Insights on the small tsunami from January 28, 2020, Caribbean Sea $M_w7.7$ earthquake by numerical simulation and spectral analysis

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Abstract
A major left-lateral strike-slip $M_w7.7$ earthquake occurred in the vicinity of the Caribbean Sea on January 28, 2020. As a result, a small-scale tsunami was generated. The properties of the seismogenic source were described using observational data gathered for the earthquake and tsunami, as well as information on the regional tectonic setting. The tsunami was simulated with the COMCOT model and Okada’s dislocation model from finite fault solutions for $M_w7.7$ Caribbean Sea earthquakes published by the United States Geological Survey. The simulation results were compared to tide gauge records to validate whether the seafloor’s vertical displacement generated by the strike-slip fault caused a small-scale tsunami. We conducted a spectral analysis of the tsunami to better understand the characteristics of tsunami records. The tsunami simulation results showed that the co-seismic vertical displacement caused by a strike-slip $M_w7.7$ earthquake could have contributed to the small-scale tsunami, but the anomalously large high-frequency tsunami waves recorded by the George Town tide gauge 11 min after the earthquake were unrelated to the earthquake-generated tsunami. According to the spectrum analysis, the predominant period of noticeable high-frequency tsunami waves recorded by the George Town tide gauge occurred only two minutes after the earthquake. This indicates that the source of the small-scale tsunami was close to the George Town station and the possible tsunami source was 150 km away from George Town station. These facts suggest that a submarine landslide was caused by the strike-slip earthquake. The comprehensive analysis showed that the small-scale tsunami was not caused solely by co-seismic seafloor deformation from the strike-slip event but that an earthquake-triggered submarine landslide was the primary cause. Therefore, the combined impact of two sources led to the small-scale tsunami.

Keywords 2020 Caribbean Sea earthquake · Strike-slip fault · Tsunami · Numerical simulation · Spectral analysis · Submarine landslide
1 Introduction

At 19:10 on January 28, 2020 (UTC), a large earthquake measuring $M_W 7.7$ (Harvard CMT) with a focal depth of 14.8 km, struck the Caribbean Sea region (19.421° N, 78.763° W) between Jamaica, the Cayman Islands, and Cuba (Fig. 1). According to reports, the strong shakes were felt across many Caribbean countries, especially those south of Cuba and northwest of Jamaica, as well as in the Cayman Islands. They were also felt as far away as the state of Florida in the USA and in parts of Mexico (https://www.usatoday.com). Although this Caribbean Sea earthquake was large and occurred at an unusually shallow depth, its epicenter was far away from the densely populated coastal regions. As a result, the loss of human life and destruction of property were reduced the further a location was from the epicenter. According to social media reports (https://www.newsweek.com), the earthquake had a significant local impact on the Cayman Islands, causing some damage to buildings, roads, and sewage pipes, as well as creating massive sinkholes. Following the earthquake, the Pacific Tsunami Warning Center (PTWC) issued a tsunami warning message (https://tsunami.gov/), forecasting that the earthquake could generate a small-scale tsunami with a maximum wave height of 0.3–1 m in parts of the Caribbean and adjacent regions such as Cuba, Jamaica, the Cayman Islands, Honduras, Mexico, and Belize. The tsunami wave observations from coastal sea level gauges in George Town, Cayman Islands indicated that small tsunami waves with a 12-cm heights were recorded on a tide gauge 11 min after the earthquake. In addition, a weak tsunami wave was also measured at a sea level facility at the port of Morelos in Mexico. Nevertheless, there were no significant impacts on the lives of local residents from the minor tsunami.

