An integrated structural and GPS study of the Jalpatagua fault, southeastern Guatemala

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ABSTRACT

The Jalpatagua fault in Guatemala accommodates dextral movement of the Central America forearc. We present new global positioning system (GPS) data, minor fault analysis, geochronological analyses, and analysis of lineaments to characterize deformation along the fault and near its terminations. Our data indicate that the Jalpatagua fault terminates at both ends into extensional regions. The western termination occurs near the Amatitlan caldera and the southern extension of the Guatemala City graben, as no through-going structures were observed to continue west into the active volcanic arc. Along the Jalpatagua fault, new and updated GPS site velocities are consistent with a slip rate of 71 ± 1.8 mm yr⁻¹. Minor faulting along the central section of the fault includes: (1) N-S striking normal faults accommodating E-W elongation; and (2) four sets of strike-slip faults (oriented 330°, 020°, 055°, and 295°, parallel to the Jalpatagua fault trace). Minor fault arrays support dextral movement along a major fault in the orientation of the Jalpatagua fault. GPS and fault data indicate that the Jalpatagua fault terminates to the east near the Guatemala–El Salvador border. Data delineate a pull-apart basin southeast of the fault termination, which is undergoing transtension as the Jalpatagua fault transitions into the El Salvador fault system to the east. Within the basin, minor faulting and lineations trend to the NW and accommodate NE-directed elongation. This faulting differs from E-W elongation observed along the Jalpatagua fault and is more similar to minor faults within the El Salvador fault system.

INTRODUCTION

Moving forearc slivers typically result from strain partitioning due to oblique convergence between the subducting and overriding plates (e.g., Fitch, 1972; Jarrard, 1986; McCaffrey, 1992). In these cases, strike-slip faults are typically found within or adjacent to an active volcanic arc (e.g., de Saint Blanquat et al., 1998; Sieh and Natawidjaja, 2000; Garibaldi et al., 2016). While forearc slivers are common features around the world, the way in which strike-slip motion is accommodated at their boundaries varies greatly between each system. A singular strike-slip fault occurs in the Sumatra fault system in Indonesia (e.g., Sieh and Natawidjaja, 2000), series of en echelon faults are interpreted to occur in El Salvador (e.g., Garibaldi et al., 2016; Martínez-Díaz et al., 2004), and a complicated fault network containing coeval areas of transpression and transtension are present along the Andean fault system in southern Chile (e.g., Grocott and Taylor, 2002). It is unclear what guides the type of faulting that will accommodate forearc movement in each setting, particularly in the presence of an active volcanic arc, which complicates the rheological behavior of the upper crust (Martin et al., 2014).

The Central American moving forearc, which may have resulted from multiple factors within an uncoupled subduction zone, provides an opportunity to investigate along-strike variations in the character of strike-slip faulting. The forearc region in Central America accommodates dextral movement and extends from Costa Rica to southern Guatemala, along the active volcanic arc, and parallels the Middle America Trench (Fig. 1; DeMets, 2001; Guzmán-Speziale et al., 2005; Lyon-Caen et al., 2006; Franco et al., 2012). The dextral forearc fault system is the widest in Nicaragua, with NE-oriented sinistral faults that suggest bookshelf faulting may accommodate dextral movement rather than arc-parallel dextral faults (NFS in Fig. 1; Weinberg, 1992; La Femina et al., 2002). In El Salvador, the El Salvador fault system progressively narrows to the northwest and consists of a zone of right-stepping strike-slip faults, related pull-apart basins, active volcanoes, and calderas (ESFS in Fig. 1; Martínez-Díaz et al., 2004; Alvarado et al., 2011; Canora et al., 2014; Alonso-Henar et al., 2014, 2015, 2017; Garibaldi et al., 2016; Staller et al., 2016). In southeastern Guatemala, dextral movement occurs on the Jalpatagua fault, which begins near the Guatemala–El Salvador border and continues for nearly 70 km before terminating at the southern extension of the Guatemala City graben (JF in Fig. 1). The Jalpatagua fault is arguably the termination of the forearc fault system, as no clear evidence for discrete strike-slip faulting is apparent geologically or geodetically (Ellis et al., 2019) west of Guatemala City.

The goal of this study was to document and interpret deformation along and near the Jalpatagua fault system. The Jalpatagua fault is relatively unstudied (Carr, 1974, 1976; Pfafker, 1976; Duffield et al., 1982; Authemayou et al., 2011), likely because of poor exposure resulting from abundant vegetation and tropical weathering. Here, we present new global positioning system (GPS) data and an associated elastic block model, minor fault analysis, geochronological analyses, and analysis of lineaments associated with the Jalpatagua fault. Minor faulting supports dextral movement along the...
Jalpatagua fault, although with along-strike variations. In southeastern Guatemala, the Jalpatagua fault terminates at its eastern end into a complex zone of faulting associated with a step-over in the El Salvador fault system. The fault terminates at its western end near the Amatitlan caldera and the southern end of the Guatemala City graben.

TECTORIC FRAMEWORK OF SOUTHEASTERN GUATEMALA

Geodetic Constraints

Deformation in southern Guatemala is the result of the relative movements of the North America, Caribbean, and Cocos plates, which meet in a zone of diffuse deformation in southwestern Guatemala (Fig. 1; Lyon-Caen et al., 2006; Alvarez-Gomez et al., 2008; Rodriguez et al., 2009; Authemayou et al., 2011; Franco et al., 2012). The North America–Caribbean plate boundary is defined by the arcuate left-lateral Polochic-Motagua fault system in central Guatemala, as the North America plate moves ~18 mm yr⁻¹ westward relative to the Caribbean plate (Ellis et al., 2019; also see Weyl, 1980; Mann et al., 2007; Lyon-Caen et al., 2006; DeMets et al., 2010; Authemayou et al., 2011, 2012; Franco et al., 2012). The Cocos plate subducts ~73–76 mm yr⁻¹ (toward N27.5–30°E) beneath the forearc sliver of the Caribbean plate off the southwest coast of Central America (Ellis et al., 2019). Within this system, an active volcanic arc (Central American volcanic arc) and the dextral moving forearc extend from western Guatemala to Costa Rica, parallel to the Middle America Trench.

Forearc movement may result from: (1) strain partitioning from oblique convergence between the Cocos and Caribbean plates in an uncoupled subduction zone, (2) pull from the North America plate where the forearc is pinned and moves to the northwest as the Caribbean plate moves eastward, (3) westward push from a collision of the Cocos Ridge beneath the Costa Rican forearc and/or (4) a combination of pushing of the Cocos Ridge and forearc pinning (DeMets, 2001; Lyon-Caen et al., 2006; La Femina et al., 2009; Alvarez-Gomez et al., 2008, 2019; Franco et al., 2012; Staller et al., 2016). In Guatemala, the Jalpatagua fault defines the forearc boundary, which creates a clear topographic lineament oriented ~295° that parallels the volcanic arc and the Middle America Trench (Fig. 1; Williams, 1960; Carr, 1974, 1976; Weyl, 1980; Wunderman and Rose, 1984; Alvarez-Gomez et al., 2008, 2019; Authemayou et al., 2011).

Based on a regional elastic block model that best fits a new 200+ station GPS velocity field in northern Central America and southern Mexico,
Ellis et al. (2019) estimated that the Central America forearc sliver moves 7.6 ± 2.1 mm yr⁻¹ toward N75°W ± 12° relative to the lithosphere inland from the Jalpatagua fault, −25% slower than the −10 mm yr⁻¹ Jalpatagua fault slip rate estimated by Lyon-Caen et al. (2006) from the first GPS measurements in southern Guatemala. Farther east, the new block model predicts that the rate of dextral forearc movement increases to 9.7 ± 1.4 mm yr⁻¹ in western El Salvador, 10.3 ± 1.2 mm yr⁻¹ in central El Salvador along the El Salvador fault system, and 12.5 ± 1.0 mm yr⁻¹ across the Nicaraguan volcanic arc. Along the El Salvador fault zone, the forearc sliver motion is accommodated by approximately E-W strike-slip faults and NW-oriented en échelon fractures in El Salvador, dextral river valley (Los Esclavos River; Fig. 2) offsets of −9−12 km along the lineament, and focal mechanisms from the San Salvador 1963 earthquake indicating right-lateral movement on a 295° orientation. Carr (1974) also noted the 500-m-high fault scarp of the Jalpatagua fault north of the town of Jalpatagua, which he suggested was created by subsidence related to eruption of pyroclastic material.

**Structural Constraints**

Early work by Williams (1960) and Carr (1974, 1976) established a right lateral-sense of motion along the Jalpatagua fault. Their evaluation was based on conjugate left-lateral faults in the area, NW-oriented en échelon fractures in El Salvador, dextral river valley (Los Esclavos River; Fig. 2) offsets of −9−12 km along the lineament, and focal mechanisms from the San Salvador 1963 earthquake indicating right-lateral movement on a 295° orientation. Carr (1974) also noted the 500-m-high fault scarp of the Jalpatagua fault north of the town of Jalpatagua, which he suggested was created by subsidence related to eruption of pyroclastic material.

Later work by Eggers (1971) and Wunderman and Rose (1984) on the Lake Amatitlán caldera to the west, near the westernmost terminus of the Jalpatagua fault, suggested that the Jalpatagua fault continues through the caldera, as evidenced by the linearity of Lake Amatitlán and 1 km offsets of outer rim faults on the east side of the caldera. Additionally, young N-S-striking faults were mapped within the caldera (Eggers, 1971).

