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Five major 3arthquakes since the Late Classic Maya Period on the Motagua Fault in Guatemala

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Abstract

In 1976, the Motagua Fault along the North American-Caribbean plate boundary ruptured in a devastating M 7.5 earthquake. Despite its considerable scientific importance and its potential for catastrophic societal impact, very little is known about the seismic history of this major fault. Here, we show direct on-fault paleoseismic evidence for five ground-rupturing earthquakes on the Motagua Fault in the last 1,300 years that led to cultural and architectural adaptations. Radiocarbon ages at the base of fault scarp-derived colluvial wedges, along with damage and repair at Maya and Colonial sites, provide constraints for three earthquakes during the 8th-13th centuries and two during the 18th-20th centuries, separated by a six-century interval of seismic quiescence. The research presented here provides new insight into the seismic

character of the Motagua Fault and illustrates that earthquake recurrence on the fault is variable, allowing for improved estimation of current and future seismic risk in Guatemala.

Introduction

At 3:02 a.m. the morning of February 4, 1976, Guatemala was violently shaken by a magnitude 7.5 earthquake. The earthquake caused over 23,000 deaths and left more than a million people homeless[1]. Left-lateral, strike-slip surface rupture on the Motagua Fault (Fig. 1A) was traced for approximately 240 km, where it terminated into a mountainous region of landslides to the west, and into swampy land of the lower reaches of the Motagua River to the east[1,2] (Fig. 1B). Body wave and teleseismic analyses[3] indicate a bilateral rupture with asymmetrical directivity that triggered multievents as it propagated westward. The largest subevents occurred approximately 150 km west of the epicenter in the region of the maximum measured coseismic slip of 3.4 m, although the average slip was 1 m[1,2]. Maximum intensity of IX on the Modified Mercalli intensity scale (MMI) was experienced along the western portion of the ruptured segment of the fault[1] (Fig. S1). This location lies near the large Guatemala City population center and the point where the Motagua Fault splayed south during the 1976 event and triggered rupture of the N-S trending Mixco Fault that bounds the west side of the Guatemala City Graben.

Understanding the earthquake history of Guatemala is challenging, as there are three potential types of seismic sources (Fig. S1). The Motagua Fault and parallel Polochic Fault (Fig. 1A) accommodate sinistral strike-slip motion along the transform plate boundary between the North American and Caribbean plates, while earthquakes originating on the convergent plate boundary between the Cocos and Caribbean plates follow the interface of the subducting slab from the Middle America Trench to depths of >150 km. Subduction zone megathrust earthquakes here have exceeded magnitude M7.5. In addition, the overriding Caribbean Plate experiences shallow crustal (<15 km) earthquakes (M<6.5) along the Central America Volcanic

Arc that is detached along a dextral strike-slip fault bounding a forearc sliver, and also experiences seismicity due to eastward extension of the Caribbean Plate[4-6].

Although a half century has passed since the destructive 1976 Guatemalan earthquake, little is known about the earthquake rupture history of the Motagua Fault and the behavior of the transform plate boundary in general. In this paper, we present geological evidence of five ground-rupturing earthquakes that occurred over a span of nearly 1,300 years on the Motagua Fault at La Laguna, located 30 km northeast of Guatemala City, and the site of maximum coseismic displacement in the 1976 earthquake.

Results

1976 fault offset data

The La Laguna Basin is a linear valley formed along the Motagua Fault approximately 150 km west of the 1976 earthquake epicenter (Fig. 1C). The valley is bordered on the north and south by highly fractured Cretaceous limestone bedrock. Fluvial terraces, colluvial scree slopes, alluvial fans, and terraces of tuff from major volcanic eruptions, including the 79.5 ka supervolcanic event of Los Chocoyos[7, 8], abut the bedrock within the La Laguna Basin.

Aerial and ground photographs, 35 mm slides, and field notes from the collection of George Plafker (USGS Archive), who documented the La Laguna site on April 20, 1976, provide unequivocal evidence for the location and nature of the 1976 earthquake ground rupture (Figs. S2-S11). These data show the offset of stone walls and a tree line that is offset by 3.25 m[2]. Our high-resolution digital elevation models of the La Laguna site (Fig. 1D), produced from two uncrewed aerial vehicle laser scanning campaigns, capture the location of Wall 1 (offset measured as 3.4 m in 1976) and Wall 2 (offset not measured in 1976). Measurements taken during our research indicate an offset of 4.8 m for Wall 2, which we interpret to be the cumulative offset from 1976 (3.4 m) and the penultimate event (1.4 m). The vertical slip component of the offset in Wall 1 was measured as 83 cm in 1976. The present-day 120 cm-high fault scarp also records slip in a prior earthquake (Figs. S10-S13).

Paleoseismic data

The La Laguna paleoseismic trench was hand-dug adjacent to offset Walls 1 and 2 and across a ruptured segment of the 1976 Motagua Fault that bends toward the south across a terraced agricultural field (Figs. 1C and 1D). The left bend in this sinistral strike-slip fault creates a component of extension, along with lateral slip, that causes the southern block to subside during earthquakes. This creates a fault scarp where degradation of the upthrown side (footwall) provides sediment to the downthrown side (hanging wall), where it forms a colluvial wedge at the base of the newly formed fault scarp, as shown in the trench logs (Fig. 2, S14, S15).

The oldest unit (Unit G), exposed exclusively in the footwall of the trench, is composed of yellowish brown, sandy silt with gravel interbeds and lenses deposited in the floodplain of an older fluvial terrace phase within the valley (Fig. 2). Unit G is capped by a brown silty clay and cobble-sized gravel (Unit F) that is also only exposed on the north side of the trench. The upper stratigraphic units, Units A-E on the north side of the fault and Units 1-6 on the south side, all contain cultural debris, indicating that the valley had been converted to agricultural fields and was inhabited and under cultivation. These anthropogenic units show evidence of five discrete earthquake ruptures and fault-scarp forming events (Fig. 2.).

