Seafloor observations eliminate a landslide as the source of the 1918 Puerto Rico tsunami

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Key points

-Seafloor observations indicate that a landslide could not be the source of the 1918 Puerto Rico tsunami

-Tsunami from a M7.2 rupture of a two-segment fault in eastern Mona Rift fits the observations well

-Our analysis shows the need for seafloor observations and sampling in natural hazard studies

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Abstract

The October 11, 1918, devastating tsunami in northwest Puerto Rico, had been used as an example for earthquake-induced landslide tsunami hazard. Three pieces of evidence pointed to a landslide as the origin of the tsunami: the discovery of a large submarine landslide scar from bathymetry data collected by shipboard high-resolution multibeam sonar, reported breaks of submarine cable within the scar, and the fit of tsunami models to flooding observations. Newly processed seafloor imagery collected by remotely-operated-vehicle (ROV) show, however, pervasive Fe-Mn crust (patina) on the landslide walls and floor, indicating that the landslide scar is at least several hundred years old. ^{14}C dates of sediment covering the landslide floor verify this interpretation. Although we have not searched the region systematically for an alternative

tsunami source, we propose a possible source, a two-segment normal fault rupture along the eastern wall of Mona Rift. The proposed fault location matches published normal faults with steep bathymetry and is close to the ISC-GEM catalog locations of the 1918 main shock and aftershocks. ROV observations further show fresh vertical slickensides and rock exposure along the proposed fault trace. Hydrodynamic models from a M7.2 earthquake rupture along the eastern wall of the rift faithfully reproduce the reported tsunami amplitudes, polarities, and arrival times. Our analysis emphasizes the value of close-up observations and physical samples to augment remote sensing data in natural hazard studies.

1. Introduction

The damaging October 11, 1918 earthquake offshore NW Puerto Rico was followed within minutes by a tsunami that mostly affected the west coast of Puerto Rico. The tsunami caused more than 100 casualties and the damage exceeded $4,000,000 in 1918 U.S. dollars (Reid and Taber, 1919). A repeat of such an event today has the potential to be catastrophic due to the increased population, tourism, and development along the coast of Puerto Rico. Hence, the interest in understanding the source of the event. The location and focal mechanism of the earthquake and aftershocks could not be determined with certainty, given the small number of operating seismometers globally and the lack of any local instruments at the time (Location quality of B and C in the International Seismological Center-Global Earthquake Model (ISC-GEMS) catalog (Di Giacomo et al., 2018). The most recent estimate by ISC-GEMS, also adopted by the USGS Advanced National Seismic Systems (ANSS) Comprehensive Catalog (ComCat), is several kilometers east of the eastern boundary of Mona Rift (Figure 1) (18°42’ -67°11.34’) with some aftershocks of estimated magnitudes between M5.8 and 6.35, were located along the eastern boundary of the rift (ISC-GEMS catalog). An earlier epicentral estimate (Russo and Bareford, 1993), quoted by Doser et al. (2005), was located within Mona Passage (18°16.8' - 67°37.2', Figure 1) with an estimated location uncertainty of 50 km. Note, however, seismic and multibeam bathymetry data do not show a recent seafloor or sub-seafloor rupture in the vicinity of the Doser et al. (2005) epicenter (Chaytor and ten Brink, 2010). The proposed magnitude of the main shock is Mw7.1±0.3 (Di Giacomo et al., 2018) to Mw7.2 (Doser et al., 2005), and the proposed focal depth is 15 km (ISC-GEMS catalog). The proposed focal mechanism is normal slip on a steep N-S fault, but with large uncertainties; namely, strike, dip, and rake of 207° ± 22, 54° ± 8, and –127° ± 28, respectively (Doser et al., 2005).

Reid and Taber visited the area shortly after the earthquake and tsunami and took detailed notes of the events based on interviews with eyewitnesses and inspections of the damage. Their meticulous notes and insightful interpretations, published in the Bulletin of the Seismological Society of America in 1919, formed the basis of later modeling of the tsunami source and are summarized in Table 1. Reid and Taber (1919) observed that the wave amplitude was highest along the northwest corner of the island and decreased to the south and west. The wave was reported to have come from the NW. The water along the shoreline first receded exposing reefs never exposed at low tide before returning quickly. They determined the maximum wave height from visible damage and from eyewitness testimonies and interviewed eyewitnesses about the estimated time between the beginning of felt shaking and the initial withdrawal of the sea. The initial felt shaking was vertical, which they contrasted with the initial horizontal felt shaking during the San Francisco 1906 earthquake. Mercado and McCann (1998) modeled Reid and Taber's (1919) tsunami observations by assuming rupture along a fault trace marked by a dashed blue line in Figure 1. Their fault trace has a total length of 67 km and runs along the base of the entire east wall of Mona Rift and crosses the rift diagonally to the SW toward Desecheo Island at its southern end. Mercado and McCann (1998) assumed an average downdip width of 23 km and a slip of 4 m resulting in an earthquake magnitude of 7.47. Their model results, however, did not fit some of the documented observations. An initial positive polarity (i.e., flooding) of 0.7 m and 0.4 m was predicted in Aguadilla and Mayagüez, respectively, contrary to eyewitness reports. The maximum amplitudes were also much lower than observed. Some of the discrepancy between model predictions and the observations could probably be attributed to the coarser bathymetry grid available at the time (9.25 km cell size, interpolated near shore to a 90 m cell size), to the lower resolution numerical model that was utilized, and also to the choice of fault trace location and orientation.

The discrepancy between the tsunami observations and Mercado and McCann's (1998) predictions from a fault rupture model led López-Venegas et al. (2008) to explore an alternative tsunami source. High-resolution multibeam bathymetry and seismic reflection data collected since Mercado and McCann's publication revealed a 9 km x 9 km x 0.14 km landslide scar at the southern end of Mona Rift (Figure 1 inset A) with an estimated volume of evacuated material of 10 km^3 (López-Venegas et al., 2008). Breaks and damage to submarine telegraph cables assumed to be due to burial under and impact by sedimentary debris were reported within the scar area following the earthquake (Reid and Taber, 1919). The cable breaks and damage were located within the mapped landslide scar. This led López-Venegas et al. (2008) to propose that the tsunami was caused by an earthquake-triggered slope failure, which produced the scar (Figures 1 and 2). A similar event of earthquake-triggered landslide and turbidity currents generating a deadly tsunami was documented in Canada's Grand Banks in 1929 (Fine et al., 2005, and references therein). The López-Venegas et al. (2008) landslide hydrodynamic model produced the initial negative polarity of the wave reaching shore, but the calculated wave amplitude was generally too high. Hornbach et al. (2008) reduced the volume of the modeled landslide and modified its shape to fit the observed wave amplitude. A more sophisticated modeling scheme of landslide-generated tsunami by López-Venegas et al. (2015) simulated the tsunami amplitude at three of the reported sites (Pt. Borinquen, Aguadilla, and Pt. Higüero; see Figure 1 for location), but their calculated amplitudes (4.8-5.4 m, 4.8-7.2 m, and 7.1 m, respectively) did not match the Reid and Taber (1919) observed values (4.5 m, 2.4-3.4 m, and 5.2 m, respectively).

In this paper, we revisit the landslide-generated tsunami hypothesis proposed by López-Venegas et al. (2008) using video of the seafloor in the floor and walls of the landslide scar, collected by a remotely operated vehicle (ROV) and processed into a Structure-from-Motion (SfM) 3-D photogrammetric model. We also date core samples to determine the scar's age. We find that the landslide scar is older than 1918 and was likely not formed by that earthquake. We propose instead an earthquake rupture source fault which fits the negative polarity, amplitude, and arrival time of the tsunami in the reported tsunami sites, and we present seafloor images of possible fault plane striations along the proposed source fault.

2. Data

2.1 Seafloor imagery and photogrammetry

Seafloor imagery and sediment core samples within the landslide scar and along its walls were collected by the ROV *Hercules* during Dive H1301 of the Ocean Exploration Trust expedition

NA-035 aboard the ship E/V *Nautilus* from October 4–18, 2013 (ten Brink et al., 2014). The ROV *Hercules* tethered to the E/V *Nautilus*, is equipped with a high-definition video camera, a manipulating arm for collecting rock and biological samples, push cores for collecting sediment samples, and equipment for sampling water. Throughout the dives *Hercules* was illuminated by its companion ROV *Argus* hovering above it. Additional seafloor imagery of the proposed fault wall was collected during Dive 05 of the NOAA's Ocean Exploration Program expedition EX1502 from April 9-30, 2015 aboard the NOAA Ship Okeanos Explorer using its tethered ROV *Deep Discoverer* (Kennedy et al., 2015). Throughout the dives, *Deep Discoverer* was illuminated by its companion ROV *Seirios* hovering above it.

