RAPID: Collaborative Research: Offshore coseismic effects of the Port au Prince earthquake, Haiti

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Intellectual Merit: The national catastrophe in Haiti calls for an immediate response from the geoscience community. Urgent field research includes offshore areas of Haiti where some of the active and seismogenic structures associated with the broad plate boundary have their expressions and a tsunami was generated. We propose a survey of faults and related structures along the coast of Haiti in the vicinity of the January 12 rupture. This rapid response effort will provide a critical contribution to the near surface effects of the earthquake offshore and the characterization of seismogenic structures. We will survey the offshore portion of the main rupture and of some of the secondary structures associated with it along the southern peninsula and the Baie de Port au Prince. We propose a 21 day survey (~16 days of survey and 5 of transit) to make shallow water (<300 m) multibeam maps, acquire coincident and targeted sidescan, chirp (0.5-12 kHz) profiles, and conduct spot coring. Ephemeral structures related to the earthquake should be mapped before they are erased by shallow water processes and storms. The survey will concentrate along the Baie de Port au Prince and along the southern coast of the Canal de Sud.

The M7 January 12 mainshock ruptured a relatively small segment of the Enriquillo-Plantain Garden fault zone (EPGF), the southern of two parallel E-W sinistral transforms accommodating most of the motion between the North America and Caribbean plates. The EPGF follows the core of the southern peninsula and is associated with several large historic earthquakes, but its pre-1700's paleoseimicity is unknown. A number of NW-SE faults and folds intersect the EPGF and may also be active. Many of these structures are unmapped, especially offshore, including a possible one in the Baie de Port au Prince. Reliable models of strain accumulation and seismogenic release along the EPGF are urgently needed. They require improved characterization of the ruptured EPGF segment, including the 20km long offshore part. No rupture has yet been found on land; did it reach the sea floor? The proposed offshore survey will contribute to mapping the fault and characterizing coseismic features along it from this earthquake and possibly from paleoseismic ruptures. Interferograms of the earthquake and a small tsunami and coastal subsidence near Grand Goave show that considerable motion was offshore in our proposed study area.. Thus a rapid-response marine geophysical data acquisition and sediment sampling in Haitian waters will contribute to the growing multinational scientific response to the disastrous earthquake. We are in direct communication with most of this effort. The marine survey is urgent, not only because civic authorities now require advice from earthquake experts, but also because the survey needs to capture detailed sea-floor features related to rupture and mass wasting. They include scarps, offset sedimentary or erosional features, such as channels, gas-escape and related bacterial mats. Terrestrial sediments from the earthquake can be identified with ^{7}Be (half-life 53 days). All these features are short-lived in the energetic shallow-water environment of the shelf. Such features will be important in investigating the nature of the localized tsunami near Grand Goâve-Fouche. It may have originated from vertical coseismic motion at the EPGF, on a secondary fault, or may mark a submarine slump triggered by shaking.

Broader Impacts: Of critical and timely importance is direct information about the January 12th earthquake and implications for future geohazards to the government of Haiti and neighboring countries as well as the science community. We intend to integrate the geoscience community of Haiti and potentially Haitian-Americans into the sea-going expedition. We are in contact with the Director of Mines and Energy who has expressed interest in sending a Haitian geologist to join the research cruise and by extension aid local natural hazards education and mitigation. Scientific progress during the survey will be broadcasted by the PIs via blog-sties to students in undergraduate and graduate classes currently being taught by PIs at CUNY, UMissouri, and UT-Austin to illustrate for them the myriad applications of marine geosciences. The proposed research will help to initiate and develop exchange programs by which Haitian students could come to Queens College and other CUNY colleges for studies and interact with the large Haitian community in Queens and New York City.

Introduction: The national catastrophe in Haiti calls for an immediate response from the geoscience community. Urgent field research is needed in the offshore areas of Haiti where some of the active and seismogenic structures that are associated with the broad plate boundary, and with the Jan 12, 2010 earthquake, have their expressions (Fig. 1). Satellite interferometry indicates that vertical deformation was centered in the offshore region west of the Léogâne delta, and a tsunami was generated in this region. The following is a preliminary justification and plan for a survey of faults and related structures in shallow water (<300m) along the coast of Haiti, focusing in the vicinity of the January 12 mainshock rupture. Mapping the offshore ephemeral structures related to the earthquake before they are erased by time and storms will provide much needed information on that rupture.

