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Paleoseismic analysis of the San Vicente segment of the El Salvador Fault Zone, El Salvador, Central America

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ABSTRACT

The El Salvador earthquake of February 13th 2001 (Mw 6.6) was associated with the tectonic rupture of the El Salvador Fault Zone. Paleoseismic studies of the El Salvador Fault Zone undertaken after this earthquake provide a basis for examining the longer history of surface rupturing earthquakes on the fault. Trenching at five sites along the San Vicente segment, a 21km-long and up to 2km-wide central section of the El Salvador Fault Zone, shows that surface fault rupture has occurred at least seven times during the past 8ka. Single-event displacements identified at each trench vary from several decimetres to at least 3.7m. Fault trace mapping, geomorphic analysis, and paleoseismic studies indicate a maximum magnitude for the El Salvador Fault Zone is *c.* M_w 7.6, with a recurrence interval of around 800yr. Earthquakes of M_w 6.6 or smaller, such as the February 2001 event are unlikely to be identified in the paleoseismic trenches, so our observations represent the minimum number of moderate to large earthquakes that have occurred on this part of the El Salvador Fault Zone. We observe significant variability in single-event displacement in the trenches, which we interpret as possible cascade rupture of several segments of the El Salvador Fault Zone. Combining displacements of river courses and the timing of events revealed in the trenches, we calculate a slip rate of *c.* 4mm/yr for El Salvador Fault Zone, identifying the fault zone as a major tectonic feature of the region, and a major source of seismic hazard and risk in El Salvador.

KEYWORDS El Salvador Fault Zone. Active fault characterisation. Strike-slip fault. Volcanic arc. Paleoseismic studies.

INTRODUCTION

At least 11 destructive earthquakes have occurred in El Salvador during the past 100 years (Fig. 1; Martínez-Díaz *et al*., 2004). These events have caused more than 3,000 deaths as a consequence of strong ground motions and/or subsequent landslides (Bommer *et al*., 2002). In February 2001, a M_w 6.6 strike-slip earthquake struck the central part of El Salvador causing hundreds of casualties, thousands of injured, and extensive damage. This earthquake was associated with reactivation of the San Vicente segment of the El Salvador Fault Zone (Canora *et al*., 2010), an E-W oriented strike-slip fault that extends for 150km through central El Salvador. The El Salvador Fault Zone is a major structure in Central America, associated with high rates of historical seismicity. However, very few tectonic and structural studies of this fault system have been reported, and the likelihood and maximum earthquake magnitude of large earthquakes along the El Salvador Fault Zone are not known.

We describe the deformational style and paleoseismic history of the San Vicente segment of the El Salvador Fault Zone. The study involved geomorphic mapping of active fault scarps and offset landforms, and paleoseismic trenching across fault scarps, to establish the timing and size of past surface fault displacement. Fault mapping and data from five trenches were used to evaluate possible rupture segments of the El Salvador Fault Zone and earthquake recurrence. We have used fault-rupture scaling relations to examine possible fault lengths associated with observed single-event displacement, and then estimate the earthquake magnitudes associated with past fault ruptures. Paleoseismic data from only one segment of the fault are available, and thus several possible models for past fault ruptures are apparent. Our study contributes with new data for the evaluation of seismic hazards in the region.

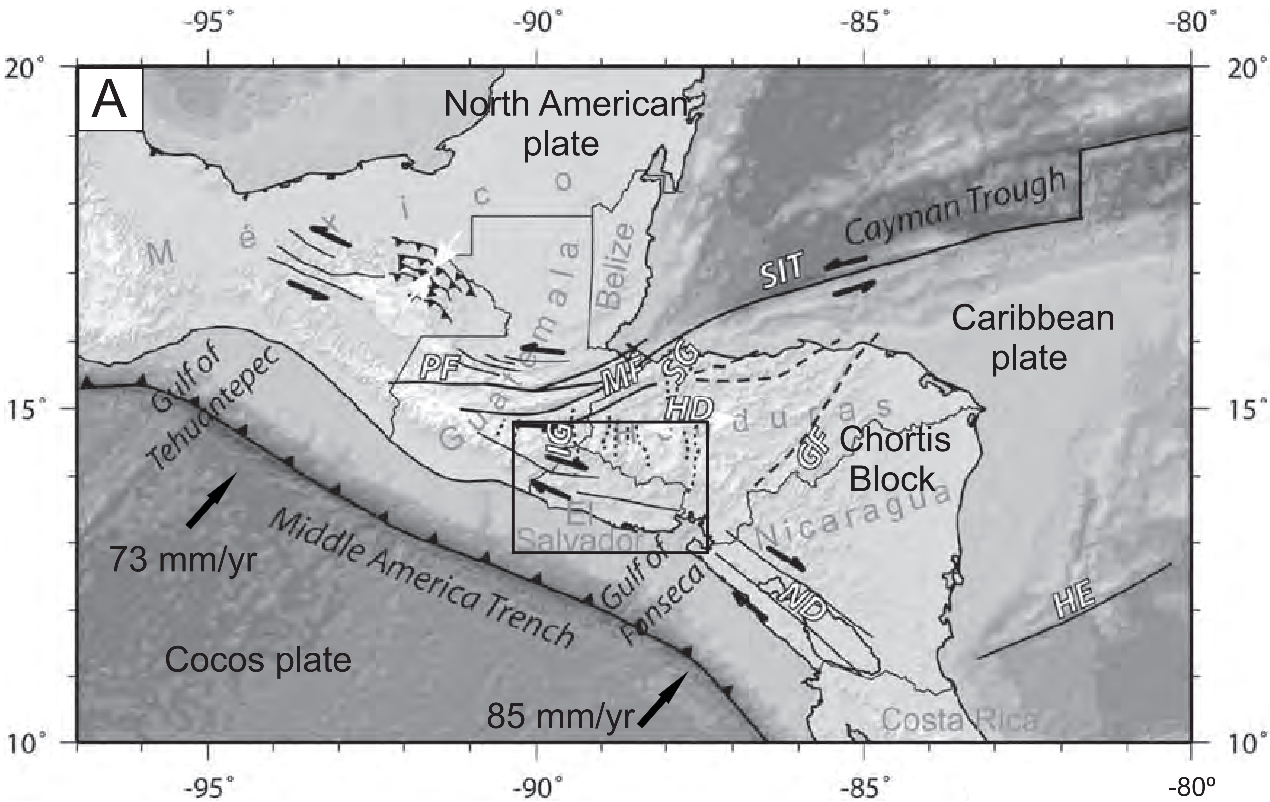
GEOLOGICAL AND SEISMOTECTONIC SETTING

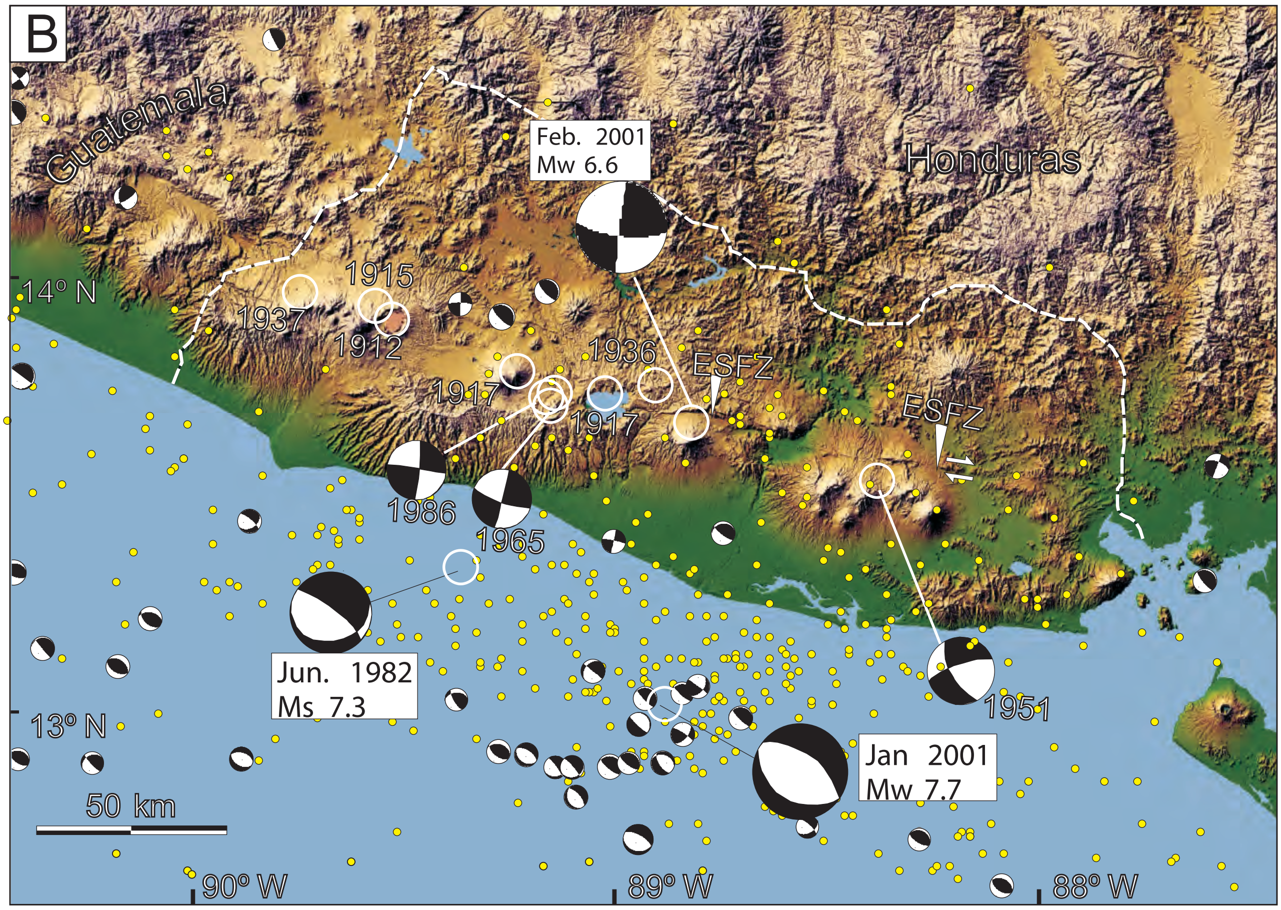
El Salvador is located in northern Central America, at the Pacific Ocean margin of the Caribbean plate (Fig. 1A). The area consists mainly of a block of continental crust, the Chortis block, comprised of a Paleozoic basement overlain by Mesozoic marine sediments, and volcanic materials associated with the subduction of the Cocos Plate at the Middle American trench. The El Salvador Fault Zone is located within the Central American Volcanic Arc which runs parallel to the Middle American trench from Guatemala to Costa Rica. The arc ends abruptly in Guatemala at the junction with the Polochic fault (Fig. 1A). This fault is the western tip of the Motagua–Polochic-Swan Island transform (Motagua Fault, Polochic Fault, and Swan Island Transform of Fig. 1A) which forms the northern boundary between the Caribbean and North American plates. The intersection of the North American, Caribbean and Cocos plates form a diffuse triple junction in Guatemala where tectonic strain is distributed over a wide area (Fig. 1) (Guzmán-Speziale *et al*., 1989; Guzmán-Speziale and Meneses-Rocha, 2000; Lyon-Caen *et al*., 2006; Plafker, 1976). To the south of El Salvador, the volcanic arc continues into Nicaragua and Costa Rica.

Convergence between Cocos and Caribbean plates has a NE trend with a relative velocity of 70–85mm/yr and little obliquity, and the Caribbean plate moves eastwards relatively to the North American plate with a rate of 18–20mm/yr (DeMets *et al*., 2000), as has been confirmed by recent GPS studies in northern Central America by Lyon-Caen *et al*. (2006). High relative motions at the plate boundaries around El Salvador are responsible for the very high rates of seismic activity. Two principal zones of seismic activity exist in the El Salvador region (Fig. 1B), one along the Pacific coast associated with subduction and the other within the volcanic arc deformation zone.

Seismicity at the Middle American trench subduction zone occurs with two different deformation mechanisms; thrusting along the subduction interface, and normal faulting within the subducting slab due to extensional forces generated by slab-pull forces or bending of the subducting plate (Isacks and Baranzagi, 1977). Earthquakes associated with the subducting slab have been larger than M_w 7 and occur at shallow-intermediate depths of <200km (Fig. 1B). Subduction earthquakes tend to cause moderately intense shaking across large parts of southern El Salvador. The most recent example of such an event is the M_w 7.7 earthquake of 13 January 2001 (Bommer *et al*., 2002). The largest earthquakes in the area (M_w 7.4 in 1921, M_w 7.1 in 1932, M_w 7.3 in 1982 and M_w 7.7 on January 2001) occurred within the subducted slab and have almost identical normal-slip mechanisms with planes oriented N120º–130ºE.

FIGURE 1 | Tectonic setting of northern Central America. A) Tectonic sketch of northern Central America. The arrows show relative displacements and the abbreviations are: PF: Polochic fault; MF: Motagua fault; SIT: Swan Island transform; SG: Sula graben; IG: Ipala graben; HD: Honduras depression; GF: Guayape fault; ND: Nicaraguan depression; HE: Hess escarpment. B) RADAR SRTM image of El Salvador with historical destructive earthquakes (white circles) and instrumental epicenters (M_s >2.5, period 1977-2001) from USGS-NEIC catalogue (small dots). Small focal mechanisms are from events with M_w >5.5 (1977-2001, Harvard CMT database) and large earthquake mechanisms are from Buforn *et al.* (2001). ESFZ: El Salvador fault zone.