The high-definition video collected by both *Hercules* and *Deep Discoverer* was processed into a 3-D photogrammetric model. First, individual frames were extracted from the dive videos at one second increments using Agisoft Metashape Pro©. Because video images at water depths of 1000-4000 m are only illuminated by the ROV light, their color, contrast, and brightness vary between and within each frame due to the varying illumination distance and the effect of differential light attenuation by sea water. To compensate for the varying illumination distances, we balanced the brightness and contrast of the frames using OpenCV's Contrast Limited Adaptive Histogram Equalization (CLAHE) algorithm in Python. The balanced images were then imported into Agisoft Metashape Pro© for processing, where some color balance and additional brightness modification was carried out manually in addition to masking out the edges of the ROV and deleting frames where the ROV was not moving. Although image intensity was balanced, the image color depends on the light source distance from the target rock, resulting in yellower surfaces closer to the light source and bluer surfaces farther away. From here, common processing steps were followed (e.g., Hansman and Ring, 2019) to attain a 3-D photogrammetric model. The steps included aligning the images to acquire a sparse elevation/depth point cloud, refining and optimizing the camera paths using known distances and control points, building a dense point cloud from the imagery, building a 3-D mesh from the dense cloud, adding navigation for georeferencing, and finally draping the imagery onto this 3-D mesh, and stitching 3D models into a larger matrix. These processing steps were carried out using Agisoft Metashape Pro©. 3-D manipulation and display of the virtual outcrops were carried out using VOG Lime©.

2.2 Hydrodynamic modeling

Tsunami simulations were carried out using the Method of Splitting Tsunamis (MOST) based on the depth-integrated nonlinear shallow water equations (Titov et al., 2016). MOST simulation starts from tsunami source generation by instantaneous co-seismic deformation of the seafloor. MOST then efficiently computes tsunami propagation and inundation using three nested grids to achieve increasing resolution of nearshore bathymetry and topography. Because it is the standard model used operationally at the National Oceanic and Atmospheric Administration (NOAA)'s Tsunami Warning Centers, the MOST model has been extensively verified and validated using laboratory experiments, model benchmarks, and modern tsunami events (Synolakis et al., 2008; Tang et al., 2012; 2016; Wei et al., 2008; 2013). Nearshore grids of 1/3 arc sec (~10 m) resolution were created using newer bathy/topo lidar (NOAA Center of Environmental Information, NCEI) collected since Andrews et al. (2013) database for the NE Caribbean was published. Tsunami runup and inundation are computed. Elsewhere a reflective boundary, and thus no inundation calculation, is applied along the 1-m depth contour offshore at a grid resolution of 3 arc sec (~ 90 m). The MOST model uses a uniform bottom friction (Manning's) coefficient of 0.03 in all telescoped grids.

3. Observations – Landslide scar is older than the 1918 earthquake

3.1 Seafloor imagery

Seismic reflection data show that the landslide scar is cut into a layered carbonate platform that had been tilted downward to the north, and both the walls and floor are made of competent limestone and dolomite (López-Venegas et al., 2008). Our seafloor imagery observations show that the floor of the scar is heavily sedimented but shows evidence of jagged texture oriented in a downhill direction (e.g., Figure 3) possibly representing frictional damage from the movements of cohesive rock against a cohesive bottom at the time of failure. The gouges are 4-8 m wide, and their edges range from a few centimeters to 1.5 meters tall. The massive or layered rock faces, exposed along the edges of some gouges, are covered with black patina, and show no sign of fresh breaks (e.g., Figure 3).

The observed black patina is a Fe-Mn crust composed of Mn oxides and Fe oxyhydroxides with Mn/ Fe ratios mostly around 1–2, which precipitate from seawater and envelope exposed rocks ((Koschinsky and Hein, 2017; Figure 4A, B). The patina is found throughout the world oceans. Except near hydrothermal vents, Fe-Mn crust grows at a very slow rate (1-5 mm/Ma, Maciag et al., 2019; 3.05-4.85 mm/Ma at the water depths of the dive, 1250-2000 m, Conrad et al., 2017). A grab sample taken by ROV *Hercules* (Figure 4C) along a deep gulley in the scar floor (See Figure 5A for location) shows a thin (>1 mm) veneer of Fe-Mn crust on limestone. (Figure 4B). Even a 1-micron-thick crust requires 200-1000 years to develop. Hence, the observation of Fe-

Mn crust on the gouges suggests that the gouges did not form by an earthquake-triggered landslide in 1918.

The ROV traversed a narrow gulley cut into the scar's floor (Figure 5A). The gulley's wall is layered and most of the rock face is black indicating the presence of Fe-Mn crust. A few rocks at the top bench of the wall appear to lack patina. The shaking from the 1918 earthquake could have dislodged a few rocks which rolled downslope. However, the gully itself does not seem to have been carved by a landslide during the 1918 earthquake. Another gully shows a white rock face at the bottom few meters of its wall (Figure 5B). The remainder of the gully wall, however, is composed of rock ledges covered by black patina and by talus, suggesting that they were not affected by the shaking from the 1918 earthquake. Hence, it appears that some rocks may have been dislodged sporadically from a pre-existing floor of the landslide scar.

The ROV traversed the eastern and southern scar walls, each >100 m high (See Figure 6A, B for sections of these walls). The southern wall is layered showing steep competent rock faces separated by talus and rubble (Figure 6A). Signs of downslope sediment flow are visible, but none of them appear to be mass transport deposits from a high-volume landslide. All the exposed rock faces are black, presumably because they are covered by Fe-Mn crust (Figure 6A). The eastern wall appears to be composed of a continuous rocky slope with pitted texture and potential layering at the base of the scarp (Figure 6B). The primary rock texture may be hidden by the texture of the Fe-Mn crust. Fresh rock surfaces were not observed along either the eastern or southern scar walls, suggesting that the scar's walls were created before 1918. In summary, neither the floor nor the walls of the scar indicate that they formed recently, hence, we propose that the previously modeled landslide scar predates the 1918 earthquake and could not be the source of the observed tsunami.

3.2 Sediment cores

Surficial sediments recovered from ROV push cores collected within the scar (PC-038, see Figure 2 for location and Figure 4D for image of the push core being pulled out of the sediment) and immediately adjacent to the crest of the eastern headwall (PC- 040, Figure 2) are similar in both texture and composition. Push cores 038 and 040 penetrated 14 cm and 18 cm, respectively, but did not reach the hard rock floor of the landslide scar. Sediment recovery was close to 100%. The sediments are composed of mixed intact and fragmented biogenic carbonate material dominated by foraminifera and pteropod tests with a small fraction of gastropod and other mollusk shells. The minor non-carbonate fraction of the sediment is composed of siliceous spicules and detrital lithic fragments and mineral grains. The sediments are quite uniform down the cores and show no obvious signs of transport by a landslide. Texturally, the bulk of the sediments are classified as very poorly sorted (sorting > 2) clayey silts (mean grain size between 8 and 6.55 φ), with minor variations in the major grain size fractions down the length of the short cores. Calcium carbonate content of the > 63 µm fraction of these sediments determined by loss on ignition (Chaytor et al., 2021), exceeds 60 % (by weight).

Accelerator mass spectrometry (AMS) ^{14}C dating was performed on planktonic foraminifera extracted from a single 1 cm thick interval in ROV push core 038, located 3 cm below the seafloor within the scar floor at a water depth of 1973 m (See Figure 2 for location). A calibrated age of 440 ± 120 years BP was determined. The calibrated age (BP) was calculated using Calib

8.2 (Stuiver et al., 2021) and the Marine20 calibration curve (Heaton et al., 2020), with only the 550-year reservoir correction (i.e., no delta-R) applied. Based on this age, sedimentation rate appears to be relatively high on the scar's floor (between 6.8 cm/1000 yr). We conclude that sediment accumulation above the floor of the landslide scar likely took hundreds if not a few thousand years to develop.

4. Discussion – Segmented fault as tsunami source

The landslide scar in southern Mona Rift likely formed several hundreds to thousands of years before 1918, hence, the tsunami could not have been generated by the associated landslide movement, as previously suggested in López-Venegas et al. (2008, 2015) and Hornbach et al. (2008). Fe-Mn crust covering both the side escarpment and gouges and a gully on the scar's floor attest to an age of at least a few thousand years because of the slow rate of mineral precipitation from seawater onto the rock surface. A thick sediment cover of the scar's floor is dated at being older than 1918 and another obvious landslide source was not identified. Consequently, we re-evaluate the possibility of a fault rupture as the source of the tsunami.

4.1 Tsunami models

We did not explore systematically an alternative tsunami source, but we propose here one possible source based on bathymetry, seismic profiles, dive observations, and the description of the earthquake. Our proposed fault trace is 40 km long and follows the steepest part of the bathymetric slope along the eastern and SE walls of Mona Rift (Figure 1). Seismic reflection profiles (Figure 7, and Figure 8 in Mondziel et al., 2010; See Figure 1 for locations) suggest a possibly active normal fault across both orientations (Figure 1). Dive observations discussed below show a rock face with slickensides across the N-S segment. Reid and Taber (1919) described a severe shaking event followed ~two minutes later by a less severe one. We propose a two-segment fault rupture scenario: a rupture of 29-km-long N-S-oriented fault followed by a rupture of an 11-km-long NW-SE-oriented fault (red rectangles in Figure 1; Table 2). The centers of the two faults segments are ~20 km, which for an average water depth of ~3000 m will lead to positive interference between tsunami waves generated by two ruptures two minutes apart. The earthquake was initially felt as vertical motion, indicating normal faulting, which Reid and Taber (1919) contrasted with their experience during the 1906 San Francisco earthquake.