After the $M_W 7.7$ Caribbean Sea earthquake, the USGS and the Global Central Moment Tensor Project (GCMT) published the focal mechanism solutions online. They indicated that the earthquake was a pure strike-slip shallow event. In general, megathrust earthquakes are far more likely to generate tsunamis. A sudden vertical deformation of the seafloor due to a dip-slip on the ruptured fault is thought to be the fundamental mechanism of tsunami generation. In recent years, megathrust dip-slip earthquakes have caused tsunamis, e.g., the 2004 Indian Ocean tsunami and the 2011 Japan tsunami (Okal & Synolakis 2008; Fujii et al. 2011). Strike-slip earthquakes involve motion that is parallel to the fault’s strike. The motion of the blocks during a strike-slip event is predominantly horizontal and typically considered unfavorable for tsunami generation. However, historical major strike-slip earthquakes, such as the 1929 $M_W 7.2$ Grand Banks earthquake; the 1976 $M_W 7.1$ Mindanao; Philippine earthquake; the 1989 $M_W 6.9$ Loma Prieta earthquake; the 1994 $M_W 7.1$ Mindoro, Philippines earthquake; the 1999 $M_W 7.4$ Izmit, Turkey earthquake; the 2010 $M_W 7.0$ Haiti earthquake; and the 2018 $M_W 7.5$ Sulawesi, Indonesia earthquake, have resulted in destructive local tsunamis (Hasegawa and Kanamori 1987; Stewart & Cohn 1979; Ma et al. 1991; Imamura et al. 1995; Altinok et al. 2001; Hornbach et al. 2010; Heidarzadeh et al. 2019). Why do strike-slip earthquakes generate tsunamis? Most of the large strike-slip earthquakes have triggered submarine landslides, which then produce local tsunamis with significant wave height. However, tectonic deformation from strike-slip faulting should not be overlooked. Large strike-slip fault zones are frequently complex and exhibit significant geometrical variations. They often consist of numerous en echelon step-overs, which are associated with restraining and releasing bends where topographic uplift and subsidence occur. These structures provide an effective mechanism for inducing local tsunamis (Legg and Borrero 2001; Legg et al. 2003). In addition to the factors mentioned previously, deep-water seamounts or other major ocean floor features can play a role in tsunami generation.
So, how did the $M_{\text{w}}7.7$ strike-slip earthquake in the Caribbean Sea occur, and what caused the tsunami? Was the tsunami triggered by tectonic deformation from the $M_{\text{w}}7.7$ strike-slip earthquake or by such non-tectonic sources as submarine landslides?

The purpose of this study is to investigate the seismogenic source of the $M_{\text{w}}7.7$ strike-slip earthquake in the Caribbean Sea and find out how it generated a tsunami. We gathered and analyzed available data and information on the earthquake and its regional tectonic setting to reveal the earthquake’s characteristics. Then, we ran tsunami simulations using slip distribution on a finite fault model to see how well the observed and simulated tsunami waveforms matched. In addition, we performed spectral analysis with a wavelet method to shed some light on the characteristics of the observed tsunami wave. Finally, we conducted additional research into the mechanisms by which a tsunami can be generated by tectonic or non-tectonic sources. This study provides a better understanding of tsunami-generating sources in the Caribbean Sea and has important implications for tsunami risk assessment of the Caribbean Sea and its surrounding areas.

### 2 Regional tectonic setting

The 2020 $M_{\text{w}}7.7$ earthquake struck in the Caribbean Sea between Jamaica, eastern Cuba, and the Cayman Islands. The epicenter was located at an active boundary between the North American and the Caribbean plates (Fig. 1). This plate boundary stretches over 3200 km from the northern part of Central America through the Greater Antilles to the northern end of the Lesser Antilles subduction zone. This is a typical left-lateral strike-slip fault zone (Mann et al. 2004). The $M_{\text{w}}7.7$ earthquake’s location and source parameters are
highly correlated with active tectonic structures. According to current GPS measurements, the Caribbean plate is moving east-northeastwards at a rate of about 20 mm/yr relative to the North American plate (DeMets et al. 2010). The strike-slip deformation of two tectonic plates is generally accompanied by varying degrees of transpression and transtension (Grindlay et al. 2005), creating an intricate tectonic setting. An additional complication is that the northeastern Caribbean plate boundary splits into smaller blocks or microplates (van Benthem et al. 2014), i.e., the Gonâve Microplate, the Hispaniola microplate, and the Puerto Rico-Virgin Islands microplate from west to east (Byrne et al. 1985; Rosencrantz and Mann 1991; Mann et al. 2002).

