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New constraints on the processes that control cliff erosion and sediment dispersal using ground-based LIDAR

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New Constraints on the Processes that Control Cliff Erosion and Sediment Dispersal Using Ground-Based LIDAR

A thesis submitted in partial satisfaction of the requirements for the degree Master of Science in Earth Science by Jessica Hall Raymond

Committee in charge:

Professor Neal Driscoll, Chair
Professor Graham Kent
Professor Lisa Tauxe

2011
The thesis of Jessica Hall Raymond is approved, and it is acceptable in the quality and form for publication on microfilm and electronically:

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__________________________________________

Chair

University of California, San Diego

2011
I would like to dedicate this thesis to Black’s Beach, the most beautiful and inspiring place in my life. You ignited a passion in me that will always burn.
And so castles made of sand fall in the sea, eventually

Jimi Hendrix
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ABSTRACT OF THE THESIS

New Constraints on the Processes that Control Cliff Erosion and Sediment Dispersal

Using Ground-Based LIDAR

by

Jessica Hall Raymond

Master of Science in Earth Science

University of California, San Diego, 2011

Professor Neal Driscoll, Chair

The nature of the short-term processes that govern long-term seacliff retreat remains poorly constrained, primarily because conventional approaches, such as digital and softcopy photogrammetry and to some degree airborne LIDAR used to monitor these processes focus more on the recession of the cliff top due to limited coverage of the cliff face. Terrestrial LIDAR, however, is not limited by oblique viewing angles and accurately records wave undercutting, groundwater sapping, and the evolution of the cliff morphology to a precision of 7-10 cm. Here we present a detailed 3.5 year times series with numerous high resolution digital terrain models
(DTMs) derived from terrestrial LIDAR data for three near vertical cliff sites in the southern end of the Oceanside Littoral Cell to resolve better the processes responsible for cliff erosion with minimal overprinting by natural processes or anthropogenic changes. The results reveal both marine and subaerial processes operate in the study area with a spatial focus on areas of groundwater saturation caused by changes in facies. In addition, we present a new detailed approach to determining the sediment contribution from cliff erosion using LIDAR volumes derived for each geological formation and a cutoff grain size of 125 µm. Erosion of the three sites, a total length of 350 m, liberated 4,697 m³ of sediment in a 3.5 year period, with 3,230 m³ above the cut-off grain size. Applying a littoral cutoff diameter (LCD) reduces the sediment input to the littoral environment by 31%.
Introduction

Many studies have examined long term cliff erosion rates through a variety of shoreline mapping techniques, such as aerial photographs and topographic maps (Best and Griggs, 1991; Bowen and Inman, 1966; Robinson, 1988), empirical methods (Everts, 1990), softcopy photogrammetry (Hapke, 2005), and digital photogrammetry (Moore et al., 1999; Moore and Griggs, 2002). Despite this increase in knowledge, these approaches introduce uncertainty regarding the processes responsible for cliff erosion over the time frame of interest. Recent advances in remote sensing technology have improved our ability to measure accurately changes in cliff morphology. Airborne and ground-based LIDAR capture topological data through the transmission and reception of light pulses directed at a target surface. Airborne LiDAR is a rapidly growing field in coastal cliff studies (Young and Ashford, 2006; Sallenger et al., 2002; Zhang et al., 2005), due to its extensive spatial coverage. Nevertheless, it is not an ideal method for imaging vertical cliff sections due to oblique scanning angles and expensive acquisition costs. Conversely, ground-based LIDAR has been proven to be an effective tool to study seacliff failures and morphology (Collins and Sitar, 2004; Lim et al., 2005; Rosser et al., 2005; Young and Ashford, 2007; Olsen et al., 2008). A mobile platform configuration allows for rapid data acquisition and ease in repeatability, thus making it a cost effective method to monitor changes in seacliff and beach morphology and calculate volumetric contributions of seacliff material. Young et al. (2010) compared cliff erosion rates derived from airborne versus ground-based LIDAR along a 400 m stretch of coast in
Delmar, CA. The results showed that the systems are complementary; airborne LIDAR has a wide spatial footprint and maps in detail the cliff top and ground-based LIDAR provides better resolution in areas with steep relief and complex morphology. Estimates of eroded material were approximately 30% higher with the ground-based LIDAR. Despite being a small sample size, this research highlighted how these two systems can be used in concert to understand and model cliff erosion

Cliff erosion reflects the complex interplay between environmental conditions (wave characteristics, tides, sea level, climatic variations, precipitation, temperature, earthquakes) and inherent properties of the seacliffs (lithology, material strength, degree of jointing and faulting, and dip of bedding planes) (Benumof and Griggs, 1999). Two major styles of erosion are observed along most seacliffs, subaerial and marine. Marine erosion, predominantly associated with wave-based undercutting, is an effective agent at removing support from the base of the cliff through the mechanical action of waves and entrained sediment (Wilox et al., 1998; Carter and Guy, 1988; Vallejo and Degroot, 1988; Edil and Vallejo, 1980; Edil and Haas, 1980). Conversely, subaerial erosion is a more diffusive process that operates on the entire cliff face via a variety of processes such as, groundwater sapping, surficial run-off, root burrowing (Trenhaile, 1987), and salt-crystallization and salt-expansion (Mottershead, 1989).