The earthquake magnitude was assumed to be Mw7.2 following Doser et al. (2005). A downdip width of W=15 km was assumed starting 1 km below the seafloor, to avoid a singularity in the calculation (Figure 8). A generic dip of 60° was modeled following Doser et al. (2005) focal plane solution, the felt motion by eyewitnesses, and the suggested normal motion from seismic reflection data (Figure 7; Mondziel et al., 2010). The modeled fault parameters are listed in Table 2.

The calculated tsunami amplitude, polarity, and arrival time from this rupture source fit Reid and Taber's (1919) reported observations (Table 1, Figure 9). The misfits in wave amplitude are < 1 m. Reid and Taber's (1919) observations did not specify the tidal level during the tsunami, which around Puerto Rico is ≤ 0.5 m (https://tidesandcurrents.noaa.gov/). Reid and Taber (1919) did not specify the tsunami observation location along the Aguadilla shoreline. However, LaForge and McCann (2017) and López-Venegas et al. (2015) used archival petitions for funds to repair tsunami damage to identify the exact street in Aguadilla, which suffered the maximum damage. The shoreline coordinate facing that street was used in Table 1. A map of the maximum predicted flooding from the two-segment fault rupture is shown in Figure 10.

The modeled first wave polarity at all reported sites fits the eyewitness reports. Reid and Taber (1919) reported initial withdrawal in all locations except in Loíza (Figure 9). Except for Boquerón, the calculated arrival time fit the eyewitness reports in Reid and Taber (1919). Flooding at 5-6 minutes and 25-30 minutes after the shaking was felt was reported in Aguadilla and Mayagüez, respectively. A withdrawal followed by flooding 25-30 minutes after the earthquake was reported in Loíza, and withdrawal about 1 hour after the earthquake was reported in Boquerón.

4.2. Fault plane imagery

Exposed fault planes may have been encountered on a dive across the fault trace proposed by our tsunami model. Video observations collected by ROV *Deep Discoverer* along the east wall of Mona Rift between depths of 3300-4000 m, encountered Late Cretaceous to Middle Eocene meta-volcanic and plutonic rocks that form the core of Puerto Rico Island underlying the Late Oligocene to Pliocene platform carbonate sequence. Slickensides (smooth striated and corrugated surface) were identified at depths of 3884-3882 m (Figures 1A, 11A). Slickensides are thought to be produced by frictional rock movement along a fault. Note that the rock surface of the slickensides is free of Fe-Mn crust, indicating that this rock face is likely recently exposed. The striations point downward indicating sub-vertical movement. Their slope, 20±8°, is lower than the 60° slope assumed in our tsunami model, and their dip direction is 190°±10°, suggesting that the striations have developed along a subsidiary fault plane. A smooth rock face lacking patina is also observed a few meters above the striations (Figures 1A, 11B). A blueish-color exposure at the bottom of the image with possible striations may be a small fault plane exposure and/or a freshly exposed blueschist (Enlargement in Figure 11B). The dip direction of this exposure is 280°. A late Cretaceous blueschist belt extending along the continental slope eastward from Samaná Peninsula in the NE Dominican Republic was proposed by Perfit et al. (1980) from analysis of outcrops and dredges.

5. Conclusions

The source of the devastating 1918 western Puerto Rico tsunami had previously been ascribed to both an earthquake fault rupture (Mercado and McCann, 1998) and an earthquake-triggered landslide (López-Venegas et al., 2008; 2015; Hornbach et al., 2008). Documented landslide tsunami sources are rare, and the landslide source for the 1918 tsunami had been cited as an example for landslide tsunami hazards (e.g., National Research Council, 2011). The landslide source suggestion was based on the then-newly available ship-board high-resolution multibeam bathymetry and seismic reflection data, coupled with reports about submarine cable breaks within the landslide scar area (Reid and Taber, 1919). An in-situ examination of the floor and walls of the landslide scar, using high-definition video from a remotely operated vehicle (ROV), and core samples collected by the ROV suggest, however, that the scar is at least several hundred years old and therefore the landslide that formed could not have been triggered by the 1918 earthquake. The evidence includes a relatively thick sediment cover of the hard carbonate scar floor, dated at several hundred years old or more, and the observations of extensive Fe-Mn crust of the exposed rock faces of the eastern and southern escarpment, the gouges in the scar floor, and in gullies cut into the scar floor. Published estimates of Fe-Mn crust precipitation from seawater in the absence of hydrothermal activity is 1-5 mm/Ma. The reported submarine cable damage and breaks could be caused by smaller rock falls from steep outcrops, and not by the presumed movement of a 140 m thick, 9 km wide tsunami-generating landslide.

We propose an alternative tsunami source, namely, a two-segmented normal fault rupture along the steepest parts of the eastern wall of Mona Rift NW of Puerto Rico. Our proposed fault rupture has a total magnitude of Mw7.2 and parameters that are compatible with seismic reflection observations and with seismic analysis of the historical seismograms (Di Giacomo et al., 2018; Doser et al., 2005). Although we have not performed a rigorous search for the best tsunami source location and parameters, our hydrodynamic model simulates with fidelity the amplitudes, the first wave polarities, and the arrival times at eight sites along western and northern Puerto Rico, which were reported by Reid and Taber (1919). An ROV dive along the proposed ruptured fault reveals possible corrugated striations in the exposed hard rock (slickensides) that can be interpreted as being formed by friction along a fault plane. Some of the hard rock face in the surrounding area is devoid of Fe-Mn crust. Our analysis, thus, demonstrates the importance of in-situ observations and sampling for natural hazard studies in the ocean.

Data and resources

Videos collected during NOAA's Ocean Exploration cruise EX1502 are available from NOAA's video archive portal https://www.ncei.noaa.gov/access/ocean-exploration/video/. Core samples are available at: https://web.uri.edu/gso/research/marine-geological-samples-laboratory/. Ocean Exploration Trust videos from expedition NA-035 are available upon request at https://nautiluslive.org/science/data-management. Seismic parameters of the 1918 earthquake were retrieved from the ISC-GEMS catalog at http://doi.org/10.31905/D808B825 accessed

6/6/2022. OpenCV's (https://opencv.org) Contrast Limited Adaptive Histogram Equalization (CLAHE) algorithm can be downloaded from the openCV package https://opencv.org/releases/ The seismic profile in Figure 7 is available from https://walrus.wr.usgs.gov/namss/survey/p-30-06-cb/

Following is the description of the observed tsunami arrival times and their polarities in Reid and Taber (1919): Aguadilla: "*Estimates of the time interval between the earthquake shock and the arrival of the sea wave, made by different observers, range from four to seven minutes, one of the best being five to six minutes.*" Mayagüez: "*In the interval between the earthquake and the arrival of the sea wave, an automobile traveled from the Central Corsica near Rincon to Mayagüez, a trip that is estimated to require twenty-five or thirty minutes.*" El Boqueron: "*An observer states that the ocean withdrew about an hour after the earthquake, the water going out gradually during a period of twenty minutes.*" Loíza*:"..reported to have subsided and then to have risen about one meter above normal, the phenomenon occurring twenty-five or thirty minutes after the earthquake.*"

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Figures

Figure 1. Shaded relief bathymetry of Mona Rift and Mona Passage off western Puerto Rico. Circles – Reported observations sites of tsunami flooding listed in Table 2. Solid red rectangles – Surface projection of the two-segmented normal fault, modeled as the tsunami source (see Discussion). Dash-dotted blue line – Tsunami source fault modeled by Mercado and McCann (1998). Yellow curve – Landslide tsunami source of López-Venegas et al. (2008; 2015). Large and small white star – proposed epicenter of the 1918 earthquake and aftershocks (ISC-GEMS catalog). Black stars – Proposed epicenter of Doser et al. (2005) and isoseismal epicenter of Reid and Taber (1919). Black lines – ROV dive tracks NA035-H1301 and EX-1502-05. Double lines – Seismic lines Pelican Line 62 shown in Figure 7 and EW9605-1298 shown in Figure 8 of Mondziel et al. (2010). Dashed rectangle – Location of inset A. Inset A - Enlargement of the eastern wall of Mona Rift with dive track EX-1502-05. Brown contours – 500 m depth contours. Inset B – Regional location map showing extent of map (dashed rectangle) and location of the Loíza site in Puerto Rico.

Figure 2. Enlargement of the landslide scar at the southern end of Mona Rift. See Figure 1 for location. Black line - dive track NA035-H1301. Arrows point to site of dive images samples shown in Figures 3-6 and locations of push cores 038 and 040 discussed in text. Brown contours –Contours of water depth at 500 m interval.

Figure 3. Image of jagged gouges in the floor of the landslide scar. Downslope direction is into the page. See Figure 2 for location.