The $M_W$7.7 earthquake on January 28, 2020, occurred near the boundary of the Gonâve microplate, a small roughly rectangular strip of oceanic crust squeezed between the North American plate and the Caribbean plate. It is bounded to the west by the ultra-slow (15–17 mm/yr) Mid-Cayman Spreading Center (MCSC) (Hayman et al. 2011). The Cayman Ridge spreads gradually in an east–west direction due to upwelling magma from the mantle, creating the seafloor and oceanic lithosphere. The Cayman Trough is a transforming fault zone and pull-apart basin with a depth of over 7000 m, the deepest in the Caribbean Sea (Einsle 2000; Lemenkova 2020). The microplate extends eastward until Hispaniola Island or may be unclear (Benford et al. 2012). It is bounded to the north by the Septentrional-Oriente fault zone (SOFZ), which has mainly left lateral strike-slip motion at $\sim$10 mm/yr (Symithe et al. 2015). The SOFZ begins northeast of Puerto Rico, extends to the west and across the north coast of Hispaniola, and runs continuously along the southern end of Cuba until it reaches the Cayman Islands. Both the Walton fault zone (WFZ), which extends west along the southern margin of the Cayman Trough, and the Enriquillo–Plantain Garden fault zone (EPGFZ), which extends across the southern part of Hispaniola through the Caribbean to eastern Jamaica, are major left lateral strike-slip faults with a slip of $\sim$9 mm/yr (Symithe et al. 2015). The WFZ and the EPGFZ are interrupted in Jamaica by a series of faults known as the Jamaica restraining bend (JRB) (Benford et al. 2015).

Because plate interactions lead to strain accumulation and energy release at the plate boundaries, large magnitude earthquakes in the Caribbean have occurred mainly along the boundaries of the Gonâve microplate, where the region. As a result, this region has high seismicity. According to the US Geological Survey’s historical earthquake database, 25 earthquakes with $M \geq 6.0$ have occurred in the Gonâve microplate and its vicinity ($14^\circ$N–$24^\circ$N, $84^\circ$W–$70^\circ$W) since the 1900s. They include two other earthquakes with $M \geq 7.0$, an $M7.0$ Haiti earthquake in 2010, and an $M7.5$ Honduras earthquake in 2018. The $M_W$7.7 Caribbean earthquake appears to have been the most powerful event in this region. The mainshock appears to have occurred in a seismic gap along the Oriente fault, which is the western segment of the SOFZ. This was most likely a typical earthquake for this seismic gap (Fig. 1).

The yellow star denotes the epicenter of the 2020 $M_W$7.7 Caribbean earthquake, and the filled circles indicate historical earthquakes from the USGS earthquake database. The black beach balls show the focal mechanism of the $M_W$7.7 earthquake provided by USGS and GCMT. The black lines indicate the main tectonic-plate faults: MCSC = mid-Cayman spreading center, OFZ = Oriente fault zone, SFZ = Septentrional fault zone, WFZ = Walton fault zone, EPGFZ = Enriquillo-Plantain Garden fault zone, JRB = Jamaica restraining bend.
3 Data and methods

3.1 Earthquake and tsunami observation data

Following the $M_w$7.7 earthquake in the Caribbean Sea, various earthquake agencies quickly provided data and information. The USGS (https://earthquake.usgs.gov/earthquakes/eventpage/us60007idc/finite-fault) provided a finite fault model of the $M_w$7.7 Caribbean earthquake source based on the inverse algorithm (Ji et al. 2002) of the telesismic broadband waveform from the Global Seismic Network (GSN). The spatial distribution of the mainshock and aftershock sequences is depicted in the top panel of Fig. 2. A cross section of the slip distribution for the $M_w$7.7 earthquake is shown in the bottom panel. The largest slip on the fault plane is over 24 m. The slip on the Oriente fault zone is mainly strike slip, but there is a significant reverse slip component around the area of the largest slip. The slip around the Cayman Islands quickly decreases to zero due to interference from the Cayman Ridge. The Caribbean earthquake ruptured unilaterally to the west of the initial rupture point spanning 180 km along the strike of the Oriente fault zone. The rupture was concentrated mostly in the oceanic lithosphere at a relatively shallow depth of 5–25 km. The slip distribution revealed two distinct isolated asperity ruptures: a large slip patch 80–90 km away from the rupture nucleus, and a shallow small patch located at the termination of the rupture, where the west end of

![Figure 2: Map view of mainshock and aftershocks and cross-section of the slip distribution of the $M_w$7.7 Caribbean earthquake. Black lines denote the main faults. The mainshock and aftershock are denoted by a yellow star and filled circles, respectively. The solid red circle shows the largest aftershock ($M_w$=6.1). The color bar shows the slip amplitude. Black arrows indicate the slip direction.](image-url)
the Oriente fault zone connects with the Cayman Ridge. The spreading center may have obstructed the propagation of a forward rupture.

