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Sedimentary signatures of large earthquakes along the submerged Enriquillo–Plantain Garden transpressional plate boundary, northern Caribbean

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ABSTRACT

The Enriquillo–Plantain Garden fault (EPGF), the southern branch of the northern Caribbean left-lateral transpressional plate boundary, has ruptured in two devastating earthquakes along the Haiti southern peninsula: the M_w 7.0, 2010 Haiti and the M_w 7.2, 2021 Nippes earthquakes. In Jamaica, the 1692 Port Royal and 1907 Great Kingston earthquakes caused widespread damage and loss of life. No large earthquakes are known from the 200-km-long Jamaica Passage segment of this plate boundary. To address these hazards, a National Science Foundation Rapid Response survey was conducted to map the EPGF in the Jamaica Passage south of Kingston, Jamaica, and east of the island of Jamaica. From the R/V *Pelican* we collected >50 high-resolution seismic profiles and 47 gravity cores. Event deposits (EDs) were identified from lithology, physical properties, and geochemistry and were dated in 13 cores. A robust ^{14}C chronology was obtained for the Holocene. A Bayesian age model using OxCal 4.4 calibration was applied. Out of 58 EDs that were recognized, 50 have ages that overlap within their 95% confidence ranges. This allowed for their grouping in multiple basins located as much as 150 km apart. The significant age overlap suggests that EDs along the Enriquillo–Plantain Garden plate boundary resulted from large and potentially dangerous earthquakes. Most of these earthquakes may derive from the EPGF but also from thrust faulting at this strain-partitioned transpressional boundary. The recent increase in Coulomb stress on the EPGF from the M_w 7.2 Nippes earthquake in southwestern Haiti and the discoveries reported here enhance the significance for hazard in the Jamaica Passage.

INTRODUCTION

Paleoseismology has been rapidly expanding the sedimentary record of earthquake ruptures in submarine environments (e.g., Marco et al., 1996; Ikehara et al., 2016; Polonia et al., 2021; Strasser et al., 2023). Steady long-term sedimentation in marine basins offers unique advantages due to the completeness and duration of this record far into prehistory. The EPGF between Haiti and Jamaica is an ideal location to continue to test submarine paleoseismology because the basins within this fault zone are isolated from sediment input from rivers and submarine canyons and their sources are below wave base even in the most severe storms. Submarine paleoseismology is particularly important along transform plate boundaries where earthquake recurrence has remained challenging to determine, such as at the North Anatolian Fault, Turkey (McHugh et al., 2006; Beck et al., 2007; Çağatay et al., 2012), and the Dead Sea Fault (Ken-Tor et al., 2001). One of the greatest challenges of reconstructing the record of earthquake ruptures along submerged transform boundaries is obtaining accurate temporal and spatial resolution for distinguishing event deposits (EDs).

The Enriquillo–Plantain Garden fault (EPGF) is a left-lateral transform that forms part of northern Caribbean plate boundary. The Caribbean plate moves east-northeast relative to the North American plate at a rate of 2 cm/yr (Mann et al., 1995; DeMets et al., 2010; Fig. 1). Along the northern plate boundary, the motion is accommodated by two left-lateral transform fault systems that bound the Gonâve microplate (Fig. 1): the Septentrional and Oriente faults to the north and the Enriquillo–Plantain Garden and Walton faults to the south (Mann et al., 1995; Leroy et al., 2000; Benford et al., 2012). The EPGF extends from Port-au-Prince, Haiti, to Kingston, Jamaica. It accommodates ~7 mm/yr of strike-slip and ~4 mm/yr of thrust motions (Manaker et al., 2008; Calais et al., 2010; Benford et al., 2012).

