Tsunamis versus Storm Waves: Relative Impacts on the Formation & Change of Rippled Scour Depressions in Monterey Bay, California

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INTRODUCTION

Rippled Scour Depressions (RSDs), a class of sorted bed forms, are indented patches of coarse sediment ranging in size from 30-250 m wide and 100-1000 m long (Bellac et al. 2010,Cacchione et al. 1984, Hallenback et al. in review, Phillips 2007). RSDs have been described in many locations on continental shelves around the world (Garnaud et al. 2005, Gutierrez et al. 2005, Iacono & Guillen 2008, Bellec et al. 2010). The California State Waters Seafloor Mapping Project has now revealed RSDs to be the most commonly occurring and widely distributed bedform on the California continental shelf, covering > 180 km^2 of the 7700 km^2 mapped to date (Davis et al. in prep). Speculation on the environmental factors responsible for the formation and change of RSDs includes storm-induced down-welling (Diesing et al. 2006, Garnaud et al. 2005), strong cross-shore bottom currents (Garnaud et al. 2005), alongshore currents (Murray and Thieler 2004), and tidal scour (Bellac et al. 2010). The purpose of the work presented is to test the general hypothesis that there is a positive relationship between the degree of RSD field change and wave energy. Specifically we evaluated the relative response of an RSD field located in Monterey Bay near Pacific Grove (Fig. 1), California to large storm wave events and a serendipitous tsunamic surge that occurred during the one year study period. Our general approach was to use bathymetric time series mapping of the RSD field to quantify geomorphic change in the aerial extent, spatial distribution and percent cover of RSDs at 10 y, 1 y, and 1 mo temporal scales as well as pre- and post-wave events. Previous analysis of this RSD field completed by the students in this CSUMB research class last year found significant rearrangement of the RSD features within the field, but virtually no change in the aerial extent or percent cover of RSDs within the RSD field over a ten year period from 2000 to 2010. Our hypotheses for this study therefore, were that the overall percent cover of RSDs and the aerial extent of the RSD field would remain constant over time, but that the spatial distribution of RSDs within the field would change in direct proportion to or at some threshold wave energy. We also predicted, given the relationship of wave energy ~ wave height^2 x wave period, that even relatively low amplitude tsunamic surges would produce large changes in RSD field geomorphology comparable to those associated with high amplitude storm wave events.

METHODS

The CSUMB Seafloor Mapping class collected bathymetry data on February 3rd, February 25th, March 13th, and March 22nd, 2011 using RESON 7125 and Swath Plus Interferometric Sidescan sonar systems, and compared it to January 2000 and February 2010 data. Survey dates were selected to capture change due to long and short term wave events. Data was processed with CARIS and exported to Digital Elevation Models (DEM). In ArcGIS, the DEMs were used to calculate areas, extents, and centroids of RSD fields. The area for each field was determined by manually tracing the outer most extent of each RSD field. Benthic Terrain Modeler was used to quantify change in the RSD field by analyzing the distribution of plateaus and depressions at survey dates. In order for intra-survey raster analysis to be valid, the relative positional precision of the paired datasets were evaluated using 6 control points established at stable, rocky features visible in each dataset. Horizontal and vertical positions of each control point for sequential survey dates were compared using a paired t-test (Table 2). Wave height and dominant wave period data from Station 46240 Cabrillo Point Buoy were obtained from the National Data Buoy Center and used to calculate relative wave energy using $T \quad H^2$, where T = wave period in seconds and H = wave height in meters (Minerals & Management 2006). These values were used to compare the relative energy of wave events during our study period. NOAA National Ocean Service tide gauge data from the Monterey Station (ID 9413450) were used to determine the timing and magnitude of the tsunamic surge.

