Tsunami Potential of the Enriquillo-Plantain Garden Fault: Past, Present, and Future

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Jamaica and the Tiburon Peninsula: an analog for Northern Haiti

• Jamaica and Southern Haiti rest at the boundary between the Caribbean and Gonave microplate.

• The nature and location of this plate boundary across Jamaica and Haiti is not well constrained (e.g. DeMets & Wiggins-Grandison, 2007; Calais et al. 2010; Hayes et al; 2010).

• “In the past 300 years, Jamaica has been struck by several tsunamis.” Really?

(Wiggins-Grandison and Atakan, 2005)
Historic Tsunamis in Jamaica: an apparent paradox

Why so many tsunamis when...

1. Low regional seismicity
   (Mw 7.0 recurrence interval ~300 yrs)
   (DeMets and Wiggins-Grandison, 2003)

2. Predominantly SS faulting

3. Several major faults on land
   *(but are we sure?)*

4. Relatively sheltered from most far-field tsunami

EQ: Greater than Mw ~5 in past 50 years
Jamaica’s surprisingly rich tsunami history

- As many as 8 reported tsunamis since English occupation in 1655.
- Some may be storm surges, but most associated with regional earthquakes
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(Ann. Reg., 1781; Poey, 1857)
(e.g. Mallet, 1855)
(Tomblin & Robson, 1977)
Jamaica’s surprisingly rich tsunami history

- As many as 8 reported tsunamis since English occupation in 1655.
- Some may be storm surges, but most associated with regional earthquakes.
- At least two high-quality tsunami reports, but probably a minimum of three tsunami in the past 300 years in Jamaica.

(Philosophical Transactions, 1694)
(Ann. Reg., 1781; Poey, 1857)
(e.g. Mallet, 1855)
(Tomblin & Robson, 1977)
(Hall, 1907; Fuller, 1907; Brown 1907)
Commonalities between Past Jamaican (and Haitian) Tsunamis

1. Wave arrival within minutes (or less) of the EQ, often on opposite sides of the island.

2. Draw-down followed by run-up typically observed.

3. Liquefaction and along-shore slope failures often exist where tsunamis came ashore.

4. Moderate EQs (some--1907, 1860--less than Mw 7) triggered events.

Several commonalities are consistent with slide-generated events and match accounts of several historic Haitian tsunamis as well.
Haiti 2010: tsunamis on the Northern Tiburon Peninsula occurred adjacent to slides

(adapted from Hornbach et al., 2010)
--Observation of rapid draw-down followed by large wave within 1-3 minutes of EQ
--all of coast uplifted, but some areas significantly more affected by wave.
Extending across the Gonave Microplate . . .

Past Tsunamis:
--Nine potential events in the past ~300 years: On average, one every ~30 years.
--Yet recurrence intervals for significant (>Mm 7) EQ is long (300-1200 yrs) (e.g., ten Brink et al., 2013; Prentice et al. 2003).

Two working hypotheses:
(1) Perhaps we are underestimating the frequency/magnitude/complexity of regional EQs.
Alternatively, (2) perhaps we are underestimating the potential for smaller EQs inducing slide-generated tsunamis?

--to constrain tsunami risk, we must constrain not only regional tectonics and seismicity but slope stability.
Present (and Future) Tsunami Risk: A case study of Kingston, Jamaica
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Testing part II of the hypothesis: How much ground shaking is needed to trigger slope failure along the coast of Port Royal?
Some Background on Kingston

1. Population is ~1 million (>1/3 the nation).
2. Civil, economic, and cultural center of Jamaica.
3. Two (perhaps as many as four) tsunamis reported here in past ~350 years, with two that were damaging, in areas of now dense urbanization.
Key Project Goals

1. Search for young/unrecognized active faults

2. Determine areas in harbor most susceptible to slope failure, liquefaction, and tsunamis.

3. **Quantify Risk.**

5. Educate, inform, and work with Jamaican citizens, government, industry, and academia to increase awareness and prepare for future earthquakes in this region.
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Chirp Track Lines (2009)
Chirp Seismic Survey Results:
Evidence for active deformation and a possible blind fault in the harbor

( adapted from Hornbach et al., 2011; McDonald et al., in Prep)