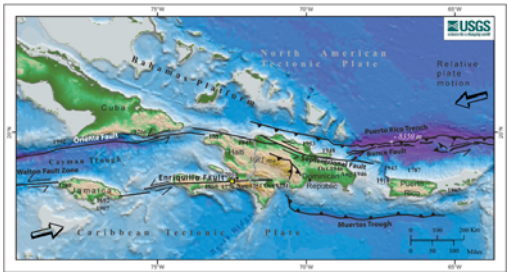
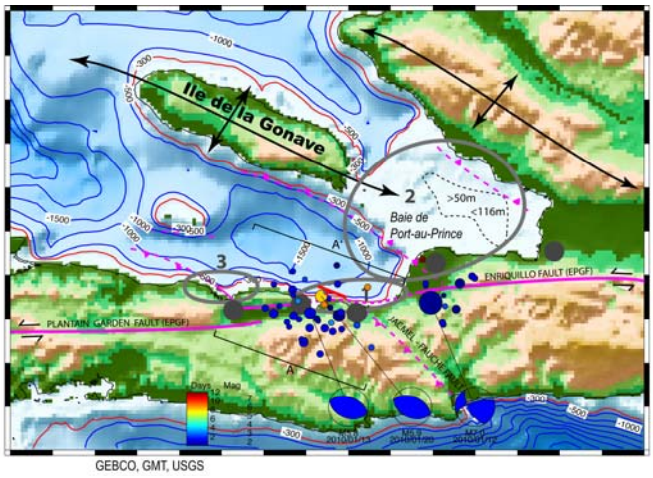


Fig. 1. Northern margin of the Caribbean plate where the Gonave microplate is bounded to the south by the left lateral transform Enriquillo-Plantain Garden fault (EPGF) where the Jan 12, 2010 earthquake occurred. Haiti is characterized by high relief and by deep basins that suggest localized subsidence as well, particularly in the enclosed basins offshore. The main EPGF fault follows the core of the southern peninsula, which appears to be an active transpressional structure.

General Setting: The transform boundary that forms the northern margin of the Caribbean plate consists of two strands for much of its length, defining the Gonave microplate between them (Fig. 1) (Mann et al., 1995). The southern branch of the sinistral transform consists of a number of ~E-W striking contiguous fault segments through southern Haiti, which are known collectively as the Enriquillo-Plantain Garden fault zone (EPGF). Several large historic earthquakes are associated with the EPGF (e.g., 1751, 1770, 1860). Strain is partitioned: the master EPGF absorbs the sinistral motion and secondary thrust faults and related folds striking ~WNW-ESE absorb the shortening. Activity of these secondary structures is manifested by ridges that are oblique to the transform (Fig. 2), many marked by uplifted terraces. Some of these branch faults, such as a possible one in the Baie de Port-au-Prince are unmapped and have not been included in Coulomb stress models (e.g., Lin et al., 2010). Tsunamis were associated with large historic earthquakes (e.g., Lander et al., 2002) and a local one occurred on Jan 12, 2010. The latest manifestation of secondary thrusting is in the ongoing aftershock sequence with numerous thrust focal mechanisms occurring in the western part of the main rupture. This may also explain the coastal uplift mapped last week by P. Mann, E. Calais, and R. Bihlam. These secondary faults are important because: 1) they can be sources of future large earthquakes and 2) these faults can warp and segment the master fault.

Fig. 2. Proposed survey areas 1, 2, 3 (in order of priority) are within the gray ellipses. The survey will extend to ~ 300 m contour. 1 contains the submarine portion of the EPFG where coseismic rupture could have reached the sea floor. 2 is a large shallow area of the Gonave Gulf that contains an isolated basin, which is likely to be maintained by subsidence and active structure(s) given the abundant sediment supply. 3 is the intersection of a NW-striking thrust (?) fault and the EPGF. The star and small red circles are the mainshock and aftershock epicenters (USGS).



