El Salvador fault zone segment (Fig. 1B; Martínez-Díaz et al., 2004). The February 2001 event may have loaded an El Salvador fault zone segment extending east of Rio Lempa with a positive change in Coulomb failure stress (Benito et al., 2004; Martínez-Díaz et al., 2004). This scenario has important implications for seismic hazard in this area.

ACTIVE DEFORMATION ASSOCIATED WITH THE EL SALVADOR FAULT ZONE

In order to better characterize and map the El Salvador fault zone, we conducted geological, structural, and geomorphologic field studies implemented with analysis of satellite images, aerial photos, and digital elevation models. This analysis (Fig. 2) shows that the main active faults strike ~E-W and are characterized by right-lateral kinematics; these faults, subparallel to and located north of the volcanic arc, constitute the El Salvador fault zone in the area. Major E-W strike-slip faults extend between the Ilopango caldera and the San Vicente volcano, in the area affected by the February 2001 earthquake. The fault system displaces the late Pleistocene–Holocene fall deposits related to the eruption of the Ilopango caldera (Tierra Blanca Formation; age <40 ka; Rose et al., 1999) and is characterized by geomorphic features typical of active strike-slip faults (e.g., offset streams, prominent fault scarps). Fault-slip analysis north of San Vicente (site 1, Fig. 2B; see Data Repository Fig. DR1; Table DR1[1]) support a dominant transcurrent stress field, with horizontal σ_1 and σ_3 oriented ~NNW-SSE (~N160°E) and ~ENE-WSW (~N70°E), respectively.

Detailed field work focused in the area near the Berlin caldera, between Rio Lempa and the San Miguel volcano (Fig. 2). Although the El Salvador fault zone is associated with low historical seismicity, our analysis suggests that this segment is characterized by active deformation. In particular, besides being characterized by an important geomorphic signature (Fig. 2), the strike-slip faults affect Holocene–present river terraces and alluvial fans in the Rio Lempa area (Fig. DR2) and a volcanic sequence formed by lavas, ignimbrites, and tephra deposits of late Pleistocene–Holocene age (Fig. 2). This sequence, which overlies early-late(?) Pleistocene lavas and scoria of the Berlin volcano, is characterized by the occurrence of two important late Pleistocene ignimbritic units (black and gray ignimbrites), covered by ignimbrites and tephra of the Blanca Rosa Formation, which in turn underlie younger late Pleistocene(?)–Holocene tephra deposits (Fig. 2C; Fig. DR3). Both the black and gray ignimbrites are composed of huge volumes (~50 km^3) of andesitic ignimbrites, which formed in response to the collapse of the Berlin caldera during the late Pleistocene. An age of ca. 100 ka can be inferred for the black ignimbrite (Comisión Ejecutiva Hidroeléctrica del Río Lempa, 1995), whereas the pyroclastic flows of the gray ignimbrites that crop out north of the Berlin geothermal field have been dated by ^{14}C analysis as 36.5 ± 1.7 ka (Comisión Ejecutiva Hidroeléctrica del Río Lempa, 1994) and 35.7 ± 0.5 ka (Comisión Ejecutiva Hidroeléctrica del Río Lempa, 1995).

The second collapse of the Berlin caldera and the consequent deposition of the gray ignimbrite had an important impact on the morphology and local drainage system close to the Berlin volcano. In particular, the large volumes of erupted ignimbrites gave rise to a planar surface, still visible north of the Berlin geothermal field, which was subsequently incised by a late Pleistocene–Holocene (<36 ka) river drainage. Both the paleosurface and the river drainage are displaced by the E-W strike-slip faults (Fig. 2), providing constraints on the late Pleistocene–Holocene horizontal and vertical motion of the El Salvador fault zone in the area. In particular, close to the El Triunfo (Fig. 2C), rivers display a consistent right-lateral horizontal offset (d_h) of ~400 m (Fig. DR4; see footnote 1), except near Mercedes Umaña, where the fault scarp creates a local drainage barrier that forces rivers to shift their flow in a direction opposite to that of strike-slip displacement (Fig. 2; Fig. DR4). Given this lateral displacement and the younger than 36 ka age of the drainage system, estimates of minimum slip rates along the strike-slip fault yield values of ~11 mm yr^{-1}, consistent with the rates suggested by plate kinematic models (DeMets, 2001). Topographic profiles perpendicular to the fault trace (Fig. DR5) show that the paleosurface is downthrown toward the south with an average vertical offset of ~35 m, yielding a vertical slip rate of ~1 mm yr^{-1}, i.e., ~1/10 of the horizontal velocity.