The source characteristics of the $M_{W}7.7$ earthquake in the Caribbean Sea indicate that this strong shallow earthquake had a predominantly left-lateral strike-slip motion, with a long surface rupture and concentrated energy release. The depth and shape of the seafloor around the earthquake source region are extremely complex. Even a minor seafloor uplift or subsidence has the potential to generate tsunamis. Using a tsunami simulation with a finite fault model provided by the USGS, this paper focuses on determining whether the tsunami was caused by vertical co-seismic deformation of the seafloor caused by a large strike-slip motion.

The General Bathymetric Chart of the Oceans (GEBCO_2020) with 15 arc-sec bathymetric data was used for the tsunami simulation. When the earthquake struck, two coastal tide gauge stations in George Town, Cayman Islands and Puerto Morelos, Mexico recorded clear tsunami signals. The tide gauge data were acquired from the Sea Level Station Monitoring Facility of IOC (UNESCO) website (http://www.ioc-sealevelmonitoring.org/list.php). To better identify the tsunami, we checked the sea level data for spikes or other potentially abnormal data and then removed the tidal contribution from the data using a least-square harmonic method from T-tide package with MATLAB (Pawlowicz et al. 2002). A band-pass filter was applied to remove high-frequency noise from the tsunami signals. This data pre-processing was only for extracting tsunami signals from raw data, not for spectral analysis. We used de-tided but unfiltered data for spectral analysis with Matlab wavelet toolboxes. The findings of this study are being considered in order to determine whether the tsunami was caused primarily by the earthquake’s co-seismic deformation or by non-seismic sources.

3.2 Tsunami numerical simulation

The Cornell Multi-grid Coupled Tsunami (COMCOT) model’s (Liu et al. 1998; Wang and Liu 2006) nonlinear shallow water-wave equation was used for numerical tsunami simulations using GEBCO bathymetric data with a resolution of 15 arc-sec. Tsunami waves (time series) with a time step of 0.5 s at coastal tide gauge stations were simulated using static vertical seafloor deformation calculated with Okada’s (1992) formula based on the earthquake focal mechanism solutions and finite fault source models provided by USGS. The simulated waveforms were compared with the available tide gauge station records. The Geoware’s (2011) Tsunami Travel Times (TTT) software was used to calculate first-arrival travel time in order to backtrack the potential tsunami sources.

4 What causes a micro-tsunami?

4.1 Tsunami simulation with a finite-fault source model

We considered only vertical displacement when calculating the initial sea surface height distribution at the tsunami source. The maximum vertical component for co-seismic seafloor displacement associated with the $M_{W}7.7$ strike-slip earthquake reached about 1.5 m and appeared 80–90 km southwest of the epicenter. The maximum uplift displacement close to the Cayman Islands was only ~0.5 m (Fig. 3a).
The distribution of the maximum tsunami amplitudes by numerical modeling (Fig. 3b) shows that the tsunami energy was mostly directed toward north and south of the Caribbean Sea. This can be attributed to the effect of tsunami directivity. The largest tsunami waves are expected at the normal direction to the fault strike. Since the source fault trends in a roughly E–W direction (Fig. 1), most of the tsunami energy is expected to travel in the N–S direction according to the directivity effect. The effects of bathymetric features on tsunami energy distribution are also evident in Fig. 3b. Some of the high-energy channels coincide with the locations of submarine seamount chains and ridges in the Caribbean Sea floor. We cannot verify the maximum tsunami wave height recorded in the direction normal to the fault strike due to the lack of tide gauge observation data.

Figure 4b shows a comparison of the observed and simulated waveforms of the 2020 Caribbean tsunami. Noticeable sea level fluctuations were recorded at the George Town
tide gauge station near the earthquake, ~280 km away from the epicenter. The recorded signals show two distinct phases: within and beyond 30 min of the origin time of the earthquake. The first phase of the signals was a leading depression wave, followed by a
maximum positive amplitude with higher frequency and short duration, resulting in a relatively short tsunami travel time (~5 min), as measured at the George Town station. The waveform that occurred about 30 min after the earthquake had the characteristics of low-amplitude, long period and continuous oscillation. The numerical simulation predicted that the tsunami waves would arrive at the George Town station about 25 min after the earthquake. The waveforms’ arrival and amplitude correlate well with the simulated waveforms. The numerical model, based on a finite-fault earthquake, was unable to fully reproduce the tsunami amplitude and arrival time recorded at the George Town station. The maximum heights of the simulated tsunami waves at George Town station are much smaller than those recorded by the tide gauge. The Morelos station, located approximately 860 km from the epicenter of the earthquake, detected weak tsunami waves after the earthquake. The observed and simulated waveforms had similar shapes and oscillation characteristics. Based on these comparisons, the $M_w7.7$ strike-slip earthquake could have resulted in a tsunami caused by co-seismic vertical displacement. It is worth noting that the tsunami simulation was insufficient to support the high-frequency tsunami wave shape and the short arrival time recorded at the George Town station following the early stages of the earthquake. Therefore, the characteristics of the first phase wave cannot be explained by numerical simulation of the earthquake-generated tsunami, and the early and late tsunami waves recorded at the George Town station may have been triggered by two completely different sources and mechanisms. The rapid arrival time of the tsunami waves indicates that the source was close to the George Town station. Furthermore, we did not account for the influence of the limited resolution of the bathymetry and topography data on the model, the uncertainties of the finite fault model, or the focal mechanism solutions.