Reynolds (1977, 1980, 1987) completed field mapping of three quadrangles north of the Jalpatagua fault near the town of Cuiapa. His work focused on the Santa Rosa de Lima caldera. He suggested that the southern portion of the caldera intersects the Jalpatagua fault and is deflected around the edge of the caldera.

Investigations by Duffield et al. (1992) on the Tecuamburro volcano, south of the Jalpatagua fault and near the Los Esclavos River, reported evidence for cataclasis along the Jalpatagua fault. In this locality, lavas and tuffs are sheared into cataclastic breccias, and nonwelded tuffs are pulverized into rock flour along the fault. The Los Esclavos River has also been used as a geomorphic feature by multiple studies to determine fault offset (Duffield et al., 1992; Authemayou et al., 2011). Authemayou et al. (2011) calculated 6.5–8.7 km of dextral offset along the Jalpatagua fault using the large bend in the Los Esclavos River along the fault trace. These authors also estimated that a decapitated alluvial fan near Oratorio indicates 1.2 ± 0.2 km of dextral offset. While nearly all these studies utilized geomorphic analyses using aerial/satellite photos and elevation maps, Authemayou et al. (2011) was the only study to record fault orientation and lineation measurements (n = 10) related to the Jalpatagua fault, measured within 1 km of the interpreted fault trace. The lack of published structural data highlights the lack of outcrops on or near the Jalpatagua fault.

**Stratigraphy along the Jalpatagua Fault and Terminations**

We present a general overview of stratigraphy along the Jalpatagua fault, with specific unit correlation provided in the data description section, Table 1, and Figure 3. The stratigraphy of southern Guatemala along the Jalpatagua fault is dominated by Quaternary and Neogene volcanic deposits and reworked sediments that were deposited during multiple periods of volcanic activity within this time period (Koch and McLean, 1975; Bethancourt et al., 1976; Reynolds, 1977, 1980, 1987; Wunderman and Rose, 1984; Duffield et al., 1992; Rose et al., 1999). With numerous eruptive centers in space and time, the stratigraphy is highly variable from location to location, often making unit identification difficult.

There is a distinction between Quaternary and Neogene deposits within the literature and in stratigraphic columns of Guatemala: (1) Quaternary tephras are identified individually; and (2) Neogene deposits are bulked into three formations: the upper Cuscatlán, middle Básalmo, and lower Chalatenango formations (Fig. 3; Williams, 1960; Koch and McLean, 1975; Reynolds, 1980). In general, recent Quaternary tephras, lavas, and reworked deposits are better described, defined, and mapped in the literature due to widespread exposure across
Figure 2. A 20 m digital elevation model [OpenStreetMap contributors, 2015] of southeastern Guatemala showing major structures and lineaments and locations of faulted outcrops. Data were collected within three study areas along and near the Jalpatagua fault: western, central, and eastern sections. Fault data collected from each location are displayed below the map. GCG—Guatemala City graben.

| Western Section | Central Section | Eastern Section |
|-----------------|-----------------|-----------------|
| ![Map](image)   | ![Map](image)   | ![Map](image)   |

**Western Section**

1. n=7
   - Max Elong: 051°

2. n=37
   - Max Elong: 100°

**Central Section**

3. n=22
   - Set 1: 326°-trending
   - Set 2: 017°-trending
   - Set 3: 059°-trending

4. n=11
   - Max Elong: 093°

5. n=14
   - Max Elong: 065°

6. n=9
   - Max Elong: 073°

**Eastern Section**

7. n=41
   - Set 1: 334°-trending
   - Set 2: 022°-trending
   - Set 3: 054°-trending
   - Set 4: 299°-trending

8. n=14
   - Max Elong: 065°

9. n=9
   - Max Elong: 073°
TABLE 1. DESCRIPTIONS AND PUMICE MINERALOGY OF COLLECTED SAMPLES

| Sample       | Unit description                                         | Additional descriptions                              | Present structures          |
|--------------|----------------------------------------------------------|------------------------------------------------------|----------------------------|
| 17JF23a Location 1 | 8–10-m-thick, white pumice–rich lapilli tephra containing mostly pumice fragments (centimeters to tens of centimeters long), phenocrysts, and ash. Unit has a granular appearance due to the abundance of pumice fragments. Unit is poorly indurated and easily eroded by wind. Interpreted as E tephra from Amatitlan caldera. | Pumice mineralogy; Pumice contains 73% glass, 4% mafic phenocrysts, and 23% felsic phenocrysts. Mafic phenocrysts are dominantly biotite, with lesser amounts of hornblende, and trace hypersthene. Magnetite makes up 12% of the mafic phenocrysts. Pumice vesicles range from frothy to linear within pumice fragments. | N-S–trending normal faults |
| 17JF23b Location 1 | 2–6-m-thick, white pumice–rich lapilli tephra containing pumice fragments (centimeters long) of similar shape and size, along with phenocrysts and ash. Pumice fragments are smaller and less abundant than those in unit 17JF23a. Interpreted as C tephra from Amatitlan caldera. | Pumice mineralogy; Pumice contains 86% glass, 5% mafic phenocrysts, and 9% felsic phenocrysts. Mafic phenocrysts are dominantly hornblende with trace amounts of hypersthene, with magnetite being 38% of the mafic phenocrysts. | Normal faults |
| 17JF26 Amatitlan caldera | Tan, coarsely-grained granite with highly weathered biotite crystals. Much of the tan color comes from oxidation surrounding biotite crystals. | Thin section: Large quartz and plagioclase crystals with deteriorated biotite crystals. | |
| 17JF65 Location 3 | Crystal-rich welded tuff. White, highly indurated welded tuff with plagioclase and mafic crystals and aphanitic groundmass. Reduced to powder in highly faulted areas containing epidote in fault gouge. | Thin section: Very fine-grained groundmass of quartz showing signs of healing, no vesicles visible, few plagioclase and mafic crystals. | NW-striking and NE-striking strike-slip faults |
| 14JF2 Location 4 | Highly weathered gray, biotite-rich granite. Granite has a granular appearance as it crumbles easily in the hand to gravel-sized grus. Biotite fragments are relatively small and weathered, but abundant. | Too weathered to create a thin section. | Strike-slip faults ranging from NW-N-NE-striking |
| WH19S1 Location 7 | Lower tephra; ~3.3-m-thick, light-colored pumice–rich lapilli tephra containing light-gray pumice fragments (0.5–16 cm long), with occasional dark-gray pumice fragments (17–36 cm long), 25% ash matrix and 3%–4% small, angular basalt lithics. Pumice fragments are highly vesiculated. Tephra is poorly indurated. At the base of the tephra, there is a 50–70 cm layer of basaltic lithics (2.5–13 cm) with upward grading into the tephra. | | NW-striking normal faults |
| WH19S2 Location 7 | Upper tephra; 4.9-m-thick, light-colored tephra with similar gray pumice to the lower tephra (0.5–6 cm long), lack of dark-gray pumice, 50%–60% matrix, and very few lithics. Tephra is poorly indurated and erodes easily. | | NW-striking normal faults |

southern Guatemala. Detailed descriptions of individual eruptions often include isopach maps and suggested sources (Koch and McLean, 1975; Rose et al., 1999). Quaternary silicic tephras are typically identified as very white or light colored and poorly indurated, while Neogene tephra deposits are darker in color and well indurated. This distinction aids in a first-order identification in the field, which can be followed by a comparison to the major Quaternary tephras or Neogene formations. Figure 3, modified from Rose et al. (1999), displays the spatial and temporal record of the major Quaternary tephras across south-central and southeastern Guatemala. Smaller-volume Quaternary tephras, lavas, and reworked deposits from individual volcanic centers also exist in southern Guatemala, which complicate unit identification. In some cases, geologic studies have been conducted on smaller volcanic sources south of the Jalpatagua fault, which aided unit identification at our outcrops (Bethancourt et al., 1976; Duffield et al., 1992). However, detailed stratigraphy is generally absent from southeastern Guatemala.

In general, the Neogene rocks of southeastern Guatemala—adjacent to the Jalpatagua fault—are composed of granites, rhyolitic, andesitic, and basaltic tephras and lavas, and reworked sediments (Reynolds, 1977, 1980, 1987). Individual eruptions or events are not defined as they are for the Quaternary tephras. Instead, three bulk formations have been established for Neogene deposits across this region of Central America (Fig. 3): (1) the upper Cuscatlán formation (Pliocene); (2) the middle Básalto formation (only present south of the volcanic arc, approximately Upper Miocene to Pliocene); and (3) the lower Chalatenango formation (Middle to Upper Miocene; Reynolds, 1977, 1980, 1987). Formation names follow the nomenclature established for El Salvador, as adopted by Reynolds (1980, 1987) and established by Wiesemann (1975).