In the east, Long Mountain is likely active. Our most recent survey (2013) suggests a network of older relatively inactive faults also exist in the Harbor to the west. Fault system is BROAD AND DIFFUSIVE.
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Primary Factors Defining Slope Stability and Liquefaction

Peak cyclic shear (PGA)
Requires knowing:
- regional seismicity
- Location/orientation of active faults
- regional geology (and response to shaking)

Onshore/offshore slope angle and subsurface structure
Requires good surveys
(Lidar/Multibeam/chirp/seismic)

Sediment physical properties
Requires knowing:
- porosity
- density
- grain size (and roundness)
- grain type (clay vs. sand ratios)
- permeability
- Shear strength

In-situ pore pressure
Typically via
- Consolidation tests
- Vp/Vs measurements
- Sedimentation models

Once we have these data, we develop risk assessment models.
Port Royal Example: Pseudostatic inertia slope stability analysis using iterative (Monte Carlo) methods

Slope: 5-15 deg.
C = 0-10kPa
Porosity = 35 – 55%
Sediments= 90% sand (+/- 10%)
Pressure= hydrostatic

--Assumes Shear strength is maintained (no liquefaction). This is a best-case scenario.

For 6 million iterations in radius and headwall location:
FS=~2.04
PGA= ~0.25g

(McDonald et al., in prep)
Port Royal Example: Liquefaction Analysis

Port Royal: CRR/CSR Liquefaction analysis

PGA required for liquefaction at Port Royal (FS<1):

\[ \text{PGA} = 0.098g - 0.148g \]

(Mw 7.5 – Mw 5.25)

(methods from Seed et al., 1975; Kayen et al., 1992)
Placing Port Royal slope failure results in context

Slope failure will occur for ruptures as distant as

- ~20 km $\rightarrow$ Mw $>$ 7 EQ
- ~11 km $\rightarrow$ Mw 6 EQ
- ~5 km $\rightarrow$ Mw 5 EQ

Liquefaction will occur for ruptures as distant as

- ~50 km $\rightarrow$ Mw $>$ 7 EQ
- ~23 km $\rightarrow$ Mw 6 EQ
- ~12 km $\rightarrow$ Mw 5 EQ

In Short: A Mw 6-7 EQ within ~20 km of Port Royal can trigger both liquefaction and slope failure

(Adapted from Campbell and Bozorgnia, 2008)
Placing Port Royal results in context

Seismicity in Jamaica (2004-2009)

Using Gutenberg-Richter laws, the EPGF-Wagwater Fault in Eastern Jamaica experiences on average a Mw 6 event near Kingston once every ~162 yrs +/- 65 (1-sigma). This implies a ~100-200 year recurrence interval for slope failure (and potential tsunamis) at Port Royal (McDonald et al., in prep).
Why is Port Royal so susceptible to slope failure and tsunami generation?
A call for more quantitative geomorphology
Erosion/Deposition for the last 120 years (1887-1990): (McDonald, et al., in prep)
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- Dredging for Container Ships
- Dredging for Runway

(McDonald, et al., in prep)
Erosion/Deposition for the last 120 years (1887-1990):

10 -10 0 meters

Dredging for Container Ships

Dredging for Runway

(McDonald, et al., in prep)
Erosion/Deposition for the last 120 years (1887-1990):

Shoreline progradation: >2 m/yr

(McDonald, et al., in prep)
Conclusions

- Landslides (hypothesis 2) represent a potentially significant source of past tsunamis along the EPGF system. Moderate magnitude (< Mw 7) can trigger such events, and occur more frequently. (For Port Royal, even regional Mw 5-6 can trigger limited liquefaction).

- Assessing the risk of seismically-generated tsunamis (ie. hypothesis 1) remains a challenge due to limited constraints on regional tectonics.

- Quantifying the risk of future tsunamis at the EPGF (and Northern Haiti) requires not only better constraints on seismicity and tectonics, but slope stability via detailed geophysical analysis.

- Focus sites for tsunami/slope stability analysis should include not only river deltas but shallow submarine environments and prograding coastlines near population centers.
Thank You
Why So Many Slide-Generated Tsunami?