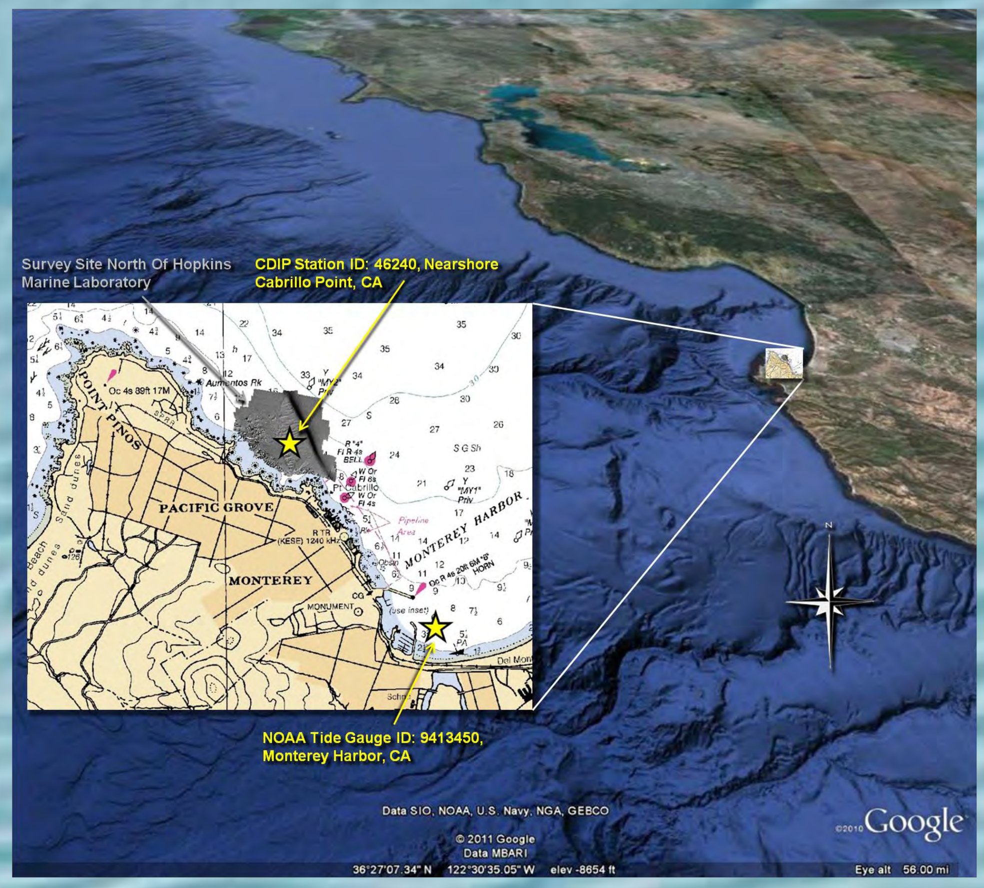


Figure 1: Monterey Bay RSD study area offshore of Pacific Grove, California. Yellow stars indicate wind, water, and weather data loggers. The gray area shows a hill-shaded Digital Elevation Model (DEM) of the specific study site. Background image provided by © GoogleEarth 2011, Data SIO, NOAA, U.S. Navy, NGA, GEBCO.

Date	RSD Field Area (m^2)	Sequential Field Area Change (m^2)	Field Area Percent change	RSD Field Centroid Easting (m)	Sequential Easting Change (m)	RSD Field Centroid Northing (m)	Sequential Northing Change (m)
2000	300,632			597,709		4,054,100	
Feb 12, 2010	281,569	19,063	6.3 %	597,724	15	4,054,090	10
Feb 3, 2011	287,108	5,539	2.0 %	597,720	4	4,054,090	0
Feb 25, 2011	287,108	0	0 %	597,720	0	4,054,090	0
Mar 13, 2011	287,108	0	0 %	597,720	0	4,054,090	0
Mar 22, 2011	287,108	0	0 %	597,720	0	4,054,090	0
Total Change (2000-2011)		13,524	4.5 %		11		10

Table 1: Change of RSD field area extent (m^2) and centriod location (m) between sequential surveys. Sequential change denotes the difference between surveys in chronological order. Total change denotes the change between RSD field area extent 2000 and RSD field extent March 22, 2011. Measured in UTM and calculated in ArcGIS.