GEOLOGIC AND GEODETIC DATA

Geologic Data

The Jalpatagua fault has a clear fault trace across southeastern Guatemala, which was identified on photos or digital elevation models (DEMs) and was the focus of prior geomorphic studies. However, with the tropical, vegetated environment in Guatemala, no outcrops of the fault zone are reported in the literature or were found during our field work. Therefore, we relied on analysis of minor faulting, often called secondary faulting, collected in road outcrops and quarry exposures adjacent to the Jalpatagua fault trace to understand the finer details of movement and deformation along the fault trace. Fault data were collected in three areas: (1) central section: multiple sites along the Jalpatagua fault trace (locations 3, 4, and 5; Figs. 2 and 4); (2) eastern section: near the Guatemala–El
Salvador border (to characterize faulting near the eastern termination; locations 6 and 7; Figs. 2 and 4); and (3) western section: within the Amatitlan caldera (to characterize faulting near the western termination; locations 1 and 2; Figs. 2 and 4). At each outcrop, structural data (fault orientations, lineations, bedding orientations, and outcrop transect length) were collected along with rock samples for unit correlation and age dating.

**Observations of Secondary Faulting**

**Central section.** Data were collected from three outcrops along the Jalpatagua fault trace: Strike-slip faulting was observed in quarries at locations 3 and 4; and normal faulting was observed within a road cut at location 5 (Figs. 2 and 4). Quarrying activity at locations 3 and 4 within the central section provided exposed horizontal surfaces, which allowed us to directly recognize strike-slip faulting.

Minor strike-slip faults \((n = 79)\) were observed in two lithologies: (1) a white, welded tuff at location 3; and (2) a coarse-grained Miocene granite at location 4 (Table 1). The welded tuff of location 3 most closely correlates to a similarly described Miocene welded tuff of the Chalatenango formation (Fig. 4; Reynolds, 1987). The coarse-grained granite of location 4 contains large biotite crystals, is highly weathered, and is pervasively cataclastically shattered, consistent with its location <1 km from the Jalpatagua fault. Additionally, at least two basalt dikes crosscut the granite, providing offset markers for only two faults (Fig. 4); A sample of the granite was collected for \(^{40}Ar/^{39}Ar\) dating analysis (sample 14JF2).

Strike-slip faults measured at locations 3 and 4 have a large variation of orientations but can be separated into four subsets, which correlate to minor fault arrays commonly observed in field-based and experimental studies (Fig. 2; Tchalenko, 1970; Logan et al., 1979):

- **Set 1:** average 330°-oriented strike-slip faults (−35° clockwise from Jalpatagua fault trace orientation) with slickenline rakes of −10° from the NW and SE (similar to R shears; red planes in Fig. 2);
- **Set 2:** −020°-oriented strike-slip faults (−85° clockwise from Jalpatagua fault) with slickenline rakes of −20° from NE and SW (similar to R’ shears; green planes in Fig. 2);
- **Set 3:** −055°-oriented strike-slip faults (−60° counterclockwise from Jalpatagua fault orientation) with rakes of −15° from SW (X shears, nearly perpendicular to P shears; blue planes in Fig. 2); and
- **Set 4:** faults with an average orientation of −300°, subparallel to the Jalpatagua fault (or Y shears; yellow planes in Fig. 2).

We could not determine the sense of motion for each strike-slip fault, but field observations, and the expected motion of secondary faults based on the Riedel shear model, suggest right-lateral motion along set 1 and set 4 (Jalpatagua-parallel) faults, along with the NW and SE rakes from Set 3 (X shears, nearly perpendicular to P shears).
and left-lateral motion along set 2 and set 3 faults (Fig. 5; Tchalenko, 1970; Logan et al., 1979).

We could only determine offset amounts for two strike-slip faults within the biotite granite quarry that offset a single, roughly subvertical basaltic dike (location 4; Fig. 4). The first fault zone is oriented nearly parallel to the Jalpatagua fault (~300°) and dextrally offsets the dike by 6 m, and the second fault zone is oriented ~320°, with 7.5 m of dextral offset. The exposure of the quarry bottom allowed the direct observation of fault offsets.

Normal faults were measured at the final outcrop within the central section at location 5, within a white, loose ash to the north of the Jalpatagua fault scarp (Figs. 2 and 4). The color and nonindurated nature of the deposit suggest a Quaternary age for the layered deposit, but a more precise tephra identification could not be made. Normal faults have an average N-S orientation (n = 11), with tens of centimeters of normal offset, and the few observable slickensides (n = 4) indicated downdip movement (Fig. 5). All measured normal faults continue into the soil horizon to the surface.

**Eastern section.** In the eastern section, normal faults were observed at two outcrops southeast of the Jalpatagua fault termination and ~1.8 km from the El Salvador border (locations 6 and 7; Figs. 2 and 4). Faults were measured in two different lithologies: (1) highly indurated, thinly bedded ash and reworked ash deposits at location 6, most likely part of the waterlain sediments of the Neogene Cuscatlán formation (Reynolds, 1987); and (2) loose, white and gray tephra deposits at location 7, containing mafic lithics and pumice, in a flat valley less than 2 km NE of location 6. The tephra deposits of location 7 do not correlate to any of the major Quaternary ashes, based on location and thickness of depositions; therefore, two tephra samples were collected at location 7 to correlate to the known stratigraphy (Table 1; samples WH19S1 and WH19S2). Normal faults strike NW, with centimeters to meters of normal offset (location 6: n = 13; location 7: n = 9; Figs. 2 and 4). Slickensides with pitches ranging from 78° to 88° were observed on a few fault planes at each outcrop (location 6: n = 5; location 7: n = 2), indicating downdip movement. At both outcrops, faults reach the surface.

Figure 4. Annotated outcrop photos from faulted outcrops documented in the three study sections. White lines trace faults, and yellow lines identify marker horizons. For location 3 and 4 photos, left photos display strike-slip faults, while right photos show faults that indicate measurable offset. Remaining outcrop photos all document normal faulting.
Figure 5. (A) Velocities of global positioning system (GPS) sites in mm yr\(^{-1}\) near the Jalpatagua fault with respect to a stationary Caribbean plate and corrected for time-dependent effects associated with large regional earthquakes in 2009 and 2012 (see text). Sites with red arrows have velocities that were derived using the same GPS data as in Ellis et al. (2018, 2019). Sites with black arrows have velocities that incorporate all the data from Ellis et al. (2018, 2019) and additional observations described in the text. (B) Estimates of fault slip rates in mm yr\(^{-1}\) and deforming block strain rate magnitudes and principal axis orientations for an elastic block model updated from Ellis et al. (2019) using the Ellis et al. 200+ station GPS velocity field and new GPS data described herein. Slip rates at the strike-slip fault nodes are color coded according to the color scale on the map. Each red arrow and its adjacent number specify the velocity that is estimated for the plate or block on which the arrow originates with respect to the plate or block located on the other side of the adjacent block-bounding fault. The fault slip velocities and strain rates predicted by the Ellis et al. (2019) model are shown for comparison in the inset map. The shaded regions define the five elastic blocks for which rotation and deformation parameters were estimated in our inversion (see text). GCG—Guatemala City graben; ES—El Salvador. Figure is modified from Ellis et al. (2019).
Additional isolated NW-striking faults were found within this area.

**Western section.** Two faulted outcrops were studied within the Amatitlan caldera to determine if any evidence of Jalpatagua-related faulting could be observed west of the fault trace. Outcrops are located on the north (location 1) and south (location 2) sides of the caldera (Fig. 2). Field work identified no other faulted features past the western termination of the Jalpatagua fault trace or on the eastern slope of Pacaya volcano.

In general, the stratigraphy and faulting are very different between the two western section outcrops. On the north side of the caldera (location 1), normal faults \( (n = 9) \) strike E and NNW with meters of normal offset and occur in thick Amatitlan tephra deposits (Figs. 2 and 4). No recorded fault planes had observable slickenlines. Within the tephra deposits, we observed possibly three stages of normal faulting, as faulted lithologies are capped by younger deposits with additional faults or younger unfaulted deposits. Samples were collected to correlate to the known stratigraphy to constrain fault timing (samples 17JF23a and 17JF23b).

On the south side of the caldera (location 2), the stratigraphy is dominated by volcanic flows and more recent activity related to the Pacaya volcano (Fig. 4). Numerous NNW-oriented normal faults \( (n = 33) \), with centimeters to tens of centimeters of normal offset, cut a thin layered deposit of scoria, pumice, and ash, most likely from small eruptive events from Pacaya volcano (Figs. 2 and 4). A few fault planes with observable slickenlines \( (n = 4, \text{ pitches between } 80° \text{ and } 90°) \) indicate down-dip movement. In addition, the faulted outcrop is overlain by an un faulted, white pyroclastic flow, which was sampled to constrain fault timing (sample 17JF13).

**Lineaments**

Besides the secondary faulting observed in quarries and road cuts, a set of NW-trending lineaments is present southeast of the eastern termination of the Jalpatagua fault near the El Salvador border (Fig. 2; mapped on the 20 m DEM of Guatemala; OpenStreetMap contributors, 2015). We suggest that the lineaments represent faults, since many of the lineaments were mapped and identified by previous workers in the 1960s and 1970s using aerial photos (Williams, 1960; Carr, 1974). Additionally, many of the lineaments likely represent normal faults, as transects show the presence of asymmetric hills, suggesting a fault scarp and tilted fault block, and downward movement of a hanging wall typically toward the direction of the Jalpatagua fault (Fig. 5). The mapped lineaments in Figure 2 range in orientation from 132° to 181° with lengths from 0.5 km to nearly 10 km, with a peak trend at −155°.