Areas in Haiti with highest sedimentation most susceptible to failure

--- Most slides occurred at/near river deltas

(Hornbach et al., 2010)

~3 m/yr shoreline progradation near river mouth

shoreline locations
Jan. 2010  May 2005

Fissuring of the sand at the base of the Palisadoes spit (source, West Indies Reference Library)
1. At least three tsunami along the Gonave Microplate (1/3 of all reported) are linked to slope failure.

2. Two of these events (1907, 2010) that triggered large waves involved EQ with magnitudes borderline for coseismic tsunami generation.

3. Shoreline slope failure in Haiti and Jamaica generally occurs in areas where steep-slopes and high sedimentation rates exist (Deforestation may be a red-herring).

4. Given the frequency of slide-generated tsunami, and the minimal magnitude required to trigger slope failure along this plate boundary, we are substantially underestimating the likelihood of slide-generated tsunami in these environments.
Haiti may not be the worst case scenario.
Shelter from Tele-tsunami: class project results:

--wave coherency often breaks across island arcs and hot-spot chains

--this is precisely why places like Tonga have historically very few reports of tele-tsunami (and places like Hawai’i are frequently bombarded.)
Key results of land survey:

- Shoreline experience (tens of cm), BUT no clear surface rupture or fault trace (See Prentice et al., 2010, and Hayes et al. 2010)
- Most co-seismic slip was on land.
- Deeper transpressive fault(s) north of main trace probably activated but

Colored areas show estimated coseismic slip (Hayes et al., 2010)
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The Search for Active Faults near Kingston Jamaica:

--GPS indicates steady reduction in motion from North to South; East to West
--Motion fails to converge to zero even off shore (ie. plate boundary location is unclear)
--What faults accommodate strain?
The Search for Faults and Slides near Kingston

-- JSN has recorded 32 shallow EQs >Mw 2 near Kingston in the past 12 years

--to determine if a trend exists, we conducted a smooth bootstrap statistical analysis. This suggested EQs occur along a preferred strike of 135 +/- 30 deg. (2 sigma).

--statistical simulations of EQs at this site indicate that there is ~91% probability that this trend is not a random occurrence (although better error ellipses still needed).

--Trend is consistent with regional fault strikes but fail to clearly follow known faults.
The Search for Active Faults near Kingston Jamaica:

Seismic data, GPS, and marine Chirp all support active deformation in and around Kingston Harbor since the last deglaciation (~14-21k).

Detailed chirp analysis and future sediment cores will further constrain timing.
--clear offsets exist along the EPGF
--This offset is recent (seafloor bulge, plus, sedimentation rates are high)
--If it didn’t activate in 2010, this fault activated recently (1770 EQ?)
Maximum Wave Amplitude of Slide-Generated Tsunami Model

Modeling Method/Assumptions:
--Non-linear Boussinesq wave-equation, Finite-Difference Leap-Frog Approach (e.g. Wie and Kirby, JWPCOE, 1995)
--Translational slides moving perpendicular to slope (acceleration dependent on slope angle)
--one-way vertical coupling of seafloor deformation to ocean.
--50 x 50 m cells
Slide-Generated Wave Amplitude, Phase, and Timing, Generally Match Observations

Maximum amplitude of slide-generated tsunami

Areas reporting largest tsunami

Baie de Grand Goâve

Beloc reef

Petit Goâve

Grand Goâve

L’Acul reef

Approximate slide location and direction
Fitting coseismic surface deformation using a half-space solution (Okada, BSSA, 1985) to observed coastal uplift (least-squares iterative approach):

- Dip = 64 deg (65% strike-slip, 33% thrust consistent with reported USGS focal mechanism)
- Strike = 82 deg (consistent with offshore faults)
- Scalar moment = 10^{19} Nm,
- Fault centroid depth = 10 km
- Fault length = 35 km
- Fault width = 10 km
- Fault center = 72.72 W, 18.49 N

This produces a coastal uplift consistent with shoreline uplift observations.

--We use this for earthquake tsunami modeling

--Earthquake may have played direct role in tsunami formation (explains sustained draw-down and smaller, distal wave reports). . . .
A Combined Model Offers the Best Explanation for the Tsunami

--Slides explain focused, severe run-up

--coseismic deformation explains broad regional drawdown

(Hornbach et al 2010)