M7.1 12 Jan 2010 rupture of the EPGF: This rupture is steep and primarily left lateral with a minor reverse component. The surface geology at the western end of the Jan 12 rupture shows an extensional

jog, where the Microgoane Lake pull-apart structure forms the segment boundary. The aftershocks are strongly concentrated at the western end of the rupture and they are primarily from thrust fault(s?) striking NW. The aftershocks are thus not on the EPGF and point toward a transpressional western boundary to the mainshock rupture. The most immediate concern aside from the continuing aftershocks themselves is the possibility of triggering a large rupture of the next segment of the EPGF to the west.

Inferferograms the earthquake area (Fig. 3) display ellipses of line-of-sight motion that are centered on this offshore region. A surface rupture has not yet been identified. However, about 17 km of the segment that ruptured is offshore. A localized tsunami and permanent subsidence was reported on the coast just east of Grand Goâve, facing the offshore part of the EPGF. In turn, corals have been raised just above the sea surface at the periphery of the Leogane fan delta. Thus, a primary candidate for surface features associated with the January 12 earthquake lie offshore.

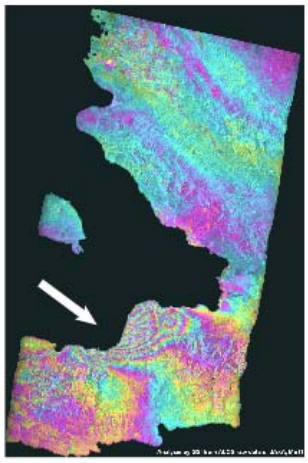


Fig. 3 PALSAR Interferogram constructed from radar imageries acquired before and after the Jan 12, 2010 earthquake. Closely-spaced color fringes indicate areas of enhanced ground deformation. One full color cycle indicates 11.8 cm of deformation in the direction of the satellite line-of-site (WNW-ESE in this case). http://vldb.gsi.go.jp/sockuchi/sar/result/sar_data/urgent/20100112_haiti-e.html. This interferogram shows little vertical motion on the eastern part of the main shock, but considerable vertical motion on the western part of the rupture zone at the coastline. In addition, there is significant motion seen in the Léogâne fan delta where surface mapping reveals considerable lateral spread and liquefaction.

Intellectual Merit & Need for a Rapid-Response Cruise: Improved time-space models of strain accumulation and seismogenic release along the EPGF are urgently needed. They require (1) improving maps of the EPGF in the rupture area and near its termini, (2) determining whether the rupture reached the surface, (3) characterizing the rupture pathway offshore and onshore, (4) establishing the paleoseismic record of the EPGF, (5) determining what secondary faults may be involved in the transpression manifested by the aftershocks, (6) determining how such a secondary fault interact with the transtensive jog further west, and (7) investigating the origin of the tsunami and patterns of subsidence and uplift. Onshore efforts include mapping the surface deformation and search for fault scarps (P. Mann, R. Bilham), resurveying of all GPS sites in Haiti and the Dominican Republic (Calais et al.), Coulomb stress modeling (Lin et al.; Calais), imagery of the damage (JPL, DLR, SERTIT), interferometric studies (Hong et al., Fielding et al., JAXA, DLR). Many of these efforts can be accessed via links from http://www.unavco.org/research_science/science_highlights/2010/M7-Haiti.html. We are in direct communication with Charvis et al. that are deploying OBSs from the French vessel L'Atalante

Offshore mapping is needed and must to be integrated with the multinational scientific response to the disastrous earthquake that has been started using satellite data and onshore field work. We propose to provide a critical contribution to addressing these questions with a rapid-response marine geophysical survey and spot coring of the offshore portion of the EPGF and of some of the secondary structures associated with it. Our focus areas (Fig. 2), in order of priority are (1) the offshore segment of the EGPF with likely vertical motion and where a tsunami was generated, (2) the Baie de Port-au-Prince including the Léogâne delta with lateral spreads and the possible tectonic basin in the center of the bay, and (3) the western end of the rupture and juncture with other fault segments. We propose a 21 day survey to make shallow water (<300 m) multibeam acquired coincidently with sidescan and chirp subbottom (0.5-12 kHz) data. We will supplement this survey strategy with targeted profiles run perpendicular to structure and fault related and deeper tectonic basins where we will conduct spot coring.