In addition, cliff erosion provides vital sediment to the beaches, which buffers the cliff from marine processes. Sediment supply to the beach in Southern California is event driven and relies on episodic deliveries from rivers, seacliffs, gullies, and
upland terrace erosion (Inman and Jenkins, 1999; Warrick and Milliman, 2003). Previous studies considered sediment yield from seacliff erosion as subordinate with the dominant source delivered from rivers (Brownlie and Taylor, 1981). Recent research (Haas, 2005; Young, 2006) suggests that sediment provided by seacliff erosion is more important than previously thought. Haas (2005) found through sedimentological provenance studies that the seacliffs contribute upwards of 50% of the littoral sand to the beaches compared to the 5-10% determined by Brownlie and Taylor (1981). Young (2006) found that sea cliffs provide an estimated 67% of the beach-size sediment to the Oceanside Littoral Cell over a six-year time series conducted during relatively dry climatic conditions. Furthermore, Warrick and Milliman (2003) found that Southern California rivers discharge hyperpycnal concentrations of suspended sediment during flood events, typical of El Nino Southern Oscillation (ENSO) conditions, which suggests that much of the sediment load discharged bypasses the nearshore littoral circulation cell and is deposited offshore. This has implications for the littoral contribution of rivers since much of the riverine sediment delivered to the beaches occurs during large storm events (Inman and Jenkins, 1999).

Only a portion of the sediment delivered to the littoral system contributes to the beach sediment budget because hydraulic processes keep the finer-grained sediment in suspension and transport it offshore (Hicks, 1985; Limber et al., 2008). Previous sediment budgets for beach systems that failed to consider a littoral cutoff diameter (LCD) and employed the sand/silt division of 63 µm based on the
Wentworth Classification system most likely overestimated the sediment input (Limber et al., 2008). As human activities such as, damming of inland watersheds, extensive urbanization, and emplacement of shoreline protection structures (e.g. seawalls and rip-rap) increase into the future, it is important that we can accurately quantify the littoral contribution of each sediment source in order to formulate proper management strategies.

Here we present a detailed times series of cliff erosion with numerous high resolution digital terrain models (DTMs) derived from ground-based LIDAR data to resolve better the processes responsible for cliff erosion. Such a time series minimizes overprinting by other processes and allows us to examine the link between process and product. Sea level is rising at an unprecedented rate of 2-3 mm/yr due to global warming and raises concerns about the stability of beaches and adjacent sea cliffs. We are using ground-based 3D LIDAR Digital Terrain Model (DTMs) to quantify the erosion rate of the sea cliffs through time. The LIDAR data together with sediment grain size analysis of the failures allows us to define the volume of sand liberated by cliff erosion that remains on the beach. We have been examining the fate of failures in a 5 km stretch of coastline in the Oceanside Littoral Cell to assess their volumetric impact on the coastal sediment budget.
Study Area

This study focuses on three sites within a 5 km stretch of coastline in the southern end of Oceanside Littoral Cell from Torrey Pines State Reserve in the north to Scripps Institution of Oceanography in the south (Figure 1). Due to the close proximity to the shoreline, the Scripps and La Jolla Submarine Canyons may intercept some of sediment transported downcoast by littoral drift (Inman and Frautschy, 1966), but not all (LeDantec et al., 2010). The area is characterized by a semiarid Mediterranean climate, with a winter rainy season, from October to April and a warm dry summer from May to September. The climate is influenced by changes in El Niño Southern Oscillation and Pacific Decadal Oscillation events that results in alternating decades of strong and weak El Niño. Strong El Niño events are associated with anomalously high precipitation during the winter rainy season, whereas, La Niña events are associated with moderate to low rainfall. The Three sites (A, B, and C) were selected for analysis based off of erosion activity, lithology, proximity to development, and degree of wave exposure.

Site A lies 100 m south of the Torrey Pines State Reserve Entrance. Site B, referred to as Flat Rock, is located 1 km south of Site A where a resistant slab of mudstone creates a low relief headland. This site is a threat to public safety as numerous failures have occurred on a pedestrian pathway frequently used to access the southern end of the Torrey Pines State Reserve. Both Site A and Site B have little to no cliff top development aside from hiking trails and a visitor center that is situated over 500 m from the cliff edge. Site C is located in a highly developed residential...
community 1 km north of Scripps Pier. The fronting beach at Site C is exposed to some of the highest energy waves in the region due to the channelization of deep water currents by the La Jolla Submarine Canyon (Inman et al., 1976), however, little of the wave energy is focused at the cliff base because of the high beach elevation and large beach width. Generally, wave attack at the cliff base at Site A and Site C only...
occurs during the combination of high wave activity and spring tides during the winter season.