Two earthquakes close in time and space ruptured the EPGF along the southern peninsula of Haiti, M_w 7.0 on 2010 and M_w 7.2 in 2021, with devastating loss of life and damage to infrastructure (Fig. 1; Bakun et al., 2012; Calais et al., 2010, 2022). The two ruptures were contiguous and displayed similar partitioning of transpressional strain between the

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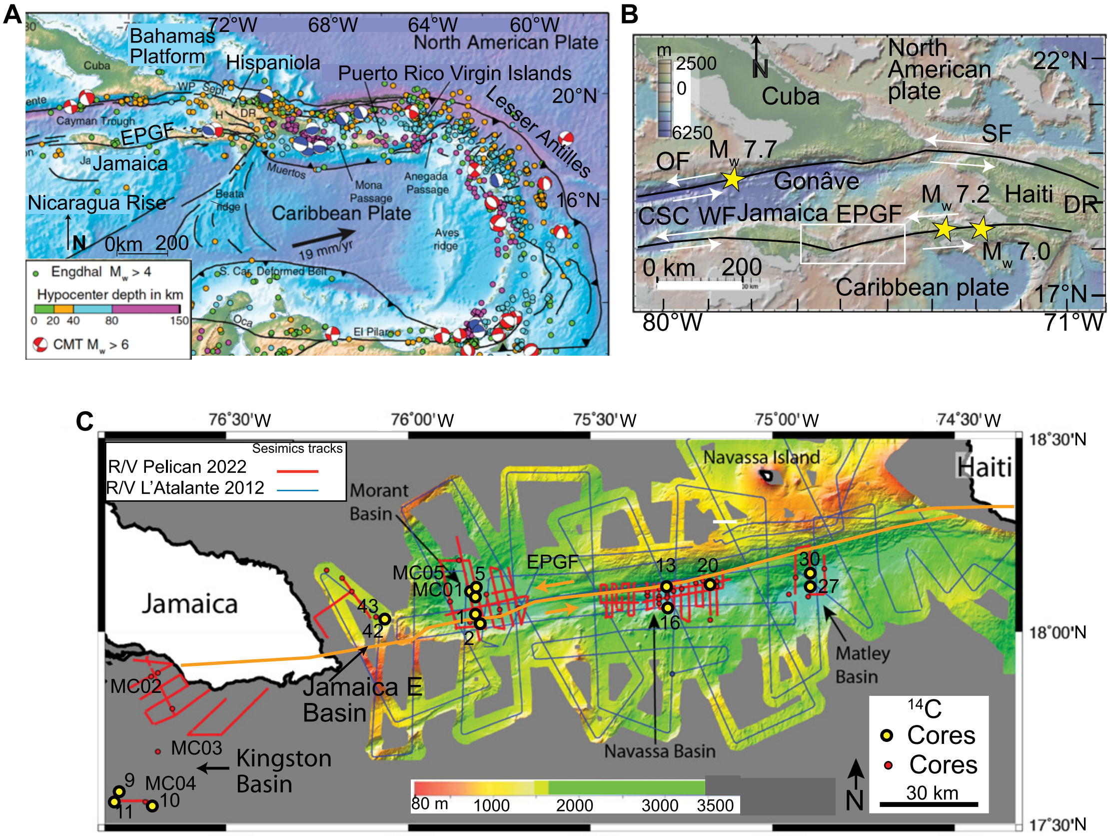

Figure 1. (A) Overview of setting and seismicity in the Caribbean. Caribbean plate motion relative to North American plate is 2 cm/yr, from Calais et al., 2022. (B) Detail of northern Caribbean plate boundary with location of our study area (white box) and Haiti 2010 M_w 7.0, Nippes 2021 M_w 7.2, and Oriente Fault (OF) 2020 M_w 7.7 ruptures (stars; USGS, 2020). SF—Septentrional Fault; DR—Dominican Republic; EPGF—Enriquillo–Plantain Garden Fault; WF—Walton Fault; CSC—Cayman Spreading Center. (C) Multibeam bathymetry (Leroy et al., 2015; R/V *Pelican* 2022 [red tracks] and R/V *L'Atalante* 2012 surveys [blue]) with location of Morant, Navassa, and Matley Basins and study areas offshore Kingston, Jamaica, and east of island of Jamaica.