The ground surface at the time of the oldest earthquake (Event 5) was a black anthropogenic, organic-rich soil overlying a cobble-sized gravel (Unit E). Unit E, containing obsidian flakes, projectile points, charcoal, and pottery sherds, is redeposited on the hanging wall at the base of a paleo-fault scarp in a colluvial wedge (CW5). Radiocarbon dating within Unit E and CW5 indicate that Unit E developed between the 3rd century BCE and the 7th century CE (see Fig. 3 and supplementary information for an overview of radiocarbon ages). Unit E is sheared by secondary faulting across the scarp. Given the long interval of human occupation indicated by Unit E and the very thick colluvial wedge, CW5 may represent deposition in more than one earthquake. Furthermore, mixing of Units E and F within a fault-bound fissure on the footwall suggests rupture in an earlier event. Given the limitation of trench depth, we can only constrain the latest scarp-forming earthquake involving colluvial wedge CW5. Pre-event ages are constrained by charcoals T17 and T20 from CW5 and by samples T1, T18, and T21 from the footwall unit E (Figs. 2, 3). The post-event age comes from charcoal T19 from the base of Unit 6, which is a fine-grained, brown silt and clay layer that overlies the CW5 scarp-derived colluvium. Thus, Event 5 occurred between 672-987 CE (830 ± 158 CE) (Fig. 3).

A unique, clast-supported, well-sorted, subangular to subrounded, pebble- to small cobble-sized limestone gravel (Unit D) rests unconformably on the fault scarp of Unit E and is in contact with it at the fault. Unit D is not a natural deposit but anthropogenic in origin, likely the remnants of a stockpile of quarried limestone gravel used in lime production[9]. Unit D was faulted and dragged down across a scarp in Event 4 and then deposited at the base of the scarp in colluvial wedge CW4. The stratigraphic position of charcoal in Unit 5 overlying CW4 and the age model for older units suggests that Event 4 occurred between 928-1126 CE (1027 ± 99 CE).

Continued slope wash deposition or debris from additional construction of terrace walls produced the silty gravel of Unit C that contains freshwater *Pachychilus* species gastropods. Unit C, which was the ground surface at the time of Event 3, thickens on the footwall and is redeposited as colluvial wedge CW3. Radiocarbon dates from within the dark brown clayey silt and pebbly gravel of Units 3-4 above CW3 constrain Event 3 to 1061-1199 CE (1130 ± 69 CE).

Evidence for the youngest two earthquakes (Event 1: 1976 and Event 2) exhibits a distinct sedimentologic pattern as compared to the fault scarp-derived colluvial wedge gravels of the older earthquakes, likely denoting a change in landscape management or other environmental/climatic factors. The relatively thin, clayey and silty layers in the footwall (Units A and B) are exposed and actively eroding across the degrading 1976 fault scarp. Layers in the hanging wall (Units 1 and 2) are predominantly fine-grained and are back-tilted toward the fault.

While gravel was present at the ground surface during older earthquakes, the penultimate earthquake (Event 2) occurred when fine-grained sediments of Units A and B in the footwall and Unit 2 in the hanging wall were at the land surface. Deposition below the fault scarp includes a northward thickening colluvial wedge CW2, which is composed of redeposited Unit A and B soil. Subsidence of the down-dropped block allowed fine-grained sediments to fill a fissure along the fault, which contains *Pachychilus* gastropods from units A, B, and 2. The stratigraphic data for Event 2 show that sedimentary layers in Unit 2 were faulted in an earthquake that pre-dates 1976, as the faulted sediment underlies the colluvium formed by the 1976 earthquake. Age modelling of faulted Unit 3 and overlying ash from an anthropogenic burn in Unit 2/CW2 constrains Event 2 to 1728-1976 CE.

The 1976 fault cuts the full stratigraphic sequence in the trench and intersects the ground surface (Fig. 2). The footwall units A, B, and C, which once formed a vertical, free-face scarp, have eroded and retreated northward to expose the units along a slope. A boulder sits upright within the 1976 fault fissure at the base of the fault scarp on the NE trench wall. A thick organic-rich, fine-grained sediment forms the colluvial wedge CW1 that developed above a pebble-sized gravel draping the base of the scarp on the SW wall. Radiocarbon analyses of samples yield modern, post-bomb dates and mixed older carbon, placing the deposits as those after the 1976 earthquake.

Discussion

To further refine the interval for each of the earthquakes, we review the excavation reports for archaeological sites that lie near the fault[10-13]. Two Maya sites, Quirigua and Mixco Viejo (Fig. 1B), located along the eastern and western limits of the 1976 rupture, respectively, were damaged in 1976 and also provide evidence for seismic destruction and repair activities during Maya occupation (See Discussion in the Supplementary Information).

The Maya site of Quirigua, founded ca 450 CE is located along the lower Motagua River Valley and about 20 km SW of the 1976 epicenter[14]. The site sustained damage in the 1976 CE earthquake, including cracking at the base of two massive, sculpted stelae and partial collapse of the reconstructed masonry walls of buildings on the central stepped Acropolis[14]. Archaeological data from excavations at Quirigua indicate that at least two pre-1976 earthquakes on the Motagua fault are documented at the site[14] (Figs. S18-S22).