**Geological Setting**

The study area is characterized by actively eroding steep uplifted marine terraces formed by wave abrasion over a long history of transgressive and regressive cycles (Jenkins, 2005). The sea cliffs are composed of Eocene marine sedimentary rocks mantled by Pleistocene alluvium deposits (Kennedy, 1974; Kennedy, 2005). The Eocene rocks belong to the La Jolla Group, the members found within the study area ordered from oldest to youngest are the Delmar Formation, Torrey Sandstone, Ardath Shale, and the Scripps Formation. Detailed stratigraphic columns of the geological formations and their respective positions on the cliff face were made by examining the facies changes in concert with the elevation data and digital photographs derived from ground-based LIDAR surveys (Figure 2). The Delmar Formation, found in Site A, is a dusky yellowish-green sandy claystone interbedded with medium to coarse grained sand layers that increase in thickness up section (Kennedy, 2005). Fossil assemblages of brackish water mollusks and bioturbation indicate a lagoonal origin. Dissolution of shell fragments increases the CaCO₃ content in the pore water that subsequently acts as a cementing agent making the beds more resistive to erosion. The transition from the Delmar to the Torrey Sandstone is delineated by an oxidized layer, which is a light purple sandy claystone (Figure 2). The Delmar Formation outcrops at Site B and is the edge of an ancient paleo channel,
characterized by a higher-energy facies. The Torrey Sandstone, observed at Site A and B, is a white to light brown, medium to coarse grained, moderately well lithified arkosic sandstone. It is characterized by blocky bedding with broad cross bedding and is interpreted to be a barrier beach deposit that was deposited during a sea level transgression. The Ardath Shale, observed at Site C, is a weakly fissle, gray shale that is overlain by the Scripps Formation (Kennedy, 2005). Fossil assemblages, soft sediment deformation and recumbent folding indicate an outer shelf or upper slope origin. The Scripps Formation, found in Site C, is a light yellowish-brown, medium-grained, moderately-lithified sandstone containing numerous channels with fill ranging from sand to conglomerates. The section exhibits a coarsening-upward trend with channel occurrence increasing upsection. (Kennedy, 2005). The Lindavista is a nearshore marine and non-marine deposit composed of moderate reddish-brown interbedded sandstone and conglomerate deposited in the late Pleistocene (Kennedy, 2005). The Bay Point is composed mostly of marine and non-marine, poorly lithified, fine to medium grained, light brown fossiliferous sandstone (Kennedy, 2005). The base is characterized by a beach cobble lag that represents the local tectonic uplift that initiated approximately 120,000 years ago due to a vertical component of displacement along the Rose Canyon Fault System (Masters and Bada, 1978; Jenkins, 2005).
Figure 2. Stratigraphic columns depicting the different facies and geological formations found in Site A (top), Site B (bottom) and Site C (next page).
Oceanographic Setting

Wave Climate

Waves that arrive at the coast are generated from three principal sources: the northern hemisphere swell, the southern hemisphere swell, and local wind swells, which vary according to season and climatic cycles (i.e., El Niño, Pacific Decadal Oscillation) (Storlazzi and Griggs, 2000). The northern hemisphere swell dominates in the winter (November-April), when storms are generated off of the Aleutian Islands in the Northern Pacific Ocean. The southern hemisphere swells dominates in the summer (May-October), when storms are generated off of the Pitcairn Islands, New
Zealand, Indonesia, Central America and South America. Northern hemisphere swells on average have a higher significant wave height and more energy compared to southern hemisphere swells as shown in Figure 3A. This is due to the fact that they travel shorter distances before arriving at the San Diego coast and therefore experience less decay than swells originating in the Southern Hemisphere. Although southern hemisphere swells generally produce smaller waves than the northern hemisphere swell, they often have very long periods (~ 20 seconds) as shown in Figure 3B because of the intensity and persistence of storms in the southern oceans (Storlazzi and Griggs, 2000). In general, southern hemisphere swells cause little to no cliff erosion along the San Diego coastline because they usually occur when the beach width and beach height are at a maximum and are often unassociated with the storm events (Benumof and Griggs, 1999). Local wind swells are generated in both the winter and summer by low pressure systems that come into close proximity to the coast and by strong sea breezes. Systems that produce wind swells have a smaller fetch than the ones that produce groundswells, therefore they are characterized by shorter periods.

Climatic conditions, such as the Pacific Decadal Oscillation (PDO) may modulate the strength of the El Niño Southern Oscillation (ENSO) and impact southern California’s wave climate due to the change in the position and strength of the Alaskan low pressure systems (Figure 4). Positive values of the PDO index correlate with warm and wet conditions along the California coast. The El Niño events that occur during these time periods are more intense, such as the 1982-83 and
1997-98. Conversely, negative values of the PDO index correlate with cool and dry conditions along the California coast. El Niño events that occur during these time periods are less intense. In addition, an analysis of 50 year deep water hindcasts revealed that during a cool-dry phase of PDO waves were on average smaller and approached the Oceanside Littoral Cell from a more northerly direction and during warm-wet phase of PDO waves were on average bigger and approached the Oceanside Littoral Cell from a more southerly direction (Jenkins and Wasyl, 2005). Wave-based erosion is accelerated during El Niño events in both cool and warm phases of PDO due to elevated water levels, increased wave energy, and narrowed beaches, which makes the cliffs more vulnerable to wave attack and accelerates erosion at the cliff base (Griggs and Johnson, 1983; Griggs and Savoy, 1985; Komar, 1986, 1998b; Storlazzi and Griggs, 1998).
Figure 3. Rose diagrams of A.) significant wave height and B.) peak period for winter (November-April) and summer conditions (May-October).
Figure 4. Monthly values for the PDO index. Positive values (red) indicate warm wet conditions and negative values (blue) indicate cool dry conditions. Typical winter time sea surface temperature (colors), sea level pressure (contours), and surface wind stress (arrows) anomaly patterns during warm and cool phases of PDO (bottom). (Modified from Jenkins, S.A. and Wasyl, J., 2005)