A
North American plate
Cayman Trough
SIT
Caribbean plate
Belize
PF
MF
SG
HD
IG
GF
Chortis Block
Gulf of Tehuantepec
73 mm/yr
Middle America Trench
Gulf of Fonseca
El Salvador
Nicaragua
ND
HE
Cocos plate
85 mm/yr
Costa Rica
-95°
-90°
-85°
-80°
20°
15°
10°


B
Guatemala
Honduras
Feb. 2001
Mw 6.6
14° N
1915
1937
1912
1936
ESFZ
1917
1917
ESFZ
1986
1965
Jun. 1982
Ms 7.3
1951
13° N
Jan 2001
Mw 7.7
50 km
90° W
89° W
88° W

The second seismicity belt occurs as shallow crustal seismicity (<20km deep) coincident with the chain of Quaternary volcanoes through El Salvador (*e.g.*, Dewey *et al*., 2004), and accommodate a small component of trench-parallel relative plate motion (White *et al*., 1987). Historically, these earthquakes have had smaller magnitudes (M_w 5.5-6.8) than those within the subduction zone. The M_w 6.6 event of 13 February 2001 is an example of one of the largest of these earthquakes (Bommer *et al*., 2002). Historically, the lower magnitude upper crustal earthquakes have produced far greater destruction in El Salvador than the less frequent large-magnitude earthquakes in the subduction zone (White and Harlow, 1993), due to their shorter recurrence intervals, shallow depths and proximity to population centers.

The 11 destructive shallow crustal earthquakes that occurred in the 20th century are aligned with the volcanic arc (Fig. 1B). On 8 June 1917, an M_s 6.4 earthquake occurred 30–40km west of San Salvador volcano, followed by an M_s 6.3 earthquake. On 28 April 1919 San Salvador was damaged again, this time by a shallow, M_s 5.9 earthquake with the epicenter situated at about the same location of a M_w 5.7 earthquake in 1986. The epicenter of the 1986 event was within the volcanic arc and propagated along a nearly vertical, north-northeast-striking fault plane (White *et al*., 1987). Reliable focal mechanisms are available for four of the more recent major events in 1951, 1965, 1986, and February 2001 (Fig. 1B; Martínez-Díaz *et al*., 2004). They are all strike-slip events with one of the planes oriented approximately east-west, parallel to the volcanic arc.

EL SALVADOR FAULT ZONE

The El Salvador Fault Zone is a 150km long and 20km wide zone of distributed strike-slip faulting located within the El Salvador volcanic arc (Fig. 1B). The main fault plane trends east-west and dips to the south (Martínez-Díaz *et al*., 2004). The El Salvador Fault Zone extends to Guatemala where it is known as the Jalpatagua Fault (Fig. 2) and to the east the fault probably continues into Nicaragua within the Nicaraguan Depression (Fig. 1A) but the trace there is not clear. The El Salvador Fault Zone consists of a complex set of traces which comprise five major geometric fault segments from Guatemala to Golfo de Fonseca (Fig. 2; Canora *et al*., 2010). In this study we have completed a paleoseismic study along the westernmost segment, the San Vicente segment, within the source region of the most recent destructive earthquake (February 13th, 2001 earthquake) along the El Salvador Fault Zone (Canora *et al*., 2010).

This study focuses on the San Vicente segment of the El Salvador Fault Zone. The San Vicente segment is a *c.* 21km long, N87ºE strike-slip fault strand (Fig. 3) that predominantly dips 70º to the south (Martínez-Díaz *et al*., 2004). Secondary strike-slip, northwest-trending faults are also prominent features in this fault segment. The fault strands displace Holocene-age river terraces, and alluvial and volcanic sequences. The exposed alluvial and volcanic sequences include lavas, and

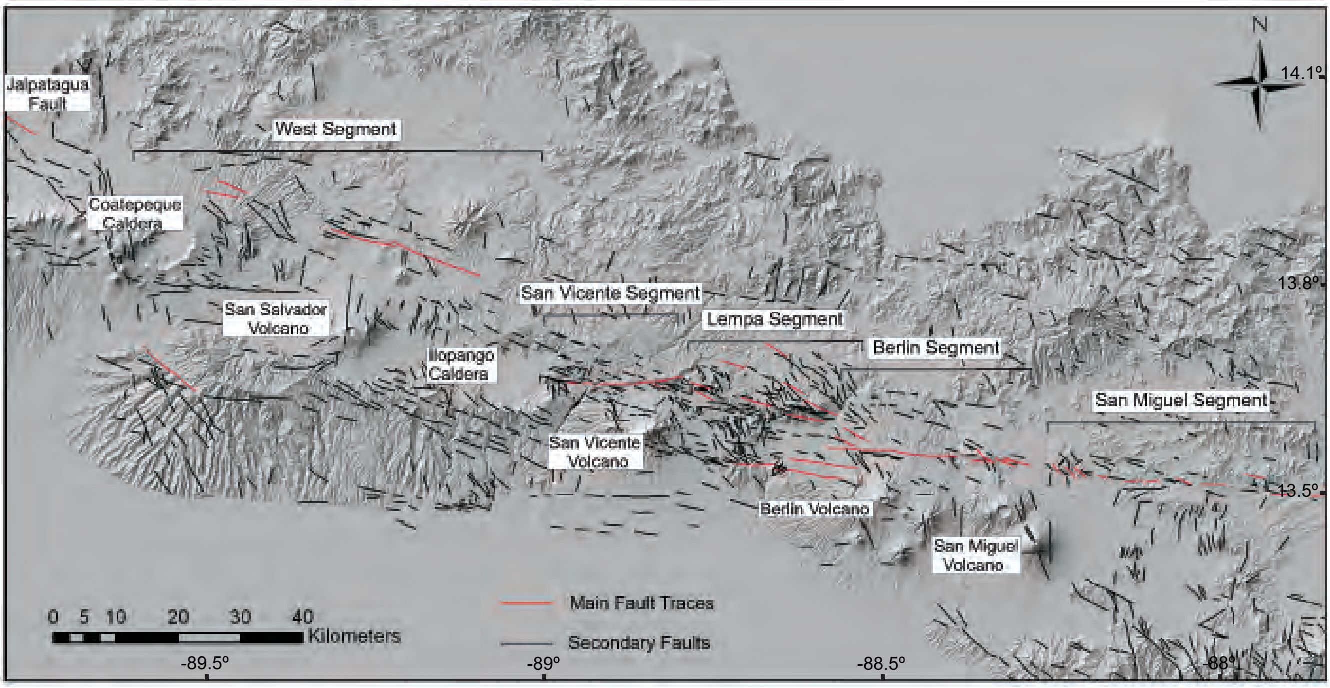


FIGURE 2 | Active fault strands and segments of the El Salvador Fault Zone overlaid onto ten-metre-resolution Digital Terrain Model (DTM) derived from 1:25.000 topographic map.

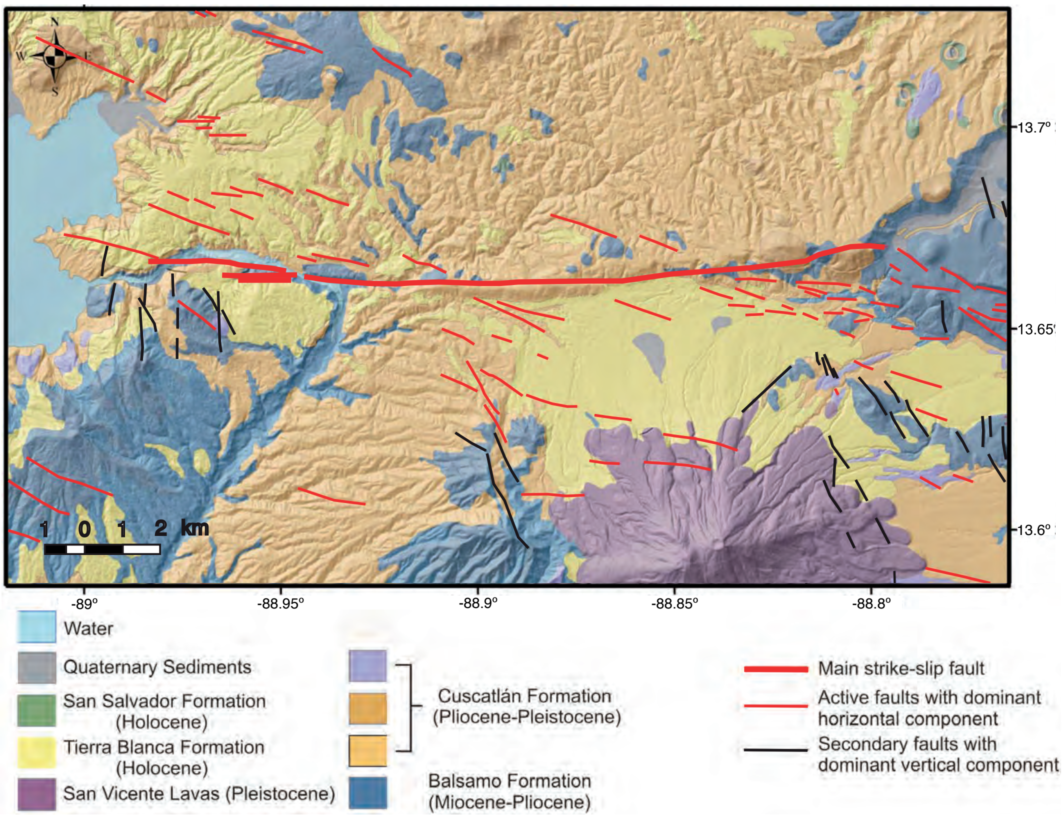


FIGURE 3 | Geological and fault trace map of the San Vicente segment of the El Salvador Fault Zone. Geological units are from Bosse *et al.* (1978). Active fault traces have been mapped in this study.

primary and reworked ignimbrites and tephras deposits of late Quaternary age. Present-day valley floors developed by fluvial incision into this constructional landscape represent potential sites for paleoseismic investigation.

PALEOSEISMIC INVESTIGATIONS

The objectives of this paleoseismic investigation of the San Vicente segment of El Salvador Fault Zone are two-fold: 1) to determine the recent earthquake history of the fault, and 2) to examine the deformation style of the fault. One of the main difficulties in trenching the El Salvador Fault Zone is to identify the fault trace in volcanic environments where the landscape is reset by frequent ingnimbrite deposition and accompanying airfall deposits mantle a pre-existing, but most likely eroded, scarp. Selecting a trench site with metre-scale lateral offsets of geomorphology where net displacement associated to individual surface rupture events might be distinguished has proven to be particularly difficult. For that reason, we have had to combine vertical single event displacement with the rake of fault plane striae to estimate possible strike-slip components of single event, net slip, displacement.

We excavated five trenches on the San Vicente segment (Fig. 4): two on the west part in the fault segment in the Desague River area; and three on the east part of the fault segment in the Verapaz area, to the north of the San Vicente volcano. From these trenches we assess the recent rupture history of the whole segment, as well as single event displacement and fault length. From these data we estimate the sequence, size, and timing of large earthquakes generated by rupture of this segment of the complex strike-slip fault.

To determine the timing of large earthquakes, we identified and dated stratigraphic units that have been displaced along the fault plane. The ages of non-displaced and displaced stratigraphic units associated to each surface rupture event bracket the age of movement. Ages for stratigraphic units in the trenches either come from the identification of a known airfall tephra in the trench whose radiocarbon age has been determined from elsewhere in the district (*e.g.*, Dull *et al.*, 2001; Hernández, 2004), or by radiocarbon dating of organic samples in this study (Table 1).