**Paleostress**

Paleostress orientations were estimated from fault slip data collected at the two strike-slip–dominated outcrops along the Jalpatagua fault (locations 3 and 4; central section), and three normal-fault–dominated outcrops along the Jalpatagua fault and near the eastern termination (location 5, central section; locations 6 and 7, eastern section). The paleostress inversion software Fault and Stress Analysis (FSA; Célérier, 2018) was used to determine the reduced stress tensors that best fit the given data.

Paleostress inversion methods estimate principal stress orientations with given fault slip data. This analysis is done by calculating the reduced stress tensor, which has four unknowns: the orientations of the three principal stress axes \( \sigma_1, \sigma_2, \) and \( \sigma_3 \) (where \( \sigma_1 > \sigma_2 > \sigma_3 \)) and \( R \), the aspect ratio, which represents the shape of the stress ellipsoid \( (R = (\sigma_1 - \sigma_2)/|\sigma_1 - \sigma_3|; Célérier, 1988; Célérier et al., 2012). Multiple assumptions must be met for a stress inversion analysis to be valid (e.g., Carey, 1976; Etchecopar et al., 1981; Angelier et al., 1982; Michael, 1984; Angelier, 1984, 1994): (1) Faults occur in an isotropic medium; (2) the stress state is homogeneous, no torque is present, and it can be described by a symmetric stress tensor; and (3) slip on faults is parallel to the resolved shear stress on the fault plane. Common criticisms of the dynamic analysis of fault slip data include: (1) Fault slip data better describe strain rather than paleostress; and (2) the stress field is perturbed near major

**Methods**

**Fault System Structural Analysis**

**Fault Slip Assumptions**

The following paleostress and strain methods heavily relied on the assumption that our observed normal faults have true down-dip movement and reliable fault slip data. While we observed slickenlines on only 20% of fault planes, the pitches were always greater than 78°, and a large majority centered around 88°. Therefore, we only observed evidence of nearly true down-dip motion for faults with normal offsets, and we extended this observation to faults without any observable slickenlines. The greatest uncertainty lies with location 1, where no slickenlines were observed; however, we still extended the assumption of down-dip motion.

**Geodetic Data**

Prior to this work, the most recent estimate of the Jalpatagua fault slip rate was based on an inversion of more than 200 GPS site velocities on seven blocks or plates in northern Central America and southern Mexico to estimate their relative motions, their internal deformation, and slip velocities and interseismic locking for the faults that separate the blocks (Ellis et al., 2019). Relevant to this study, most of the GPS site velocities in southern Guatemala were estimated from only two occupations spanning a 2.0 yr period. For this study, we incorporated new GPS data that we collected at 10 preexisting stations and three new stations (ALAR, DANT, and JUAY in Fig. 5A) in western El Salvador and southern Guatemala (locations and velocities given by the black arrows in Fig. 5A). The new data extend the time series at all the GPS sites in our study area to at least 5 yr and include sites in western El Salvador that are well located for constraining the eastern termination of the Jalpatagua fault.

**Lineaments**

Besides the secondary faulting observed in quarries and road cuts, a set of NW-trending lineaments is present southeast of the eastern termination of the Jalpatagua fault near the El Salvador border (Fig. 2; mapped on the 20 m DEM of Guatemala; OpenStreetMap contributors, 2015). We suggest that the lineaments represent faults, since many of the lineaments were mapped and identified by previous workers in the 1960s and 1970s using aerial photos (Williams, 1960; Carr, 1974). Additionally, many of the lineaments likely represent normal faults, as transects show the presence of asymmetric hills, suggesting a fault scarp and tilted fault block, and downward movement of a hanging wall typically toward the direction of the Jalpatagua fault (Fig. 5). The mapped lineaments in Figure 2 range in orientation from 132° to 181° with lengths from 0.5 km to nearly 10 km, with a peak trend at −155°.
faults and by fault interactions (e.g., Marrett and Allmendinger, 1990; Twiss and Unruh, 1998; Gapais et al., 2000; Žalohar and Vrabec, 2008; Kaven et al., 2011; Lejri et al., 2015; Riller et al., 2017). However, paleostress data are useful for comparison between different areas and to check consistency with the present-day (only two-dimensional [2-D]) strain rate tensor derived from GPS.

To determine best-fitting paleostress tensors for a given fault slip data set, the FSA program uses a random search method to generate a particular number of reduced stress tensors (Etchecopar et al., 1981). For each generated stress tensor, predicted slickenlines are calculated for each given fault, which represent the direction of slip that would occur on the fault given the particular stress tensor (Wallace, 1951; Bott, 1959). Misfit angles are calculated between the predicted and real slip data, and this information is used to determine how well a reduced stress tensor represents the data. For normal fault data sets (locations 5, 6, and 7), the assumption of downdip motion was used to generate slip vectors for the fault planes with no observable slickenlines. The program reports the best-fitting stress tensors based on the lowest collective misfit angles. Additional examples of methods and application of FSA can be found in Burg et al. (2005) and Garibaldi et al. (2016).

For the FSA of fault slip data from locations 3, 4, and 5, 10,000 stress tensors were randomly generated and compared to each data set. Of the 10,000 random stress tensors, the best 50 were retrieved and plotted on a stereonet to determine the mean and variance of the stress orientations that would best represent the given data. The top 50 were used because this number of points showed a clear main cluster with visible variance, yet the variance was not large enough to cause the mean to deviate from the main cluster. For each location, all fault slip data were initially analyzed in the FSA program, but faults that consistently produced large misfit angles (typically greater than 30°) for the top five stress tensors were removed, and the analysis was rerun. Data removal resulted in two faults being removed for location 3, four faults removed for location 4, and no faults removed from location 5. Figure 6 contains contoured stereonet plots of the central and eastern section data.
combined resulting c3 orientations (maximum elongation) and c1 (maximum compression) for all three locations. Modified Kamb contouring was applied with 1° contours, which indicated that each data set had clear clusters of points that were significantly different from a data set of random orientations. Outliers were removed from each data set to preserve the calculated mean of the main cluster, then eigenvectors were calculated to find the mean of each data cluster, and the 95% confidence cone was calculated using the Bingham statistical model. Countouring and statistics were all done in software program Orient, which provides statistics and plotting features (Vollmer, 1995, 2015). The same method outlined in the this section provides statistics and plotting features (Vollmer, 1995, 2015). The same method outlined in the this section

**Strain**

**Maximum elongation direction.** One-dimensional strain was estimated for each of the five normal-fault-dominated outcrops observed in the central, eastern, and western sections (excluding locations 3 and 4, which lacked markers to record offset). At each outcrop, normal faults (orientations and fault separations on the outcrop face) were recorded along a transect of measured length that started and ended at a fault. The orientations of marker beds were also recorded along with any visible slickenlines on fault plane surfaces (20% of fault planes). For each transect, all faults were used to calculate the direction of maximum elongation (Figs. 2 and 7). Titus et al. (2007) found that the direction of maximum elongation for dominantly dip-slip faults is the orientation with the highest ratio between apparent heave, $h_{app}$ and total heave, $h_{tot}$, for all faults in a given population. Plotting the $h_{app}/h_{tot}$ ratio by azimuth provides a graphical method to determine maximum elongation, and it allows comparison of various fault samples simultaneously or analysis of any abnormalities within a data set (Fig. 7). The azimuth with the highest value (meaning that the apparent heave is closest to the total heave) represents the maximum elongation direction for a given transect/fault population. Table 2 and Figure 8 illustrate the variation of maximum elongation directions among outcrop locations.

**Elongation estimate.** To estimate elongation for each transect, two sets of calculations were completed: (1) offsets from observable faults (elongation); and (2) offsets derived from observable faults and unobservable faults using power-law

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**Image Description:**

- **Figure 7:** Method for estimating elongation. (A) Block diagram demonstrating the geometric difference between true displacement and heave along a fault (TD in red), the measured displacement and heave along an outcrop face (MD in green), and the displacement or heave along the estimated direction of maximum elongation (MED in blue). Figure is based on figure 1 in Xu et al. (2009). (B) Annotated outcrop photo of normal faults measured at location 6. (C) Map-view schematic of location 6 transect B used to determine elongation. (D) Apparent heave/total heave ($h_{app}/h_{tot}$) chart from location 6 data, indicating a maximum elongation direction of 068°. Green-shaded regions show the portions of the curve that represent apparent heaves. The red-shaded portion indicates the range of azimuths where true heaves were observed. The blue dashed line is the maximum elongation orientation. To the right of the chart, stereonet of location 6 data with a 50° red-shaded window centered on the 068° maximum elongation direction shows which data were used in the elongation estimation. Only one datum falls outside of the threshold and, therefore, was excluded from the elongation estimation.
relations (e.g., Scholz and Aviles, 1986; Walsh and Watterson, 1992; Marrett and Allmendinger, 1991, 1992; Gross and Engelder, 1995). To estimate the elongation from observable faults, the true displacement of each fault was first calculated following the method outlined in Xu et al. (2009), since initial fault measurements from outcrop faces actually represent apparent offsets (green heave in Fig. 7A). For this method, fault orientation, marker bed/unit orientation, slickenline pitch, and transect orientation must all be specified. To reiterate, down-dip slip (rake of 90°) was assumed for moderately (30°–70°) dipping normal faults where slickenlines were not visible but where normal offset and slip sense were observed on other faults within the same outcrop. With true displacement calculated in this manner, the true horizontal displacement component (heave) was determined for each fault (red heave in Fig. 7A).