Tides and Sea-Level Changes

Tides and other sea level changes are important variables in determining the susceptibility of seacliffs to marine wave-based erosion (Benumof and Griggs, 2000). Maximum tidal fluctuation in San Diego County is approximately 2.7 meters,
however, additional factors including storm surge, large scale changes in water temperature and wind patterns, climate-related fluctuations, and relative sea level rise contribute to increased local sea surface elevations (Flick and Cayan, 1985). For example, large scale changes in oceanic and atmospheric mechanisms linked with El Nino events can elevate sea level along the West Coast on the order of tens of centimeters over durations of several months (Flick, 1998; Storlazzi and Griggs, 1998). The increase in sea surface elevation and wave heights associated with the strong El Niño events of 1982-1983 and 1997-1998 intensified wave induced erosion of beaches and cliffs (Griggs and Johnson, 1983; Flick, 1994; Storlazzi and Griggs, 1998).
Methodology

Ground-based LIDAR

A ground-based LIDAR system was used to create georeferenced digital terrain models (DTMs) of the coastline to record changes in cliff morphology and beach topography. LIDAR data is collected by the transmission and reception of light pulses reflected off of a target surface. This study used an I-Site 4400 terrestrial LIDAR system, a time of flight laser scanner, which calculates the two-way travel time and return angle of the light pulses emitted along a known trajectory in space. The system has a frequency of 4,400 points per second at a wavelength of 0.905 nm (I-Site 2008). Each return is assigned a XYZ coordinate, RGB value and intensity value and becomes a single point in a dense “point cloud”. A Real-Time Kinematic Global Positioning System (RTK-GPS) was attached to the scanner to record the position of the scans in each survey. Accurately defining the scanner position allows for easier alignment and georeferencing of the data during the processing stages. A typical scan can acquire anywhere from 250,000 to 1,000,000 points in a duration of 3-8 minutes depending on the desired resolution and coverage. In a controlled lab test environment the scanner has an accuracy of 2 cm at a range of 50 m (I-Site 2008), however, in the beach environment it is accurate to ~5 cm at a range of 5-500 m (Olsen et al., 2009). The RTK-GPS data was calibrated to fixed monuments in the study area and has an overall accuracy of 2.2 cm (Trimble 2008). Overall, given the accuracy of the scanner and the accuracy of the RTK-GPS positions, georeferenced LIDAR data is accurate to ~7.2 cm.
Ground-based LIDAR surveys were conducted semi-annually beginning in November 2006 to the end of July 2010. Individual failures sites were monitored more frequently to assess reworking of the failure talus and to record additional activity. The ground-based LIDAR system used consists of an I-Site 4400 laser scanner, data acquisition control device, and a DGPS unit (Figure 5). To maximize the available beach width and scanning time, surveys were performed during negative and low tides. The scanner was stationed orthogonal to the cliff and scanned from 45 deg to 80 deg in the vertical and from 180-360 deg in the horizontal. In an earlier study of the region, Olsen (2009) found the optimum scan spacing to be 50-70 m with a scan distance of 30-40 m from the cliff base. However, in order to capture the cliff top in sections of high elevation, such as Site A and C, a larger scan distance from the cliff base was needed, but not always possible given the tidal conditions. Ground-based laser scanners only collect data that is within line of sight, therefore areas with complex geometry, such as notches and caves, will have occlusions or shadow zones. To reduce or avoid shadow zones, the area of interest must be scanned from multiple perspectives (Collins and Sitar; Olsen et al., 2009).

Raw point cloud data was filtered, aligned, georeferenced, surfaced, and analyzed in I-Site Studio 3.0 software. Data is filtered to exclude people, vegetation,
and points out of the acceptable range of the scanner. Scans with GPS points were georeferenced in a UTM NAD83 Zone 11 coordinate system using Pointreg, an automated algorithm developed by Olsen et al. (2009) that determines the optimal rotation angle for each scan that yields the lowest root mean square (RMS) error.
Scans without a GPS point were manually aligned and run through an I-Site Studio algorithm that adjusts the alignment based on similar surface features of overlapping scans. Photographic surfaces were generated using both spherical and topographic triangulations and the RGB data collected by the on board digital camera. Photographic surfaces are a great visual aid to detect geological formation boundaries, sharp changes in facies, vegetative growth, and zones of groundwater saturation. Spherical triangulations were used in areas of complex morphology (i.e. overhangs and sea notches), whereas, topographic triangulations were used in areas that had a more relaxed gradient such as the beach or relatively featureless cliff surfaces.