EPGF and the thrust belt north of the transform. The spatial and temporal relation of these earthquakes suggests that they may be mechanically related and part of a sequence (Calais et al., 2022) that could conceivably advance farther west along the 200-km-long segment of the EPGF in the Jamaica Passage between Haiti and Jamaica. The earthquake prehistory presented here for this submerged segment of the boundary adds urgency to this question.

The main historical earthquakes and much of the recent instrumental seismicity are concentrated in the east, near Kingston. This city, with 1.3 million inhabitants, just south of the EPGF, is built on alluvial soil that contributes to seismic amplification (Salazar et al., 2013). The city experienced highly destructive earthquakes in 1692, with liquefaction along the coast to the south, and in 1907, a widely destructive M_w $\sim$6.2 earthquake with a tsunami along the north coast of Jamaica (Fuller, 1907). In summary, large destructive earthquakes along the EPGF have occurred in both Haiti and Jamaica (McHugh et al., 2011; Bakun et al., 2012; Calais et al., 2022), but no large earthquakes are documented along the Jamaica Passage. The main goal here is to establish whether the EPGF and related faults along the Jamaica Passage and in southeastern Jamaica are active and capable of damaging earthquakes based on geologic evidence of large prehistoric earthquakes.

METHODS

To address these hazards, a National Science Foundation (NSF) Rapid Response survey was conducted to map the EPGF along the Jamaica Passage, offshore Kingston and east of Jamaica (Fig. 1). The survey took place in January 2022 aboard the R/V *Pelican*. We collected $>$50 high-resolution seismic profiles, 47 gravity cores 1–5 m long, and five multicores that recovered the sediment-water interface. We used two approaches for the identification of EDs: core analyses and statistical age dating and correlation. The sediment cores were analyzed for their physical properties with a Geotek multisensor core logger. High-resolution digital photography, X-ray radiography, and X-ray fluorescence elemental analyses were conducted at a millimeter scale with an Itrax core scanner. Benthic and planktonic foraminifers from the same core and interval were dated to find out whether there were any ^{14}C differences in age due to changes between bottom and surface waters entering the basins. There are no major age differences, and the subsequent ^{14}C chronology was obtained from multiple species of planktonic foraminifers picked centimeters below EDs. We carefully avoided sampling bioturbated intervals in between and above EDs due to potential mixing and dated all EDs for the upper $\sim$1 m of 13 cores. The length of cores dated varies from 45 cm to $\sim$100 cm.

The ages were calibrated with OxCal 4.4 (Bronk Ramsey, 2009) using the Marine20 modeled ocean average curve (Heaton et al., 2020). The ΔP was obtained from the marine database (Stuiver and Braziunas, 1993) for the Caribbean region by averaging points in Jamaica (Broecker and Olson, 1961), Cape Haïtien, Haiti (DiNapoli et al., 2021), and Oriente, Cuba (DiNapoli et al., 2021). The weighted mean used ΔR is -144 ± 34.

The survey builds upon prior work from French surveys by the R/V *L'Atalante* in 2012 (Leroy et al., 2015) and on results from an NSF Rapid Response survey to Haiti after the 2010 earthquake (McHugh et al., 2011, 2014; Hornbach et al., 2010). Initial processing of the high-resolution seismic data was conducted shipboard with Landmark and Seismic Unix software, with additional processing carried out at Sorbonne University (Paris) (R/V *Pelican* Cruise Report, 2022).

RESULTS

The Jamaica Passage between Jamaica and Haiti is a 3000-m-deep trough, 200 km long and 15 km wide (Fig. 1; Leroy et al., 2015; Corbeau et al., 2016). It includes three basins, from west to east: Morant, Navassa, and Matley. These basins developed during Paleogene extension and are now being deformed due to transpression initiated during the Neogene (Pubellier et al., 2000). Except for Morant Basin, which contains very rare wood fragments, these basins are located in areas that are distal from rivers and submarine canyons in relatively deep