Verapaz Area

In the Verapaz area, along the eastern part of the San Vicente fault segment, we found typical

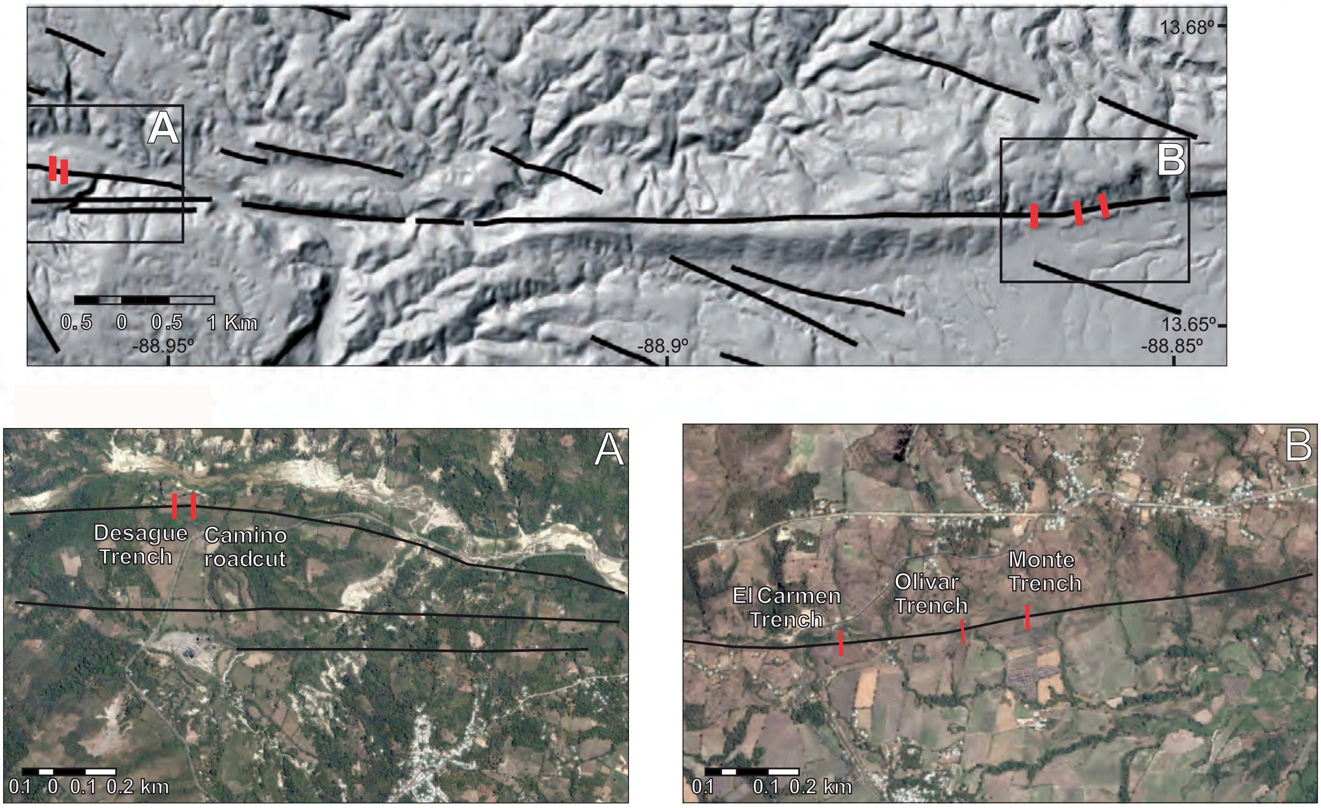


FIGURE 4 | Fault traces and the paleoseismic trenches (in red) of the San Vicente segment over ten-metre-resolution DEM. Inserts are: A) Quickbird image of Desague area showing location of the two westernmost trenches, and B) Quickbird image of Verapaz area showing location of the three easternmost trenches.

strike-slip fault surface structures, including a very straight E-W single fault trace to the west (Fig. 5). Dextral movement along the fault has resulted in a shutter ridge morphology that has blocked the fluvial drainage, producing a linear valley parallel to the fault on the northern side of the ridge. The east end of the shutter ridge is a prospective site to undertake paleoseismic investigations because a large amount of potentially dateable late Quaternary-age sediments are ponded against the shutter ridge, and the fault scarp height is moderate, enabling excavation. We excavated one trench across the western-most part of the shutter ridge. This is the El Carmen Trench (Fig. 5).

Immediately to the east of El Carmen trench, the fault changes strike from E-W to ENE, resulting in a change from a small normal component of faulting to a small reverse component (Fig. 5). At this locality the strike slip fault has split into several strands, some of which have a normal component and some have a reverse component (Fig. 6). We excavated two paleoseismic trenches in the vicinity of this structure, the Olivar and Monte trenches (Fig. 5). These trenches were excavated across the northern part of the push-up structure and thus may not capture the complete paleo-earthquake record.

Analysis of faulting exposed in the El Carmen Trench

The El Carmen trench (located at 88º51’54”W, 13º39’43”N) was excavated at the base of a *c.* 5m scarp formed by the shutter ridge on the east part of the San Vicente segment (Fig. 4). The scarp parallels a small linear valley that is incised into gravel deposits. The trench was 12m long and *c.* 5m deep and was excavated with a middle ~1m-wide bench, cut for stability and safety reasons (Fig. 7). The exposure revealed a prominent rhyolitic tephra and ignimbrite sequence in the middle of the trench wall corresponding to the 1478±64 cal. yr BP Tierra Blanca Joven eruption, the most recent eruption from Ilopango caldera (Rose *et al.*, 1999; Dull *et al.*, 2001). Alluvial deposits and paleosols occur above and below the Tierra Blanca Joven. At the bottom of the trench, and partly eroded by deposition of the Tierra Blanca Joven is a dark brown paleosol (age of 7070±49 cal. yr BP; sample Sc4, Table 1) with charcoal accumulations (unit 10). Tierra Blanca Joven Formation (unit 9) consists of 6 recognisable units (Fig.8):

a) Initial fall and minor pyroclastic surge deposit of coarse ash and fine lapilli.

b) Main plinian fall comprising a thicker lower coarse ash and upper centimetre-sized lapilli.

TABLE 1 | Radiocarbon sample ages of units observed in this study

Sample I.D.	Laboratory Nº.	$\Delta^{13}C$ (□)	Radiocarbon age (yr BP)	Calibrated age 2σ cal yr BP	Calibrated age 2σ cal yr	Unit & trench
Sc1[1]	NZA 29114	-32.6	199 ± 15	187-147 (167 ± 20)	AD 1763-1803	2, El Carmen
Sc2[1]	NZA 29111	-25.4	335 ± 20	465-313 (389 ± 76)	AD 1485-1637	3, El Carmen
Sc3[1]	NZA 29117	-24.7	906 ± 15	908-770 (840 ± 68)	AD 1042-1180	4, El Carmen
Sc4[1]	NZA 29120	-21.6	6219 ± 15	7119-7020 (7070 ± 49)	5170-5071 BC	15, El Carmen
So1[1]	NZA 30106	-13.4	-1363 ± 20	The Sample is modern. Late 20th century		2, Olivar
So2[1]	NZA 30105	-26.5	156 ± 25	229-166 (198 ± 30)	AD 1721-1784	3, Olivar
So3[1]	NZA 30070	-25.3	222 ± 20	304-273 (288 ± 15)	AD 1646-1677	5, Olivar
So4[1]	NZA 30633	-24.2	4541 ± 30	5187-5051 (5119 ± 68)	3238-3102 BC	11, Olivar
So5[1]	NZA 30755	-26.4	4737 ± 45	5584-5444 (5514 ± 70)	3635-3495 BC	13, Olivar
Sd1[1]	NZA 26965	-27.7	1081 ± 40	1064-926 (995 ± 69)	AD 886-1024	6, Camino exposure
Sd2[1]	NZA 26669	-34.2	7096 ± 40	7997-7843 (7920 ± 77)	6048-5894 BC	10, Camino exposure

Unit	Calibrated age	Source
Tierra Blanca Joven Formation	2σ 1478 ± 64 cal yr BP	Dull et al., 2001
Tierra Blanca 3 Formation	c. 40300 ± 167000	Rose et al., 1999

[1] This study. Conventional radiocarbon age before present (AD 1950) calibrated using Calib 5.0 (Stuiver and Reimer, 1993). Ages are mid-point 2σ range. Laboratory: Institute of Geological & Nuclear Sciences Rafter Radiocarbon Laboratory, New Zealand.

c) Early phreatomagmatic pyroclastic flow and surge deposit, rich in fine ash.

d) Fine and very fine ash fall that is planar-bedded and rich in well-formed concentrically banded accretionary lapilli.

e) Bedded phreatomagmatic ash and lapilli fall comprising coarse ash to fine lapilli and alternating with very fine ash beds. The fine ashbeds are characterised by irregular-shaped and accretionary lapilli.

f) Main pyroclastic-flow deposit (ignimbrite) comprising multiple layers of very poorly sorted ash to block sized material, including both pumice and mafic particles.

Thick (2-3m) alluvial deposits with intervening paleosols unconformably overlie the top of the volcanic sequence. The basal alluvial deposit is a reworked ignimbrite (unit 8) which is eroded in some parts by a channel alluvial deposit (unit 6). Between the reworked ignimbrite and the alluvial deposits, there is locally a small colluvial wedge (unit 7) formed of mixed materials. At the top of the upper alluvial sequence there are two paleosols; unit 4 (840±68cal. yr BP; sample Sc3, Table 1) and unit 2 (167±20cal. yr BP; sample Sc1, Table 1), with a colluvial wedge in between (unit 3; 389±76cal. yr BP; sample Sc2, Table 1). The topmost unit (unit 1) represents the current top soil which has been modified by agricultural activity.

The excavation exposed a highly fractured *c.* 6-m-wide fault zone with one main vertical fault plane and multiple secondary planes. The main fault ruptures through all of the stratigraphic sequence except for the topsoil (unit 1). We interpret that all fault planes merge to a single plane at depth based on the geometry displayed in the trench. The main fault plane shows a maximum vertical displacement of *c.* 1.6m. Oblique striae (rake 15º±5ºNE) on the principal fault plane at the bottom of the trench is consistent with dextral-normal slip. From the rake of the striae and the total vertical displacement we estimate a total net displacement exposed in the trench of 6.2±1.3m.

Analysis of faulting in the El Carmen trench indicates three surface-faulting events (Fig. 7). The events are identified by: 1) fault terminations of different sedimentary units; 2) the presence of two colluvial units that are interpreted to be scarp-derived, and; 3) stratigraphic horizons where blocks falls are identified in the fault zone. The oldest event, El Carmen 3 (C3), displaces paleosol 1 (unit 10), Tierra Blanca Joven Formation (unit 9) and the reworked ignimbrite (unit 8). Colluvial wedge 1 (unit 7) was formed after this event as was the blocky collapse structure close to the main fault plane. Timing of event C3 is older than unit 8, somewhat older than Tierra Blanca Joven Formation (1478±64cal. yr BP), and younger than

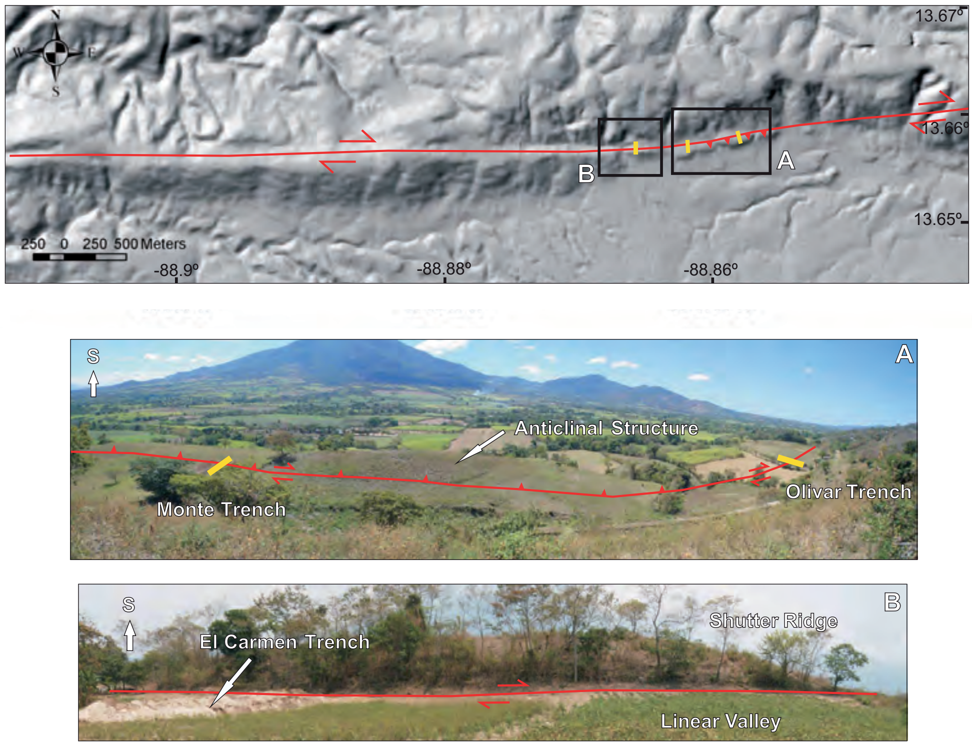


FIGURE 5 | Location of paleosesimic trench at Verapaz (over ten-metre-resolution DEM). Inserts are: A) photograph of the "Restraining Bend" structure and the position of the Olivar and Monte trenches, and B) photograph of the "Shutter Ridge" structure and the El Carmen trench.

the deposition of the alluvial material (unit 6; which not dated but is younger than unit 4, *i.e.* <840±68cal. yr BP). This event is associated with a minimum vertical displacement of *c.* 1m., which suggests 3.9±0.8m of net displacement if we use the rake of fault striae found in the trench. The second event, El Carmen 2 (C2), is represented by displacements of unit 6 and 4 and formation a scarp-derived deposit (unit 3). The timing of the event is younger than the age of organic material within the colluvial wedge (unit 3) at 389±76cal. yr BP and older than unit 2 (167±20cal. yr BP). Vertical displacement of *c.* 0.6m in this event converts to a net displacement of 2.3±0.5m. The youngest event exposed in the trench, C1, is interpreted from small displacements of the colluvial wedge 2 (unit 3) and paleosol 3 (unit 2). This event could correspond with the February 13th 2001 earthquake although not all fault strands displace the top soil (unit 1). However, ploughing of the land could have obscured displacements of unit 1 and, thus the simplest interpretation is that there is only one event after deposition of wedge 2 (unit 3). This event seems to be a pure strike-slip based on the geometry exposed. Because we could not find any piercing points at the trench site for event C1, we will assign a net fault displacement of 0.6m as measured elsewhere for the February 13th 2001 surface rupture by Canora *et al.* (2010)

FIGURE 6 | Sketch showing a typical positive flower structure in the area of the Monte trench site.