An extensive building phase at Quirigua included new structures on a higher elevated platform center, expansion of the monument plaza, and emplacement of the largest monolithic carved stelae in the Maya world. In this phase, structures 1B-3 and 1B-4 (Temples 3 and 4)[15] were built between 756-785 CE[16]. Archaeological excavation of these structures exposed external buttresses and internal benches that were added later as structural supports. This type of reinforcement is often used to shore up weakened walls as a common response to earthquake damage[17, 18]. Construction of the buttresses was completed before the final monumental renovation phase at the site, which included a newly-built structure (IB-1) with a hieroglyphic frieze dating to 810 CE[16, 19]. These data suggest an earthquake may be bracketed at Quirigua between 756 and 810 CE, when the site was prospering. Our earthquake Event 5, with a modelled age interval of 672-987 CE, falls within this period. These data suggest that Event 5 may have occurred during the late 8th century CE and before 810 CE.

The final occupation at Quirigua is marked by a sudden structural collapse that trapped two victims in rubble. Sylvanus W. Morley, who directed excavations at Quirigua, notes in his May 16, 1919 diary entry that during excavation of 1B-3 (Temple 3), part of a human skeleton was found "on the floor level and almost looked as though their owner had lost his life when the doorway lintel collapsed"[20]. Penn Museum Quirigua Project excavated a structure 1B-18 on top of the Acropolis that is interpreted as a domestic kitchen that included 16 smashed *in situ* pots on a floor and partial remains of a child beneath debris of the collapsed adobe and stone walls[21]. Sharer[16] places the collapse of 1B-18 at 850 CE or later (not 830 CE as sometimes cited[22, 2]). Excavation by the Penn Museum Quirigua Project showed that the final construction phase at Quirigua included the filling of a platform between structures 1B-3 and 1B-4 which contained Plumbate pottery that is dated to the Terminal Classic to Early Postclassic Period[16, 24]. While there is no direct dating of the collapsed structures, the latest phase of occupation at Quirigua was assigned to Terminal Classic Maya (850-950 CE) or possibly later[16]. These data corroborate the timing of an earthquake likely in the 10th century CE, which could correspond to Event 4 at La Laguna in the interval of 928-1126 CE.

Corroborative archaeological data from Mixco Viejo (*Chwa Nima Ab'äj)*[25], a highland Postclassic Maya site, may further support the paleoseismic record (see supplement). Mixco Viejo, located 5 km northeast of the western end of the Motagua Fault, sustained extensive damage and collapse of the reconstructed structures in the 1976 CE earthquake, as well as open cracks, and significant landsliding of the margins of the site[26]. Mixco Viejo is situated on a high defensive hill surrounded by deep ravines and contains over 120 structures, including pyramids, platforms, and two ball courts. Excavation data[27, 28] show three phases of construction for the monumental platform and pyramids with the first phase built of carved pumice (pumaceous tuff) blocks[27], and later phases with schist, gneiss, and marble. It is not clear when the initial construction of Mixco Viejo began, but the first massive retaining wall was radiocarbon dated to the 13th century CE[27]. This construction may have been in response to a major earthquake on the Motagua Fault that could correlate to the latest interval of our Event 3 (1060-1199 CE) in the late 12th to the beginning of the 13th century. Mixco Viejo was abandoned after it was conquered by the Spanish in 1525[25, 27].

Historical documents provide further insight into the La Laguna paleoseismic record. While White[10] concluded that the penultimate event on the Motagua Fault must have occurred before 1560 CE, our paleoseismic data constrain the penultimate event to later than 1728 CE. As historical records of earthquakes since Guatemalan independence in 1821 CE are relatively complete, the penultimate earthquake is thus likely to have occurred sometime during the Colonial Period[10-13]. Peraldo and Montero[12] placed the 1751 CE and 1773 CE events on the Motagua Fault, however, White et al.[13] interpreted the five major Colonial Period earthquakes as subduction-zone earthquakes[13] not involving the Motagua Fault. They based this conclusion on an area exceeding 10,000 km^2 where structures are described as “ruined” or where MMI was VII or greater, indicating magnitudes commonly associated with subduction zone earthquakes.

Maximum shaking intensity for the 1976 CE earthquake occurred along a narrow stretch of land parallel to the Motagua Fault and within a broader region to the west of the rupture terminus, an area of >9,000 km^2 with 50-100% damage to adobe-type architecture (MMI VII)[1, 29]. This demonstrates that the area of intensity for the 1976 CE Motagua Fault earthquake is similar in size to ruptures that White et al.[13] assigned to subduction zone earthquakes. Therefore, we suggest that a historical earthquake assigned to a subduction zone source may have actually originated on the Motagua Fault

To test this hypothesis, we used the MARCA-GEHN v2.0 macroseismic database, which is a collaborative project that has compiled all known primary historical accounts and verified the data using standardized historical seismology methods for earthquakes in Guatemala, El Salvador, Honduras, and Nicaragua since the early 1500s[30, 31]. Drawing from this data, we generated macroseismic data point maps for major earthquakes that may have ruptured the Motagua Fault in the 18th century (1717, 1733, 1751, 1765, and 1773 CE) and compared them to the intensity map for the 1976 CE earthquake (Fig. S17). The macroseismic data point maps for the earthquakes of 1751 CE (M 7.3) and 1765 CE (M 6.9) are consistent with the isoseismal map (Fig. S17) of the 1976 CE event, although the 1765 CE earthquake has been assigned to a graben structure south of the Motagua Fault[12]. We also consider 1773 CE as a candidate for rupture of the Motagua Fault. White et al.[13] estimate the magnitude of the July 29, 1773 earthquake as M 7.5 and that of the December 13, 1773 event as M 7.1. Either of these earthquakes could be a candidate for Event 2.