Marine data acquisition in Haitian waters is urgent, not only because civic authorities now require competent statements from earthquake experts in this data-starved area, but also because the survey needs

to capture detailed features that may be related to seafloor rupture and mass wasting. They include scarps, offset sedimentary or erosional features, such as channels, or even anchor drags, gas-escape and related bacterial mats. Terrestrial sedimentation from the earthquake can be identified with ^{7}Be (half-life 53 days). *All these features are ephemeral in the energetic shallow-water environment of the shelf.* In addition to mapping fault strands and whether or not they ruptured, such features will be important in investigating the nature of the localized tsunami near Grand Goâve. It may have originated from vertical coseismic motion at the EPGF (e.g., Sladen 2010, Hong et al., 2010) or on a secondary thrust, or may mark a submarine slump triggered by shaking or coseismic motion along the EPGF (Fig. 4).

Capturing the signature of large submarine earthquakes is important as a "ground truth" for subsequently recognizing similar buried features associated with earlier earthquakes and thus being able to read the offshore paleoseismic record. This is critical because little is known about the paleoseismic history of the EPGF beyond the 1700's. The region in Haiti is similar to other strike-slip related basins in the Marmara Sea and California Borderland and so insight gained in Haiti can be applied to ongoing NSF and USGS-funded projects in California Borderland and Turkey. The EPGF is contiguous from Haiti to Jamaica and implicated in the Jamaica earthquakes of 1692 and 1907, and each of these also caused local tsunami. An SEG funded UTIG study to investigate the Jamaica faulting to take place in March-April of this year. The combination of the Haiti RAPID effort and this Jamaica study could be significant for interpreting the geohazards of the EPGF system and northern margin of the Caribbean plate.

Work Plan: Our team includes personnel with a wide variety of expertise in multiple types of marine data acqusition, seismology, marine paleoseismology, tectonics, stratigraphy, tsunami modeling and Haitian geology. Personnel include C. McHugh, L. Seeber, J. Diebold and M. Steckler (LDEO), S. Gulick and M. Hornbach (UTIG), M. Cormier (University of Missouri) and C. Sorlien (UCSB). We are proposing a 21 day expedition (16 days of survey and 5 days for transit). The fieldwork will produce a multibeam bathymetry map of the field areas with coincident sidescan images and chirp sonar profiles. Multibeam profiles and sidescan tracks will primarily be contour parallel, and not optimally oriented for subbottom profiles. Therefore, after mapping the seafloor, we will acquire targeted chirp profiles orthogonal to structure using the multibeam to locate and orient the profiles. Subbottom profiles collected during the first part of the cruise will help establish a grid profiles enabling us to correlate reflectors and map near-surface faults within each region. Finally, we will identify coring sites for geologic interpretation, to begin to extract the paleoseismic history of the region and determine a chronology. The >100 m deep elongated basin in the Baie de Port au Prince may contain a valuable paleoseismic record of earthquakes in the Port au Prince region, which we will target for coring.

Multibeam bathymetry: We propose to lease a portable multibeam bathymetric sonar to be mounted on a pole alongside the ship. The system we are considering is the Reson SeaBat 8101ER. That system is a 240 kHz system capable of comfortably mapping seafloor as deep as 300m (technically, as deep as 450 m). As most modern system, it acquires data over a 150° angle, corresponding to a swath width up to 7 times the water depth. In practice, the outer beams are commonly too noisy for inclusion in the final map, so we will plan our survey with a 20% swath overlap, ensuring the production of a quality maps. The data will be processed at sea in near-real time using the NSF-supported software MBsystem. This system is the same as that available with the UNOLS *R/V HUGH SHARP*, and PI Cormier has already analyzed multibeam data acquired with that ship in Long Island Sound.

Side scan sonar: In addition to depth sounding, most modern multibeam bathymetric sonar systems also produce "backscatter" imagery. Similarly to true sidescan sonar imagery, these backscatter data provide very useful information about seafloor texture to complement topographic data. The Reson SeaBat 8101ER, does provide such backscatter data. However, true sidescan sonars provide higher resolution, crisper imagery, commonly detecting objects as small as cables, anchor drag marks, and hairline cracks. Hence, we propose to also tow the sidescan sonar owned by the University of Missouri - Columbia. That sonar system, a Klein 3900, includes a 100m-long cable, a GPS, and a motorized winch, and can be run using a set of AGM marine batteries, making it a stand-alone system that can be operated from any ship of opportunity. It is appropriate for work on continental shelves (up to 100m water depth), and should provide invaluable data off the Leogane delta where lateral spreading, coral uplift, and a tsunami

occurred. While at sea, Cormier and MU graduate student will mosaic the sidescan sonar data with the software SonarWiz to guide the operations, especially for siting of gravity cores or dredges. After the cruise, she and the MU graduate student will collaborate with the team to precisely co-register all the data that will be acquired and for their joint interpretation.