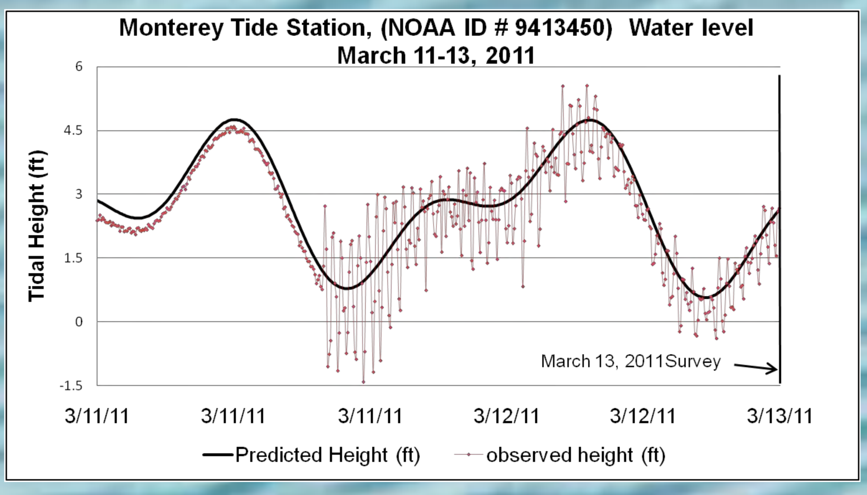
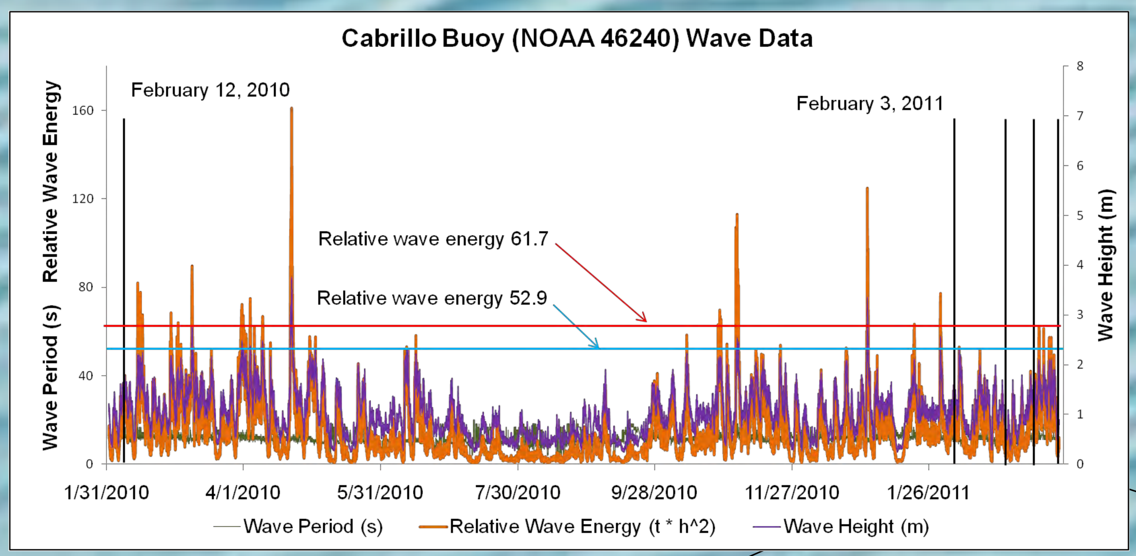


Figure 3: Predicted and observed tidal heights retrieved from NOAA tide buoy (station ID: 9413450) from March 11-16, 2011. Observed fluctuations in tidal height (red) coinciding with the arrival of a tsunami event created by the Tohoku Earthquake in Japan on March 11, 2011, are plotted against predicted tide values (black).