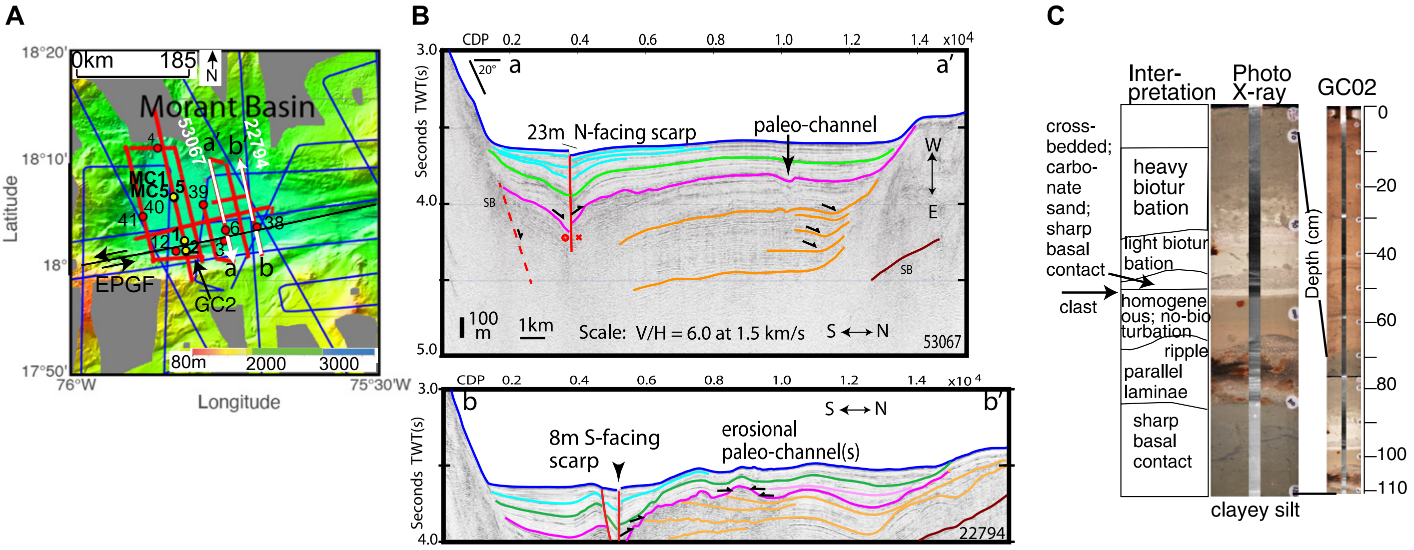

Figure 2. Morant Basin. (A) Multibeam bathymetry from Leroy et al. (2015) with navigation tracks, core locations, and trace of Enriquillo–Plantain Garden Fault (EPGF). Red tracks indicate multichannel seismics (MCS) collected with the R/V *Pelican* in 2022: blue MCS from the R/V *L'Atlante* 2012. Red dots are R/V *Pelican* cores; yellow dots, ^{14}C-dated cores (MC—multicore). (B) MCS revealing an erosional unconformity (purple) marking transition from transtensional Paleogene to transpressional Neogene (Leroy et al., 2015). Orange reflectors show evidence of prior extensional regime. Folding is most prominent in Navassa Basin but subtle in western Morant Basin. Significant vertical offset marks Enriquillo–Plantain Garden Fault (EPGF, red line) at seafloor, showing the fault is active. Scarps and sediment ponding suggest large seismogenic displacements of EPGF consistent with event deposits identified in cores. TWT—two-way travel time; CDP—common depth point; V/H—vertical/horizontal. (C) Notable event deposit highlighting contrasting lithologies in core PE22-17-GC02-2, 80–120 cm. From right to left are core photo and X-ray image (central vertical stripe) of Section 2/5, and event deposit with interpretation (core log in Fig. S3 [see text footnote 1]).

water (3000 m) well below the wave base. Their isolation is to a great extent due to their tectonic formation, making Morant, Navassa, and Matley Basins ideal locations for the study of earthquake-triggered sedimentation. Offshore southeastern Kingston, Kingston Basin and east of Jamaica, Jamaica E Basin, some of the cores contain woody material likely derived from terrestrial sources.