True horizontal displacements were estimated for all faults within ±25° of the maximum elongation direction, which maximizes components of heave parallel to the elongation direction (Fig. 7). To ensure unbiased elongation calculations, the offsets/heaves from bounding faults were not used in elongation calculations. Finally, each true horizontal heave value was projected onto the maximum elongation direction (blue heave in Fig. 7A). Projected heave values were summed to determine the change in length ($\Delta L$) for each traverse. The measured length of each transect was also projected onto the maximum elongation direction for each traverse ($L_f$). Elongation for each transect was calculated as follows:

$$e = \frac{L_f}{L_i - \Delta L} - 1,$$

where $e$ is elongation, $L_i$ is the final length of each traverse projected onto the maximum elongation direction, and $\Delta L$ is the change in horizontal length (the sum of all fault heaves used in the calculation) in the maximum elongation direction. Elongations for all transects, as well all $L_i$ and $\Delta L$ values, are included in Table 2.

**Revised elongation.** Previous research has shown that small faults and small offsets can greatly affect elongation measurements, up to 60%
in some studies (Marrett and Allmendinger, 1991, 1992; Walsh et al., 1991). Therefore, revised elongation estimates were also calculated to include the contribution of small faults with unobservable, yet significant offsets, following the methods outlined by Gross and Engelder (1995). Fault populations were plotted as the log of cumulative frequency (where 1 is the largest displacement, and $n$ is the smallest displacement) versus the log of each corresponding displacement. If the fault population follows a fractal fault geometry, faults with intermediate displacements will show a linear relationship on frequency-displacement plots (Fig. 9). The ends of the frequency-displacement plot typically do not show a linear relationship because small faults and large faults are often undersampled. A line can be fitted to the linear portion of the frequency-displacement plot (Fig. 9), and the value of the slope ($-C$) is then used to compute the horizontal displacement due to small faults ($h_0$) using the equation:

$$h_0 = h_n \frac{C}{1-C} \left( \frac{N+1}{N} \right)^{1/2}$$

(2)

where $h_0$ is the smallest displacement used to calculate the slope, and $N$ is the number of faults used in the regression. Frequency-displacement plots with regression lines for all five outcrops are shown in Figure 9. This equation only works when $C > 1$. A revised $\Delta L$ was calculated by adding $h_0$ to the previously calculated $\Delta L$, with the result being the revised elongation. The revised elongations, along with the calculated $h_0$ and revised $\Delta L$ values, are also included in Table 2. Revised elongations were not completed for those transects that contained too few faults to confidently determine the value of $C$. In these cases, the calculated elongations reflect a minimum elongation value.

**Geochemistry**

Geochemistry was used to correlate units to the known stratigraphy. Major- and trace-element geochemistry of seven samples was obtained by X-ray fluorescence (XRF) analysis (conducted by the Geoanalytical Laboratory at Washington State University; Table 3A). Unit correlation was only applicable for the two tephra samples collected from location 1 (17JF23a and 17JF23b), since the samples were located within the documented area of Quaternary tephra deposition. Similarity coefficients were calculated between the two tephras and 10 Quaternary tephras that had documented geochemistry in the literature to aid in unit correlation (Table 3B; Borchardt and Harward, 1971; Wunderman and Rose, 1984; Rose et al., 1987; Sarna-Wojcicki et al., 1984; Sarna-Wojcicki, 2000). Similarity coefficients were calculated using the normalized weight percent of the following major elements: SiO$_2$, FeO, TiO$_2$, Al$_2$O$_3$, MgO, CaO, Na$_2$O, K$_2$O, and parts per million of the following trace elements: Sc, Ba, Rb, Sr, Zr, and La. Based on geochemistry data alone, sample 17JF23a was most similar to the E tephra, using a 20 m DEM (OpenStreetMap contributors, 2015). Based on the topographic profiles and previous observations of downdip movement on normal faults in this area, we assumed that these lineaments represented normal faults with true downdip movement. A transect orientation of 067° was determined by calculating the maximum elongation orientation for all lineaments used in the three transects. With the absence of a paleosurface, the current topography was used as an offset marker by determining the general dip between faults (Fig. 10). Similar to Authemayou et al. (2011), fault dips of 50° and 80° were used to calculate end-member offsets and elongation estimates. Last, to calculate a final length for elongation estimates using the same method as above for minor faults, an average fault spacing was calculated for each transect, and the distance was added to the first and final faults. The purpose of this step was to create synthetic bounding faults that allowed the use of all lineaments for the elongation estimation.

**Lineaments**

Maximum elongation direction and elongation amounts were estimated for the lineaments identified near the eastern termination of the Jalpatagua fault. Authemayou et al. (2011) estimated elongation on lineaments in western Guatemala using a paleosurface to estimate fault displacement based on an assumed 50°–80° normal fault dip. However, this approach was not possible within our field area due to the absence of a reliable paleosurface. Therefore, we applied a similar process, with additional assumptions, to estimate elongation along three lineament transects that best displayed an occurrence of normal faulting. The locations of the three transects are presented in Figure 10 along with the topographic profiles, which were created with the calculated end-member offsets and elongation estimates. Last, three transects are presented in Figure 10 along with the topographic profiles, which were created with the calculated end-member offsets and elongation estimates.

### TABLE 2. MINOR FAULT ANALYSIS RESULTS

| Location                  | $L_f$ (m) | Maximum elongation (azimuth) | No. of faults | $\Delta L$ (m) | Elongation (%) | $h_0$ (m) | $\Delta L_r$ (m) | Revised elongation (%) |
|---------------------------|-----------|------------------------------|---------------|----------------|----------------|-----------|------------------|------------------------|
| Amatitlan caldera         |           |                              |               |                |                |           |                  |                         |
| 1                         | 221.0     | 075                          | 6             | 1.3            | 0.6            | –         | –                | –                      |
| 2                         | 11.0      | 106                          | 38            | 1.6            | 17.3           | 1.7       | 3.3              | 43.5                   |
| Jalpatagua fault          |           |                              |               |                |                |           |                  |                         |
| 5                         | 12.8      | 093                          | 11            | 1.7            | 15.4           | 0.2       | 1.9              | 17.8                   |
| Guatemala–El Salvador border |         |                              |               |                |                |           |                  |                         |
| 6                         | 4.6       | 068                          | 9             | 0.3            | 7.2            | –         | –                | –                      |
| 7                         | 15.5      | 073                          | 6             | 2.2            | 16.5           | 1.7       | 3.8              | 33.0                   |

Notes: Dash indicates calculations could not be made for revised elongation. $L_f$—final length of transect; $\Delta L$—change in transect length; $h_0$—amount of horizontal displacement (heave) due to movement on small faults; $\Delta L_r$—revised change in transect length.

**Notes:**

1. **C** = end-member offsets and elongation estimates.
2. **h** = amount of horizontal displacement (heave).
3. **N** = number of faults used in the regression.
4. **L** = length of the transect.
5. **Δ** = change in transect length.
and sample 17JF23b was most similar to the C or Z2 tephas (Table 3B). The geochemistry data were combined with a comparison of the field appearance, pumice mineralogy, and mapped isopachs of the major tephas outlined in the literature.

**Geochronology**

The \(^{40}\)Ar/\(^{39}\)Ar geochronology method was applied to a granite sampled within the Amatitalian caldera and a granite sampled at location 4. Results from \(^{40}\)Ar/\(^{39}\)Ar dating of the two samples are displayed in Table 4 (full data table in Supplemental Material).

Feldspar grains were picked from crushed bulk samples of both granite samples. Feldspar (500–1000 μm) was isolated from both of the samples via crushing, sieving, and magnetic sorting. The feldspar was treated with 10% HF in an ultrasonic bath for 5 min and then rinsed thoroughly with deionized water. The leached feldspar separates were wrapped in an aluminum foil packet and irradiated with 28.201 Ma Fish Canyon tuff sanidine (FCs). At the University of Wisconsin–Madison WiscAr Laboratory, single feldspar crystals were incrementally heated using a 25 W CO\(_2\) laser and analyzed using a MAP 215–50 mass spectrometer following the procedures outlined in Jicha and Kay (2018). The age uncertainties shown in Table 4 and Figure 11 reflect analytical contributions at the 2σ level; the decay constants are from Min et al. (2000).

Mass discrimination was assessed by analysis of atmospheric argon prior to and following the analytical session, and it was calculated using a linear law relationship relative to \(^{40}\)Ar/\(^{39}\)Ar = 298.56 ± 0.31 (Lee et al., 2006). Ages were calculated relative to a FCs standard age of 28.201 Ma (Kuiper et al., 2008).