Figure 4. (A) grab sample 2013 NA-03-039 from a gully at the scar floor at water depth of 1987 m (see Fig. 2 and 5A for location) White spots are scratches caused by the ROV arm extracting the sample. (B) Sample cut in half to reveal the thickness of the Fe-Mn coating and fossiliferous biomicrite interior. (C) Photo of the ROV arm dislodging the sample from the surrounding rock. Only the rock surface exposed to seawater will show Fe-Mn coating. (D) Photo of the ROV arm extracting the push core used for sediment dating.

Figure 5. (A) Image of a gully cutting the floor of the landslide scar. (B)An asymmetric gully within the floor of the landslide scar. Note the white rock ledge at the base of the slope. See Figure 2 for locations of (A) and (B). Other apparent color variations in the rock face are due to variations in distance between the lighting source and the rock face. W.d. – Water depth.

Figure 6. Images of part of (A) the southern and (B) the eastern escarpments of the landslide scar. See Figure 2 for locations of (A) and (B).

Figure 7. Portion of high-resolution multichannel seismic Line 62 crossing the SE wall of Mona Rift, the possible rupture location of the 1918 earthquake and tsunami. See Figure 1 for location. Red lines – interpreted normal fault traces. The line was collected by the USGS aboard the R/V Pelican.

Figure 8. Initial sea surface and sea floor displacement in the tsunami model due to the rupture of a two-segmented normal fault discussed in the text. Contours are simplified bathymetry (in m).

Figure 9. Calculated marigrams at the observation sites listed in Table 1. Observation sites are shown in Figure 1. Missing negative parts of the marigrams at several sites occurs when the seafloor gets exposed (dry) during water withdrawal because calculated sites are located at water depths between 0.5 m and 2 m. Dashed red line - Maximum observed tsunami height from Reid and Taber (1919). Two lines are marked where a range of heights was quoted. Red arrows - Observed arrival time of the tsunami wave, described in Reid and Taber (1919) and listed in "Data and Resources". The arrow directions describe rising water (up arrow) or receding water (down arrow). Arrows are separated by a horizontal line denote range of arrival time.

Figure 10. Calculated maximum tsunami wave amplitude along the west coast of Puerto Rico due to the two-segmented normal fault along the east wall of Mona Rift. Rectangles – Areas modeled using 10 m grid spacing. White circles – Locations of tsunami observations in Reid and Taber (1919). Insets A and B – Enlargements of the rectangles near Mayagüez and Boquerón.

Figure 11. (A) Slickensides (pointed by white arrows) on plutonic(?) rock. See inset B in Figure 1 for location. "White flower" – Sponge (B) massive plutonic(?) rock without Fe-Mn crust. Enlargement - A small blueish smooth surface, possibly, an exposed fault plane in direction 280°. The rock may be a blueschist outcrop.

Table 1. *Comparison between Reid and Taber (1919) tsunami observations and model calculations. See Figure 1 for locations of observation.*

	Location of observation	Lat. (Degree Decimal minute)	Long. (Degree Decimal minute)	Obs. Wave height (m)***	Calc. pos-itive amp. (m)	Obs. first wave polarity	Calc. first wave polarity	Reported arrival time (min.) and its polarity ****	Calc. arrival time(min.) matching polarity description
1	Pt. Agujereada	18°30.47	-67°08.24	5.5-6	6.7		N*		
2	Pt. Borinquen lighthouse	18°29.32	-67°09.7	4.5	4.6	N*	N		
3	Aguadilla	18°25.5	-67°09.3	2.4-3.4	2.4		N	5-6 P	6 P
4	Columbus (Colon) Park, Aguadilla	18°24.83	-67°09.73	>4	4		N		
5	Pt. Higüero lighthouse	18°21.82	-67°16.25	5.2	6	N	N		
6	Mayagüez	18°12.33	-67°09.2	1.1-1.2	1		N	25-30 P	25-32 P
7	Boquerón	18°01.56	-67°10.47	1	0.8	N	N	60 N	43-49 N
8	Rio Grande de Loíza	18°26.33	-65°52.61	1	0.7	Slight P*	Slight P*	25-30 N P	25-28 N P
9	Mona Is.**	18°05.28	-67°56.39	>4					

* - N-Negative (withdrawal); P – Positive (flooding).

** - The lack of near-shore high-resolution bathymetry precludes the calculation of reliable amplitude.

*** - The observations did not specify the tidal condition. Tidal range around Puerto Rico is ≤ 0.5 m (https://tidesandcurrents.noaa.gov/).

**** - Reported eyewitness arrival time and its described wave polarity. (See text in Data and Resources for detailed description).

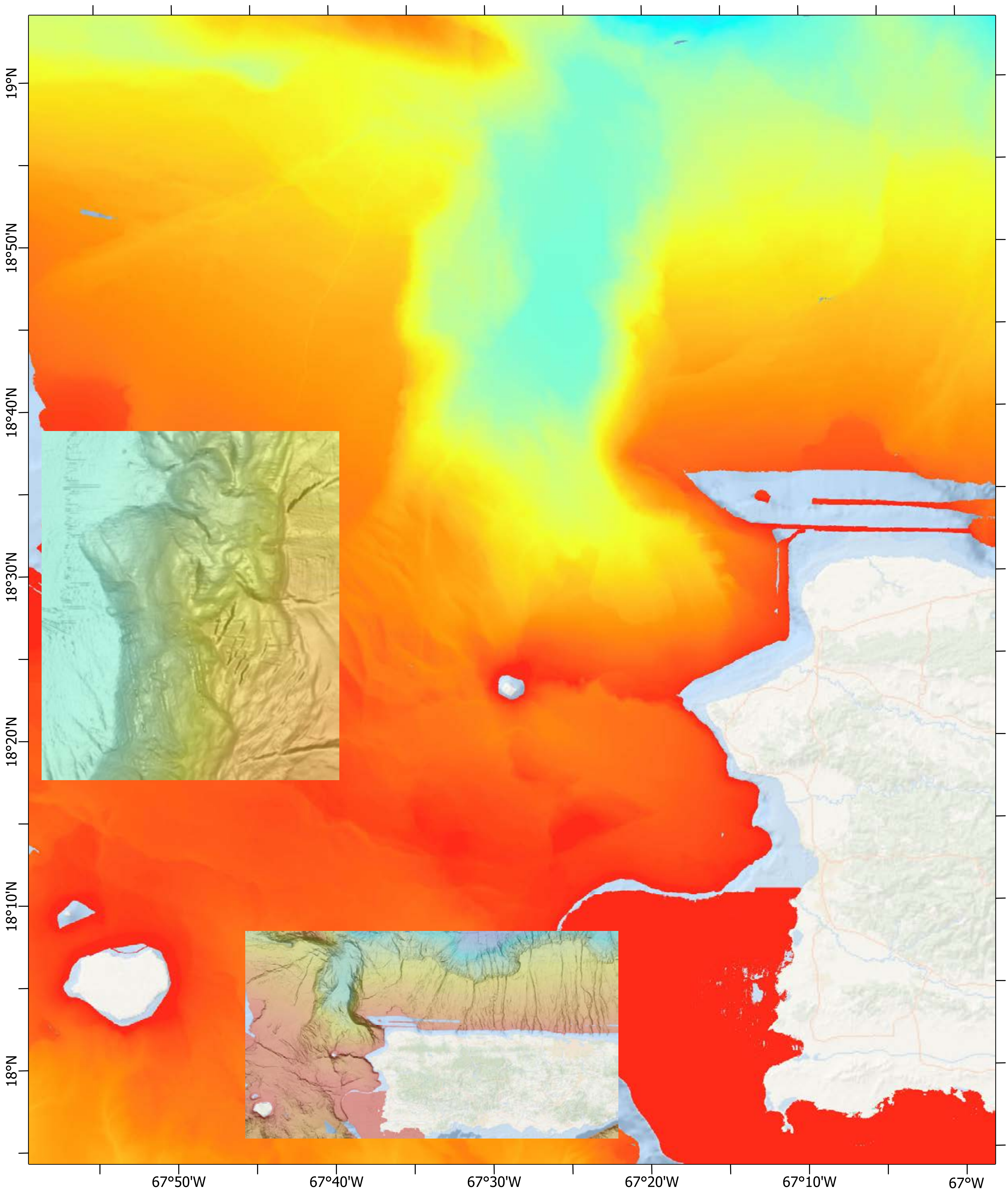
Table 2. *Fault rupture parameters for the tsunami model*

Seg-ment	Length (km)	Downdip width* (km)	Slip (m)	Lat. (deg. Dec. min.)	Long. (deg. Dec. min.)	Lat. (deg. Dec. min.)	Long. (deg. Dec. min.)	Strike (°)	Dip (°)	Rake (°)
1	29	15	4.32	18°51.67	-67°18.14	18°36.18	-67°20.98	190	60	-90
2	11	15	4.32	18°34.09	-67°18.65	18°32.18	-67°13.50	109	60	-90

*- Fault top is at 1 km depth.