4.2 Spectral analysis of sea-level observation waveform

Spectral analysis of tsunami waves may aid in determining the types of tsunami sources. Following the earthquake, we used a wavelet method to conduct a spectral analysis of sea-level observation from the tide gauge stations. We performed a wavelet analysis in Matlab using the Morlet mother function provided by Torrence and Compo (1998) to describe the features of the sea level time series. The global wavelet spectrum was provided by wavelet analysis. The wavelet parameters were set as follows. There were 20 octaves and 8 suboctaves per octave. A 95% confidence for a red-noise process with a lag-1 coefficient of 0.72 was specified. The colors of the left panel of Fig. 5 represent the intensity of the power spectrum, and the thick black line encloses regions with greater than 95% confidence for a red-noise process. The length of data used for the wavelet spectrum analysis was 450 min with data sampling of one minute for both the tsunami and the background signal.

Spectral analyses for the two tide gauge records are shown in Fig. 4. The energy distribution of the background noise at George Town station is relatively scattered. The temporal variability of the wave energy is concentrated within 30 min after the earthquake. The dominant period with maximum energy is ~2 min, which is shorter than that of the tsunami waves caused by the earthquake’s source (Higman et al. 2018). Such short-period waves are a hallmark of landslide-induced tsunamis. The later tsunami wave, which occurred ~30 min after the earthquake, had a larger energy period of ~10 min. The wave energy of the Morelos waves was concentrated in a period from 60 to 310 min after the earthquake. The significant dominant period of the tsunami waves was a period of ~30 min, around 180 min after the mainshock occurrence, which is longer than that recorded at George Town station.
The thick black line on the left plot indicates the 95% confidence interval of wavelet power.

Within minutes of the earthquake, the George Town station recorded an unusually short-period tsunami wave. The small tsunami waves could have been produced by non-tectonic sources. Bathymetric studies have shown that the Cayman Islands area has complex seafloor relief composed of horsts and grabens typical of a spreading center, abnormally deep rift valleys and mountains, and steep seafloor slopes (Holcombe et al. 1973; Leroy et al. 2000). These areas are prone to submarine landslides. Numerous videos and images shared on social media (https://www.dominicavibes.dm/news-262161/) show that sinkholes appeared at a number of places across the Cayman Islands in the aftermath of the earthquake. What causes sinkholes? Geological surveys indicate that the Cayman Islands have numerous caves and caverns, both above and below sea level, as a result of carbonates deposited and periodically eroded over the last 30 million years (Jones 1994). When the earthquake struck, the rocks above a cave or cavity may have collapsed and formed a sinkhole. We suspect that the tremors caused loose sediments or overlying rocks to move along the sloping ocean floor, resulting in submarine landslides or slumps. The tsunamis were likely generated by associated landslides. This process could be the cause of the obvious high-frequency large amplitude tsunami waves recorded at the George Town station in the Cayman Islands after the quake (Fig. 6).
4.3 Potential source locations and source length of landslide

According to the reciprocity principle, the estimated travel time from a tsunami source location to a receiver location is similar to the estimated time from an exchange location. This backward tsunami ray tracing is used to narrow down the scope of possible sources of the high-frequency tsunami observed in the Cayman Islands after the January 28, 2020, $M_W7.7$ Caribbean earthquake. Although tide gauge measurements for the Cayman Islands are limited, with only one station, tsunami ray tracing may help to narrow down the potential tsunami source locations to supplement post-tsunami surveys (Williamson et al. 2019).