**New GPS Site Velocities and Elastic Block Model**

We processed all the new GPS data with methods described by Ellis et al. (2018). We then updated the elastic block model of Ellis et al. (2019) in two stages. We first assimilated all the new GPS position time series into the time-dependent regional

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**Figure 9.** Frequency-displacement plots for locations 1, 2, 5, 6, and 7. Regression lines were fitted to the linear portion of the data to determine the slope (C. black points). The value of C was used to determine the amount of elongation due to the undersampled population of small faults. All fault samples, except location 1, had linear portions on which to conduct a regression.
Figure 10. (A) Mapped lineaments near the eastern termination of the Jalpatagua fault. Blue and red lineaments were all used for estimating the general maximum elongation direction. Red lineaments signify those used in the transects (white lines). (B) Rose diagram of lineament strike. (C) Rose diagram of the assumed dip direction of lineaments and other elongation data from this work and previous work in the El Salvador fault system. (D) Topographic profiles of the three lineament transects (white lines from A) with interpretations of offset horizons and offset amounts. Lf—final length of transect.
### TABLE 3A. X-RAY FLUORESCENCE (XRF) RESULTS

| Sample ID: | 17JF23a | 17JF23b | 17JF26 | 17JF65 | 14JF2 | WH19S1 | WH19S2 |
|-----------|----------|----------|--------|--------|-------|--------|--------|
| Location: | 1 Within Amatitlan caldera | 1 | 3 | 4 | 7 (lower) | 7 (upper) |
| Latitude (°N): | 14.49° | 14.49° | 14.45° | 14.25° | 14.25° | 14.05° | 14.05° |
| Longitude (°W): | 90.60° | 90.60° | 90.52° | 90.22° | 90.20° | 89.90° | 89.90° |

**Normalized major elements (wt%):**

- SiO₂: 71.42, 68.87, 75.14, 79.58, 78.16, 66.56, 66.67
- TiO₂: 0.403, 0.354, 0.219, 0.120, 0.131, 0.706, 0.707
- Al₂O₃: 14.88, 16.26, 13.67, 11.56, 12.21, 15.98, 16.03
- FeO*: 2.45, 3.27, 1.50, 0.97, 0.73, 4.51, 4.64
- MgO: 0.67, 1.03, 0.22, 0.13, 0.16, 1.08, 1.03
- CaO: 2.02, 3.55, 1.06, 1.32, 0.50, 2.82, 2.92
- Na₂O: 4.16, 4.24, 3.89, 2.02, 0.039, 0.019, 0.220
- K₂O: 3.81, 2.10, 4.22, 4.35, 2.70, 4.86
- P₂O₅: 0.091, 0.181, 0.039, 0.003, 0.220, 0.209
- Total: 100.00, 100.00, 100.00, 100.00, 100.00, 100.00, 100.00

**Unnormalized trace elements (ppm):**

- Ni: 4, 5, 6, 5, 2, 2, 2
- Cr: 4, 5, 4, 5, 3, 2, 2
- Sc: 4, 5, 3, 2, 1, 16, 17
- V: 29, 24, 18, 10, 5, 25, 28
- Ba: 1007, 801, 560, 1433, 749, 1019, 995
- Rb: 100, 45, 166, 84, 138, 63, 64
- Sr: 211, 441, 125, 171, 60, 262, 268
- Zr: 247, 142, 146, 93, 87, 197, 196
- Y: 23, 18, 25, 19, 16, 41, 40
- Nb: 66, 4.2, 9.8, 9.1, 7.0, 3, 8, 4, 10
- Ga: 15, 15, 17, 13, 17, 18, 17
- Cu: 6, 3, 13, 2, 1, 6, 10
- Zn: 50, 62, 30, 27, 18, 89, 87
- Pb: 15, 9, 14, 14, 17, 10, 10
- La: 18, 14, 28, 21, 17, 17, 18
- Ce: 47, 33, 58, 44, 29, 39, 35
- Th: 8, 3, 13, 8, 12, 4, 4
- Nd: 21, 16, 21, 18, 11, 23, 23
- U: 3, 1, 4, 3, 1, 2, 3

### TABLE 3B. SIMILARITY COEFFICIENTS BETWEEN GEOCHEMISTRY OF COLLECTED SAMPLES AND MAJOR QUATERNARY TEPHRAS

| Tephra          | 17JF23a | 17JF23b |
|-----------------|---------|---------|
| I falls         | 0.85    | 0.74    |
| E               | 0.92    | 0.67    |
| C               | 0.76    | 0.86*   |
| H flow, low K average | 0.79 | 0.68    |
| H flow, high K average | 0.60 | 0.47    |
| H fall average  | 0.63    | 0.50    |
| Tfall           | 0.86    | 0.62    |
| Zf              | 0.88    | 0.66    |
| Z4              | 0.89    | 0.67    |
| Z2              | 0.70    | 0.87    |
| W flow average  | 0.74    | 0.61    |
| W fall average  | 0.76    | 0.67    |
| Lt(2)           | 0.89    | 0.64    |
| Lt(1)           | 0.82    | 0.65    |
| Lt              | 0.84    | 0.62    |

*Best correlation for sample 17JF23a between the two highest similarity coefficients. Shading indicates the pairs with the greatest similarity coefficients.

### TABLE 4. RESULTS OF ⁴⁰Ar/³⁹Ar ANALYSIS

| Sample no. | Location          | SiO₂ (wt%) | Latitude (°N) | Longitude (°W) | Material | Isotopic ratio (40Ar/39Ar ± 2σ) | Isochron age (Ma ± 2σ) | N ³⁹Ar (%) | MSWD | Plateau age (Ma ± 2σ) |
|-----------|-------------------|------------|---------------|----------------|----------|--------------------------------|------------------------|-------------|------|----------------------|
| 17JF26    | Amatitlan Caldera | 75.1       | 14.4516       | 90.5151        | Feldspar | 300.0 ± 3.3, 7.25 ± 0.59       | 6 of 8                 | 94.7        | 0.20 | 7.43 ± 0.43          |
| 17JF2     | Location 4        | 78.2       | 14.2472       | 90.2018        | Feldspar | 300.1 ± 1.8, 10.11 ± 0.05      | 10 of 10               | 100.0       | 0.80 | 10.15 ± 0.04         |

Note: Ages were calculated relative to 28.201 Ma Fish Canyon sanidine standard (Kuiper et al., 2008) using the decay constants of Min et al. (2000). Atmospheric ⁴⁰Ar/³⁹Ar = 298.56 ± 0.31 (Lee et al., 2006). MSWD—mean square of weighted deviates.
elastic model described by Ellis et al. (2018) in order to correct the new and existing regional GPS time series for the effects of large earthquakes in 2009 and 2012. Figure 5 displays the updated velocities for GPS sites in our study area relative to a station-ary Caribbean plate. Following methods described in Ellis et al. (2019), we then inverted the new 200+ station regional GPS velocity field from the updated time-dependent model to estimate a revised elastic block model (Fig. 5B).

**RESULTS**

**Paleostress**

The mean \( \sigma_3 \) orientation for fault slip data from locations 3, 4, and 5 was 266/04, with mean \( \sigma_1 \) orientations of 175/09 for strike-slip faults (black dots; Fig. 6) and 261/82 for normal faults (white dots; Fig. 6). All locations suggested approximately E-W tension for faulting observed along the Jalpatagua fault, whether resulting in strike-slip or normal faulting. The \( \sigma_3 \) orientations for locations 6 and 7 (eastern section) showed a wider variance and 95% cone of confidence than those from the central section. The main cluster for the eastern section, identified by contouring, indicated \( \sigma_3 \) orientations with a mean of 066/09. The \( \sigma_1 \) orientations showed a mean of 259/83.

**Maximum Elongation**

With the elongation analysis, we observed that normal faults suggest 0.6% and 43.5% of ENE- and ESE-oriented elongation, respectively, in the Amatitlan caldera (western section), 17.8% of nearly E-W elongation along the Jalpatagua fault (central section), and 72% and 33% of NE-oriented elongation at the Guatemala–El Salvador border (eastern section; Fig. 8; Table 2). Revised elongation increased 250%, 115%, and 200% due to elongations from small, unsampled faults (locations 2, 5, and 7, respectively). The inclusion of small, unsampled faults accounted for 52%, 11%, and 45% of the revised elongations at locations 2, 5, and 7, respectively.
If we assume lineaments represent normal faults with trend-perpendicular fault movement, the collected data would indicate an elongation direction of ~065°. Estimated elongations for the three transects ranged from 0.5% to 10.3% (Table 5). While we also used topography as a marker surface and assumed 50°–80° fault dips to estimate elongation across lineament transects, this method provides a conservative estimate of elongation (Fig. 10).

**Geochemistry**

Based on similarity coefficients and field evidence, sample 17JF23a from location 1 best correlates to the E tephra, a 51 ka tephra from the Amatitlan complex, and sample 17JF23b best correlates to the C tephra, a 54 ka tephra from a source near the Amatitlan caldera (Table 1; Fig. 2; Koch, 1970; McLean, 1970; Koch and McLean, 1975; Wunderman and Rose, 1984; Rose et al., 1987, 1999; Schindlbeck et al., 2016). In the eastern section, the two tephra deposits collected from location 7 (samples WH19S1 and WH19S2; Table 1) do not correlate to any of the major Quaternary ashes, based on location and thickness of depositions. The light color, large thickness, and presence of mafic lithics and pumice suggest a possible origin from...
the Moyuta volcano to the southwest of the outcrop, which is suggested to have output andesite and eruptive material during the Quaternary (Bethancourt et al., 1976).

Geochronology

A $^{40}$Ar/$^{39}$Ar age of 7.43 ± 0.43 Ma was determined for the Amatitlán granite, and an age of 10.15 ± 0.04 Ma was determined for the location 4 granite (Fig. 11). We attempted to determine the age of the unfaulted pyroclastic flow from location 2 (sample 17JF13) using the $^{40}$Ar/$^{39}$Ar dating technique on phenocrysts, but it contained no radiogenic argon. This approach indicates that the pyroclastic flow is likely younger than 50 ka.