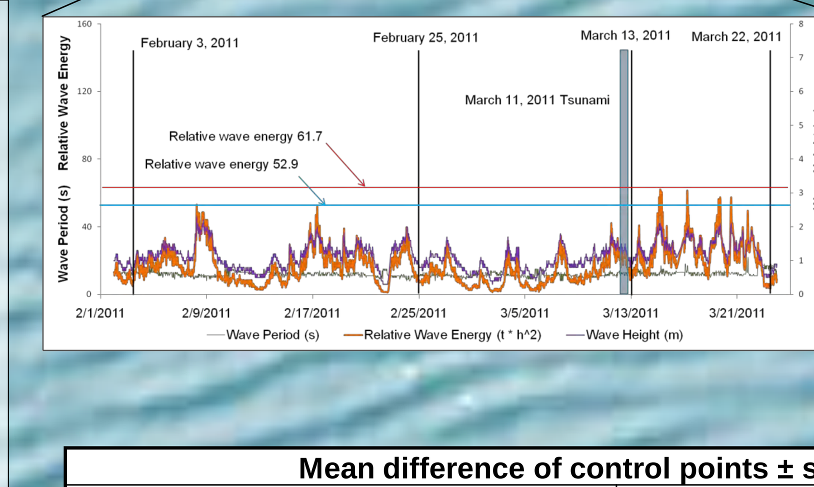


Figure 2: Plots show dominant wave heights in (m), dominant wave period (s), and relative wave energy (m^2s) as calculated by the equation ($t \times h^2$, where t = dominant wave period, and h = dominant wave height) retrieved from NOAA Buoy 46240, located offshore from Cabrillo Point, Monterey CA. The dates of bathymetric surveys conducted by the Seafloor Mapping Lab at California State University Monterey Bay are marked with vertical black lines. The arrival of a tsunami, created by the March 11, 2011 Tohoku earthquake in northern Japan is marked with a vertical blue bar shows the timing of the tsunami and does not represent wave energy. The horizontal blue line delineates relative wave energy values in excess of 53 m^2s (the maximum wave energy during February 3 – 25, 2011). The horizontal red line delineates relative wave energy values in excess of 62 m^2s, (the maximum relative wave energy recorded between February 3 – March 22, 2011).

Mean difference of control points ± standard error (meters)			
Study Period	**Easting**	**Northing**	**Depth**
February 12, 2010 to February 3, 2011	-0.17 ± 0.17	0.33 ± 0.33	-0.05 ± 0.06
February 3, 2011 to February 25, 2011	0.00 ± 0.00	-0.50 ± 0.22	-0.11 ± 0.06
February 25, 2011 to March 13, 2011	0.00 ± 0.26	0.67 ± 0.21 *	-0.05 ± 0.10
March 13, 2011 to March 22, 2011	0.00 ± 0.26	0.00 ± 0.26	0.11 ± 0.09

Table 2: Mean difference in horizontal and vertical locations of 6 control points within the study area, compared between sequential studies. Paired points were analyzed by paired t-test, * indicates a significant difference at $p < 0.05$.

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RESULTS

Our analysis assessed changes in RSDs related to specific events and time periods. During the 1-year time period between Feb 12, 2010 and Feb 3, 2011, there were 21 wave energy events with peaks higher than 53 m^2s and a maximum calculated wave energy of 161 m^2s (Figure 2). In that period, there was measurable change in the aerial extent, and redistribution of the features within the RSD field (Figure 5, Table 1), as well as a net change in RSD % cover (Figure 6, Table 3). During the following 1 month interval from Feb 3, 2011 to February 25, 2011, the peak wave energy event was 53 m^2s, which produced no detectable change in aerial extent, redistribution, or net RSD % cover. Likewise there was no detectable change following the arrival of a tsunami on March 11, 2011, which had a height of ~ 0.7 meters and period of ~ 30 minutes (Figure 3). An episode of large storm swells followed the tsunami and persisted from March 13, 2011 to March 21, 2011 with peak energies of 62 m^2s (well below the 2010 maximum of 161 m^2s). During this final period, there was no detectable change in the aerial extent of the RSD field, however there were measurable changes in net RSD cover and feature redistribution. The inter-survey positional precision for the bathymetric time series was better than 1 m horizontally and 10 cm vertically (Table 2).