Using the location of the George Town station as a hypothetical tsunami source, a tsunami propagation time of approximately 8 min was modeled. The margins of the tsunami travel distances after ~8 min defined the potential source locations (Fig. 7). A short tsunami propagation time at the George Town station indicates a potential source close to the Cayman Islands. The contour of the travel time estimation suggests that the tsunami source could have been located within circle centered on the George Town tide gauge with a 150 km radius. The possible tsunami source circle is far from the region of concentrated energy release from the $M_W7.7$ earthquake, ruling out the possibility that the high-frequency tsunami was generated by co-seismic displacement. In light of the large initial negative wave at the George Town station, we deduced that the source region must have involved significant seafloor subsidence.

Submarine landslide or slump source dimensions could be estimated based on the dominant period of tsunami equation proposed by Heidarzadeh and Satake (2015):

$$L = \frac{T}{2} \sqrt{gH}$$

where $L$ is the length of the source, $T$ is the dominant period of the tsunami, $g$ is the acceleration of gravity ($g=9.81 \text{ m/s}^2$), and $H$ is the average wave depth. A source length of
5.85 km can be estimated from a tsunami dominant period of ~2 min and a water depth of 3.5 km for a circle with a 150-km radius centered at the George Town station.

The red triangle denotes the location of the George Town station as a hypothetical tsunami source. The tsunami travel time estimation is indicated by the white line, and the possible location of the tsunami source is indicated by a black arrow. The thick red line and arrow show the length and propagation direction of rupture of the $M_W7.7$ Caribbean earthquake, respectively. The black ellipse marks the location of the concentrated energy release, and the epicenter of the mainshock is denoted by a yellow star.

Fig. 7 Tsunami travel time ray tracing in the area of the George Town station using GEBCO_2020 bathymetric data

5 Discussion and conclusions

On January 28, 2020, an $M_W7.7$ earthquake struck the Caribbean Sea, triggering a small-scale tsunami. This study integrates investigations of the regional tectonic setting, earthquake source parameters, tsunami numerical simulation, and spectral analysis to investigate seismogenic fault characterization and to find out whether or not the small-scale tsunami was generated by a tectonic source.

The GCMT and W-phase moment tensor solutions for the $M_W7.7$ Caribbean earthquake indicate a strike-slip event with an E–W trend, consistent with an earthquake occurring along the Oriente fault zone on the plate boundary between the North American and Caribbean tectonic plates. According to the USGS’ finite fault model solutions, the earthquake rupture propagated predominantly unilaterally in the shallow oceanic lithosphere, starting from the epicenter and extending approximately 180 km westward. The main rupture areas were concentrated around 80–90 km west of the epicenter. The maximum slip was ~24 m, and there was a small unclear patch distributed at the end of the rupture.
For the first two months after the mainshock, the aftershocks occurred primarily west of the mainshock near the Cayman Islands, within a much larger zone of 170 km along the Oriente fault. The largest aftershock, with a magnitude of 6.1, struck near the end of the rupture zone less than three hours and about 200 km away from the epicenter of the mainshock. The $M_w 6.1$ aftershock’s focal mechanism solution (strike = 248° dip = 53° rake = 52°) shown in Fig. 2 indicates that the earthquake occurred on a reverse fault characterized predominantly by compressional displacement. The different focal mechanisms suggest that the rupture of a strike-slip earthquake caused by the Oriente fault zone intersecting and terminating against the Cayman Rise could affect the fracture mode of the largest aftershock. The strike-slip displacement moved into the Cayman Rise, causing stress to build up and release in a branch fault from a larger strike-slip fault.

When the simulated tsunami waves were compared with the observed waves, it was clear that the $M_w 7.7$ strike-slip earthquake generated co-seismic vertical displacement components that yielded an insignificant tsunami. The co-seismic rupture of the $M_w 7.7$ strike-slip earthquake also contributed to the observed water levels from the tide gauge. However, it is clear that the heights of the simulated tsunami waves at the George Town station were much lower than those recorded at the tide gauge station, implying that the small-scale tsunami was not generated solely by a tectonic source. According to the spectral analysis of the sea-level observation waveform from the George Town station, the tsunami dominant period was $\sim 2$ min, which is much shorter than the period caused by a tectonic source. Considering the geological features of the Cayman Islands as well as videos and images from social media shared after the earthquake, we concluded that the massive earthquake may have triggered submarine landslides or slumps that resulted in a local tsunami.