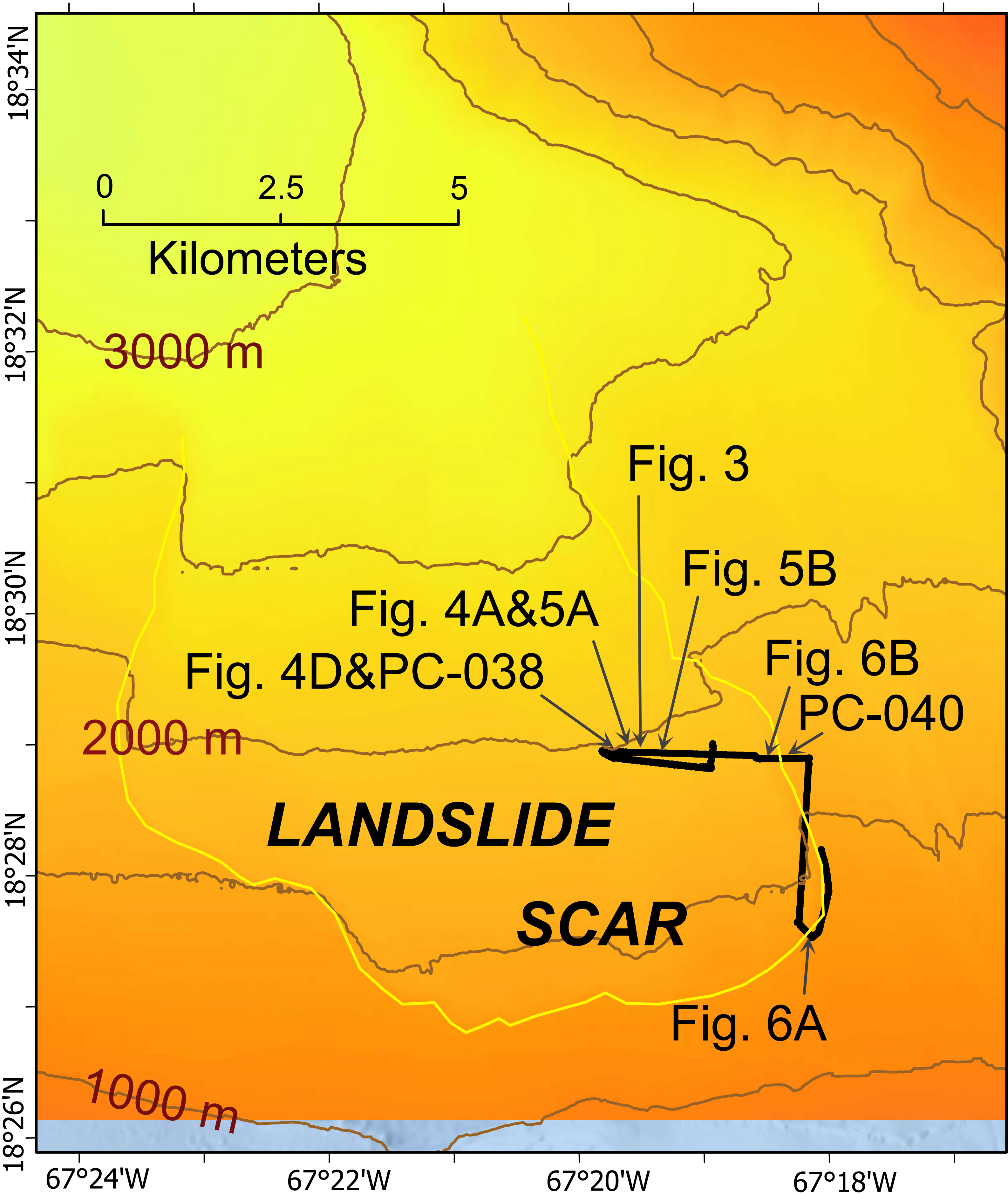
** - shear modulus, $\mu = 3\text{x}10^{10}$ Pa.

Figure 1



19°N
18°50'N
18°40'N
18°30'N
18°20'N
18°10'N
18°N
67°50'W
67°40'W
67°30'W
67°20'W
67°10'W
67°W

Figure 2



0
2.5
5
Kilometers
3000 m
2000 m
1000 m
Fig. 3
Fig. 5B
Fig. 4A&5A
Fig. 4D&PC-038
Fig. 6B
PC-040
LANDSLIDE
SCAR
Fig. 6A
18°34'N
18°32'N
18°30'N
18°28'N
18°26'N
67°24'W
67°22'W
67°20'W
67°18'W