It is important to note that very few macroseismic data points are available for any of these historical events, leading to large uncertainties in the epicentral locations and potential magnitudes of the ruptures. Furthermore, the historical documents are very likely biased towards large cities and cities with colonial importance or Spanish populations. In the 18th century, there were fewer large and important cities in the central and eastern parts of the country, adding further bias. Recent studies have shown that such biases can skew the distribution of macroseismic data points[32,33]. An additional complication involves interactions with nearby faults. Other faults that lie parallel to, and south of the Motagua Fault have been identified, but their activity is under debate or poorly documented (Fig. 1B). Moreover, recent studies have shown that surface ruptures can be very complex[34, 35] and that slip on previously unmapped structures is not unprecedented[36-38]. Therefore, not all the historical events have necessarily ruptured the Motagua or parallel Polochic faults. While these factors suggest that it is difficult to determine which specific event is associated with Event 2 at La Laguna, the evidence suggests it is likely that one of the 18th-century earthquakes in White et al.[13] is correlative with this rupture.

Other paleoseismic records further support our results from the La Laguna paleoseismic site. Analyses of sediment cores from Lake Chichój near the Polochic Fault show that the 1976 CE earthquake shook the basin with great enough force to generate a seismically-triggered turbidite[39]. Nine additional seismically-induced turbidites were discovered in the lake cores[22]. Based on a published age model, four of the turbidites occurred between 750-900 CE in the Maya Late Classic Period, and five occurred between 1000-1450 CE during the Maya Postclassic Period[12]. Our on-fault data for the Motagua Fault at the La Laguna site show clear evidence of three earthquakes during the 8th-13th centuries, which could have caused three of the older seismic turbidites in Lake Chichój, increasing confidence in both datasets. However, our Event 2 in the 18th century is not recorded as a seismoturbidite. This discrepancy could be explained by the offset data collected at La Laguna for Wall 2. Wall 2 was offset by a cumulative total of 4.8 m, suggesting that the penultimate earthquake (Event 2) had a lateral coseismic slip of only 1.4 m, which is less than the 3.4 m offset in 1976. Because of the lower coseismic slip documented for Event 2, it is likely that either the magnitude was lower or the rupture dynamics were different from the 1976 CE earthquake. For example, the 1733 CE earthquake likely had a magnitude of approximately M 7.0[13], which means it probably released only about ⅙ of the energy that was released in the 1976 CE event. It is possible that the lower coseismic slip of 1.4 m in the 18th-century earthquake resulted in less intense shaking in Lake Chichój as compared to the 1976 CE event, and did not exceed the intensity threshold required to generate a turbidite deposit. This also implies that caution should be exercised when interpreting the archaeological records, because a smaller, but locally destructive earthquake may not have ruptured the entire fault

Our combined paleoseismic, archaeoseismic, and historical data indicate that earthquakes occurred on the Motagua Fault in the 8th, 10th, 13th, 18th, and 20th centuries. Although the sample is small, it is clear that the earthquakes are aperiodic with a variable recurrence time. While this sample is consistent with the phenomenon of clustering, a much longer paleoseismic record is needed for confirmation of earthquake clusters on the Motagua Fault.

An average recurrence of earthquakes on the Motagua Fault at this site can be determined by dividing the time interval between the oldest earthquake (Event 5) and 1976 by the number of earthquakes during that period, which reduces the time uncertainty of the interseismic cycle. Using the minimum interval (989 yrs) and the maximum interval (1304 yrs) between these events, the average earthquake repeat time is 247-326 years. However, the recurrence interval between two consecutive earthquakes is variable. The last two events happened ~100-225 years apart from each other, while events E2 and E3 were separated by more than 600 years (Fig. 3).

When considering the entire plate boundary system, the determination of recurrence intervals becomes complicated because the Motagua Fault is not the only structure accommodating the eastward motion of the Caribbean Plate. The Polochic Fault is seismogenic and lies parallel to the Motagua Fault, 40 km to the north (Fig. 1). White[40], references primary historical accounts that are more extensive in the early 19th century and convincingly shows that the 1816 CE earthquake ruptured the western portion of the Polochic Fault. The earthquake damage zone of the 1785 CE earthquake suggests that this event may have also ruptured the eastern Polochic Fault[10] (Fig. S17). The long periods of seismic quiescence on the Motagua Fault could be the result of temporal switching of seismic activity between major structures of the plate boundary (e.g., Dolan et al.[41]) or different segments of the Motagua Fault rupturing independently. This indicates that the plate boundary may not maintain consistent behavior between earthquake cycles and that studying a single location on the complex Polochic-Motagua Fault System may not reveal overall system behavior.

Previous studies along the Polochic and Motagua Faults have suggested that slip can be accommodated aseismically. For example, Brocard et al.[22] found evidence of faulting dated to after the 17-19th century on the Polochic Fault at the Agua Blanca paleoseismic site, however, due to a lack of seismoturbidites in Lake Chichój during the interval of 1450-1976, they proposed fault creep as the predominant active mechanism. However, another possible explanation is a strong directivity effect during seismic events that leads to low ground motion at the lake site, as recently shown for the Motagua Fault[29]. Creep or aseismic slip may play a role in the displacement history of the plate boundary, but no on-fault or geodetic data have thus far confirmed this hypothesis. The Motagua Fault, a reactivated suture zone, should be prone to creep due to serpentinite-bearing tectonic mélanges[42], and the large amount of post-1976 afterslip supports this view[43]. Our study, however, shows that the Motagua Fault frequently hosts surface-rupturing earthquakes with the development of a fault scarp and colluvial wedges, indicating that most of the tectonic stress over the past 1,300 years has been released seismically. The offset walls at La Laguna show that 4.8 m of lateral slip occurred in the last two earthquakes. Geodetic data indicate a slip rate of ~10 mm/yr[11] or ~3-6 mm/yr[44, 45] for the Motagua Fault at our study site, requiring about 12 m of slip in the five earthquakes documented within our trench over the last approximately 1,300 years. If the events E5 through E3 produced similar amounts of slip as events E2 and E1, almost the entire geodetic strain would have been released seismically. In fact, the lower of the two slip rates could be entirely explained by slip during the earthquakes found in our trench, even if slip per event was on average less than that in the 1976 CE earthquake or less than that in the last two events combined.