Analysis of faulting exposed in the Olivar Trench

The Olivar trench was excavated across a 3m high scarp on the east part of the San Vicente segment of the El Salvador Fault Zone (at 88º51'30"W longitude and 13º39'46"N latitude; Fig. 4). At this location, the fault displaces a Holocene surface incised into gravel deposits. The stratigraphy found in the Olivar trench (Fig. 9) is similar to that exposed in the El Carmen trench (but note that unit numbers are different in both trenches). Several

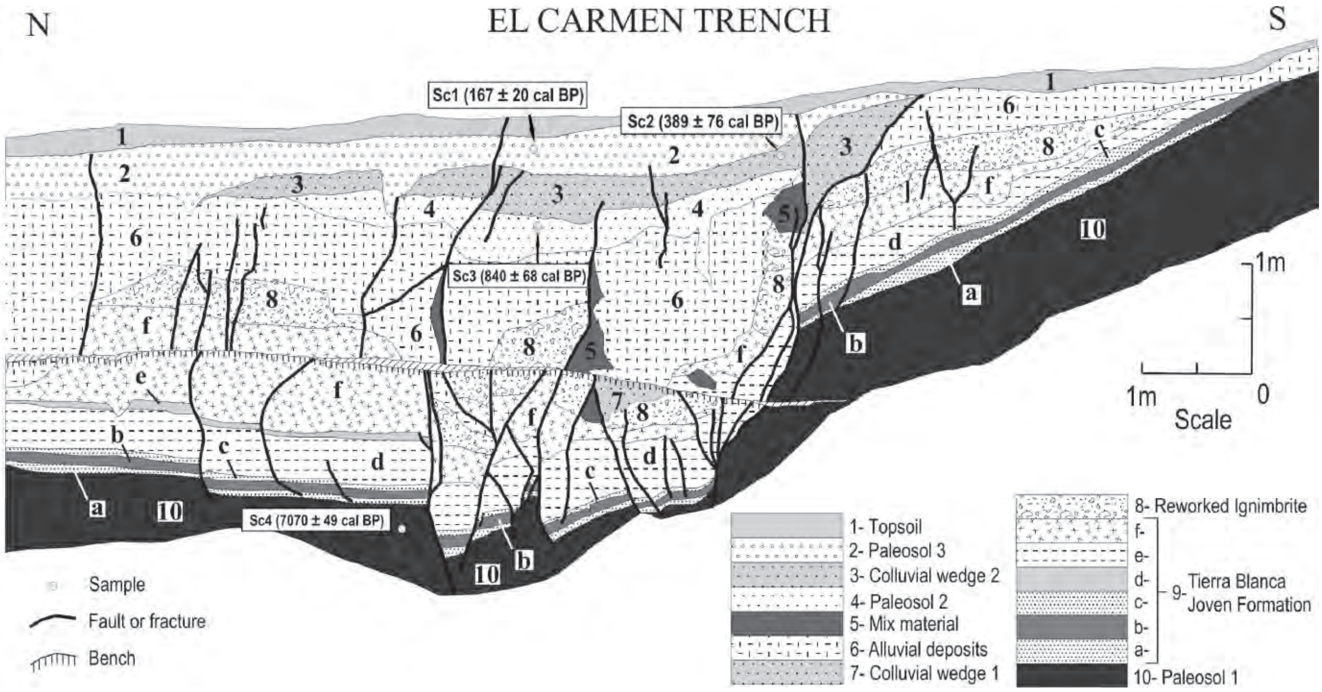


FIGURE 7 | El Carmen trench log (east wall) on the eastern end of the San Vicente segment of the El Salvador Fault Zone. See text for description and Figure 4 for location.

units can be directly correlated to El Carmen trench, the Tierra Blanca Joven Formation (1478±64cal. yr BP; here unit 6) and the underlying black soil, Paleosol 1 (here unit 7, and somewhat younger than in El Carmen trench at 5119±68cal. yr BP; sample So4, Table 1). The main ignimbrite within the Tierra Blanca Joven (unit 6f) is not present in the stratigraphy, indicating that it has either been eroded or was not deposited at this site. Two additional gravel deposits (units 8 and 9) are found below Paleosol 1. Unit 9 has been dated and yields an age of 5514±70cal. yr BP (sample So5, Table 1). Three alluvial channel deposits, unit 5 (288±16cal. yr BP; sample So3, Table 1), unit 4 and unit 2 (late 20th Century; sample So1, Table 1), and an interbedded paleosol, Paleosol 2 (unit 3; 198±30cal. yr BP; sample So2, Table 1) lay unconformably over Tierra Blanca Joven Formation. The modern soil (unit 1) overlies unit 2.

We interpret four surface-faulting events in this trench, based on fault terminations and cross-cutting relationships among the three fault sets exposed. The excavation revealed a great number of fault planes that we have divided in three sets, based on orientation and age. The two oldest fault sets (N70º/50-70ºS and N76º/75-90ºN) displace gravel units 8 and 9, and Paleosol 1 (unit 7), whereas the younger N100º/80-90ºN fault set have ruptured through the Tierra Blanca Joven Formation. Faults with NW-SE trends exhibit oblique striae (rake 12º±2ºNW) consistent with dextral-reverse slip.

The three oldest events are identified at the southern end of the trench. The oldest event, Olivar 4 (O4), involved movement on the N70º/50-70ºS faults which terminate within the base of Gravel 2 (unit 8). The second event (O3) involved movement on N76º/75-90ºN faults which terminate at the base of Paleosol 1. At some locations the older fault set (N70º/50-70ºS) is displaced by the N70º/50-70ºS fault set. Fault rupture associated with these two events (O4 and O3) is older than Paleosol 1 (5119±68cal. yr BP) and younger than the deposition of unit 9 (5514±70cal. yr BP).

The third event (O2) ruptures Paleosol I but not the Tierra Blanca Joven Formation. This event occurred after deposition Paleosol 1 at 5119±68cal. yr BP and before deposition of Tierra Blanca Joven Formation at 1478±64cal. yr BP. The youngest event (O1) involved movement on N100º/80-90ºN faults that rupture through the Tierra Blanca Joven Formation. Event O1 postdates deposition of the Tierra Blanca Joven Formation (1478±64cal. yr BP) and predates unit 3 (198±30cal. yr BP). In the trench there are some fractures going through units 3 and 2. We interpret these fractures (and possibly faults with small pure dextral shear) as probably resulting from the February 13th 2001 El Salvador earthquake. There could have been other events between O4 and O3, but the ~1200 year-long hiatus in deposition of the sedimentary unit between Tierra Blanca Joven and unit 2 impedes further interpretation.

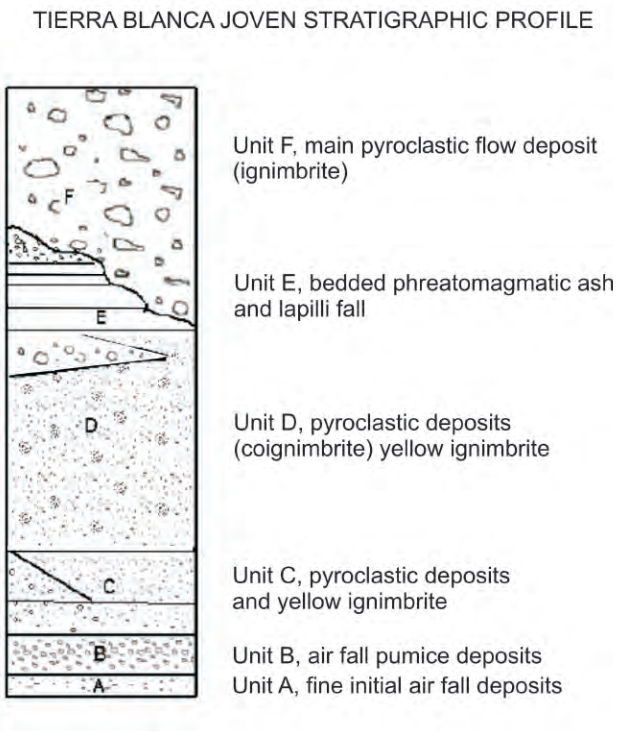


FIGURE 8 | Generalized stratigraphic column of the Tierra Blanca Joven Formation. Modified from Hernández (2004). Ignimbrite of units c and d are not deposited at the trench sites.

We cannot determine the amount of fault displacement in each event in this trench because of the complexity of fault intersections, except to note that the youngest, event O1, has a minimum net fault of 3.4±0.5m by combining the vertical component of faulting with the observed rake of fault plane striae of 12º±2ºNW.

Analysis of faulting exposed in the Monte Trench

The trench was excavated across a *c.* 3m high scarp on the east part of the San Vicente segment of the El Salvador Fault Zone (Fig. 4; 88º51’20”W longitude and 13º39’47”N latitude). The stratigraphy exposed in the Monte trench (Fig. 10) is very similar to that of the Olivar trench and includes four interbedded gravel and sand deposits (units 8, 7, 6 and 5) beneath a dark Paleosol (unit 4) that we correlate with Paleosol 1 in the Olivar trench (unit 7 there; 5119±68cal. yr BP). Above this paleosol, the trench exposed a complete record (unit 3) of the Tierra Blanca Joven Formation (1478±64cal. yr BP), a younger alluvial deposit (unit 2), themselves overlain by the modern soil (unit 1).

The excavation exposed a great number of fault planes with two principal orientations (N70º/60ºS and N100º/80-90º) displacing units 8 to 4, with a minimum total vertical displacement of 3.7m. The trench shows no fault displacement of Tierra Blanca Joven Formation or younger units which indicates no faulting post 1478±64cal. yr BP.

Based on the information from the trench log we interpret at least three faulting events in this trench. The oldest event, Monte 3 (M3), is represented by movement of N100º/80-90º faults with a minimum vertical displacement of 2m of units 8 to 6. The N100º/80-90º faults exhibit oblique striae (12º±2º) that suggest a total displacement of 9.6±1.5m (derived from the 2m vertical offset). The second and third events (M2 and M1) are identified by progressive displacement of older units by N70º/60ºS faults. The M2 event is represented by a minimum vertical displacement of 1.3m of unit 7. Oblique striae with a rake of 15º±3º on the N70º/60ºS faults suggest a minimum net displacement of 5±1.2m for this event. Timing of the two older events (M3 and M2) is difficult to determine because the gravel and sand units could not be dated. These events are older than the paleosol (5119±68cal. yr BP). It is possible that these two events correlate with the two older events in Olivar trench (O4 and O3) because the gravel materials are very

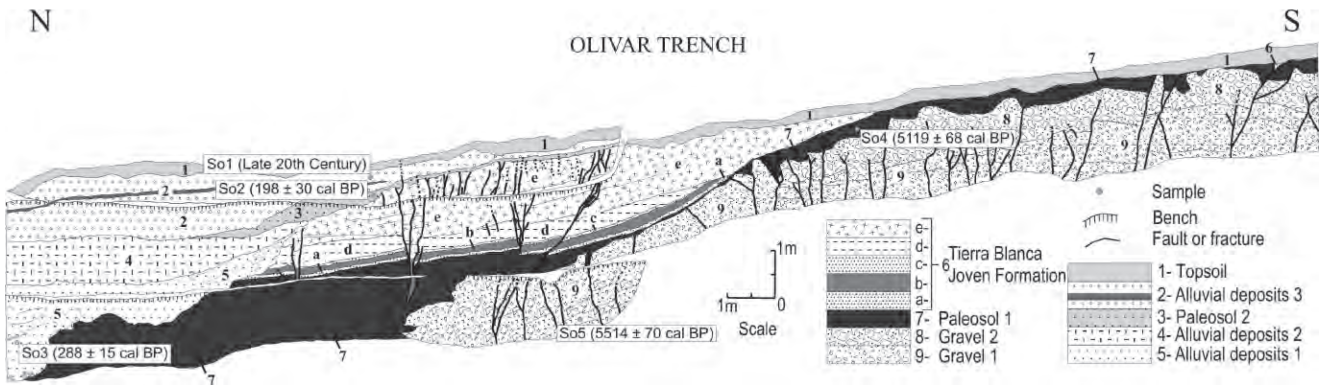


FIGURE 9 | El Olivar trench log (east wall) on the eastern end of the San Vicente segment of the El Salvador Fault Zone. See text for description and Figure 4 for location.