**Littoral Sediment Contribution**

Rendered LIDAR cliff surfaces of each survey were differenced to the previous survey to quantify the volume change from the cliff and the volume change from each geological formation. Grain size analysis was conducted on 10 samples from each geological formation to determine the percentage sand above the LCD. A LCD of 125 µm was used in this study from beach grain size data gathered by Haas, (2005). One-hundred grams of each sample were put into a standard set of 6 geological sieves (2 mm, 1 mm, 0.5 mm, 0.25 mm, 0.125 mm, 0.063 mm). Samples that contained highly consolidated rocks, such as the claystone in the Delmar Formation and the shale in the Ardath, were disaggregated and sieved a total of three times. Failure to break the rock down to its constituent particles yields a percentage
of sand that is inaccurate and too high, thereby overestimating the importance of seacliff erosion as a source of sand to the littoral budget (Limber et al., 2008). The grain size data for each geological formation was averaged and plotted on a cumulative curve (grain size vs. cumulative weight percent frequency) with an arithmetic ordinate scale. This plot allows for the analysis of important grain size statistical parameters such as the mean grain size (Equation 1), standard deviation (Equation 2), sorting, and the amount of littoral-type sediment equal to or coarser than the LCD (Boggs, 2005).

Graphic mean = $M_z = \frac{\varphi_{16} + \varphi_{50} + \varphi_{84}}{3}$  \hspace{1cm} (1)

Standard Deviation = $\sigma_i = \frac{(\varphi_{84} - \varphi_{16}) + (\varphi_{95} - \varphi_{5})}{\frac{4}{6.6}}$  \hspace{1cm} (2)

In locations such as Site B, where there is considerable variation in facies, the sand content was estimated for the entire outcrop using an average weighted by facies abundance as shown in equation 3. The thickness of the layers/facies were determined from the scaled stratigraphic columns shown in Figure 2.
Sand Content = \[ \sum_{i=n} \left( \frac{T_i \times \%LCD_i}{T_t} \right) \]  \hspace{1cm} (3)

where:
- \( n \) = number of layers
- \( T_i \) = thickness of layer \( i \)
- \( T_t \) = thickness of formation
- \( \%LCD \) = the percentage of cliff material with a grain size equal to or greater than the littoral cutoff diameter

The following equation adapted from Best and Griggs, 1991 was used to determine the littoral contribution from sea cliff erosion:

\[ Q_{\text{sand}} = (V_{\text{cliff}} \times \%LCD) \]  \hspace{1cm} (4)

where \( V_{\text{cliff}} \) is the volume eroded from the cliff (m\(^3\)) measured from differencing LIDAR surfaces.

**Modeling Environmental Conditions**

Environmental conditions such as precipitation, temperature, and wave conditions are important factors in understanding the processes that govern seaciff erosion and the reworking of failure material into the littoral system. To evaluate the role of each environmental parameter, we used proxies such as, rainfall, daily temperature range, and total water level to record the influence of groundwater saturation, thermal expansion and contraction, and wave action on seaciff erosion.
**Precipitation and Temperature**

Precipitation data was collected at NOAA station 23188 located on the San Diego Lindbergh Field. In addition, zones of groundwater saturation were identified using photographic surfaces and intensity values collected by the laser scanner. Mudstone layers, especially when saturated, have a lower intensity signal than sandstone layers (Figure 6) thereby making intensity returns from LIDAR data a mean to locate zones of groundwater saturation (Sturzenegger, M et al., 2007)

Daily temperature range was used as a proxy for the influence of temperature expansion and contraction. Hourly air temperature recordings were collected at CDIP station 073 located 6.1 meters above MLLW at the west end of Scripps pier. Gaps in the data were filled with temperature data from the NOAA station located at the San Diego Lindbergh Field. The daily maximum and minimum values were differenced to determine the range in temperature.

**Total Water Level**

Total water level is the sum of the measured tidal elevation and the vertical component of wave runup as shown in Figure 7. Removal of talus that has accumulated at the base of the cliff due to failure events by subaerial processes and direct attack and undercutting at the base of the cliff is more probable when the total
water level elevation exceeds the elevation of the cliff toe (Ruggiero et al., 2001). Measured tidal elevation takes into account the predicted astronomical tide (i.e. the regular changes of ocean water levels caused by the gravitational forces of the moon and sun) plus previously mentioned processes that alter the mean water level from the predicted tidal elevation. Wave runup requires the adoption of empirical models that change according to beach morphology, which is a function of the dominant sediment
grain size, beach slope, and local wave conditions (Wright and Short, 1983). Along this reach there are complex variations in the shelf geometry that create a high degree of variability in wave shoaling (Jenkins and Wasyl, 2005). Total water level and the results are not going to be explained in the main body of the text due to the fact that the complicated morphology of the La Jolla submarine canyon introduces error when transforming the wave field to shallow water from offshore buoy data. TWL and its application to the study area is explained in greater detail in the appendix.

**Assumption:**
When $E_T > TWL$, erosion at base of cliff  
$E_T < TWL$, no erosion at base of cliff

**Figure 7.** Schematic depiction of the variables involved in modeling marine-based cliff erosion. Total Water Level (TWL) is defined as the sum of the wave runup, $R$ and measured tide, $T$. According to the model, when the TWL exceeds the Toe elevation, $E_T$, active marine based erosion occurs.
Modeling Failure Reworking

Once cliff material is emplaced on the beach it becomes reworked into the surrounding beach environment on a variety of time scales that depends upon the prevailing wave conditions, height of the beach berm, and the fronting beach width (Edil and Vallejo, 1980). In an effort to better understand the timescales, we use ground-based LIDAR data to model the change in the talus volume and beach elevation and compare our results against wave direction, wave height, wave runup and TWL.