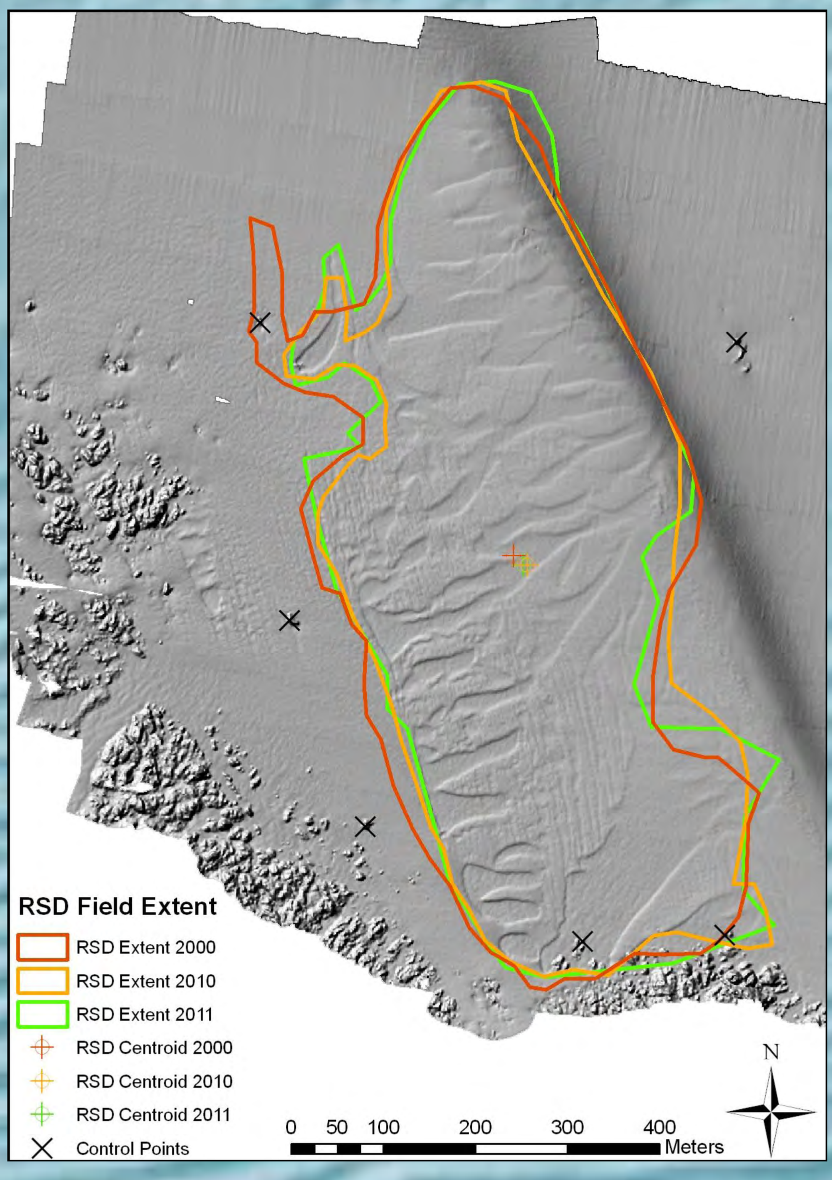

Figure 4: North Hopkins Study Area showing RSD field extent and centroids for 2000, 2010, and 2011, and control points used for quality control tests. A single centroid and extent is displayed for 2011 due to lack of change between surveys. Measurements of change can be found in table 3. Terrain hillshade from February 3, 2011 bathymetric survey.