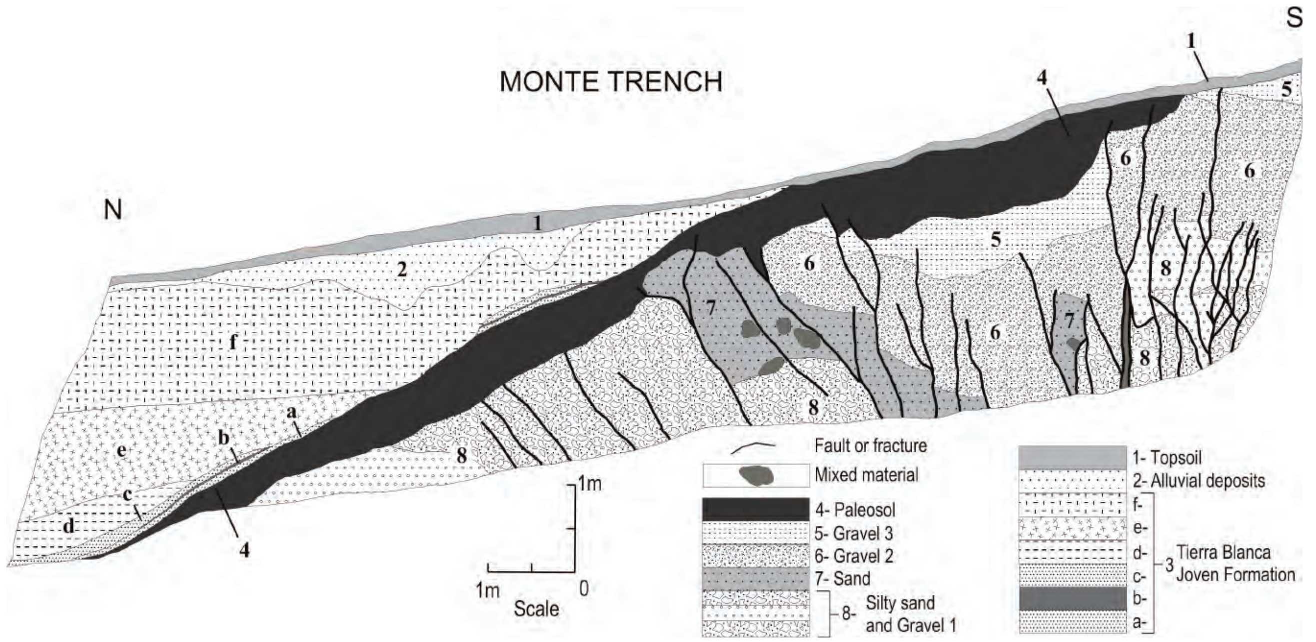


FIGURE 10 | El Monte trench log (east wall) on the eastern end of the San Vicente segment of the El Salvador Fault Zone. See text for description and Figure 4 for location.

similar. The youngest event, Monte 1 (M1) is represented by 0.4m of vertical displacement of the units 4, 5 and 6, and occurred after deposition of unit 4 (5119±68 cal. yr BP) and before Tierra Blanca Joven (1478±64 cal. yr BP). The total displacement for this event, based on the 15º±3º-rake of striations, is 1.9±0.3m.

Desague Area

Much of the San Vicente segment consists of a well-defined trace with clear geomorphic scarps. However, in the Desague area, to the west of the segment, the fault splays into at least three parallel strands (Fig. 4). Because of high erosion rates in this area, the fault traces have weak surface expression and thus it has been difficult to find a prospective site for paleoseismic investigations. The lack of well-defined scarps in this area is also consistent with a significant lateral component of slip on this part of the fault. We excavated one trench and logged a road cut exposure in this area, the Desague trench and Camino exposure (Fig. 11), both of which are on the northernmost strand of the fault. The Desague trench and the Camino road cut exposure (Fig. 4) are only 50m apart, and exposed similar stratigraphy (Fig. 11) below the same geomorphic surface.

At the base of the exposures a cemented ignimbrite forms the local bedrock (unit 15) on which Paleosol 1 (unit 14) has formed (but note that this paleosol is not the same as Paleosol 1 in the El Carmen, Olivar, and Monte trenches). Above this paleosol there is a white pumiceous pyroclastic flow, a fine rhyodacitic ash and a thick ignimbrite (units 11, 12 and 13, respectively). We infer that this ignimbrite is Tierra Blanca 3 (TB3), erupted during a large violent explosive episode at Ilopango Caldera at *c.* 40ka BP (Major *et al.*, 2001), based on similarities with the description of this unit in other locations (Pullinger, C.R., personal communication). Volcaniclastic fluvial deposits and associated paleosols occur in topographic lows associated with stream channels incised into TB3 and older units. The oldest stream deposits (units 6, 7, and 8, and labelled channel deposits 1 on Fig. 11) are reworked TB3 pyroclastic deposits. Unit 6 contains charcoal that has an age of 995±69cal. yr BP (sample Sd1, Table 1).

At the southern end of the Camino exposure (Fig. 11) the channel sequence is above Paleosol 2 (unit 10) that has an interbeded material to be a colluvial wedge (unit 9). Paleosol 2 has an age of 7920±77cal. yr BP (sample Sd2, Table 1). At the northern end of the Desague trench (Fig. 11) Palesoil 3 has formed on the channel deposits 1 package, and above the paleosol there is a younger channel deposit package (units 2 and 3 and labelled channel deposits 2 in Fig. 11), which in turn is overlain by the modern soil (unit 1).

Analysis of faulting exposed in the Camino exposure

Prior to cleaning and examining the road cut exposure, topographic breaks in the area were interpreted as either fault scarps or fluvial terrace risers (Fig. 11, 88º58'W longitude and 13º40'N latitude). The 7m-deep road cut exposes pervasive and distributed faulting and fracturing for more than 100m across strike, but only in the 30m wide zone analysed for paleoseismic purposes do the two faults (Faults A and B of Fig. 11) break the younger cover strata. Fault A appears to rupture up to the base of a colluvial wedge, unit 9. Fault B displaces younger deposits, up to unit 5 (Fig. 11).

At least two surface-rupturing earthquakes are interpreted at the Camino road cut. The oldest event (Ca2) is represented by the presence of the colluvial wedge 1 (unit 9) which has an age somewhat younger than *c.* 7920±77cal. BP. The most recent event (Ca1) is represented by the movement along fault B and the presence of colluvial wedge 2 (unit 5). The material below this colluvial wedge has been dated, so this event is younger than 995±69cal. BP. Scarp degradation models predict that, as a first approximation, the maximum thickness of the scarp-derived colluvium is half the height of the free face, and that the thickness of the wedge is a limiting minimum scarp height (Wallace, 1977). Thus we infer that event Ca2 had a minimum vertical displacement of 1m and event Ca1 had a minimum vertical displacement of 0.5m. The oblique striae (20º±2º) and the dip-slip displacement measured in the trench walls imply net fault displacement for Ca2 event of *c.* 2.9±0.3m and for Ca1 event of 1.7±0.2m. These are minimum values because it is possible that faults in unit 15 between Faults A and B also ruptured but there are no young deposits over these fault planes to assess recent rupture into the topsoil.

Analysis of faulting exposed in the Desague Trench

The Desague trench (8º58’3”W longitude and 13º40’N latitude), was located about 50m to the west of the Camino exposure, within the same geomorphic surface (Fig. 11). The trench was 30m long and 7m deep. The trench exposure shared many similar features with the road cut exposure; the trench exposed several fault planes but only two (Faults A and B) displaced young deposits. We identified at least two

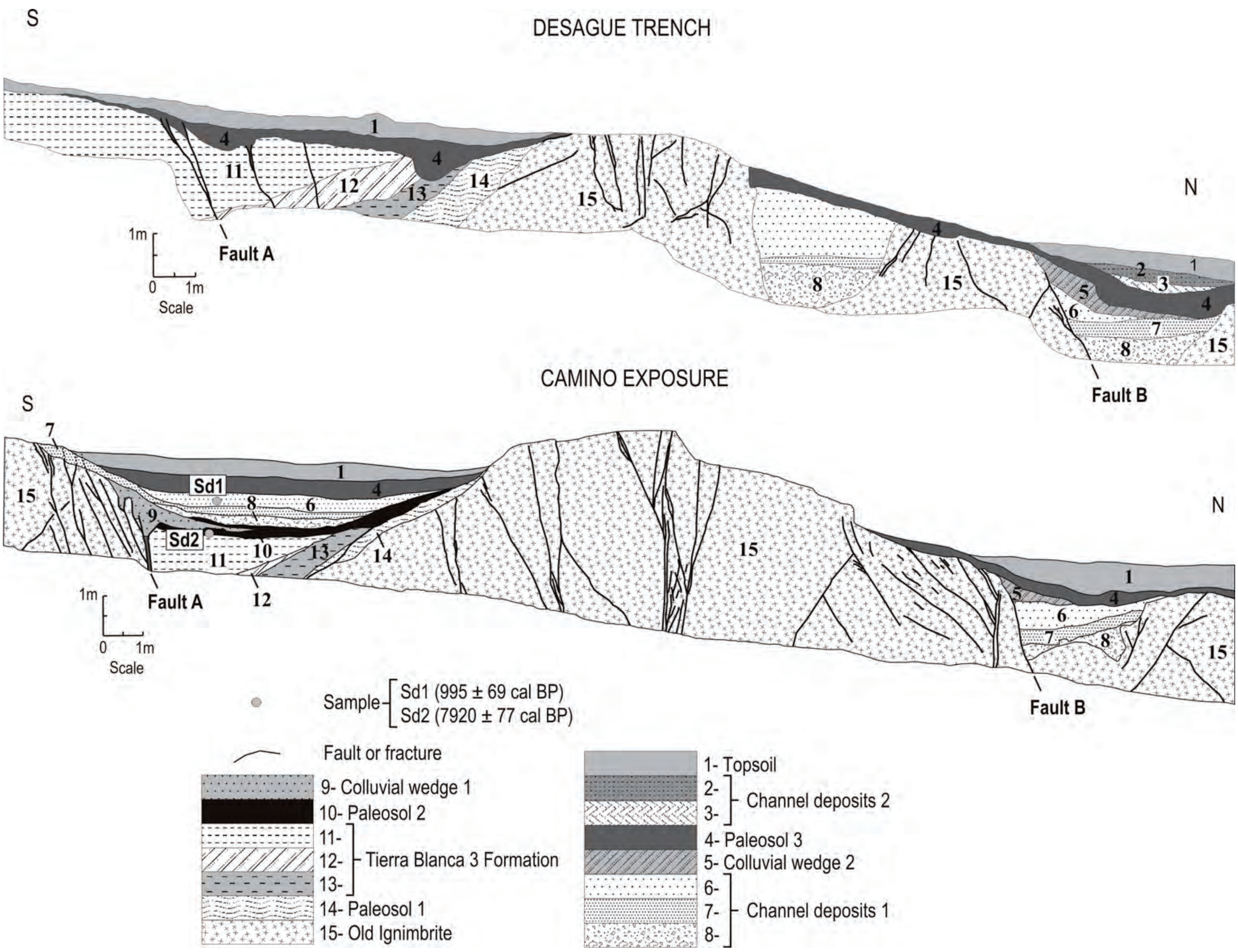


FIGURE 11 | Logs of Desague trench (west wall) and Camino road cut (east wall) on the western end of the San Vicente segment of the El Salvador Fault Zone. See text for description and Figure 4 for location.

individual surface-rupturing earthquakes in the Desague trench, among widespread distributed faulting. Fault A, at the southern end of the trench is overlain by undeformed Paleosol 3 (unit 4) but displaces Tierra Blanca 3 which implies an event (D2) with an age of ≤ *c.* 40ka. The amount of the displacement in this event is difficult to assess because it appears to be a pure strike-slip movement. Fault B, at the northern end of the trench, is very similar to that exposed in the road cut and has the same structure and age. Thus fault B and the colluvial wedge (unit 5) are showing the same young event (D1 in this case) post 995±69cal. BP. The minimum vertical displacement of this event is *c.* 0.6m so the total fault displacement using the striae observed is a minimum of *c.* 2±0.2m.

DISCUSSION

Faulting style, earthquake history and slip rate

The San Vicente segment of the El Salvador Fault Zone is generally characterised by a N87ºE strike-slip single fault. However, at the western end of the segment (in the Desague area) there are at least three distinct, parallel strands. The fault segment also includes some secondary strike-dip, northwest-trending traces that could participate in strain accommodation by dispersing strain over a broader zone or serve to transfer strain from one of the principal N87ºE strands to another. The complexity of the structure in some areas of the fault segment makes it difficult to correlate the surface rupture events among all of our trenches.

Wesnousky (1988) suggests that faults with more cumulative offset have fewer geometric irregularities. So this could be the reason for the complexity of the fault traces suggesting recent initiation and/or low slip rates for the El Salvador Fault Zone. However, in volcanic environments ignimbrite deposition and tephra fall can reset the landscape and can bury the pre-existing offsets thus making it difficult to estimate the cumulative displacement on the fault.