A survey of earthquake chronologies from shallow crustal faults in different tectonic settings shows that quasiperiodic recurrence may be typical[48], but numerous paleoseismic records exhibit earthquake clustering[47-49]. Although the mechanism remains poorly understood, several studies suggest that fault interactions or strain-rate variations may play a role in seismic clustering[50, 51]. The Polochic and Motagua faults split the recent geodetic-determined slip rate of the transform boundary by 25% and 75%, respectively[4, 52]. Interactions of the two parallel faults and periods of aseismic slip may contribute to earthquake clustering, but no aseismic slip was evident from our data on the Motagua Fault. Determining how the two parallel faults interact over multiple seismic cycles and how the western end of the Motagua fault may vary from the eastern end will require further on-fault paleoseismological data from the Polochic Fault and ideally also from the Motagua Fault.

Conclusion

Due to the unique geometry of the active trace of the Motagua Fault at the La Laguna site, with a left bend across an agricultural field that was cultivated by Maya in antiquity and through the Colonial Period, we can constrain and reconstruct five ground-rupturing earthquakes along this section of the North American and Caribbean plates. The earthquake recurrence interval between the 1976 CE earthquake and the penultimate event (1751, 1765, or 1773 CE), as determined by age modelling of radiocarbon dates, is 203-225 years, which is slightly below the mean range of 247-326 years for the past five earthquakes. However, the interval between the other documented earthquakes is not regular. Based on damage and repairs uncovered at Maya archaeological sites, three earthquakes occurred between the 8th

and 13th centuries. This was followed by an approximately 630-year period of seismic quiescence that ended with earthquakes in the 18th and 20th centuries. The earthquake recurrence variability may relate to interaction with the Polochic Fault, which is hypothesized to experience aseismic slip, or to variations of slip rate and style of the Motagua Fault along strike.

Results of this study suggest that the Motagua Fault releases most of the entire geodetically determined crustal strain seismically. This and the absence of any indications for creep show that aseismic slip likely does not play a dominant role along this part of the plate boundary at the location of La Laguna.

The impact of the last five major earthquakes on the Motagua Fault can be linked to archaeological data from two Maya sites along the plate boundary, Quirigua and Mixco Viejo. When these settlements were thriving, the response to earthquakes in the 8th and 13th centuries was to repair and reconstruct. However, when Quirigua was in decline during the final stages of occupation, earthquake victims were not recovered, and structures never rebuilt. Similarly, after a series of 18th-century earthquakes culminating in the destructive 1773 CE event, Spain decided it was better to move the capital to the present-day location of Guatemala City, rather than to rebuild what is now known as the city of Antigua. Following the 1976 CE earthquake, it was determined that adobe construction with heavy tile roofs caused a high number of fatalities, and efforts were implemented to improve building styles[53], demonstrating that resilient societies learn from disasters and make associated adaptations.

This research will support further studies that explore how Maya societies coped with major disasters and the role that earthquake damage played in the rise and demise of ancient population centers, while also shedding new light on the mechanisms at work in a mature, active fault zone with short earthquake recurrence intervals, allowing for better estimation of the current and future seismic hazard in Guatemala.

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Figure Captions

Figure 1: Maps showing the location of the study site. (A) Tectonic setting of the North American-Caribbean-Cocos plate boundaries in Central America. (B) Motion of the North American-Caribbean transform plate boundary is accommodated on the Motagua and Polochic faults. The 1976 M 7.5 earthquake ruptured 240 km of the left-lateral, strike-slip Motagua fault and a portion of the N-S trending Mixco Fault (both marked with a red line). The location of the epicenter is shown with a moment-tensor solution. GC=Guatemala City, AG=Antigua Guatemala, MV=Mixco Viejo, Q=Quirigua, LC=Lake Chichój. The La Laguna Trench site is marked with a blue circle. (C) LiDAR hillshade of the La Laguna Basin showing the 1976 fault rupture trace (marked with a red line) and the trench site. The location of the line of trees offset by 3.25 m in the earthquake[2] is identified on the image. (D) LiDAR hillshade showing the location of two stone walls offset by the 1976 trace of the Motagua fault. Red ticks mark the scarp with ticks on the downthrown side.

Figure 2: Orthophoto and detailed logs of the northeast and southwest walls of the trench with calibrated radiocarbon ages. Units A-G are on the footwall and Units 1-6 on the hanging wall across the active trace of the Motagua fault. Colluvial wedges (CW) on the hanging wall were deposited in five scarp-forming earthquakes. Numbers near sample locations indicate ages and sample numbers (in brackets) as shown in Fig. 3 and Supplementary Material. See text for discussion and figures S21 and S22.

Figure 3: OxCal age model and mean earthquake recurrence intervals. In addition to the documented 1976 rupture, archaeological data indicate that earthquakes likely occurred on the Motagua Fault at the La Laguna site in the 8th, 10th, 13th, and 18th centuries.

Methods

In January 2024, we flew a Quantum Systems F90+ fixed-wing uncrewed aerial system (UAS) that has a flight time capability of over 60 minutes, enabling the capture of a 60 km linear flight line on a single flight. The UAS carried the Qube 240 LiDAR (Light Detection and Ranging) unit, a 905 nm sensor with 240,000 shots/second. We flew at ~100 m above ground level, providing ~100 points/m² spatial density and a total area of 5.4 km². We processed the raw data, classified points as ground vs. non-ground, and created bare-earth DEMs with 0.5-m spacing using Yellowscan CloudStation. We merged DEMs from multiple flights together and generated hillshades using QGIS.