The high-resolution seismic data show that the EPGF offsets the seafloor in all three basins and is clearly active (Figs. 2 and 3; see Fig. S1 in the Supplemental Material[1]). The fault activity is expressed on the basin floors as low-relief ridges and folds. There is evidence of substantial north-south shortening, consistent with a transpressional regime that is inverting earlier extension of the crust. Shortening decreases from east to west. The north-south shortening is expressed as thrust folding with southward vergence. In Matley Basin, it is shifting the surface trace of the EPGF southward. Shortening is notably absent from west Morant Basin except for a local ridge at a fault bend (Fig. 2; Leroy et al., 2015).

EDs were identified from lithology, magnetic susceptibility, bulk density, elemental composition, and from ^{14}C age correlations derived from a statistical approach with 95% confidence range. The lithology and geochemical scans reveal that the basin sediment including offshore Kingston and east of Jamaica is dominated by mafic-rich clay and silt and calcareous oozes rich in foraminifers and pteropods (Figs. 2 and 3; see Figs. S1–S3). These microfossils form the sand-sized components of turbidites. Color differences between calcareous and mafic lithologies highlight fine turbidite structures revealing EDs (Fig. S4).

Chronology

Our ability to identify EDs and link them to earthquakes relies on a strong chronology facilitated by the abundance and preservation of calcareous microfossils and on the synchroneity of these events along the length of the EPGF. A robust ^{14}C chronology obtained for the Holocene was enhanced by a statistical approach based on the Markov chain Monte Carlo probability distribution favored for multi-parameter Bayesian analysis by OxCal 4.4 (Bronk Ramsey, 2009; Fig. 4; Table S1). The range is 95.4% of the total area distribution, and the medial probability distribution was used.

Based on a statistical approach and lithological correlations, 50 out of 58 EDs were correlated in 12 groups, each group possibly representing an earthquake or earthquake sequence (Fig. 4). Four of these groups are confined to the same basin where the cores are 8–12 km apart, while eight of them reach across multiple basins as far as 150 km apart. Only eight of the 58 EDs identified were not correlated.

DISCUSSION

EDs provide the first evidence of potentially dangerous large earthquakes from the entire submerged Enriquillo–Plantain Garden plate boundary in the Jamaica Passage offshore eastern Jamaica and in the densely populated region offshore Kingston. The ages cover much of the Holocene. Our systematic approach to establishing correlations placed most of the EDs in 12 groups, each of which likely represents one large earthquake or a sequence of large earthquakes (Fig. 4). We discovered that similar to the 2010–2021 Haiti earthquake sequence (Calais et al., 2022), deposition of these EDs may have been sequential, as revealed by the closely spaced ages that overlap within the 95% confidence range. Some EDs in distal basins are synchronous in age (Figs. 3 and 4; Figs. S2 and S3; Table S1). Such sequential earthquakes have been interpreted as clusters in other transform boundaries, such as the North Anatolian, Dead Sea, and Alpine (New Zealand) faults (Bulut et al., 2011; Wetzler et al., 2014; Howarth et al., 2021). Temporal clustering of earthquakes appears to be characteristic of transpressional plate boundaries. The EPGF shows overlap in its subaerial and submarine segments, revealing information for improving northern Caribbean hazard assessment. Of the two damaging historical earthquakes in Jamaica, the one in 1692 that destroyed Port Royal and correlated with an ED recovered ~50 km from the coast expands our understanding of destructive earthquakes for the region and demonstrates that submarine paleoseismology techniques can be used to identify earthquakes. Together, these

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[1] Supplemental Material. Figure S1: Event deposits correlations Navassa and Matley Basins. Figure S2: Event deposits correlations Kingston and Jamaica E Basins. Figure S3: Core Log GCPE22-17-02. Figure S4: Facies descriptions. Table S1: Age calibrations. Please visit https://doi.org/10.1130/GEOL.S.26376121 to access the supplemental material; contact editing@geosociety.org with any questions.