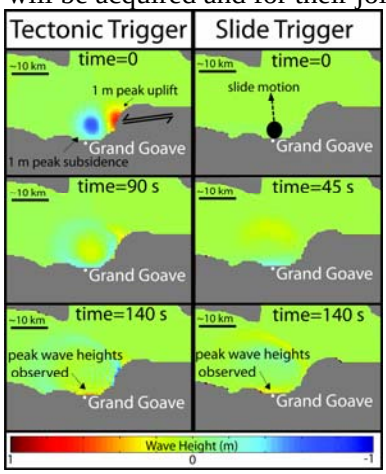


Fig. 4. Two non-linear shallow-water wave equation models showing tsunami formation from (1) tectonic deformation proposed along the fault (left) and (2) ground-liquefaction and sliding down slope near the town of Grand Goave (right). The model on the left assumes near-instantaneous seafloor deformation with uplift to the northeast of Grand Goave and subsidence to the north, immediately offshore of Grand Goave. Maximum vertical deformation is +/- 1 m however this will be scaled based on observations. The model on the right assumes a rotational slide with a maximum thickness of 5 meters transports sediments perpendicular to shore. Analysis of our preliminary tsunami models suggests either of these hypotheses can explain the observed wave. Only high resolution sub-seafloor imaging that reveals where slumps and faults exists near Grand Goave will allow us to test which hypothesis is correct.

Chirp seismic profiling: We propose to acquire ultra-high-resolution sub-bottom profiles using UTIG's Edgetech 512 Chirp sonar towfish as part of this rapid response effort; the use and shipping of this instrument come at no cost to NSF due assistance by the Jackson School Rapid Response program. The Edgetech 512 generates a sweep source from 500 Hz to 12 kHz. Our experience offshore New Jersey and in the Gulf of Mexico is that penetration can reach up to 100 m in very soft sediment, but 10s of meters are more likely. Resolution is generally 10-20 cm. We intend to run the Chirp in deep tow mode using our marine winch bearing 500 m of smart cable that serves both to tow the instrument as well as a data transmission line. In order to prevent towing artifacts we will attempt to chose a median depth for each profile such that at closest approach to the seafloor on a given line is ~25 m. Changes in penetration due to proximity of the seafloor is of less concern than the artifacts generated by winch motion while trying to maintain a constant altitude. We will post-process the data to remove tidal effects in order to properly match line ties and to remove heave artifacts if need be. The Edgetech automatically match filters the data (equivalent to deconvolution) and thus generally little other signal processing is required. However UTIG has a number of in-house scripts capable of enhancing signal should it be required.

The purpose of the Chirp profiling is: 1) to determine the origin of surface features including potential ruptures or slumps, 2) to survey for subsurface faulting, and 3) to map the shallow subsurface stratigraphy. While the penetration will not allow for deeper mapping of faults within the Gulf of Gonave, any active faulting related to the January 12th earthquake is expected to be visible within the upper few 10s of meters sub-seafloor. These data will serve as the first subsurface images of the offshore EPGF within the Gulf of Gonave and any secondary faults present in the eastern part of the bay. Additionally, we will seek to image the origin of the local tsunami near Grand Goave whether it be a fault scarp, local submarine slump, or permanently subsided coastline. These results could be invaluable to considering future risk to Haiti.