In January 2025, an area of 130,000 m² was covered in one flight using a DJI Matrice 200 quadcopter flying at an altitude of ~50 m above the ground surface. A tightly-coupled kinematic solution integrating PPK GNSS and a 9-DOF IMU was calculated using the TerraPos software processor, and this was used to align the laser returns into the point cloud with an average density of 170 points/m². Noise and foliage were removed using the PDAL software to create a bare-ground point cloud. ArcGIS was used to convert the point cloud into a DEM with high-resolution contour lines. QGIS was used to generate hillshades[54].

The paleoseismic trench was excavated perpendicular to the fault scarp by hand. The walls were straightened and cleaned manually, and a 0.5 x 0.5 m grid was installed. For the trench orthophoto, we collected hundreds of overlapping digital photographs with a Nikon SRL camera. Agisoft Metascan software was used to create orthophotos using the structure-from-motion technique[55, 56]. Trench logs of the stratigraphic layers and faults were drawn in the field, and charcoal samples were collected for radiocarbon analyses. Radiocarbon data were calibrated with IntCal20[57] and the NH2 post-bomb calibration curve[58] as shown on the trench logs (Fig. 2). An age model to bracket fault rupturing events (Fig. 3) was created in OxCal 4.4[59] following the methodology of Lienkaemper & Bronk Ramsey[60]. All radiocarbon data are given with a two-sigma uncertainty (see the radiocarbon Table S4 and age model data in the Supplement S16). All radiocarbon samples were sent to Beta Analytic, Miami, FL, for sample preparation and dating.

Data Accessibility

Digital Elevation Models and orthophotos created from uncrewed aerial surveys of the La Laguna site can be accessed at Zenodo [61, 62]. A georeferenced database of 35 mm slides, field notes, and annotated maps from the George Plafker USGS Archive of the 1976 earthquake rupture used in this study can also be accessed at Zenodo[63].

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Author Contributions:

Tina M. Niemi—Interpretation of field stratigraphy and geomorphology, drawing and editing trench logs, writing the text

Christoph Grützner—Interpretation of field stratigraphy and geomorphology, drawing, interpreting, and drafting figures, writing the text

Omar Flores Beltetón—Permission, field data

Luis Alberto Romero—Maya artifact identification

Francisco Gomez—LiDAR data acquisition and processing

Jeremy Maurer—LiDAR data acquisition and processing

Trenton McEnaney—scanning, digitally referencing, and relocating Plafker USGS Archive including 1:10,000-scale aerial photographs, black-and-white photographs, and 35 mm slides.

Robyn Daniels—OxCal age model, text editing

Aleigha Dollens—Trench logging and sample collection

Hannes Ebell— Digitally referencing, trench logging and sample collection

Carlos Pérez Arias—Permission, field data

Alison Graettinger—Field logistics, field data

Jonathan Obrist Farner—Field logistics, relocating 1976 sites

The authors declare no competing interests.

Supplementary Information is available for this paper.

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Supplement:

Additional maps

Plafker photos

Detailed trench orthophotos and trench logs

Age model

C-14 dates

Archaeoseismic data from Quirigua and Mixco Viejo

Editorial summary:
The Motagua Fault in Guatemala, part of the North American-Caribbean plate boundary, ruptured the ground surface on five separate occasions over the past 1300 years, according to direct observations from excavations coupled with radiocarbon dating