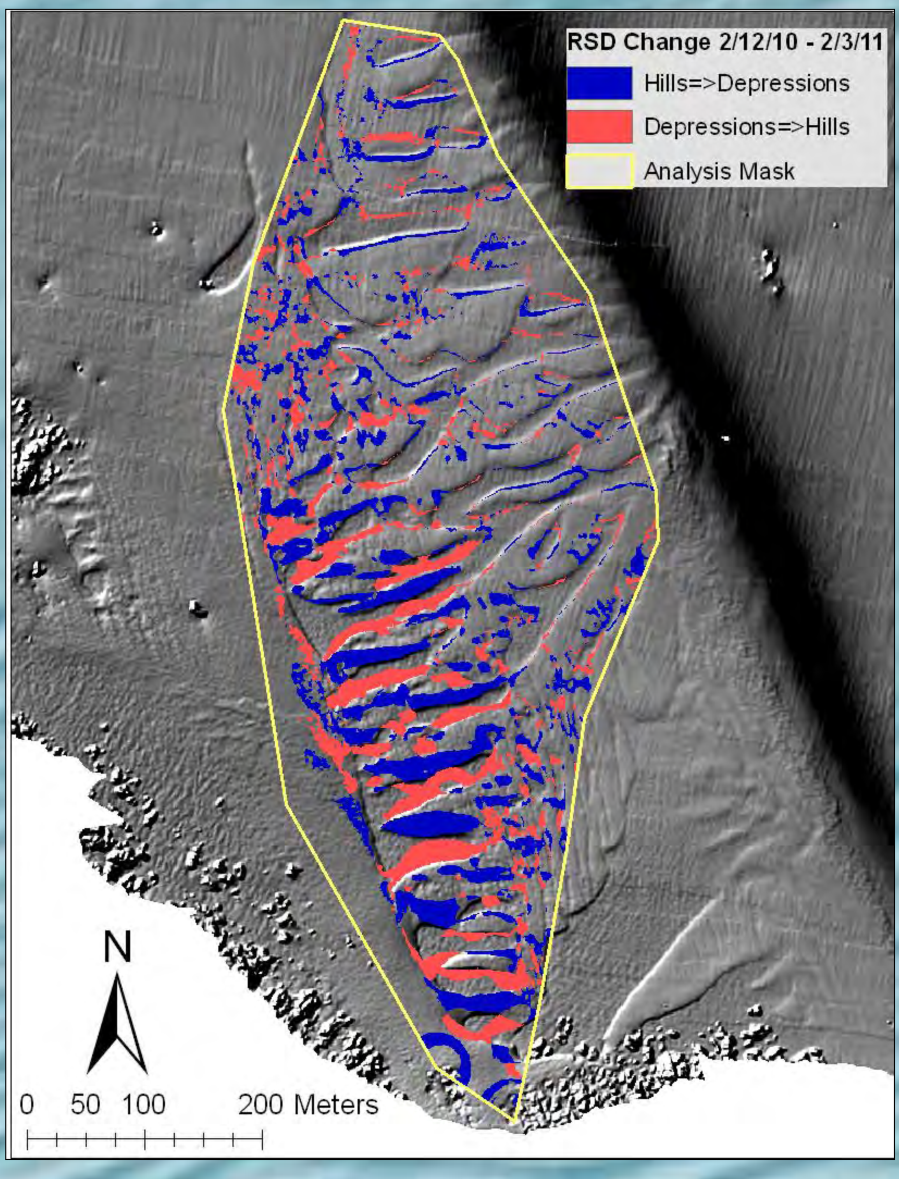

Figure 5: RSD feature conversion from February 12, 2010 to February 3, 2011, the period during which the greatest change to the RSD field occurred (3.5% net RSD change). These results were derived from Benthic Terrain Modeler and are displayed on top of a greyscale shaded relief background. The red areas depict RSD depression that were converted to plateaus. Blue depicts RSD depression that converted to plateaus. The quantitative results from the paired time series analysis of all the DEM s are shown in table 3.

	2000 - Feb 12, 2010**	**Feb 12, 2010 - Feb 3, 2011**	Feb 3- 25, 2011*	Feb 25 - Mar 13 2011*	**Mar 13 - 22 2011**
Net RSD Cover Change	1.0%	**3.5%**	0.6%	0.6%	**-1.4%**
Feature Conversion Over Time					
High->RSD	nc	14.3%	5.7%	5.2%	5.4%
No Change	nc	75.0%	89.3%	90.2%	87.8%
RSD->High	nc	10.7%	5.1%	4.6%	6.8%

Table 3: Percent changes in total area of RSD cover and percent rearrangements of features within the study area over the 11 year study period. Net RSD Cover Change is the percent change in total RSD area within the RSD field from one bathymetric survey date to the next over time periods of ten years, one year, and one month. Additional surveys were conducted following the tsunamic surge, and the long period swell events. The tsunami occurred on March 11th, 2011 and the long period swells occurred between surveys on March 13th and March 22nd. Feature Conversion Over Time includes the percentage of RSDs and plateaus (highs) that interconverted or remained the same between successive surveys: e.g. from plateau to depression (High -> RSD), depression to a plateau (RSD -> high) and No Change.
* = majority of the small but apparent change attributable to minor artifacts in the bathymetry data.
** = 2000-2010 percent RSD cover change analysis provided by the 2010 CSUMB Seafloor Mapping Class, with no calculations available for 2000-2010 Feature conversion. Bold text highlights the largest percent change between surveys.

CONCLUSIONS

Our results show that storm wave events with wave energies below 53 m^2s did not change the RSD field in terms of percent RSD cover, aerial extent of the field, or significant redistribution of the RSD features. However these RSD field parameters did change during periods when wave energy events greater than 53 m^2s up to a maximum of 161 m^2s occurred. Interestingly the change in RSD percent cover was greater during the 12 month period between February 12, 2010, to February 3, 2011 than during the 10 year period between the 2000 and 2010 bathymetric surveys (Table 3), whereas the change in aerial extent was less during the same period (Table 1). Surprisingly no changes in any of the RSD field parameters were detected following the arrival of the tsunamic surge on March 11, 2011. These results suggest a threshold of wave energy > 53 m^2s is required to produce significant RSD change.

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