Modeling the change in talus volume and beach elevation is a multi-step process outlined below:

1. Calculate the volume of the talus at the base of the cliff, $V_{\text{talus}}$, for each survey by comparing the talus surface to a fixed reference surface. A reference surface that is fixed to a constant datum, accounts for the seasonal fluctuations in beach elevation. Otherwise, the failure volume will inflate as the beach deflates or conversely it will deflate as the beach inflates.

2. Calculate the volume eroded from the cliff, $\Delta V_{\text{cliff}}$, for each survey. It is important that additional cliff input is considered, otherwise the change in the talus volume will be overprinted by the new material and consequently underestimated.

3. Difference $\Delta V_{\text{cliff}}$ from the $\Delta V_{\text{talus}}$ to compute total volume change, $\Delta V_{\text{total}}$, of the talus between successive surveys.
4. Beach elevation is measured by determining the mean elevation of LIDAR beach points. In the analysis of reworking at Site B two 25 m$^2$ areas at constant positions northwest and southeast of Site B-1 were used.
Results

Temporal

The volume eroded for the 350m of coastline of Sites A, B, and C during the 3.5 year time series totaled 4,697 m$^3$. Figure 8 shows the semi-biannual erosion volumes for each site for each geological unit and their combined total (colored gray). The Delmar formation is the lower unit for Site A and B and the Ardath Shale for Site C (colored blue). The Torrey Sandstone is the upper unit for Site A, the Baypoint Alluvium for Site B, and the Scripps Sandstone for Site C (colored green). No data is provided for the Spring of 2007 at Site B since surveys began at this site in the Fall of 2007. The total volume eroded from the cliff face at Site A was 2,169 m$^3$ with a fairly equal contribution from both geological formations, 1,073 m$^3$ from the Delmar and 1,096 m$^3$ from the Torrey. The total volume eroded from the cliff face at Site B was 897 m$^3$ with 625 m$^3$ from the Delmar and Torrey, and 272 m$^3$ from the Baypoint. The total volume eroded from the cliff face for Site C was 1,631 m$^3$ with a disproportionate amount from the Ardath Shale, 925 m$^3$ from the Ardath and 706 m$^3$ from Scripps. Although continual erosion occurred at each site, major events above 300 m$^3$ were episodic in nature, although Site A exhibited multiple large failure events.

Site A had two sites of heightened activity referred to as, A-1 and A-2 that comprised approximately 77% of the total volume eroded at Site A. Site A-1 had three failure events that contributed 988 m$^3$. The first event occurred between June 15 and 17th 2008, the second on Sept 3, 2009, and the third between May 7th and 30th,
Site A-2 had one major failure event that contributed 678 m$^3$ between December 9th and 25th, 2008.

The headland at Site B experienced erosion both to the north and to the south that accounted for 100% of the total volume eroded. The southern site, B-1 had five failure events that contributed 722 m$^3$. The first event occurred between August 22nd and 24th 2007, the second between Feb 5th and 15th, 2008, the third on September 22, 2009, the fourth between September 24th and 30th, 2009, and the fifth between October 1st and October 16th, 2009. The northern site, B-2 had one major failure event that contributed 175 m$^3$ on Aug 15th, 2009

Site C had one site of heightened activity referred to as C-1 that accounted for 53% of the total volume eroded. Site C-1 had five failure events that contributed 867 m$^3$. The first event occurred between January 10th and 30th, 2009, the second on May 5th, 2009, the third between May 23rd and June 23rd, 2009, the fourth on July 21, 2010, and the fifth on July 29th, 2010
Figure 8. Erosion volumes (m$^3$) for lower geological unit (blue), upper geological unit (green), and total for both units (shaded gray) for semi-biannual surveys at A.) Site A, B.) Site B, and C.) Site C.
Spatial

The total change that occurred on the cliff face and at the cliff base at Site A between Nov 4th, 2006 and May 31, 2010 is shown in Figure 9. Orange color indicates erosion and blue indicates accretion. The geological formation boundary of the Delmar (claystone) and Torrey (sandstone) is delineated by a dashed line.

![Surface change DTM of Site A showing erosion and deposition patterns from Nov 2006 to May 2010. The geological formation boundary between the Delmar (claystone) and Torrey (sandstone) is delineated with a dashed line. Cliff profile locations for Figure 10 are shown for reference.](image)

Cliff profiles at Site A are shown in Figure 10, the location of the profiles are shown in Figure 9. Zones of groundwater saturation, determined from the stratigraphic columns in Figure 2, are labeled with a dashed line. The evolution of failure site A-1 can be seen in profiles A and B. Profile A in Figure 10 shows failure activation at
aquitard Aq-2, located 3 m below the contact boundary between the Torrey and the Delmar. In addition, root burrowing was present at Site A-1 where large tree roots extended out of tension cracks to the boundary of the Torrey and Delmar, over 20 m below the cliff top (Figure 11). Profile B shows removal of a small block confined between Aq-1 and Aq-2. The second collapse was also focused at Aq-2. The evolution of failure site A-2 can be seen in Profile C. Profile C shows failure activation at aquitards positioned lower in the cliff face Aq-3 and Aq-4, however, the same aquitard, Aq-2, was the upper failure plane for the first failure event.