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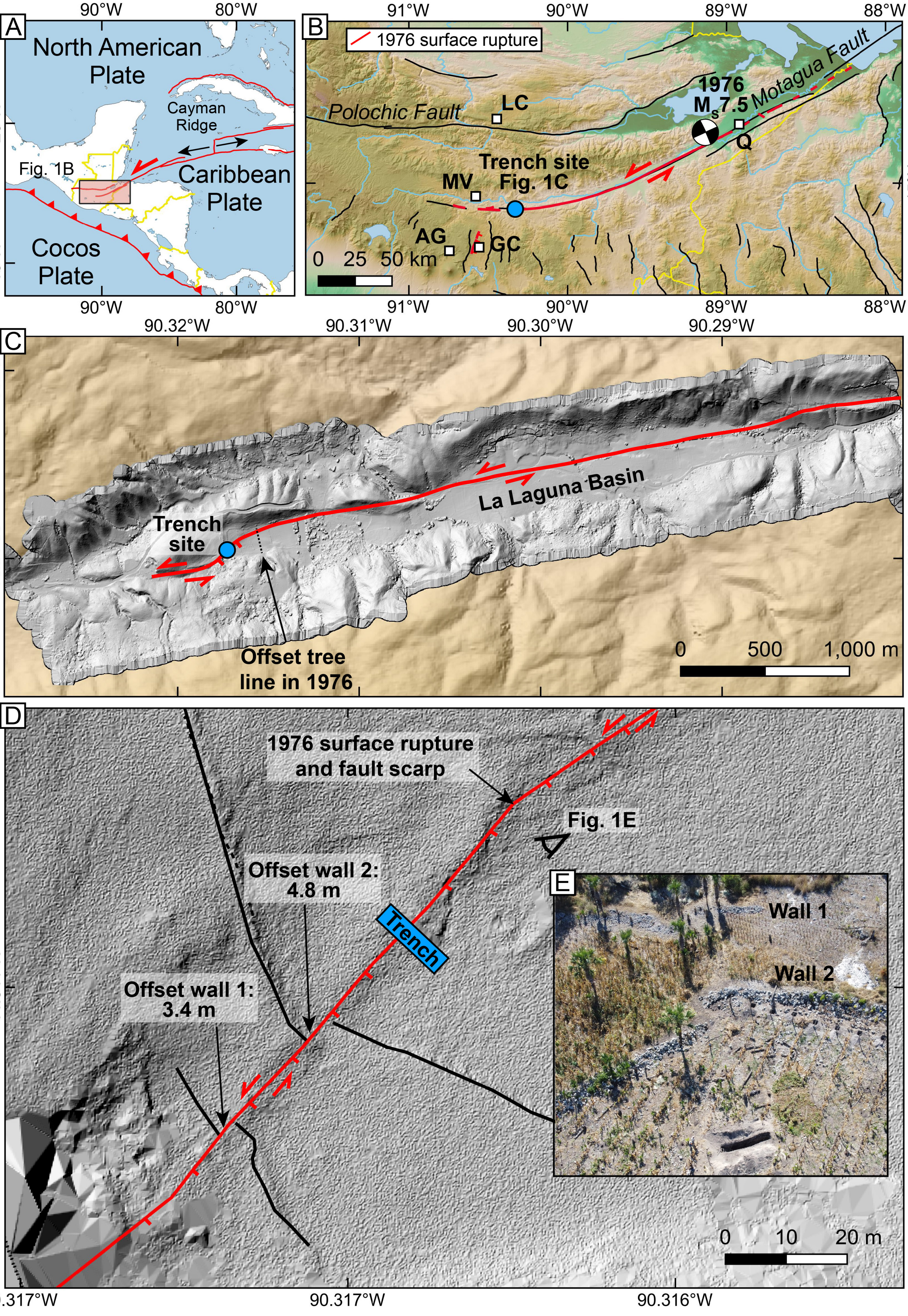
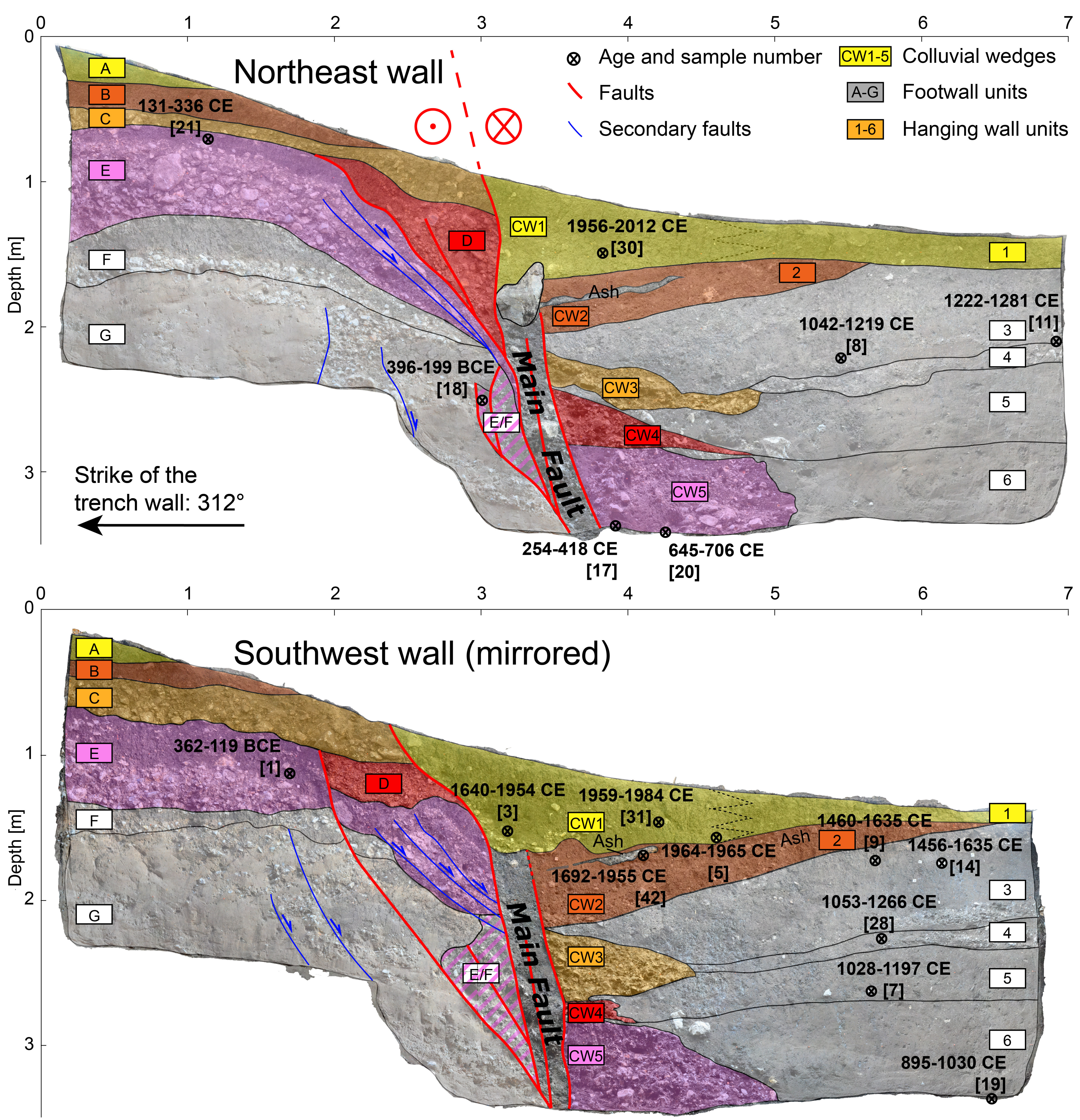
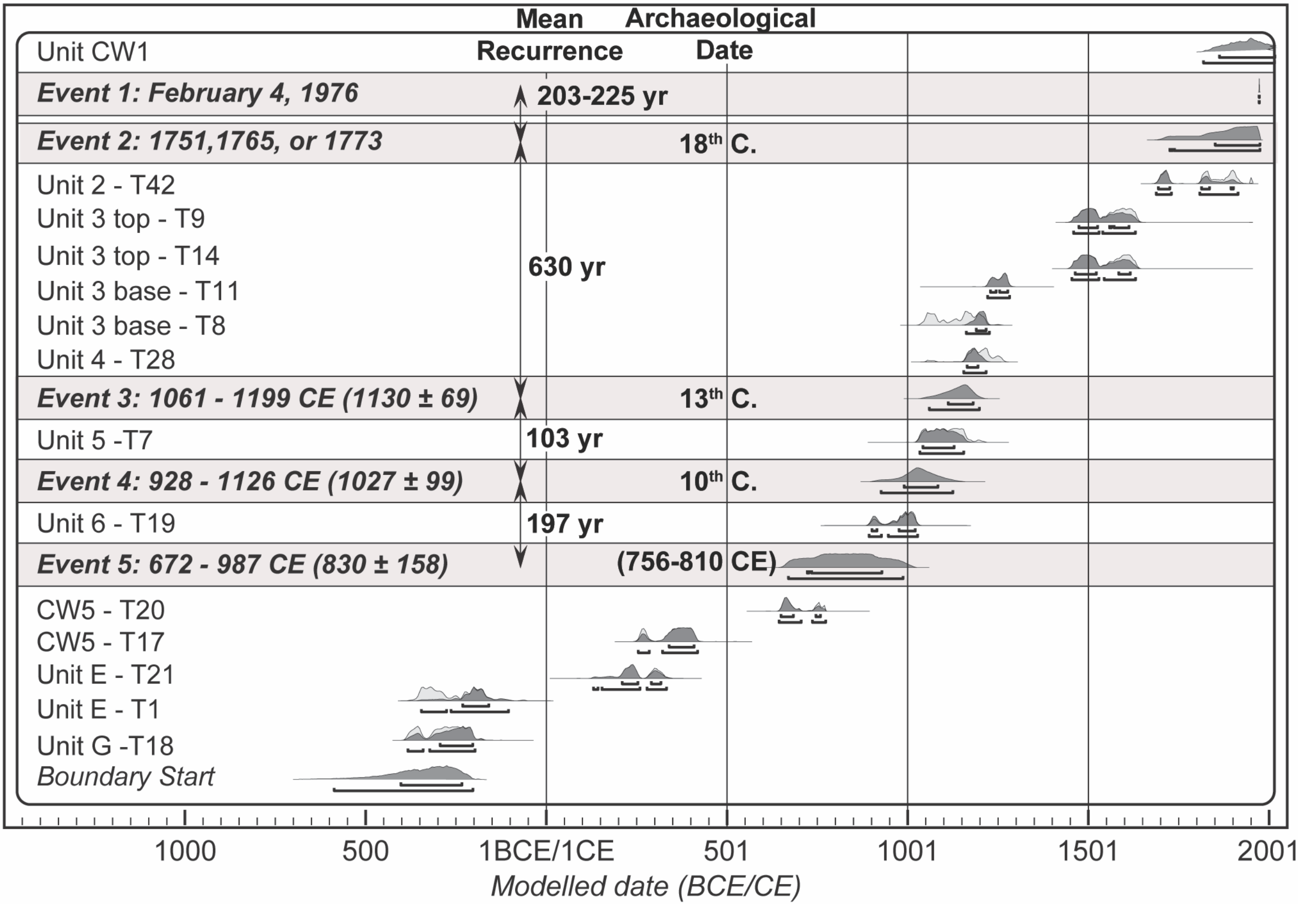