Based on backward tsunami ray tracing analysis, the possible tsunami source could have been located within a circle centered on the George Town tide gauge with a 150 km radius. Based on the USGS shaking intensity model using the Modified Mercalli Intensity (MMI) scale (https://earthquake.usgs.gov/earthquakes/eventpage/us60007idc/shakemap/intensity), it is likely that the intensity of the shaking observed was $> VI$ in the rupture propagation direction. However, this high shaking intensity resulted in few significant landslides. Most of the potential source locations were near the Cayman Islands, in the direction of the earthquake’s rupture. Due to the scarcity of available tide gauge, sea level, and bathymetric data, we could trace only the approximate domain of the tsunami source. Future work should include multibeam bathymetric sonar, side-scan sonar, seismic sounding profiles, and other techniques to investigate the actual submarine landslide or slump locations.

According to National Centers for Environmental Information/World Data Service (NCEI/WDS, 2019) global historical tsunami database, at least 26 tsunami events have occurred in our study area over the last 400 years. These events have caused large tsunamis with maximum wave heights of up to 3.21 m in the Caribbean coastal area. Throughout the entire study area, most of the tsunamis occurred along the SOFZ and the EPGFZ. On June 7, 1692, a devastating earthquake struck Port Royal, Jamaica, causing a landslide in the Royal Harbour area and triggering a tsunami with maximum wave heights over 1.8 m. Ninety percent of the city sank below sea level and close to 2000 people died as a result of the earthquake and the subsequent tsunami (Lander, et al., 2002; Parsons & Geist 2008). The 1842 Cap-Haitian earthquake with a magnitude of 8.1 triggered a destructive tsunami that devastated the northern coast of Haiti and part of the Dominican Republic, killing about 300 people. The 2010 Haitian earthquake, with a magnitude of 7.0, was followed by a deadly local tsunami, which killed at least seven people. According to previous research, the tsunami waves were caused by underwater landslides (Hornbach et al. 2010; Poupardin et al. 2020). There have been at least six landslide-generated tsunamis in the Caribbean.
Sea near the $M_w$7.7 earthquake, accounting for 23.1% of all tsunami events. According to the NCEI/WDS global historical tsunami database, only 3% of global historical tsunami events are associated with submarine landslides. Most of the landslide-induced tsunamis are closely related to the northern Caribbean’s geological structure and tectonic setting.

The black solid line shows the main boundary fault in this study area, colored circles indicate the distribution of historical tsunami sources, and red (earthquake-generated tsunami) and green (landslide-induced tsunami) colors indicate the type of tsunami source. The numbers on the circles represent the maximum tsunami heights. The historical tsunami data are from the NCEI/WDS global historical tsunami database, and the focal mechanism solutions are from the GCMT.

Since 1900, two other earthquakes of $M > 7$ have occurred in the vicinity of the Caribbean earthquake epicenter, including the $M$7.0 Haiti earthquake in 2014 and the $M$7.5 Honduras earthquake in 2018 (Fig. 8). These earthquakes, along with the $M_w$7.7 Caribbean earthquake, occurred as a result of strike-slip motion and generated small-scale tsunamis with maximum wave heights of 3.21 m, 0.4 m, and 0.11 m (Tanioka et al. 2020). Small-scale tsunamis from large strike-slip earthquakes on the northern Caribbean margin are real and have been documented. Sufficient evidence exists to suggest that the Caribbean and neighboring regions face a high potential tsunami risk from earthquakes or submarine landslides. Therefore, tsunami hazards from strike-slip earthquakes or submarine landslides should be considered as part of tsunami vulnerability and risk assessment in the Caribbean and adjacent regions, particularly in densely populated coastal areas.

Since tsunami waves propagate at a much slower rate than seismic waves, it is possible to issue tsunami warning information quickly after a major undersea earthquake occurs. However, not all major earthquakes can cause tsunamis. Therefore, it is difficult to accurately and rapidly forecast whether an earthquake will cause a tsunami, especially if it is induced by an uncommon tsunamigenic source such as a direct strike-slip earthquake or

![Fig. 8] Historical tsunamis in the study area over the past 400 years
a secondary underwater landslide. In addition, the geometric complexity of the strike-slip fault system can trigger multiple rupture segments, resulting in a complex rupture evolution. These factors create additional challenges to tsunami risk assessment and tsunami warning.

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