Figure 3

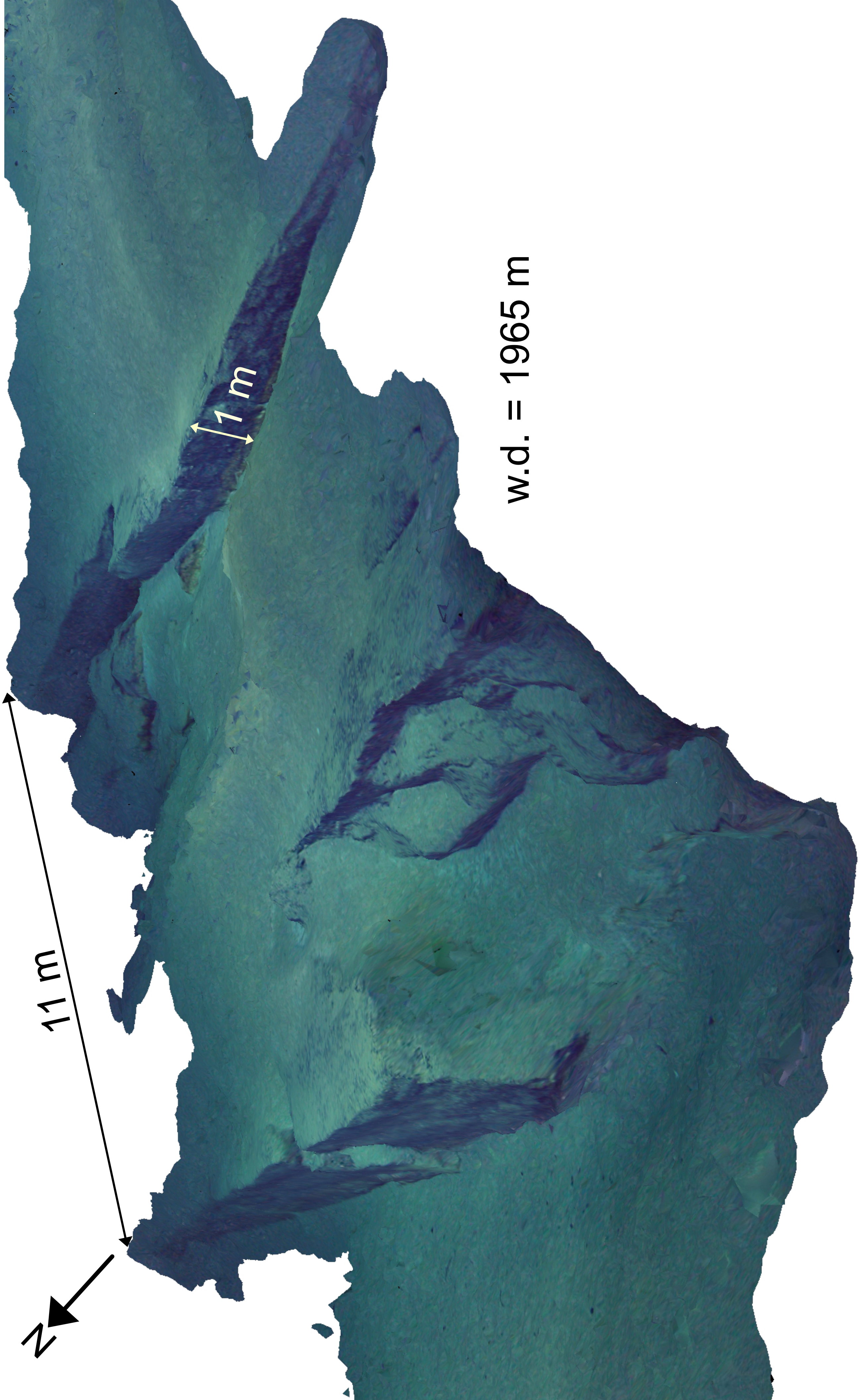


Figure 4

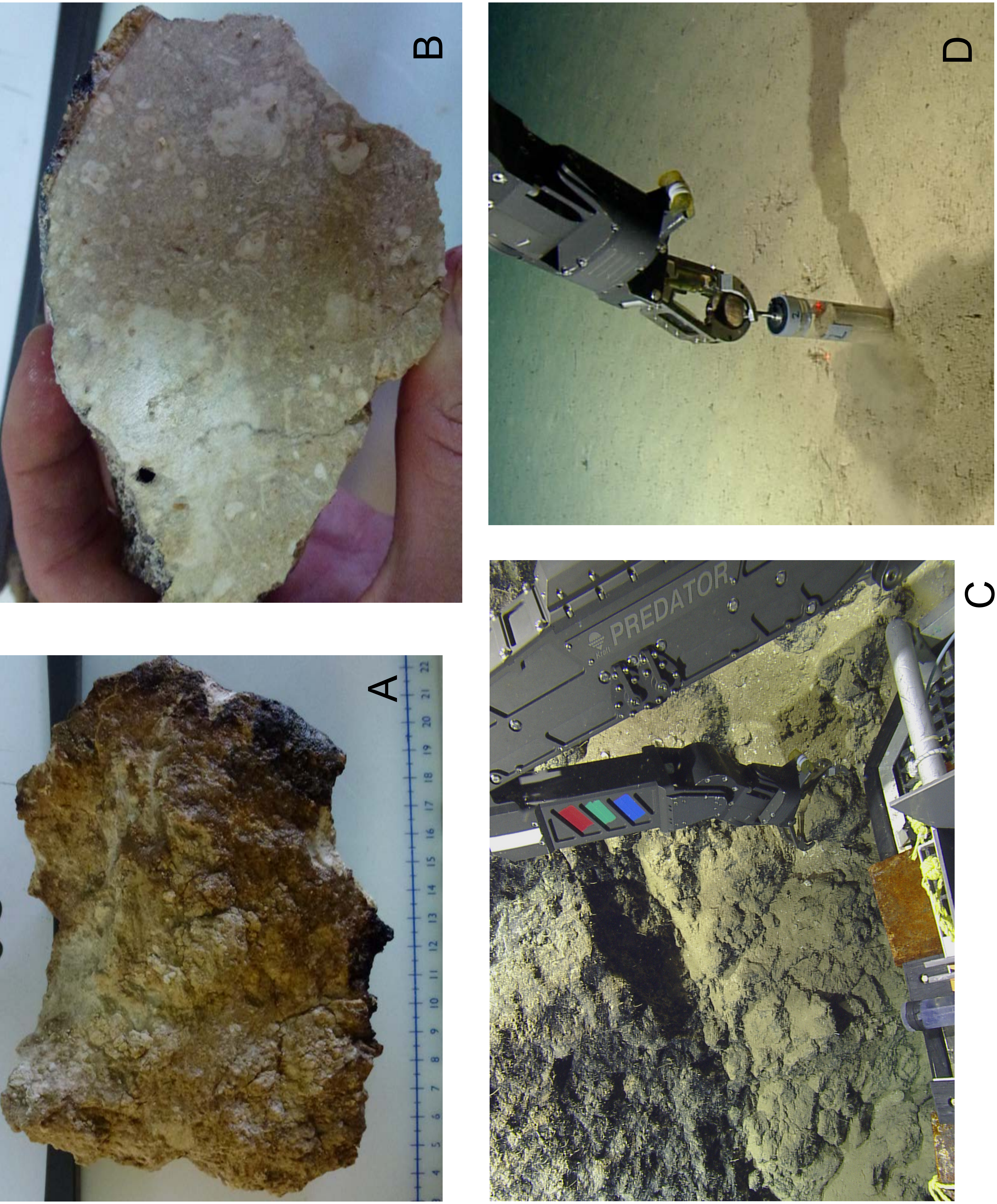


Figure 5

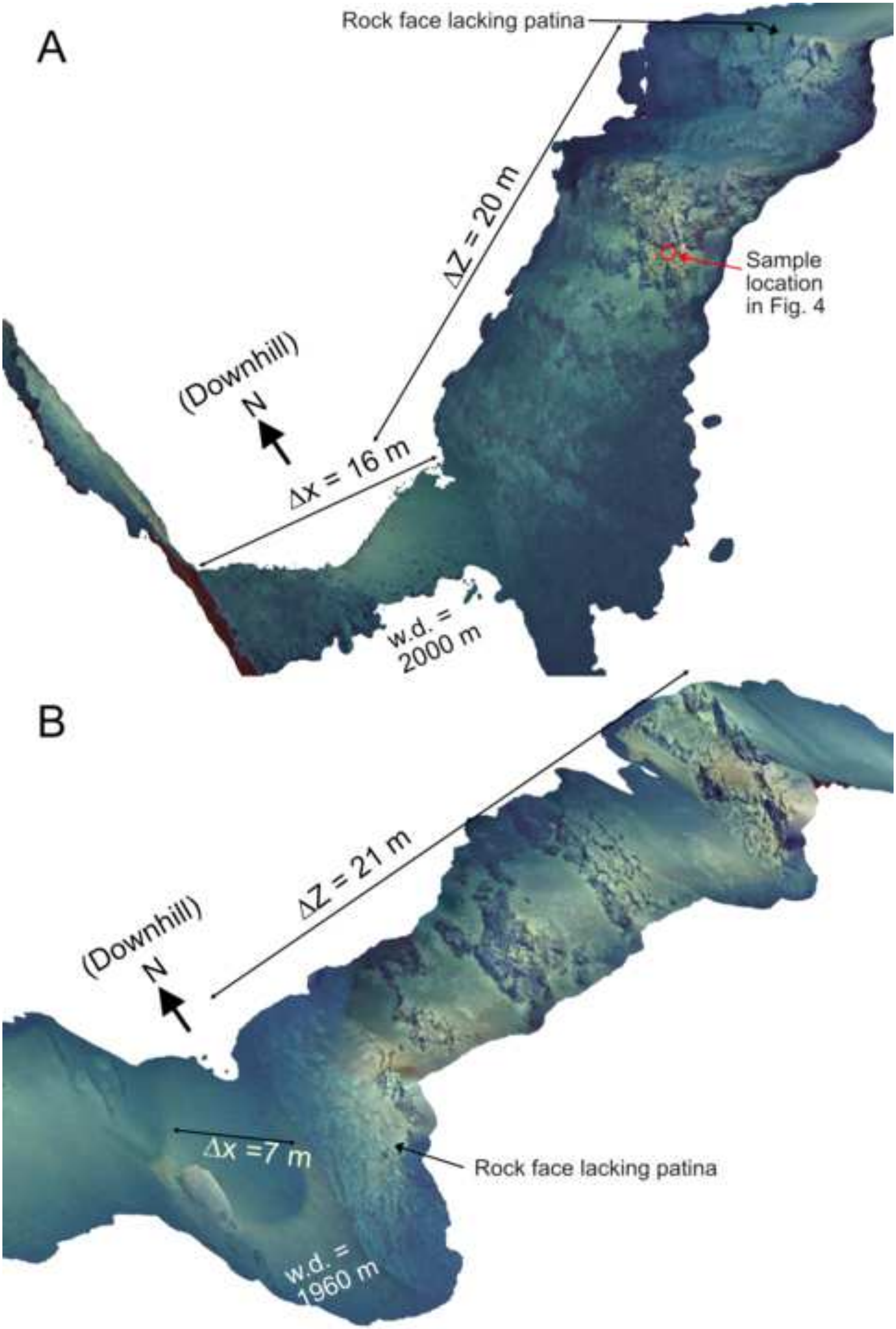
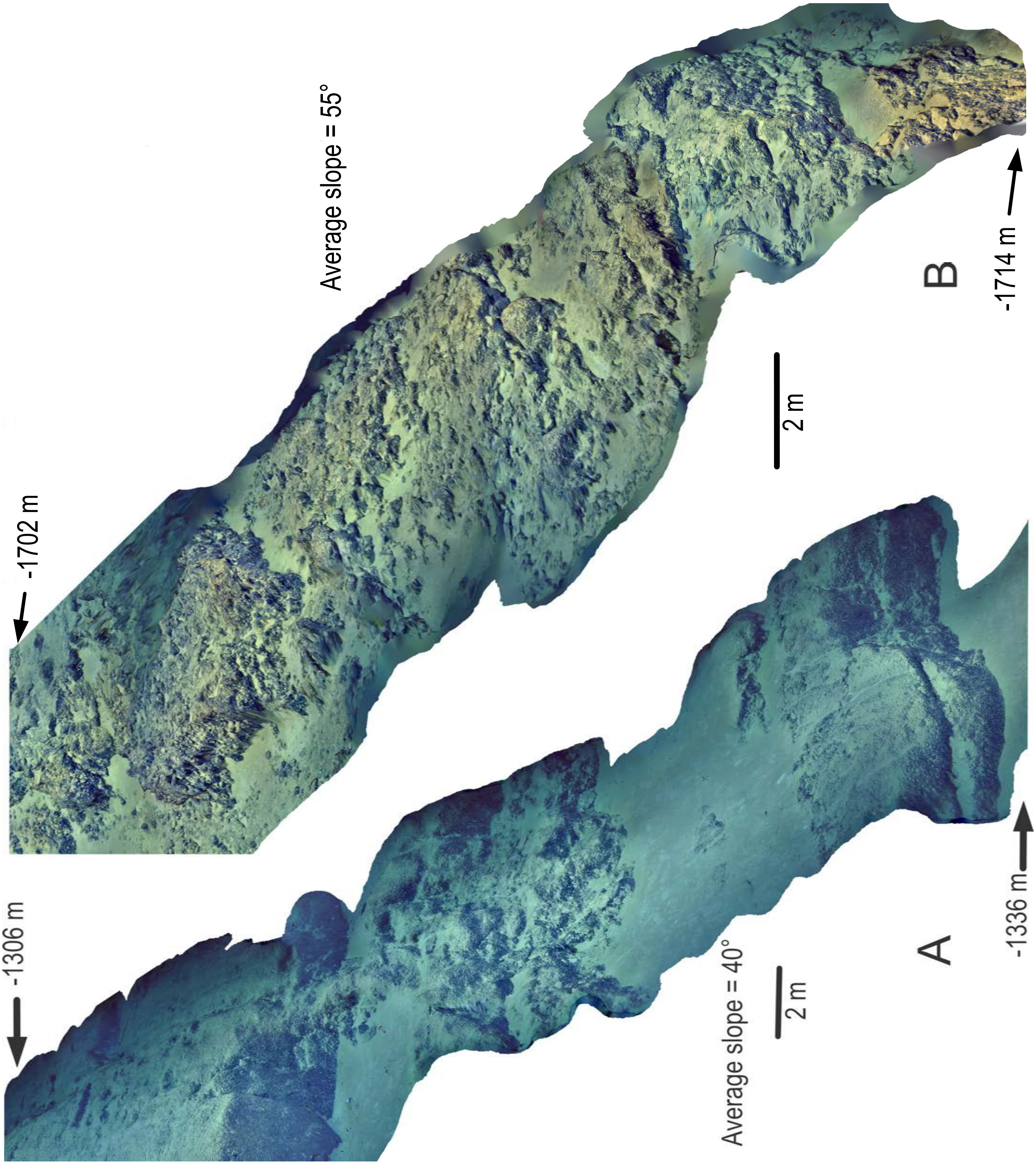
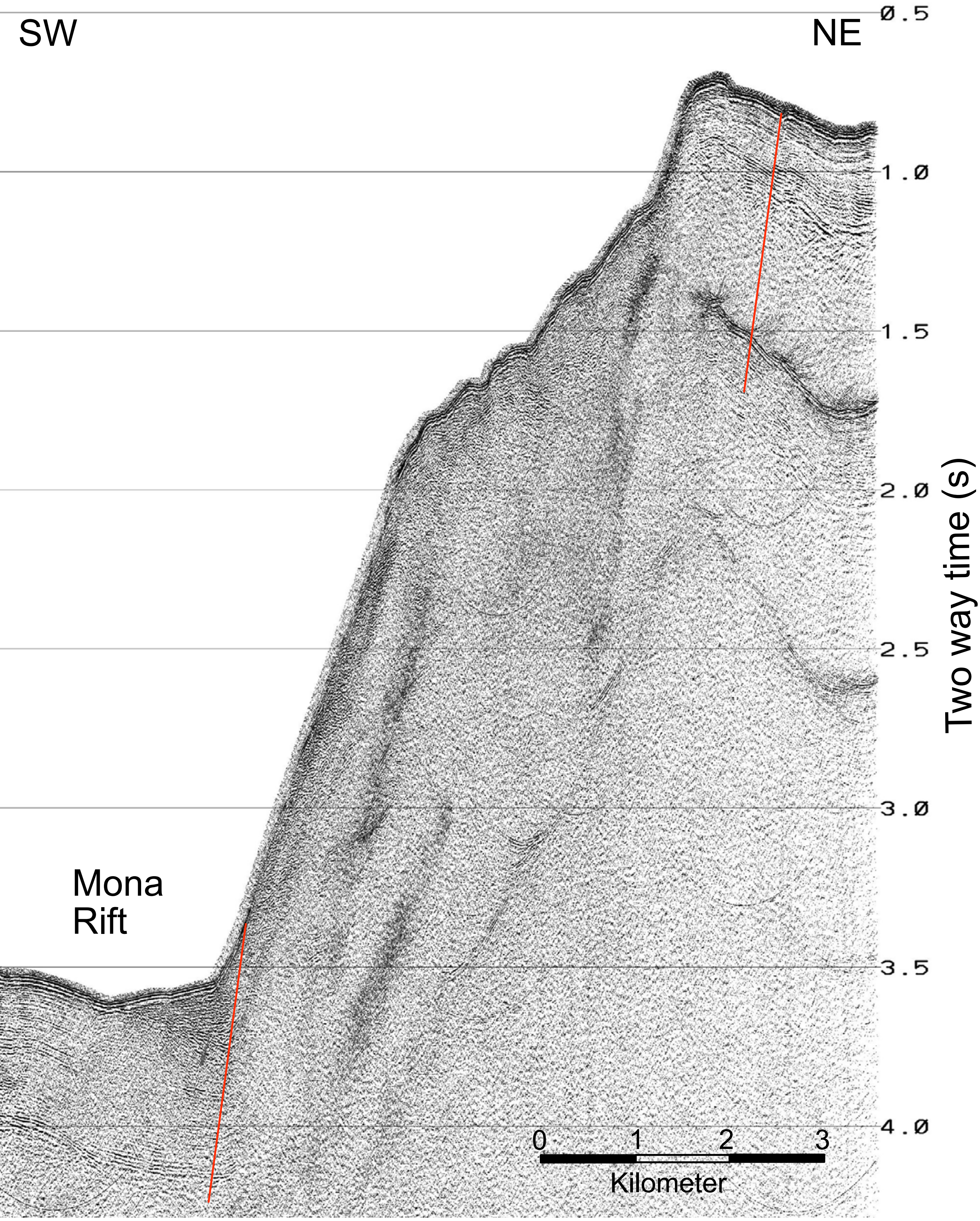