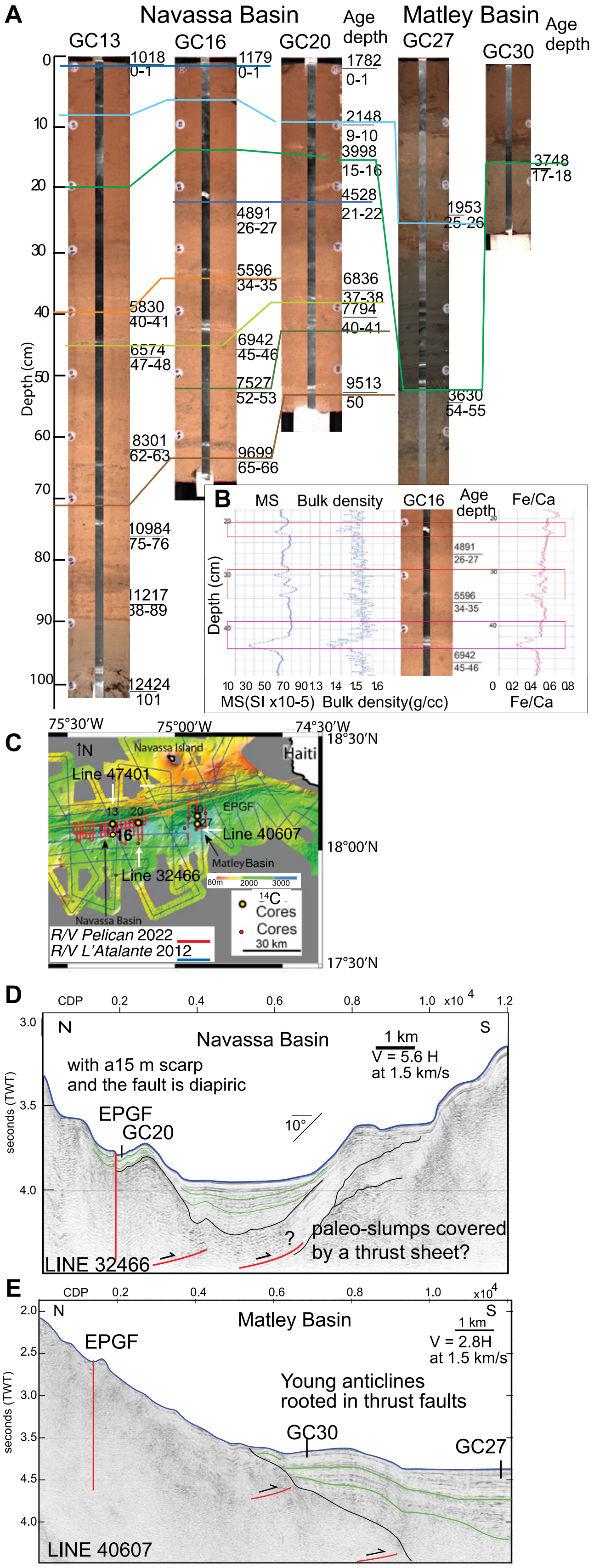

Figure 3. Holocene event deposit (EDs) correlations for Matley Basin and Navassa Basin cores. (A) Core photos, X-ray image (central vertical stripe), age in calibrated yr B.P. depth (cm). Colored lines indicating EDs. Eight EDs were correlated in two or more cores, colors match those of EDs on Fig. 4 and Table S1 (see text footnote 1). Correlations were based on medial age obtained from OxCal 4.4 (calibrated yr B.P.). (B) Example of how EDs were identified and correlated based on lithology, magnetic susceptibility (MS), bulk density, core photo, X-ray Fe/Ca, age (cal. yr B.P.), and depth (cm). (C). Multibeam bathymetry with multichannel seismic tracks (MCS; red collected with the R/V *Pelican* in 2022, blue R/V *L'Atlante* in 2012, and core locations). (D, E) MCS showing that Enriquillo–Plantain Garden Fault (EPGF) is active with prominent thrust faulting, 15 m fault scarp (possible diapir), young anticlines, and paleo-slumps; location of cores GC20, GC27, and GC30 are also shown. TWT—two-way travel time; CDP—common depth point; V—vertical; H—horizontal.

data allow for a detailed assessment of seismicity along a transpressional plate boundary with implications for transform boundaries worldwide.