The total change that occurred on the cliff face and at the cliff base at Site B between Nov 4th, 2006 to June 14th, 2010 is shown in Figure 12. Cross sections of failure B-1 and B-2 are shown in Figure 13. Profile A shows failure activation at the bottom contact of the conglomerate layer, Aq-1 and at aquitard Aq-2. Failure activity depicted in Profile B also shows failure activation at Aq-2 as well as erosion of the poorly lithified alluvium of the Baypoint. Profile C demonstrates that failure initiation occurs at Aq-1 and in the Baypoint in the survey following the major collapse.
Figure 10. Cliff profiles taken at Site A-1 (A and B) and at Site A-2 (C). Location of profiles are shown in Figure 9.
Figure 11. Photo of failure Site A-1 taken on November 2008 before collapse of arch. Inset shows the presence of root structures down to the contact boundary of the Delmar and Torrey.
Figure 12. Surface change DTM of Site B showing erosion and deposition patterns from Nov 2006 to Jun 2010. The geological formation boundary between Delmar (claystone), Torrey (sandstone), and Baypoint are delineated by the dashed lines. Cliff profile locations for Figure 13 are shown for reference.
Figure 13. Cliff profiles taken at Site B-1 and Site B-2. Location of profiles are shown in Figure 12.

The total change that occurred on the cliff face and at the cliff base at Site C between Nov 4th, 2006 to July 29, 2010 is shown in Figure 14. Cliff profiles are shown in Figure 15, the location of the profiles are shown in Figure 14. Zones of groundwater saturation where determined using surfaces colored with the intensity values of the return signal as shown in Figure 16.
Figure 14. Surface change DTM of Site C showing erosion and deposition patterns from Nov 2006 to Jul 2010. The geological formation boundary of the Ardath (shale) and Scripps (sandstone) is delineated with a dashed line. Cliff profile locations for Figure 15 are labeled for reference.
Figure 15. Cliff profiles taken from areas of failure activity at Site C. Location of profiles are shown in Figure 14.
Figure 16. LIDAR surface of Site C acquired November 2007 is colored by intensity with values returned from the scanner. Cool areas indicate low intensity returns common of zones of groundwater saturation.

Littoral Sediment Contribution

The average cumulative frequency grain size distributions of the geological formations found in the study area are plotted in Figure 17, along with a “littoral window” that brackets the littoral sediment coarser than the pre-determined LCD of $\sim 125 \, \mu m$ (3 $\Phi$). Using the grain size distributions, one can infer the total percentage of littoral-type sediment, or sediment coarser than the LCD, by noting at what percentage a distribution curve crosses the littoral window.
The total sediment yield from each site and the total littoral sediment yield calculated by equation 4 are summarized for each site in Table 1. Results show that the cliff input calculated using the littoral sediment yield are lower than the total sediment yield that does not take into account a LCD. The application of a LCD reduced the sediment input approximately 25% at Site A, 12% at Site B, and 50% at Site C. The application of a LCD of 63 µm reduced the sediment input approximately 13% at Site A, 4% at Site B, and 26% at Site C. The combined sediment yield for all the sites is 4,697 m$^3$, whereas the combined littoral sediment yield is 3,229 m$^3$, a reduction of 1,425 m$^3$ or approximately 31 percent. A summary of the different sand
contents for the different geological formations used in previous studies and for this study are shown in Table 2.

Table 1. Summary of the cliff sediment yield (m$^3$) and littoral sediment yield (m$^3$) using an LCD of 125 µm for each the upper and lower geological units as well as alluvium.

<table>
<thead>
<tr>
<th>Site</th>
<th>$Q_{\text{cliff Lower}}$</th>
<th>% LCD Lower</th>
<th>$Q_{\text{sand Lower}}$</th>
<th>$Q_{\text{cliff Upper}}$</th>
<th>% LCD Upper</th>
<th>$Q_{\text{sand Upper}}$</th>
<th>Cliff Sediment Yield</th>
<th>Littoral Sediment Yield</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>1,073.0</td>
<td>59</td>
<td>633.1</td>
<td>1,096.0</td>
<td>91</td>
<td>997.4</td>
<td>2,169.0</td>
<td>1,630.4</td>
</tr>
<tr>
<td>B</td>
<td>625.0</td>
<td>86</td>
<td>537.5</td>
<td>272.0</td>
<td>92</td>
<td>250.2</td>
<td>897.0</td>
<td>787.7</td>
</tr>
<tr>
<td>C</td>
<td>925.0</td>
<td>32</td>
<td>296.0</td>
<td>706.0</td>
<td>73</td>
<td>515.4</td>
<td>1631.0</td>
<td>811.4</td>
</tr>
<tr>
<td>Total</td>
<td>2623.0</td>
<td></td>
<td>1466.6</td>
<td>2074.0</td>
<td></td>
<td>1763.0</td>
<td>4697.0</td>
<td>3229.6</td>
</tr>
</tbody>
</table>

**Environmental Conditions**

**Precipitation and Temperature**

The time series of erosion shown in Figure 8 is taken for each individual site to compare trends in erosion with environmental conditions such as the daily temperature range and precipitation as shown Figures 18-20. The percent of time the daily temperature was greater than the mean of 7 °C and the cumulative precipitation between successive biannual surveys are shown. A time series of precipitation and
daily temperature range along with failure occurrence is shown in Figure 21. When the timing of the failure event was uncertain it is bracketed by a shaded box.