A
Rock face lacking patina
ΔZ = 20 m
Sample location in Fig. 4
(Downhill)
N
Δx = 16 m
w.d. = 2000 m
B
ΔZ = 21 m
(Downhill)
N
Δx =7 m
Rock face lacking patina
w.d. = 1960 m

Figure 6



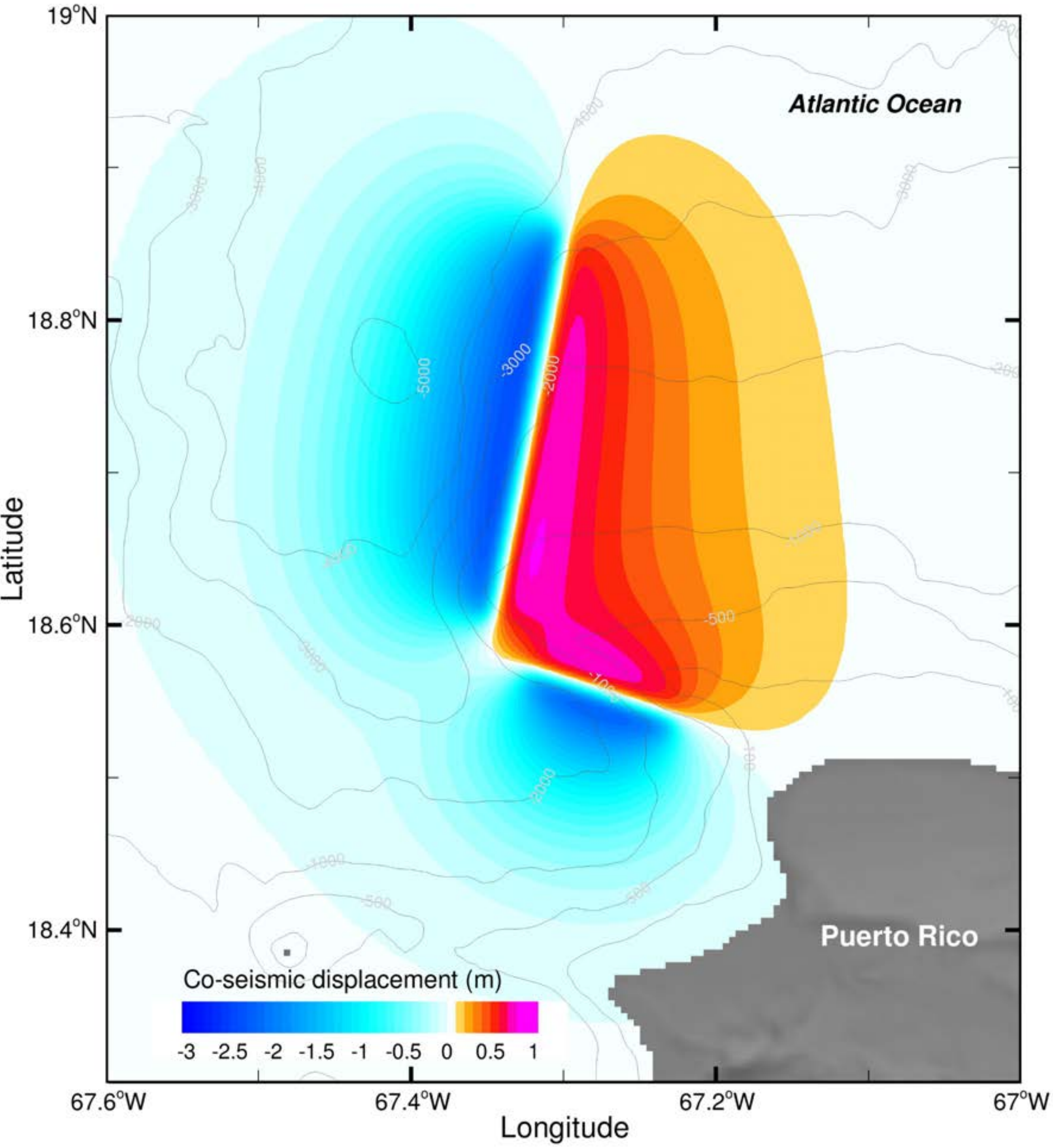
Average slope = 55°
-1702 m
-1714 m
B
2 m
-1306 m
-1336 m
A
Average slope = 40°
2 m