Sampling Program: The sampling program will consist of gravity coring (3.5 m long), multicoring to recover the sediment water interface and grabs to capture surficial processes over larger areas of the sea floor. It is estimated that ten gravity cores and multicores will be obtained at key locations revealed by the multibeam bathymetry, chirp subbottom profiles and side-scan sonar. The goal is to capture potential sea-floor ruptures, fault scarps, and mass-wasting related to the earthquake and reported tsunami. The EPGF will be mapped and a main target for coring will be small basins that form along the main strand of faults. Previous studies from the Marmara Sea, Turkey have shown that the sediments in these basins recorded fault ruptures and that unraveling the history of sedimentation can be critical for understanding the paleoseismic history of the fault (McHugh et al., 2006). The Baie du Port au Prince possibly has a larger and deeper basin that will also be targeted. Previous studies have shown that such basins are

"depocenters" for gravitational flows and mass-wasting events and can also contain a history of tectonic events. Although these "depocenters" can also accumulate sediments related to storms and floods that will need to be characterized and differentiated from seismites. To constrain the age of events, the top of the sediment will be dated with the short-lived radioisotope ^{7}Be. In this carbonate rich setting, radiocarbon should also be an effective means of determining the timing of other earthquake related events such as sea floor failures or fault offsets. Side-scan sonar images may reveal scarps due to fault offsets, submerged coral reefs, possibly carbonate crusts due to fluid and or gas escape, and soft muddy substrate possibly rich in organic matter. In these instances we will use a box corer or small dredge to recover a wider area of the seafloor. The cores will have their physical properties measured and they will be split, photographed and curated in refrigerated facilities at Lamont-Doherty Earth Observatory Core Repository that is subsidize by NSF, at no cost to the grant.

Tsunami Modeling: During the Haiti earthquake, a tsunami occurred near the town of Grand Goave (CNN report). This tsunami significantly damaged the coastline and caused at least 7 deaths in the village of Grand Goave. Reports indicate the wave and earthquake occurred almost simultaneously and that the coastline permanently subsided near Grand Goave. The occurrence of a tsunami during this earthquake represents an apparent paradox: *strike-slip earthquakes rarely produce tsunamis*. Although tectonics may ultimately explain both subsidence and the tsunami at Grand Goave, ground liquefaction and slumping offer an alternative explanation. Two competing hypotheses exist to explain this tsunami: the first, a tectonic hypothesis, implies either strike-slip transpressional/trantensional faulting occurred offshore resulting in subsidence and wave inundation at Grand Goave; the second, a sedimentary-trigger hypothesis, infers slide/ground-liquefaction occurred in the vicinity of Grand Goave and this alone triggered the tsunami (Fig. 4). Evidence for a slide in the vicinity of Grand Goave will reveal whether the tsunami represents a "red-herring" not associated with tectonics. If, however, no clear evidence for recent sliding exists near Grand Goave, tectonic deformation, however improbable for a strike-slip event, likely plays the key role in tsunami formation. High-resolution seafloor and subsurface images will reveal the source of this tsunami and whether an earthquake with mostly strike-slip motion was the trigger.

Responsibilities: S. Gulick and J. Diebold will be responsible for the Chirp profiling. M. Cormier and a graduate student (H. Johnson) from the UMissouri will be in charge of the side-scan sonar and multibeam bathymetric survey. C. McHugh and graduate student (K. Mishiki) will be responsible for the sampling program. P. Mann (cf letter of support) will assist with onshore-offshore correlations and partnerships with the Haitian geology community. M. Hornbach will conduct tsunami models while at sea based on the data acquired. L. Seeber (who will sail) and M. Steckler are in charge of coordinating the land and sea operations with teams working in the region. C. Sorlien will help with the processing of the data and enter the data into Kingdom Suite as the survey progresses for aid in planning survey lines and sampling.

Broader Impacts: Of critical and timely importance is providing direct information about the Jan 12th earthquake and implications for future geohazards to the government of Haiti and neighboring countries as well as the science community. We intend to integrate the geoscience community of Haiti and potentially Haitian-Americans into the sea-going expedition. Mann is in direct contact with the Director of Mines and Energy who has expressed interest in sending a Haitian geologist to join the research cruise and by extension aid local natural hazards education and mitigation. PIs McHugh, Cormier, and Gulick are currently teaching courses in "Oceans and Atmosphere" (CUNY geology majors, enrollment: 20 students), "The World's Oceans" (UMC introductory class, enrollment: 101 students), and "Marine Tectonics" (15 UT undergraduate and 8 graduate students). Scientific progress during the survey will be broadcasted by the PIs via blog-sties to illustrate for them the myriad applications of marine geosciences. The proposed research will help to initiate and develop exchange programs by which Haitian students could come to Queens College (where McHugh is a professor) and other CUNY colleges for studies. New York City and the borough of Queens have a large Haitian community within which students could interact.

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