Similar to the San Vicente area, fault-slip analysis indicates a dominant strike-slip stress field, with σ_1 and σ_3 oriented ~NNW-SSE (~N155°E) and ~ENE-WSW (~N65°E), respectively (sites 1–3, Fig. 2B; Fig. DR1; Table DR1). The E-W strike-slip faults are associated with minor structures that we assign to three different sets according to orientation: (1) WNW-ESE (~N110°E); (2) NW-SE (~N130°E); and (3) NNW-SSE to N-S

[1]GSA Data Repository item 2005190, Figures DR1–DR5, and Table DR1, is available online at www.geosociety.org/pubs/ft2005.htm, or on request from editing@geosociety.org or Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301, USA.

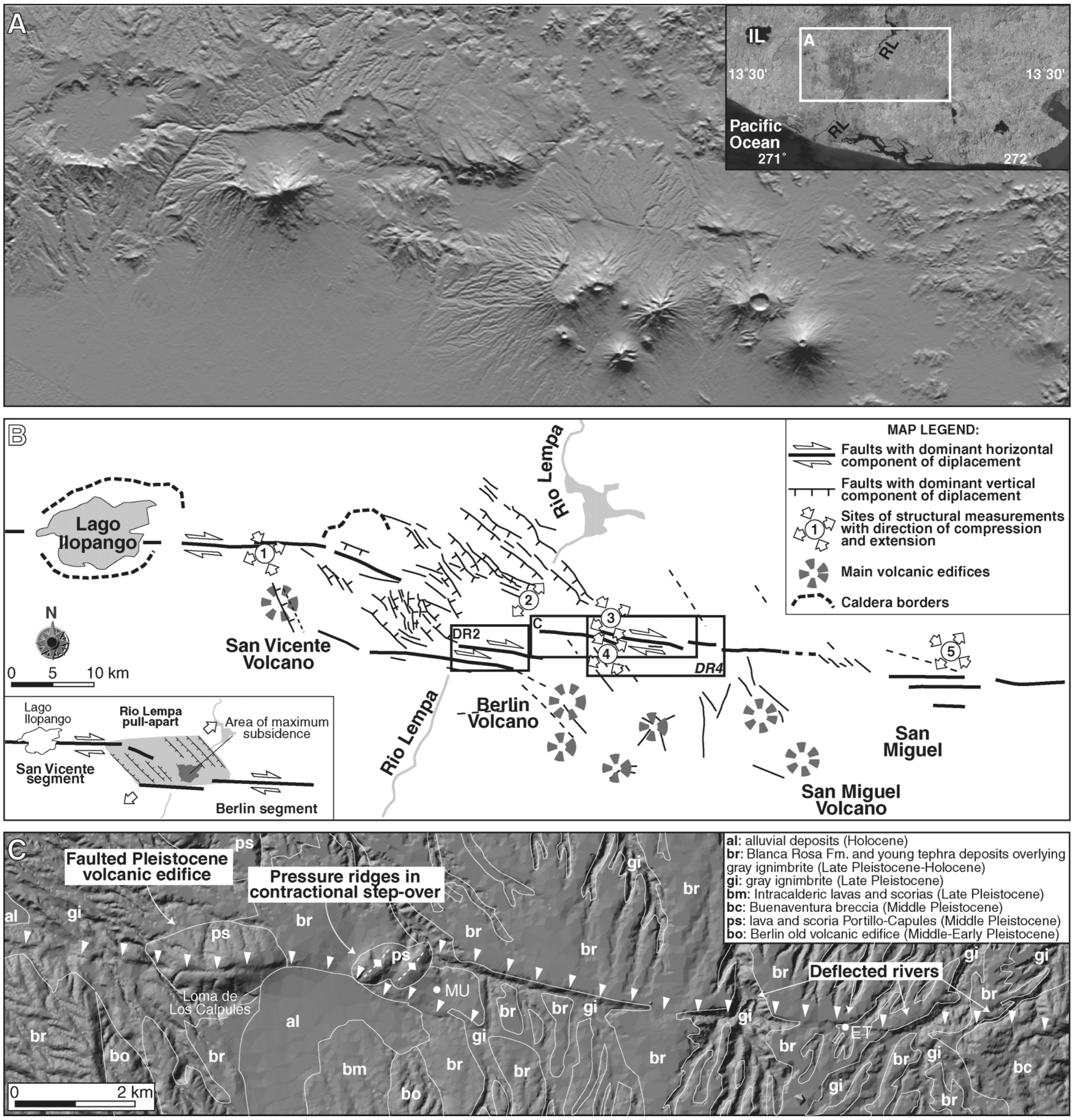

Figure 2. A: Digital elevation model (DEM) of region between Ilopango caldera and San Miguel (location shown in inset). DEM is derived from SRTM data (http://srtm.usgs.gov/) courtesy of University of Maryland, Global Land Cover Facility; Landsat ETM 7 satellite mosaic images courtesy of University of Maryland, Global Land Cover Facility. B: Line drawing of active structures forming El Salvador fault zone in area, with reported paleostress orientations computed from fault-slip data using Carey's (1979) inversion method (Fig. DR1; Table DR1 [see footnote 1]). Inset shows interpretation of regional fault pattern. C: Geological map superimposed on DEM of region between Mercedes Umaña (MU) and El Triunfo (ET). Arrows indicate fault trace. See text for details.