Figure 7



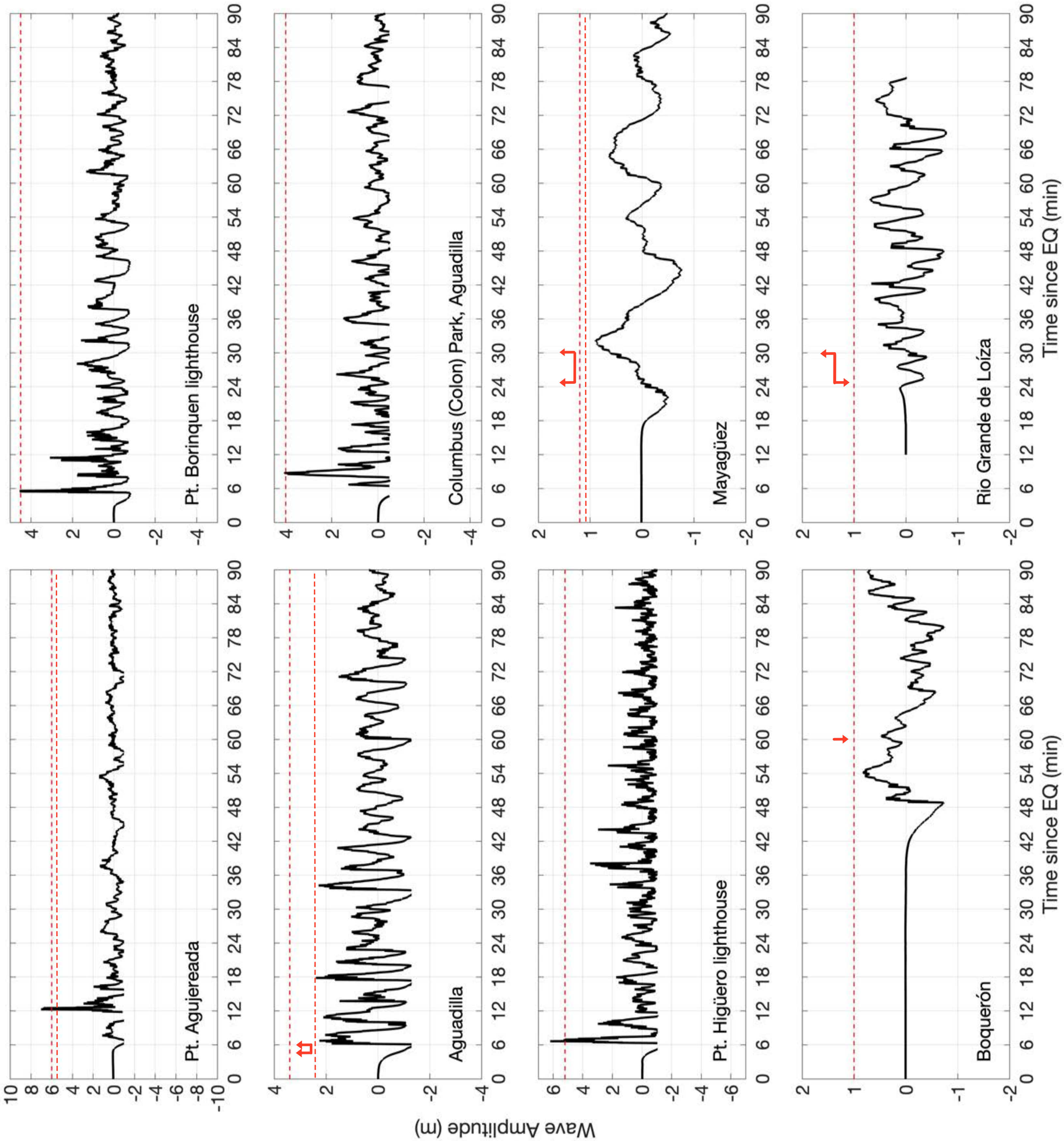
SW
NE
0.5
1.0
1.5
2.0
2.5
3.0
3.5
4.0
Two way time (s)
Mona
Rift
0
1
2
3
Kilometer

Figure 8



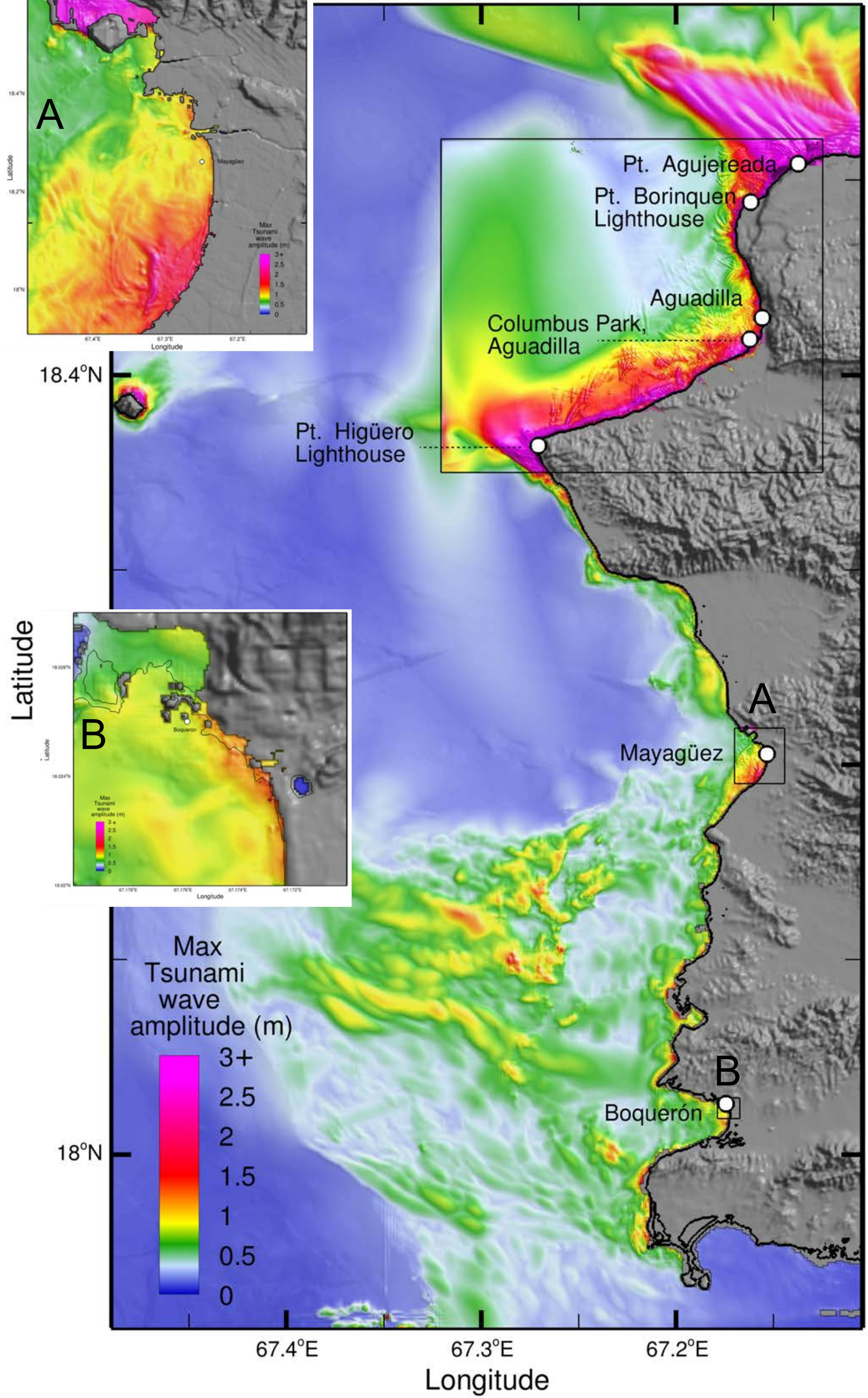
Atlantic Ocean
Puerto Rico
Co-seismic displacement (m)
-3 -2.5 -2 -1.5 -1 -0.5 0 0.5 1
19°N
18.8°N
18.6°N
18.4°N
Latitude
67.6°W
67.4°W
67.2°W
67°W
Longitude

Figure 9



Pt. Agujereada
Pt. Borinquen lighthouse
Aguadilla
Columbus (Colon) Park, Aguadilla
Pt. Higüero lighthouse
Mayagüez
Boquerón
Rio Grande de Loíza
Wave Amplitude (m)
Time since EQ (min)

Figure 10



A
Mayagüez
Max Tsunami wave amplitude (m)
Latitude
Longitude
B
Boquerón
Pt. Agujereada
Pt. Borinquen Lighthouse
Aguadilla
Columbus Park, Aguadilla
Pt. Higüero Lighthouse
18.4°N
18°N
67.4°E
67.3°E
67.2°E
3+
2.5
2
1.5
1
0.5
0

Figure 11