GPS Site Velocities and Elastic Block Model

In the vicinity of the Jalpatagua fault, our newly derived elastic block model (Fig. 5B) predicted that the forearc sliver moves 7.1 ± 1.8 mm yr$^{-1}$ toward N85°W ± 14° relative to the lithosphere north of the Jalpatagua fault (defined as the Ipala block by Ellis et al., 2019). The updated velocity is ~10% slower than and more parallel to the 295°-striking Jalpatagua fault trace than that predicted by the Ellis et al. (2019) block model (inset in Fig. 5B), although the velocities predicted by both models agree within their respective 1σ uncertainties.

Relevant to the terminations of the Jalpatagua fault, which are difficult to define based on its morphology, our new elastic block model indicated that slip between the forearc sliver and backarc west of the Guatemala City graben averages 2–3 mm yr$^{-1}$, in accord with results reported by Ellis et al. (2019), but not significantly different than zero within the 95% slip rate uncertainties. At the eastern termination of the Jalpatagua fault, the absence of a velocity gradient between GPS sites ZAPO, DANT, and ALAR in western El Salvador, which are located directly east of the eastern mapped extent of the fault (Fig. 12), clearly indicates that the fault does not continue linearly along its trajectory into western El Salvador. Instead, a 5–6 mm yr$^{-1}$ velocity increase occurs between GPS sites ALAR, DANT, and ZAPO north of the volcanic arc and GPS sites AHUA, LNUB, and JUAY within or south of the volcanic arc (Fig. 12). Therefore, dextral slip across the Jalpatagua fault and any other active structures adjacent to the fault steps 20–25 km southward in westernmost El Salvador.

Principal Strain Axes from GPS Velocities

The best-fitting strain rate ellipse has a maximum extension of 1.03 x 10$^{-4}$ yr$^{-1}$ toward 074° and a minimum extension of ~7.1 x 10$^{-7}$ yr$^{-1}$ toward 344° (Fig. 12B). These directions are consistent with the principal paleostress orientations estimated from locations 6 and 7.

Deformation Model of Southeastern Guatemala

Results from the analyses above indicate that faulting differs in each of the three studied areas along the Jalpatagua fault. Results from each area will be discussed individually followed by our proposed model of deformation.

Central Section

Paleostress analysis of strike-slip and normal faults along the Jalpatagua fault (locations 3, 4, and 5) indicates an E-W–directed stretch (266°) with shallow approximately NWW–oriented σ1 from strike-slip faults (nearly vertical σ2) and nearly vertical σ3 from normal faults (shallow N-oriented σ2; Fig. 6). These paleostress orientations are consistent with a stress regime that could produce dextral slip along a fault in the orientation of the Jalpatagua fault along with N-striking normal faults. A NNW–N-oriented σ1 also agrees with the Riedel shear model, as it should bisect the small angle between R and R’ shears (sets 1 and 2 from strike-slip fault subsets; Fig. 2; Tchalenko, 1970; Logan et al., 1979). Strain analysis of minor normal faults indicates that 178% elongation has occurred at one outcrop along the Jalpatagua fault in an E-W orientation (Fig. 8). E-W elongation along the Jalpatagua fault parallels the E-W elongation recorded geodetically across N-S-oriented grabens to the north of the Jalpatagua fault (Rodriguez et al., 2009; Ellis et al., 2019). In general, N-S-oriented normal faults and the four subsets of strike-slip fault orientations (including one orientation parallel to the Jalpatagua fault and velocity orientation of the forearc sliver) support dextral Jalpatagua movement, define the orientations of Jalpatagua typical minor faulting, and are consistent with our revised GPS data and model (Fig. 13).

Various faulted lithologies were observed along the Jalpatagua fault, from 10.15 ± 0.04 Ma (Miocene) granite and Miocene welded tuff to nonindurated Quaternary tephra. The Miocene age for the quarry granite sample at location 4, as well as the Amatitlán caldera granite sample, agrees with other intrusive rocks dated from the Atitlán caldera (8.5–13.8 Ma; $^{40}$Ar/$^{39}$Ar ages) and the Santa Rosa caldera (15.7 ± 0.06 Ma; $^{40}$Ar/$^{39}$Ar age) along the arc (Williams and Mc Birney, 1968; Reynolds, 1987; Patino, 2007).

The absence of unfaulted units suggests that Jalpatagua-related deformation has continued since the deposition of the most recent observed
Quaternary deposit. The absence of unfaulted units and a current slip rate of ~7.1 mm yr$^{-1}$ across the Jalpatagua fault suggest that dextral movement and associated normal faulting are still active along the Jalpatagua fault trace. None of our observations defined a minimum age or total offset for the Jalpatagua fault.

**Eastern Section**

Our paleostress analysis of minor normal faults near the Guatemala–El Salvador border, and eastern termination of the Jalpatagua fault, indicates ENE-oriented $\sigma_3$ (066°) and vertical $\sigma_1$ orientations, which support extensional deformation in this area with ENE-directed elongation. A comparison of the E-W–oriented and ENE-oriented $\sigma_3$ orientations of the central and eastern sections, respectively, indicates that the two $\sigma_3$ orientation samples are significantly different. The 95% confidence cones from each section do not overlap, nor do the related trend boundaries from each cone (Fig. 6). This lack of overlap indicates that it is unlikely that central and eastern section fault data belong to the same fault population (faults creating similar $\sigma_3$ orientations). This significant difference suggests that our faulting evaluation should treat the data from the two areas as separate and that the change of the $\sigma_3$ orientations may reflect a real change in faulting behavior near the eastern termination of the Jalpatagua fault.

The results from our strain analysis estimated that normal faults accommodate 7.2% and up to 33% of ENE-oriented elongation (068° and 072°), with NW-trending fault traces (lineaments) in the same area suggesting 0.5%–10% of similarly oriented elongation (065°; Fig. 8). While ENE-oriented elongation in the eastern section differs from observations along the central section of the Jalpatagua fault, NE-oriented elongation is consistent with orientations calculated from normal faults measured within the adjacent, western El Salvador fault system (Cáceres et al., 2005; Canora et al., 2014; Garibaldi et al., 2016). The observed fault traces also extend from the eastern end of the Jalpatagua fault, toward the Ahuachapan fault to the SE in El Salvador, a southern bounding fault of the El Salvador fault system (Figs. 10 and 13).

Microearthquakes also provide useful evidence about the eastern termination of the Jalpatagua fault. The absence of unfaulted units and a current slip rate of ~7.1 mm yr$^{-1}$ across the Jalpatagua fault suggest that dextral movement and associated normal faulting are still active along the Jalpatagua fault trace. None of our observations defined a minimum age or total offset for the Jalpatagua fault.

**Figure 13.** Preferred model for faulting along the Jalpatagua fault. Each stereonet indicates the average orientation of fault arrays (and respective motions) collected in the central and eastern sections. Large black arrows also indicate the elongation orientations for each section. Near the eastern termination, dashed lines and shading outline the Jalpatagua pull-apart basin (JB). Near the western termination, the dashed black line connects the Jalpatagua fault termination and the southern extension of the Guatemala City graben. ESFS—El Salvador fault system.
Therefore, faulting occurred after the most recent JB in Figs. 12 and 13. Other mechanisms, such as those labeled Jalpatagua basin) that accommodates vertical axis rotation, could also create ENE elongation. Velocity vectors indicate that dextral slip at the eastern terminus of the Jalpatagua fault near the El Salvador–Guatemala border is transferred southward by structures within an extensional step-over in the volcanic arc.

In the absence of age markers, we could not calculate strain rates for minor faulting near the eastern termination. However, we could make a comparison between maximum elongation directions and the principal strain rate axes estimated from GPS velocity data. The principal strain rate axes estimated from GPS stations ZAPO, DANT, and MOYU, which surround locations 6 and 7, indicate a maximum extension orientation of 074° (Fig. 12B), indistinguishable from the maximum elongation directions of 068°, 073°, and 067° for normal faults and lineaments (Fig. 10). Similar to observations along the Jalpatagua fault, all observed Neogene and Quaternary deposits within the eastern section were faulted without an overlying, unfaulted layer. The elongation orientations for the GPS and faulting data, which span much different time scales (present and Quaternary/Neogene), are thus consistent. Therefore, faulting occurred after the most recent deposit in this area and is likely still active, as ENE elongation is recorded by the GPS data as well.

With the GPS velocity orientations, microearthquakes, and observed NW-oriented faults, we defined and outlined a pull-apart basin in this zone (labeled Jalpatagua basin) that accommodates transtension and transition between the eastern termination of the Jalpatagua fault and the western El Salvador fault system (shaded and outlined as JB in Figs. 12 and 13). Other mechanisms, such as vertical axis rotation, could also create ENE elongations in a right step-over of this dextral fault system. However, the similarity in principal axes of infinitesimal strain and overall strain suggest coaxial deformation rather than rotation.

**Western Section**

The only observations of faulting past the western termination of the Jalpatagua fault, near El Cerinal, were located within the Amatitlan caldera, at two outcrops dominated by normal faults (Fig. 2). Faults were exposed because of new highway construction, and many were subsequently covered with concrete.

Estimated elongation directions and amounts differed from 0.6% approximately ENE-directed elongation on the north side of the caldera, to up to 43.5% ESE-directed elongation on the southern side of the caldera (Fig. 8). The lithologies and timing of faulting also differed. Faulting at location 1 (north side) suggests that faulting occurred before deposition of tephra E (51 ka; Schindlebeck et al., 2016), after deposition of tephras E and C (54 ka), and before deposition of the most recent Amatitlan J tephras, which are un faulted at location 1 (Fig. 3; Koch and McLean, 1975). Faulting at location 2 (south side) indicates that faulting occurred before deposition of a white, pyroclastic flow, most likely younger than 50 ka. We did not observe evidence of active faulting within the caldera.