Despite the complexity of faulting in some areas we are able to develop a composite rupture history for the San Vicente segment of the El Salvador Fault Zone based on interpretations of the trenches (Fig. 12). We show that at least seven ruptures occurred on San Vicente segment of the El Salvador Fault Zone in the last *c.* 8ka and that some events probably ruptured the whole segment. Individual rupture displacements appear to be highly variable, ranging from 0.6 to 9.6m of dextral slip. It is possible that the largest single-event displacements (events 5 and 6, with 5m and 9.6m respectively) either represent more than individual events on the San Vicente Segment or events that ruptured multiple fault segments. In our interpretation, we have not considered the single event displacement data from the Desague trench or Camino road cut because faulting there is clearly distributed among multiple strands and we only

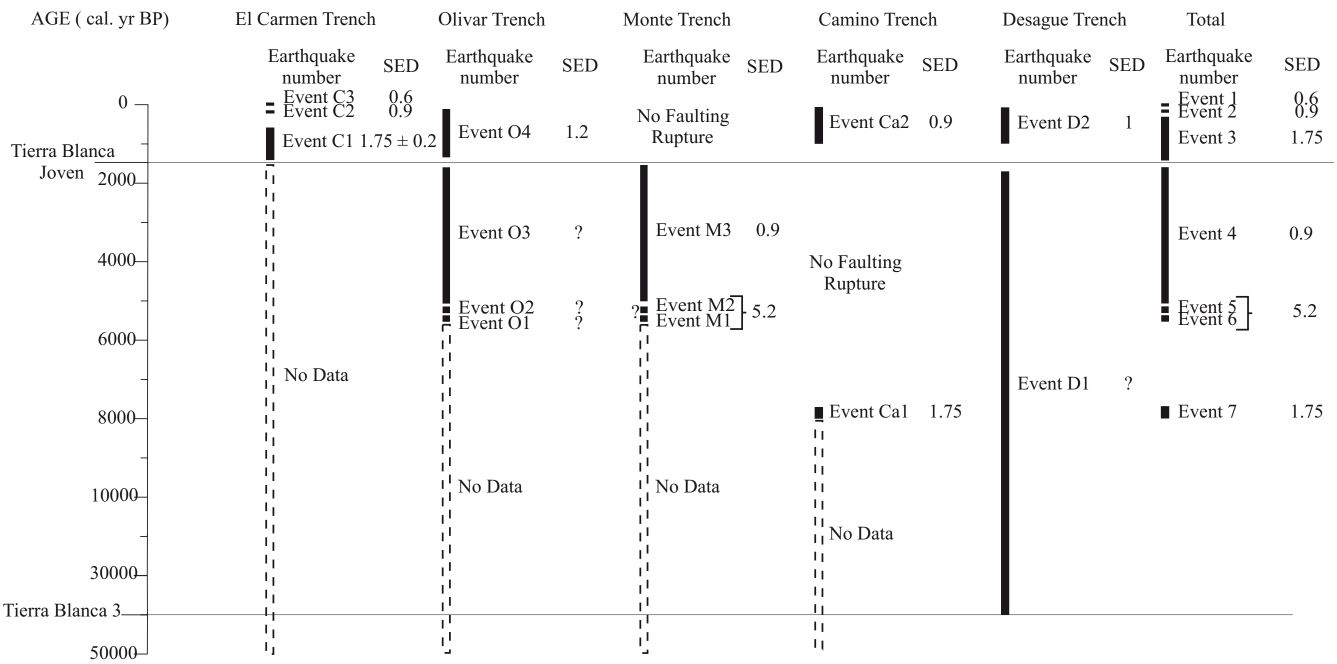


FIGURE 12 | Summary of the amount and timing of fault ruptures based on the five trenches excavated on the San Vicente segment of the El Salvador Fault Zone (ESFZ).

have slip estimates from a few of these strands. However, the information on event timing from the Desague area does provide constraints on whether rupture events identified in the Verapaz area also extended the *c.* 10km to the Desague area.

In the composite event record illustrated in Fig. 12 we interpret event 1 to be the February 13th 2001 El Salvador earthquake. It appears clearly in El Carmen trench as event C1. This event possibly ruptured the whole segment as documented by Canora *et al*. (2010), but it is difficult to identify in other trenches for several reasons: a) faulting apparently did not always reach the surface and single event displacement documented for the 2001 earthquake was small (Canora *et al*., 2010); b) faulting may have propagated on fault planes that ruptured bedrock outcrops at trench sites where there were no recent materials, and c) the topsoil at several of the trenches has been modified by agriculture, and the opportunity to identify the 2001 event has been destroyed. The maximum single-event displacements for the 2001 event is *c.* 0.6m (Canora *et al*., 2010).

The lack of evidence for event 1 in most of our trenches indicates that earthquakes with sizes similar to the 2001 event (M_w6.6) or smaller are unlikely to be found consistently in the paleoseismic trenches. Therefore, we consider we are probably missing the evidence for moderate magnitude, but damaging earthquakes of M_w6-6.5 that the El Salvador Fault Zone has probably produced. Therefore, our estimates of slip-rate are likely to be minimum (because they have been calculated from a conversion from dip-slip components of events that have been recorded), single-event displacements estimates are unlikely to record the full range and be biased toward larger events, and recurrence intervals for surface rupture are probably maximum estimates.

Event 2 is best constrained by event C2 in the El Carmen trench where it has a single-event displacement of *c.* 2.3±0.5m and an age between 167±20 and 389±76cal. yr BP. Event 3 is best represented by C3 in the El Carmen trench (Fig. 12) and occurred between 840±68 and 1478±64cal. yr BP. with a single-event displacements of *c.* 3.9±0.8m. Identifying Events 2 and 3 in the Olivar trench is uncertain because O1 could either correlate with events C2 or C3 from timing constraints. Based on single-event displacements considerations, it seems more likely that the Olivar 1 event correlates with Event 3 and thus we assign a maximum single-event displacement of *c.* 3.7±0.7m (the average between C3 and O1) to Event 3. Events Ca1 in the Camino trench and D1 in the Desague road cut exposure may also be correlated with Event 2 based on single-event displacements mesaurements. In the Monte trench, we have not found events displacing young materials but rupture post-Tierra Blanca Joven could have occurred on fault planes at the southern end of the trench (Fig. 10) where no stratigraphic units overlapping with Events 1, 2, or 3 are preserved.

Event 4 is identified as event O2 in the Olivar trench and M1 in the Monte trench. We have assigned it an approximate displacement of 1.9±0.3m, and an age between 1478±64 and 5119±68cal. yr BP. Because of the large hiatus in the stratigraphy of the Olivar and Monte trenches, it is possible that more than one earthquake occurred in the period between *c.* 5100 year cal BP. and the deposition of Tierra Blanca Joven. We discuss this below in the assessment of recurrence intervals.

Events 5, represented by event O3 in the Olivar trench and M2 in the Monte trench and Event 6 represented by O4 in the Olivar trench and M3 in the Monte trench, both display large displacements of 5.0±1.2m and 9.6±1.5m, respectively. These large apparent single-event displacements could be interpreted as two or more events that cannot be separated in time with the current stratigraphic evidence from the trenches, or the large single-event displacements could arise from a very large, multi-segment rupture of El Salvador Fault Zone. These

TABLE 2 | Minimun dextral-slip displacement rates (mm/yr) of the San Vicente segment of El Salvador Fault Zone from trench data and river offsets

Source	Displacement	Time	Slip-rate
	6m	last 1.5ka	4.1 ±0.6
Trenches	23m	last 5.5ka	4.1 ± 0.7
	26m	last 8ka	3.2 ± 0.5
River Offsets	100m	last 40ka	2.5 ± 0.2

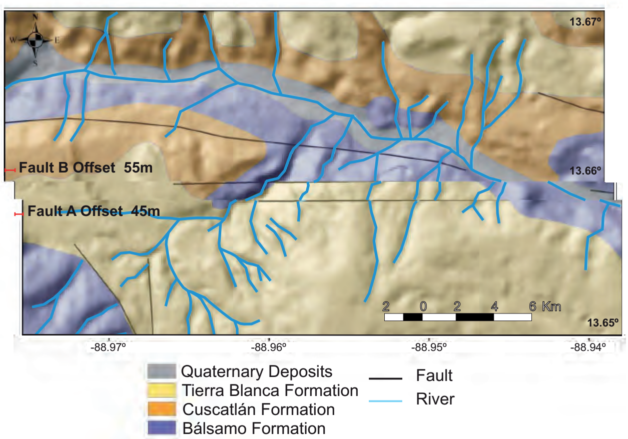


FIGURE 13 | Digital Elevation Model (DEM) of the Desague area showing the influence of the ESFZ on the local drainage pattern. The two southern strands of the fault displaced some rivers right–laterally. Lateral offsets have been estimated by restoring the initial geometry of the drainage system.

alternatives will be further analysed below. Correlation of events 5 and 6 with the Desague area is difficult because of the poor time constraints and the distributed character of faulting in that area. The lack of faulting identified in the Camino trench at the time of Events 5 and 6 does not necessarily mean that faulting did not reach that area because the events may have ruptured bedrock strands for which we have no event control (Fig. 11). Both events 5 and 6 occurred between 5119±65 and 5514±70 year cal BP.

The oldest event we identify in this study, Event 7, is only observed in the Camino road cut exposure (Fig. 12) with an approximate single-event displacement of 2.9±0.3m. The stratigraphy exposed in other trenches is not as old as that exposed in the road cut exposure. Judging by the large age gap between Events 6 and 7 (Fig. 12), it is likely that the event record is not complete for the mid-early Holocene period.

Fault slip-rate estimates for the San Vicente segment of the El Salvador Fault Zone have been derived from two sets of fault displacement data: 1) detailed logging of fault exposures in paleoseismic trenches, which provides information on fault plane attitudes and fault plane striation data, and thus calculated net slip over the age range of 8ka to present; and 2) identifying and measuring the offsets on rivers and streams that cross the fault, which provide horizontal displacements of the fault over long time periods (past *c.* 40ka since the landscape was regionally reset at the time of the TB3 deposition).

Data from the trenches, based on the vertical displacements and striations, indicate that dextral strike-slip rates have been very constant for the last 8ka (Table 2), with an average value of *c.* 4mm/yr. Longer term slip rates of the fault have been estimated from offsets of rivers that cross the San Vicente fault segment. The best locality along the San Vicente segment where the river offsets can be measured is in the Desague area (Fig. 13). The regional landscape and drainage system in this area is repeatedly reset by area ignimbrite eruptions from the nearby the Ilopango caldera. In particular, the Tierra Blanca 3 eruption and associated ignimbrite about 40ka ago filled the landscape and brought it to an almost planar surface which was subsequently incised by the river system. Figure 13 shows the principal fault strands in Desague and the *c.* 100m right-lateral horizontal offset of some rivers. This lateral displacement and the maximum *c.* 40ka age of the drainage system, provides a minimum estimate slip rate along the San Vicente segment of the El Salvador Fault Zone of 2.5±0.2mm/yr (Table 2). This value is reasonably consistent with the slip rate obtained from the paleoseismic trenches of *c.* 4mm/yr.

The *c.* 4 mm/yr of dextral slip on the San Vicente segment of the El Salvador Fault Zone differs from the plate kinematic models based on GPS velocities of DeMets (2001) and Correa-Mora *et al.* (2009), and from the geologically-based Holocene dextral slip rate estimate *c.* 11 mm/yr proposed by Corti *et al.* (2005). The GPS data provides a velocity estimate for the total El Salvador Fault Zone, which comprises the main fault and a great number of secondary faults, while our data only involves the main strike-slip fault strand. Therefore, the slip rate difference could represent the contribution of the secondary faults that form part of the El Salvador Fault Zone. The slip rate estimation of Corti *et al.* (2005) is based on drainage offsets along the Berlin segment of the El Salvador Fault Zone. Deformation on the Berlin segment appears to be more localized on the main fault strand with fewer active secondary structures than on San Vicente segment. It is thus reasonable that the main trace has a higher slip rate in that area, but whether secondary faults can add to the *c.* 7mm/yr apparent slip deficit we identify on the San Vicente segment is questionable.

Single event displacement as a clue for fault segmentation

The only historic event clearly associated with surface rupture of the San Vicente segment of the El Salvador Fault

TABLE 3 | Single-event displacement (SED) and earthquake magnitudes derived from scaling relationships for mapped lengths for the El Salvador Fault Zone

Mapped lengths	Surface Rupture length (km)	M_w*	SED (m)	M_w□
San Vicente segment	21	6.6	0.5	6.7
San Vicente and Lempa segments	49	7	1.8	7.2
San Vicente, Lempa and Berlin segments	73	7.2	3.2	7.4
El Salvador Fault Zone (from Ilopango Lake to the east)	123	7.5	7.7	7.7

[*] Regressions of Wells and Coppersmith, 1994. M_w= 5.16 + 1.12 log *SRL*, where *SRL*= surface rupture length (km) and M_w= moment magnitude. M_w= 6.81 + 0.78 log *SED*, where SED= single event displacement (m).

[□] M_w= 4.18 + 2/3 log (W) + 4/3 log (L) (Stirling et al., 2008), where W= seismogenic width (10-15km), and *L*= surface rupture length (km).

Zone is the 2001 M 6.6 earthquake. A ~0.6m single event displacement and a rupture length of ~20km have been reported for this event (Canora *et al*., 2010). However, single event displacement associated with previous events, as shown in this study, could be much larger (up to ~9.6m). This implies that longer ruptures, involving more than just the San Vicente segment of El Salvador Fault Zone should be considered.

To investigate possible segmentation models, we have estimated the expected single event displacements and earthquake magnitudes associated with different fault segment lengths. For this, we have used empirical scaling relationships (Wells and Coppersmith, 1994, and Webb's equations based on New Zealand data - see Stirling *et al*., 2008; Table 3) and compared results with the single event displacements seen in our trenches and the segmentation model for the El Salvador Fault Zone of Canora *et al*. (2010).