CONCLUSIONS

The first evidence of large prehistoric earthquakes along the submerged segment of the Enriquillo–Plantain Garden plate boundary in the Jamaica Passage, offshore Kingston and southeastern Jamaica, was documented for the Holocene. The basins in the Jamaica Passage are isolated from shallow-water sediments with mainly pelagic sedimentation remobilized by the large, potentially dangerous earthquakes. Thirteen gravity cores were dated with ^{14}C and 58 EDs identified from lithology, physical properties, and geochemistry and from age correlations based on a statistical approach within their 95% confidence range. Fifty EDs were correlated, forming 12 groups spanning the period since 10 k.y. B.P. Four of these groups are confined to a single basin where the cores are spaced 8–12 km apart, while eight of them reach across multiple basins as far as 150 km apart. The recent 2021 rupture of the next segment to the east along the southern peninsula of Haiti can be expected to have significantly increased stress along parts of the Jamaica Passage segment and adds to the implications for hazard. Moreover, timing of and spatial distribution of EDs point to the possibility of large scale ruptures not recorded in the observational record at nearby areas important for the assessment of seismic hazard risk for this and other transform boundaries worldwide.

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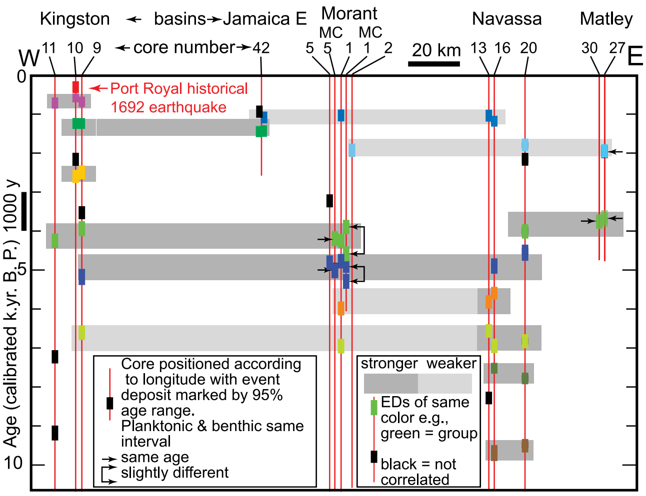

Figure 4. Time (10 k.y.)–space (9230 km) plot of 58 event deposits (EDs) along Enriquillo–Plantain Garden Fault (EGPF) in Jamaica Passage, east of Jamaica island and offshore of Kingston. Core locations are projected on east-west line with EDs marked by their 95% confidence range (see Table S1 [see text footnote 1]). Two or more EDs may be part of a sequence when their 95% confidence ranges overlap. Gray bands highlight groups of EDs interpreted as having strong (dark gray) and weak (light gray) age correlation. A weak correlation is interpreted if two or three sites are correlated by age but are spatially apart with many sites in between that don't see the event. Each band may represent a sequence of earthquakes or a single large rupture along the EPGF. Thickness of bands marks groups' age range. Fifty-eight EDs were identified, and 50 of them are correlated in 12 groups, each group possibly representing earthquakes. Four of these groups occur in the same basin where distance between cores is 8–12 km; eight of them are in multiple basins including two that span three basins from Navassa to offshore Kingston. Eight EDs cannot be correlated. Planktonic and benthic foraminifers were measured from same core and interval to determine ^{14}C differences in surface and bottom waters. There are no major differences since most of the ages overlap. Future studies will focus on this paleoceanography result. MC—multicore.

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