Two observations suggest that the faulting within the Amatitlan caldera is more likely a result of past caldera-related events, rather than Jalpatagua-related movement. First, elongation orientations are roughly parallel to the caldera rim at each location, rather than parallel to E-W elongations observed along the Jalpatagua fault. Second, we did not find field evidence—of either a through-going fault or a minor fault array—that supports the presence of an active fault transecting the Amatitlan caldera. Furthermore, there is no evidence of a through-going fault in the area between the caldera and the western terminus of the Jalpatagua fault trace.

GPS data also indicate that little to no deformation occurs along the volcanic arc west of the Guatemala City graben (Fig. 5; Ellis et al., 2019). We concluded that the Jalpatagua fault thus terminates near the Amatitlan caldera (Fig. 13). Our evidence does not rule out a past connection between the Amatitlan caldera and the Jalpatagua fault, which has been proposed by Eggers (1971), Wunderman (1982), and Wunderman and Rose (1984) based on the linearity of the Amatitlan lake. Additionally, N–S–striking normal faults have been mapped within the caldera (Eggers, 1971), and they are parallel to N–S–striking normal faults measured at location 5 along the Jalpatagua fault to the east. Last, recent earthquake swarms occurred on the west and east sides of the caldera, respectively, in 2019 and 2020.

**Role of the Jalpatagua Fault in the Central American Forearc System**

Our analysis of minor faulting and updated GPS velocities in southeastern Guatemala indicates that:

1. The faulting is related to dextral movement along the Jalpatagua fault; and
2. The fault arrays accommodate E-W elongation. Our evidence more clearly defines how and where the Jalpatagua fault terminates at each end (Fig. 13). At its eastern end, secondary faults record ENE-oriented elongation in a pull-apart basin, parallel to elongation estimated within the El Salvador fault system to the east. The presence of the pull-apart basin is further supported by the GPS data, which record transtension in the area of a right step-over. At its western end, faulting is only observed within the Amatitlan caldera, but it appears more related to caldera-forming events rather than Jalpatagua fault movement. We were unable to locate any major fault/lineament west of the Guatemala City graben that could accommodate dextral motion of the forearc. Ellis et al. (2019) reached similar conclusions regarding the absence of a through-going dextral fault within the volcanic arc based on their GPS measurements from sites west of the Guatemala City graben.

The Guatemala City graben may be related to the termination of the Jalpatagua fault. The termination of any strike-slip fault would typically result in an area of local extension, often characterized by an extensional horsetail structure. In the case of the dextral Jalpatagua fault, this extensional area...
would be located north of its western termination. In fact, both the Amatitlán caldera and the southward termination of the Guatemala City graben occur in this area of inferred extensional deformation. Additionally, the N-S–striking faults mapped within the caldera parallel the N-S–striking Guatemala City graben (and other grabens in eastern Guatemala) and normal faulting observed along the Jalpatagua fault, and they could be associated with similar E-W elongation as recorded in both areas. Alternatively stated, the Jalpatagua fault terminates on its western end into diffuse extensional structures possibly connected to the active volcanic arc, Apatitlán caldera, and/or N-S–striking bounding faults of the Guatemala City graben (dashed line in Fig. 13).

Similarly, distributed extension also occurs on the southern side of the eastern termination of the Jalpatagua fault, where dextral slip on the Jalpatagua fault is transferred southeastward across a pull-apart basin (light shaded area in Fig. 13) to the western terminus of the El Salvador fault system. The Jalpatagua basin, located south of the fault, appears to initiate near the midpoint of the Jalpatagua fault and curve to the south and east, nearly connecting to the southern bounding Ahuachapan fault of the El Salvador fault system (Fig. 13). Within this lenticular-shaped basin, the observed NW-trending faults and lineaments also extend toward and connect to the terminations of the two main faults, recording ENE elongation. Normal fault focal mechanisms indicating E-W extension have also been recorded south of the Jalpatagua fault, near the western edge of the pull-apart basin (Ellis et al., 2019). With the NW-trending Jalpatagua fault connecting to the E-W–trending strike-slip faults of the El Salvador fault system, it makes sense that the pull-apart basin shows evidence of complex internal geometry and transtensional deformation to accommodate the transition between two nonparallel faults.

Finally, two differences between the Jalpatagua fault and the El Salvador fault system should be addressed to aid in understanding along-strike variations in forearc systems: (1) the difference in orientation (WWN-oriented Jalpatagua fault and approximately E-W–oriented El Salvador fault system); and (2) the difference in complexity (continuous fault vs. en échelon fault system; Fig. 1). Both differences may be attributed to the absence/presence of an active volcanic arc. It may be more favorable for the Jalpatagua fault to maintain a stable, singular structure due to the lack of active volcanic sources along the fault trace. The orientation of the Jalpatagua fault satisfies a simple model of strain partitioning, with linear dextral movement occurring parallel to the trench, through a variety of volcanic lithologies, but no active sources. In contrast, deformation along the El Salvador fault system may be more diffuse due to the presence of multiple large volcanic centers. The E-W orientation of the diffuse fault system still accommodates trench-parallel motion, with movement along multiple right-stepping strike-slip faults.

Overall, slip along the Central America forearc boundary decreases westward and terminates near or into the Guatemala City graben. With 12.5 mm yr\(^{-1}\) of dextral slip occurring in Nicaragua across a wide zone of bookshelf faults, and 10.3 mm yr\(^{-1}\) to 9.7 mm yr\(^{-1}\) (west to east) occurring across the El Salvador fault system, forearc motion decreases further to 7.1 mm yr\(^{-1}\) across the Jalpatagua fault, and no movement (or very minor) or through-going fault is recorded across the Apatitlán caldera and volcanic arc to the west (Ellis et al., 2019). The slip rate decreases toward the Guatemala City graben, which is the westernmost structure accommodating E-W elongation to the north of the forearc boundary (Ellis et al., 2019). A similar westward decrease in slip rate toward the Guatemala City graben is observed across the sinistral Motagua fault, on the northern extension of the Guatemala City graben (Ellis et al., 2019). Overall, the second- ary faulting presented in this study characterizes the deformation related to dextral movement on the Jalpatagua fault, and the extensional deformation that occurs across a fault transition (eastern termination) and near the end of a large dextral boundary (western termination).

### CONCLUSIONS

Our analysis of GPS site velocities and secondary faulting in southeastern Guatemala and westernmost El Salvador more clearly defines deformation along the Jalpatagua fault system, as follows:

Along the central section of the Jalpatagua fault:

1. Elastic block modeling of new and updated GPS site velocities gives a revised dextral slip rate of 7.1 ± 1.8 mm yr\(^{-1}\) for the Jalpatagua main fault and adjacent forearc structures.

2. Jalpatagua-related minor faulting is characterized by four sets of strike-slip faulting (330°, 020°, 055°, and Jalpatagua-parallel 295°) and N-S normal faulting. Minor fault orientations support deformation related to dextral movement. At one outcrop, minor normal faulting accommodated 17% of E-W elongation, paralleling E-W elongation observed across grabens to the north.

3. A \(^{40}\)Ar/\(^\text{mAr}\) age of 10.15 ± 0.04 Ma was determined for a granite (location 4) collected along the Jalpatagua fault, supporting active faulting.

At the eastern termination of the Jalpatagua fault:

1. GPS and microearthquake data indicate that the Jalpatagua fault does not continue linearly into El Salvador. Dextral offset can be observed between GPS sites southeast of the termination, indicating a complex right step-over into western El Salvador. The location of microearthquakes shows that complex strike-slip and extensional structures accommodate the transition between the Jalpatagua fault and the El Salvador fault system. Principal strain rate axes calculated from GPS velocities indicate a NE-oriented maximum extension (074°) within the transition area.

2. NW-striking normal faults and lineaments near the eastern termination record NE-trending elongations (elongation estimates between 7% and 33%). The NE-directed elongation directions are statistically different than E-W elongations observed along the Jalpatagua fault, and parallel to minor faulting observed within the El Salvador fault system.
(3) GPS data, minor fault and lineament data, and geomorphology outline a transtensional pull-apart basin connecting the Jalpatagua fault to the El Salvador fault system. At the western termination of the Jalpatagua fault, in the vicinity of the Amatitlán caldera and the southern extension of the Guatemala City graben: (1) GPS site velocities indicate that discrete dextral movement of the Jalpatagua fault terminates east of, or near the Guatemala City graben/Amatitlán caldera. West of the Guatemala City graben, little to no movement occurs across the volcanic arc. (2) Normal faulting observed within the Amatitlán caldera is more likely related to caldera-forming events than Jalpatagua fault movement, with elongation directions parallel to the caldera rim and stratigraphic evidence indicating past faulting events. (3) A 4Ar/39Ar age of 7.43 ± 0.43 Ma was determined for the Amatitlán granite collected within the caldera.

Overall, the Jalpatagua fault is the westernmost structure that accommodates dextral movement of the Central American moving forearc. Dextral offset terminates into extensional structures at each end—a transtensional pull-apart basin to the east and the Guatemala City graben to the west.

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