Along the El Salvador Fault Zone, four active major geometric segments have been identified (Fig. 2) based on morphological and structural mapping. Two of these (the San Vicente and Berlin segments) have clear E-W strike-slip principal displacement zones and some secondary NW-SE faulting. The San Vicente segment runs from the Ilopango Caldera to the city of San Vicente with an approximate length of 21km and Berlin segment extends *c*. 24km from the Lempa River to San Miguel Volcano. Between these segments and extending *c*. 28km from San Vicente to Lempa River there is an intervening area (the Lempa segment) where the strike-slip deformation is distributed in a 15km wide band. The easternmost segment, the San Miguel segment, extends for *c*. 50km from San Miguel Volcano to the east and comprises short fault strands, in a dextral en-echelon array, with no clear principal displacement zone. The tectonic geomorphology, structure and seismicity of the Lempa segment are consistent with the idea that the fault is newly developed in this area. West of San Salvador (Fig. 2) the presence of another segment of the El Salvador Fault Zone (our "west segment") is not clear in terms of fault geometry and geomorphology but we infer its existence on the basis of strike-slip fault mechanisms of several large earthquakes with east-west fault planes (Martínez-Díaz *et al*., 2004) and from the presence of some isolated, but well-developed, fault traces with W-E, NW-SE and NNW-SSE trends.

Although single event displacement may vary in successive events for the same earthquake size at a location because of the natural variability of the faulting process (Hecker and Abrahamson, 2004) there is some potential in evaluating single-event displacements as a proxy for rupture length. We can assess whether the San Vicente geometric segment also represents a rupture segment or whether other segments of the fault are also likely to rupture with the San Vicente segment, and thus imply large associated earthquake magnitude. From the empirical relationships (Table 3), we see that single-event displacements of 0.6m (which were observed at some localities along the San Vicente segment in the 2001 earthquake – Canora *et al*., 2010) could be expected to be associated with rupture lengths of *c*. 20km, *i.e.*, rupture of the San Vicente segment alone. A single-event displacement of *c*. 2m implies rupture lengths of *c*. 50km, which could correspond to the rupture of the San Vicente and Lempa segments combined. Single-event displacements of *c*. 3m, corresponding to a rupture length of *c*. 70km, could be achieved by a combined rupture of the San Vicente, Lempa and Berlin segments. Rupture lengths of ~100m, necessary to produce fault displacements above 5m, would correspond to the rupture of the whole of the El Salvador Fault Zone in El Salvador, from Lake Ilopango to the east (rupture of the San Vicente, Berlin, Lempa and San Miguel segments together). Rupture associated to the indicated very large single-event displacements of >9m should be much larger (*c*. 140km long) or more likely such a large single-event displacement represents multiple episodes of rupture involving all the El Salvador Fault Zone from Guatemala to the Fonsecha gulf (rupture of the five segments).

We note that our single-event displacements estimates are in general quite uncertain because they are derived from vertical displacement and striae rakes. Within these, the single-event displacement estimates of 5m and 9m are even more uncertain because they are observed in older (~8ka) strata which lack sufficient stratigraphic resolution to discriminate whether the single-event displacements represent one or more events, and the estimates of single-event displacements are accumulated from multiple fault planes. Because of this increased uncertainty in the large single-event displacement values we restrict our interpretation to single-event displacement values of ≤3.2m to assess the frequency and magnitude of paleo-earthquakes of the El Salvador Fault Zone. With this restriction we propose that the El Salvador Fault Zone has ruptured with at least three different single-event displacements in the past 1.5kyr; c 0.6m, *c*. 2m and *c*. 3m, which correspond to events 1, 2 and 3, respectively, and to ruptures of 1, 2 and 3 geometric fault segments.

Maximum earthquake magnitude and rupture recurrence: earthquake hazard

Within the uncertainty range typical for strike-slip faults, we have shown that derived single-event displacements values for geometric segment lengths of the El Salvador Fault Zone are in good agreement with single-event displacement values obtained from paleoseismic trenches. Therefore, we use the mapped segment lengths to calculate possible earthquake magnitudes on each of the fault segments, using Wells and Coppersmith (1994) and Stirling *et al*. (2008) fault-scaling relations. The equations in Stirling *et al*. (2008) are width-limited scaling relations for use in low slip rate or immature tectonic regions and the results are very similar to those that we obtained with equations from Wells and Coppersmith (1994; Table 3). There is reasonably good consistency between the coseismic surface displacements and waveform inversion of the 2001 El Salvador earthquake (Canora el al., 2010; Kikuchi and Yamanaka, 2001), and with earthquake magnitude and frequency on the El Salvador Fault Zone implied from paleoseismic trenches and fault-scaling relations.

Based on our trench data, we show that the recurrence of large earthquakes (M_w>7) along El Salvador Fault Zone is about 750yr (events 2 and 3, see Fig. 12) during the last 1.5kyr. Information for times older than ~1500 years is incomplete in our trenches, but the long term fault slip rate of >/=4mm/yr combined with the range of single-event displacements values is also consistent with a recurrence interval for large earthquakes rupturing each part of the El Salvador Fault Zone is <1000 years.

Historically, large (M_w>7) earthquakes in the El Salvador area have been attributed to the subduction zone (White *et al*., 1987; Dewey and Suarez, 1991; White and Harlow, 1993; Harlow *et al*., 1993) with thrust events on the Wadati-Benioff zone, and normal faulting events within the subducting plate resulting from extensional forces generated by slab-pull forces or by bending of the subducting plate. Onshore historic earthquakes have been reported with moderate magnitudes. The peak Modified Mercalli intensity felt by the upper-crustal events and by the subduction zone events are similar (VII-IX) (White *et al*., 2004). Their criteria to assign a specific seismic source to historic events was the area of the Modified Mercalli intensity VII contour. For upper-crustal earthquakes the Modified Mercalli intensity VII contour area was less than 600km^2, whereas for subduction zone events, this area was larger than 10000km^2 (White *et al*., 2004). However, the February 1976 Guatemala left-lateral earthquake (M_w7.5) with ~250km of surface rupture along the Motagua fault, was a shallow (5-20km depth) earthquake which had a Modified Mercalli intensity of VII and a contour area of more than 10000km^2 (White and Harlow, 1993). Thus, we consider that earthquakes within the volcanic area of El Salvador with M_w>7 could also produce large areas of Modified Mercalli intensity VII and larger.

Our paleoseismic study of the El Salvador Fault Zone suggests the occurrence of at least two earthquakes with M_w>7 in the El Salvador Fault Zone in the last 1.5ka. This has very important implications for current perceptions of seismic hazard in El Salvador because large (M_w>7) shallow (<20km depth) earthquakes along the volcanic arc are likely to generate extensive damage and destruction at a level that is currently larger than expected.

The historic record in El Salvador goes back ~500 years and thus it is possible that event 2 recorded in our trenches could be recorded in the historic documents. We have investigated historic and instrumental seismic catalogues (Cañas-Dinarte, 2004; International Seismological Centre; Servicio Nacional de Estudios Territoriales (SNET); Unite States Geological Survey) and examined seismic data books and papers (Lardé-Larín, 1978; Harlow *et al*., 1993; White and Harlow, 1993; Peraldo and Montero, 1999; Ambraseys and Adams, 2001; Dewey *et al*., 2004; White *et al*., 2004), and conclude that some historic earthquakes are likely to have been incorrectly assigned to subduction zone sources. Event 2 from the paleoseismic trenches occurred between 1485 and 1803 AD, and could correlate to the 1719 earthquake recorded on the historic seismic catalogues. White and Harlow, proposed that the subduction zone was the source of this earthquake (see also Peraldo and Montero, 1999; White *et al*., 2004) by assigning a Modified Mercalli intensity VII, a contour area of 9243km^2 (Fig. 14) and a M_s of 7.2. The intensity contour map (Fig. 14) shows the VII contour opened to the south. However, we have found no description of damages or effects in the south of El Salvador. We suggest that this representation is because the author assumed the subduction zone was the source of the earthquake, and in fact it is likely that the isoseismal has an elliptical shape along the volcanic arc.

Moreover, the description of the 1719 earthquake effects around the cities of San Salvador and San Vicente (Lardé-Larín, 1978; Peraldo and Montero, 1999) are very similar to those reported after the February 2001 earthquake. Lardé-Larín (1978) and Peraldo and Montero (1999) compiled some descriptions of large fractures, liquefaction zones and sulphuric gas leak produced by the 1719 earthquake and also the destruction of numerous buildings, including houses, churches and monasteries, especially in the cities of San Salvador and San Vicente. Those authors also described a large number of foreshocks and aftershocks in the area. It is thought that the number of deaths at the time of the main shock was small (7 deaths) because of precautions resulting from the 150 felt foreshocks. These observations suggest to us that the source of this earthquake could have been a large (M_w>7), shallow (<20km depth) rupture within the volcanic arc of El Salvador. Our paleoseismic results suggest that this rupture could be on the El Salvador Fault Zone in a section of the fault larger than the San Vicente segment that ruptured in February 2001.

Alternatively, paleoseismic event 2 could correlate with the 1748 earthquake, for which White *et al.* (2004) estimate a magnitude of 7.1. Although Peraldo and Montero (1999)

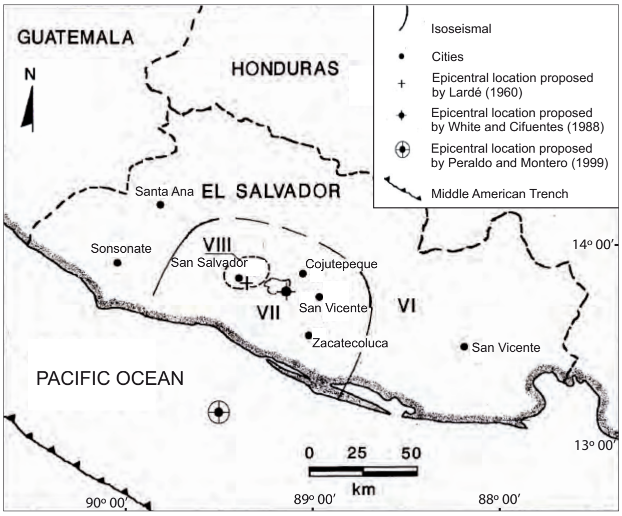


FIGURE 14 | Modified Mercalli intensity distribution reported for the 1719 El Salvador earthquake. Modified from Peraldo and Montero (1999).

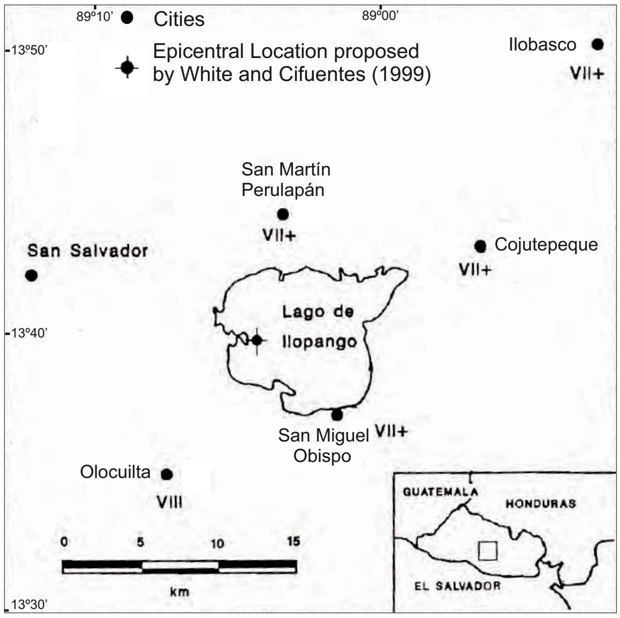


FIGURE 15 | Modified Mercalli intensity distribution reported for the 1748 El Salvador earthquake. Modified from Peraldo and Montero (1999).

and Harlow *et al.* (1993) suggested the subduction zone as the source of this earthquake, considering that the damage produced was very concentrated in the areas around Lake Ilopango (Fig. 15), we suggest a possible local upper plate origin.

We have analysed seismicity in El Salvador from 1524 to the present, in order to identify other smaller events (similar to the February 2001) associated with faults in the volcanic arc. In Figure 16 we show the well-located 20th century shallow earthquakes alongside the compilation of the historical events. All earthquakes fall in a zone of about 15km wide, broadly coincident with our mapping of the El Salvador Fault Zone. From these data we estimate a recurrence interval for intermediate magnitudes (M_w 5.7-6.4) of *c.* 15±5 years, for the whole El Salvador Fault Zone. If we only consider the earthquakes located around San Vicente segment (taking in to account the uncertainty of the epicentral location), the recurrence is *c.* 25±5 years for the same period. The recurrence on the El Salvador Fault Zone for large earthquakes (M_w>6.5) based on its historic seismicity is approximately 40±10 years. These results are a first approximation for earthquakes associated with the El Salvador Fault Zone. Further assessment of the pre-twentieth century events would be valuable to reduce the current large uncertainties of epicentral location and clarify relationships with active fault traces of the El Salvador Fault Zone.

This study has developed paleoseismic data exclusively from the San Vicente segment of El Salvador Fault Zone. Characterization of past rupture along other segments is required to corroborate inferences of the rupture history on other fault segments to refine hazard estimates for the entire fault zone.