(N170°E to N180°E). As observed in classical strike-slip physical experiments (e.g., Tchalenko, 1970), these different fault sets can be related to an E-W dextral shear coupled with the E-W structures representing the main deformation zone (Y shears) and the subordinated fault trends representing Riedel (WNW-ESE) and antithetic Riedel (NNW-SSE to N-S) shear, and tension (NW-SE) fractures. This interpretation is supported by our fault-slip analysis on different structural sites located along the major structures (Fig. 2B; Fig. DR1). Notably, pressure ridges have been observed at contractional stepover of the main strike-slip fault segments (Fig. 2C; Fig. DR2)

Normal faults are well developed close to Rio Lempa and correspond to a right step in a major E-W strike-slip fault system. ENE-WSW extension in the area (site 3, Fig. 2B; Fig. DR1; Table DR1) gives rise to strong subsidence and sedimentation in the river course. We interpret this area as a pull-apart structure resulting from the dextral en echelon overlapping of the dextral strike-slip faults (Fig. 2B).

REGIONAL SEGMENTATION OF THE EL SALVADOR FAULT ZONE

The discontinuous nature of the El Salvador fault zone between San Salvador and San Miguel (Fig. 2) matches the first-order segmentation proposed by Martínez-Díaz et al. (2004) on the basis of the analysis of regional seismicity. In particular, two major segments can be delineated in the region between San Salvador and San Miguel volcano, extending (1) from the Ilopango caldera to the San Vicente volcano–Rio Lempa area (San Vicente segment) and (2) from Rio Lempa eastward (Berlin segment; Fig. 2B).

Rupture on the first fault segment caused the February 2001 (M_w = 6.6) earthquake (Martínez-Díaz et al., 2004). Interaction between the San Vicente segment and the Berlin segment occurs in the Rio Lempa pull apart, located at the eastward termination of the aftershocks of the 2001 event. Deformation is transferred to the Berlin segment, the termination of which seems to occur at the San Miguel volcano. Although historically only low seismicity occurred on this fault segment, our new geological and geomorphological data prove the existence of important late Pleistocene–Holocene strike-slip deformation. Discrepancy between high strain and low seismicity can be explained either by locking of the fault or by aseismic creep. After the first scenario, high seismic hazard may characterize the Berlin segment, as suggested by Martínez-Díaz et al. (2004). Farther east, strain may be transferred to an additional segment (San Miguel segment); however, this segment is poorly known and requires additional structural work to be characterized.

No major compressional deformation associated with the convergence between the Cocos and the Caribbean plates has been so far reported on land, and it has not been detected by our field study. The kinematics and deformation rates deduced on the basis of the above data—together with the absence of important compressional deformation—confirm the model of strain partitioning between trench-orthogonal compression and trench-parallel transcurrent deformation at the Cocos-Caribbean plate boundary (Harlow and White, 1985). In particular, the slip rates obtained through our new data are comparable to the trench-parallel component of movement deduced from geodetic measurements (De Mets, 2001) and support the hypothesis that motion due to the northwestward transport of the fore-arc sliver relative to the Caribbean plate is concentrated along E-W dextral strike-slip faults parallel to the volcanic arc.

CONCLUSIONS

Our geological, structural, and geomorphologic analysis provides for the first time field constraints on the current activity of the El Salvador fault zone and demonstrates the dextral strike-slip nature of this fault system, previously inferred from seismotectonic and morphotectonic observations (Martínez-Díaz et al., 2004). The strike-slip system consists of main E-W faults, synthetic (WNW-ESE) and antithetic (NNW-SSE) Riedel shears, and NW-SE tensional structures. Two main active fault segments are recognized: the San Vicente segment, from the Ilopango caldera to the San Vicente volcano–Rio Lempa area; and the Berlin segment, from Rio Lempa to the San Miguel volcano. The two segments overlap in a dextral en echelon style with the formation of an intervening pull-apart basin.

The geological and geomorphological data support an ~11 mm/yr late Pleistocene–Holocene strike-slip motion on the El Salvador fault zone, despite its low historical seismicity. The assessment of the process controlling this discrepancy (either locking of the fault or aseismic creep) is crucial for the determination of the seismic hazard of the Berlin segment.

No major compressional deformation associated with the Cocos-Caribbean plates convergence has been detected by the current study. The kinematic scenario suggested by our new field data is consistent with models involving slip partitioning during oblique subduction and supports the hypothesis that the trench-parallel strike-slip component of motion between the Caribbean and Cocos plates is concentrated along E-W dextral strike-slip faults parallel to the volcanic arc (e.g., De Mets, 2001).

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