A
90°W
80°W
North American Plate
Cayman Ridge
20°N
Fig. 1B
Caribbean Plate
Cocos Plate
10°N
B
91°W
90°W
89°W
88°W
1976 surface rupture
Polochic Fault
LC
1976 M_s 7.5
Motagua Fault
Q
Trench site Fig. 1C
MV
15°N
AG
GC
0 25 50 km
C
90.32°W
90.31°W
90.30°W
90.29°W
14.85°N
14.84°N
La Laguna Basin
Trench site
Offset tree line in 1976
0 500 1,000 m
D
1976 surface rupture and fault scarp
Fig. 1E
Offset wall 2: 4.8 m
Trench
Offset wall 1: 3.4 m
14.841°N
E
Wall 1
Wall 2
0 10 20 m
90.317°W
90.317°W
90.316°W


Northeast wall
Age and sample number
Faults
Secondary faults
CW1-5 Colluvial wedges
A-G Footwall units
1-6 Hanging wall units
Depth [m]
A
B
C
E
F
G
D
131-336 CE [21]
CW1
1956-2012 CE [30]
1
2
Ash
CW2
1222-1281 CE [11]
1042-1219 CE [8]
3
4
5
6
396-199 BCE [18]
E/F
Main Fault
CW3
CW4
CW5
Strike of the trench wall: 312°
254-418 CE [17]
645-706 CE [20]
Southwest wall (mirrored)
362-119 BCE [1]
1640-1954 CE [3]
1959-1984 CE [31]
1460-1635 CE [9]
1456-1635 CE [14]
1964-1965 CE [5]
1692-1955 CE [42]
1053-1266 CE [28]
1028-1197 CE [7]
895-1030 CE [19]



Mean Recurrence
Archaeological Date
Unit CW1
Event 1: February 4, 1976
203-225 yr
Event 2: 1751,1765, or 1773
18th C.
Unit 2 - T42
Unit 3 top - T9
Unit 3 top - T14
Unit 3 base - T11
Unit 3 base - T8
Unit 4 - T28
630 yr
Event 3: 1061 - 1199 CE (1130 ± 69)
13th C.
Unit 5 -T7
103 yr
Event 4: 928 - 1126 CE (1027 ± 99)
10th C.
Unit 6 - T19
197 yr
Event 5: 672 - 987 CE (830 ± 158)
(756-810 CE)
CW5 - T20
CW5 - T17
Unit E - T21
Unit E - T1
Unit G -T18
Boundary Start
1000
500
1BCE/1CE
501
1001
1501
2001
Modelled date (BCE/CE)