CONCLUSIONS

In this first paleoseismic study in El Salvador, we have characterised the Holocene rupture history of the San Vicente segment of the El Salvador Fault Zone, and considered how the data revise our understanding of earthquake hazard in El Salvador. Strands of the El Salvador Fault Zone form part of a dextral strike-slip system within the active volcanic arc of El Salvador. Single event fault slip ranging from *c.* 0.6m to possibly as much as 9.6m, suggests the fault is capable of generating surface-rupture earthquakes up to possibly M_w7.7. Geomorphologic characteristics suggest surface rupture occurred on the fault many times within the last few thousand years. Paleoseismology studies using trenching and ^{14}C dating, combined with field data, indicate that along the San Vicente segment, there have been at least seven surface rupture earthquakes in the last 8000yr, with the most recent event occurring in 2001 during the M_w 6.6 El Salvador earthquake. Future earthquakes of M_w>7 are possible in the region. The recentness of events combined with estimates of slip rate (*c.* 4mm/yr) suggest recurrence intervals of *c.* 750yr and a fairly low probability of an earthquake within the next century, at least on the San Vicente segment. However, the small earthquakes generated by the rupture of a single segment are difficult to recognise in the trenches and the presence of those events could pose a significant seismic hazard that is difficult to achieve from paleoseismicity alone.

Characteristics of the El Salvador Fault Zone include the irregularity and multiplicity of fault traces and

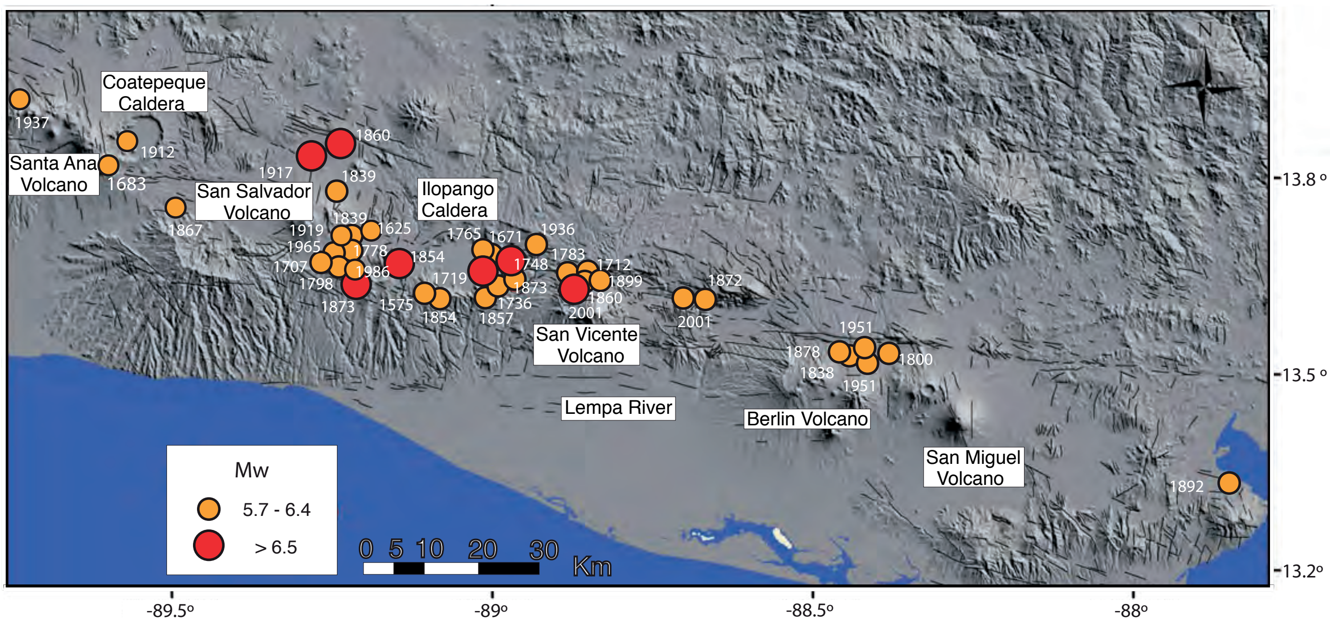


FIGURE 16 | Historical and instrumental seismicity in El Salvador from 1524 to 2008 for M_w>5.7 compiled for this study (SNET complete catalogue based on Lardé-Larín, 1978 and Peraldo and Montero, 1999). The epicentre location of the earthquakes before 1900 is based on ground effects and damage, and thus has large uncertainty.

segments, the complexity of some parts of the structure and the small cumulative offset along the fault. These are typical characteristics of a very young fault system, but the complexity makes the estimation of seismic hazards associated with the El Salvador Fault Zone more difficult.

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REFERENCES

Ambraseys, N.N., Adams, R.D., 2001. The seismicity of Central America: a descriptive catalogue 1898-1995. London, Imperial College Press, 309pp.

Bommer, J., Benito, B., Ciudad-Real, M., Lemoine, A., López-Menjivar, M., Madariaga, R., Mankelow, J., Mendez-Hasbun, P., Murphy, W., Nieto-Lovo, M., Rodríguez, C., Rosa, H., 2002. The Salvador earthquakes of January and February 2001: Context, characteristics and implications for seismic risk. Soil Dynamics and Earthquake Engineering, 22, 389-418.

Bosse, H.R., Lorenz, W., Merino, A., Mihm, A., Rode, K., Schmidt-Thomé, M., Wiesemann, G., Weber, H.S., 1978. Geological map of El Salvador Republic: Hannover Germany. Bundesanstalt für Geowissenschaften und Rohstoffe, D-3 scale 1:100,000.

Buforn, E., Lemoine, A., Udias, A., Madariaga, R., 2001. Mecanismo focal de los terremotos de El Salvador. In: Martínez-Guevara, J.M., (ed.). Memorias 2° Congreso Iberoamericano de Ingeniería Sísmica. Madrid (Spain), 115-118.

Canora, C., Martínez-Díaz, J.J., Villamor, P., Berryman, K., Álvarez-Gómez, J.A., Pullinger, C., Capote, R., 2010. Geological and seismological analysis of the M_w 6.6 February, 13th 2001 El Salvador earthquake: Evidence for surface rupture and implications for seismic hazard. Bulletin of the Seismological Society of America, 100(6), 2873-2890.

Cañas-Dinarte, C., 2004. El Salvador: cronología de una tierra danzarina. El Diario de Hoy. Last visit: September 2009. http://www.elsalvador.com/noticias/terremoto/cronologia.htm

Correa-Mora, F., DeMets, C., Alvarado, D., Turner, H.L., Mattioli, G., Hernández, D., Pullinger, C., Rodríguez, M., Tenorio, C., 2009. GPS-derived coupling estimates for Central America subduction zone and volcanic arc faults: El Salvador, Honduras and Nicaragua. Geophysical Journal International, 179(3), 1279-1291.

Corti, G., Carminati, E., Mazzarini, F., Garcia, M.O., 2005. Active strike-slip faulting in El Salvador, Central America. Geology, 33, 989-992.

DeMets, C., 2001. A new estimate for present-day Cocos-Caribbean plate motion: Implications for slip along the Central American volcanic arc. Geophysical Research Letters, 28, 4043-4046.

DeMets, C., Jasma, P.E., Mattioli, G.S., Dixon, T.H., Farina, F., Bilham, R., Calais, E., Mann P., 2000. GPS geodetic constraints on Caribbean-North America plate motion. Geophysical Research Letters, 27(3), 437-440.

Dull, R., Southon, J.R., Sheets, P., 2001. Volcanism, ecology and culture: A reassessment of the Volcan Ilopango Tierra Blanca Joven eruption in the southern Maya realm. Latin American Antiquity, 12, 25-44.

Dewey, J.W., Suárez, G., 1991. Seismotectonics of Middle America. In: Slemmons D.B., E. R. Engahl, M. D. Zovak and D. Blackwell (eds.). Neotectonics of North America. Geological Society of America, 309-321.

Dewey, J.W., White, R.A., Hernández, D.A., 2004. Seismicity and tectonic of El Salvador. In: Rose, I., Bommer, J.J., López D.L., Carr M.J., and Major J.J. (eds.). Natural Hazards in El Salvador. Geological Society of America, 375(Special Paper), 363-378.

Guzmán-Speziale, M., Meneses-Rocha, J.J., 2000. The North America-Caribbean plate boundary west of the Motagua-Polochic fault system: A fault jog in southeastern Mexico. Journal of South American Earth Sciences, 13, 459-468.

Guzmán-Speziale, M., Pennington, W.D., Matumoto, T., 1989. The triple junction of the North America, Cocos, and Caribbean plates: Seismicity and tectonics. Tectonics, 8, 981-997.

Harlow, D.H., White, R.A., Rymer, M.J., Alvarez, S., 1993. The San Salvador earthquake of 10 October 1986 and its historical contex. Bulletin of the Seismological Society of America, 83(4), 1143-1154.

Hecker, S., Abrahamson, N.A., 2004. Low slip-at-a point variability: implications for earthquakes-size distribution, fault rupture hazard, and ground-motion modelling. Reno-Sparks (Nevada), Basin and Range Province Seismic Hazards Summit II, Western States Seismic Policy Council, 21-22.

Hernández, W., 2004. Características geomecánicas y vulcanológicas de las tefras de Tierra Blanca Joven, Caldera de Ilopango. El Salvador. Master Thesis. Madrid (Spain), Universidad Politécnica de Madrid, 80pp.

International Seismological Centre. United Kingdom. Last visited: June 2009. http://www.isc.ac.uk/.

Isacks, B., Baranzagi, M., 1977. Geometry of Benioff zones: Lateral segmentation and downwards bending of the subducted lithosphere. In: Talwani, M., Pitman, W.C., (eds.). Island arcs, deep sea trenches, and back-arc basins. American Geophysical Union Maurice Ewing Series, 1, 99-114.

Kikuchi, M., Yamanaka, Y., 2001. EIC Seismological Notes, 99. Earthquake Research Institute Tokyo. http://www.eri.u-tokyo.ac.jp/sanchu/Seismo_Note/index-e.html Last visited: June 2009

Lardé-Larín, J., 1978. El Salvador: inundaciones e incendios, erupciones y terremotos. San Salvador. Biblioteca de Historia Salvadoreña, 397pp. Last visited: November 2009. http://desastres.usac.edu.gt/documentos/pdf/spa/doc15003/doc15003.htm.

Lyon-Caen, H., Barrier, E., Lasserre, C., Franco, A., Arzu, I., Chiquin, M., Chiquin, L.M., Duquesnoy, T., Flores, O., Galicia, O., Luna, J., Molina, E., Porras, O., Requena, J., Robles, V., Romero, J., Wolf, R., 2006. Kinematics of the North American-Caribbean-Cocos plates in Central America from new GPS measurements across the Polochic-Motagua fault system. Geophysical Research Letters, 33, L19309. doi:10.1029/2006GL027694

Major, J.J., Schilling, S.P., Sofield, D.J., Escobar, C.D., Pullinger, C.R., 2001. Volcano hazards in the San Salvador region, El Salvador. United States Geological Survey, USGS Open file report, 01-366: 1-23.

Martínez-Díaz, J.J., Álvarez-Gómez, J.A., Benito, B., Hernández, D., 2004. Triggering of destructive earthquakes in El Salvador. Geology, 32, 65-68.

Peraldo, G., Montero, W., (1999). Sismología Histórica de América Central. México, Instituto Panamericano de Geografía e Historia, 513, 347pp.

Plafker, G., 1976. Tectonic aspects of the Guatemala earthquake of 4 February 1976. Science, 193(4259), 1201-1208.

Rose, W.I., Conway, F.M., Pullinger, C.R., Deino, A., McIntosh, W.C., 1999. An improved age framework for late Quaternary silicic eruptions in northern Central America. Bulletin of Volcanology, 61, 106-120.

Servicio Nacional de Estudios Territoriales (SNET). El Salvador government. Last visited: February 2010. htp://www.snet.gob.sv/ver/sismologia/registro/estadisticas/

Stirling, M.W., Gerstenberger, M.C., Litchfield, N.J., McVerry, G.H., Smith, W.D., Pettinga, J., Barnes, P. 2008. Seismic hazard of the Canterbury region, New Zealand; new earthquake source model and methodology. Bulletin of the New Zealand Society for Earthquake Engineering, 41(2), 51-67.

Stuiver, M., Reimer, P.J., 1993. Extended ^{14}C database and revised CALIB radiocarbon calibration program. Radiocarbon, 35, 215-230.

United States Geological Survey. National Earthquake Information Center (NEIC). Last visited: November 2009. htttp://neic.usgs.gov/

Wallace, R.E., 1977. Profiles and ages of young fault scarps, northcentral Nevada. Geological Society of America Bulletin, 88, 1267-1281.

Wells, D.L., Coppersmith, K.J., 1994. New empirical relations among Magnitude, Rupture Length, Rupture Width, Rupture Area and Surface Displacement. Bulletin of Seismological Society of America Bulletin, 84(4), 974-1002.

Wesnousky, S.G., 1988. Seismological and structural evolution of strike-slip faults. Nature, 335, 340-343.

White, R.A., Harlow, D.H., 1993. Destructive uppercrustal earthquakes of Central America since 1900. Seismological Society of America Bulletin, 83, 1115-1142.

White, R.A., Harlow, D.H., Álvarez, S., 1987. The San Salvador earthquake of October 10, 1986: Seismological aspects and other recent local seismicity. Earthquake Spectra, 3, 419-434.

White, R.A., Ligorría, J.P., Cifuentes, I.L., 2004. Seismic history of the Middle America subduction zone along El Salvador, Guatemala, and Chiapas, Mexico: 1526-2000. In: Rose, I., Bommer, J.J., López D.L., Carr M.J., and Major J.J. (eds.). Natural Hazards in El Salvador. Geological Society of America, 375(Special Paper), 379-396.

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