Table 2. The sand content used in previous studies using different LCD values and for this study using a LCD of 125 µm for the geological formations found within the study area.

<table>
<thead>
<tr>
<th></th>
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<th></th>
<th></th>
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</tr>
</thead>
<tbody>
<tr>
<td>Delmar</td>
<td>75</td>
<td>42</td>
<td>65</td>
<td>52</td>
<td>78</td>
<td>59/86 †</td>
</tr>
<tr>
<td>Torrey</td>
<td>75</td>
<td>42</td>
<td>65</td>
<td>52</td>
<td>78</td>
<td>91</td>
</tr>
<tr>
<td>Ardath</td>
<td>75</td>
<td>42</td>
<td>65</td>
<td>52</td>
<td>78</td>
<td>32</td>
</tr>
<tr>
<td>Scripps</td>
<td>75</td>
<td>42</td>
<td>65</td>
<td>52</td>
<td>78</td>
<td>73</td>
</tr>
<tr>
<td>Alluvium</td>
<td>75</td>
<td>42</td>
<td>65</td>
<td>52</td>
<td>78</td>
<td>92</td>
</tr>
</tbody>
</table>

† Value used for Site B

Precipitation levels were highest in the winter months (November-April) with peak values in the months of January and February. The daily temperature range shows a seasonal trend with higher fluctuations in the winter months. Gaps in temperature at the Scripps Pier Station (CDIP) were filled with data from the San Diego Airport Weather Station (NOAA) (colored bold black).
Figure 18. Erosion (m$^3$) (top), cumulative precipitation (cm) between successive surveys (middle), and percent time daily temperature range is larger than the mean (7 °C) of the time series (bottom) at Site A. Precipitation and daily temperature range follow a seasonal cycle with largest values in the winter.
Figure 19. Erosion (m$^3$) (top), cumulative precipitation (cm) between successive surveys (middle), and percent time daily temperature range is larger than the mean (7 $^\circ$C) of the time series (bottom) at Site B. Precipitation and daily temperature range follow a seasonal cycle with largest values in the winter.
Figure 20. Erosion (m$^3$) (top), cumulative precipitation (cm) between successive surveys (middle), and percent time daily temperature range is larger than the mean (7 °C) of the time series (bottom) at Site C. Precipitation and daily temperature range follow a seasonal cycle with largest values in the winter.
Figure 21. Plot of precipitation (top) and daily temperature range (bottom) for the time series.

Failure Reworking

The evolution of talus material at Site B-1 was recorded through 26 repetitive high resolution scans over the course of 22 months. Figure 22 shows the cumulative cliff input and talus volume measured at Site B-1 from the first failure event on Aug 23, 2007 to the last survey on June 16, 2010. The slope of the talus volume curve is steepest after the largest failure, which indicates that reworking is a function of sediment availability. The talus material is more exposed to oceanographic conditions the further it extends seaward. The difference between the two curves indicates the volume of material reworked. For instance, the last data plotted for each curve show that the total cliff input was 722 m$^3$ and the talus volume that remains at the base of
the cliff is 15 m$^3$, therefore 707 m$^3$ of talus material was reworked into the littoral system during the time series.

Figure 22. Cumulative cliff input and talus volume at Site B-1 measured over the course of this study

The variables used to determine the total change in talus volume between successive surveys are plotted in Figure 23. The total volume change is a function of the change on the cliff face and the change of the talus volume measured at the base of the cliff. The actual amount of sediment delivered into the system is accurately recorded and not overprinted by reworking processes by subtracting the cliff input
from the talus volume that occur between surveys. The measured talus volume is greater in volume then the measured cliff input, if there was a rapid response to scan the site, due to voids and spaces created by disaggregating the rock. The expansion of the cliff material can increase the volume anywhere from 10-25% depending on the size.

Figure 23. Plot of variables needed to calculate the total talus volume change. The difference of the volume change of the talus and the cliff input.
The beach elevation is plotted with the total change in talus in Figure 24. When the total change in talus is greater than 0 the addition of cliff material outpaces reworking. When the total change in talus is less than 0 reworking outpaces the cliff addition. The relationship to the beach elevation is observed by the change in slopes of the ΔTotal curve. When the beach elevation increases the reworking decreases due to a larger protective buffer. Figures 25-26 compare the change in beach elevation to oceanographic conditions, such as peak directionality and significant wave height. Figure 25 compares beach elevation to the percentage of the time the direction falls between 250 and 310, a range typical of northern hemisphere swells and local wind swells. Directional data smoothed daily is shown in the lower plot. Failure events greater than 30m$^3$ are denoted by gray lines. The mean direction of the time series was 238 deg with a standard deviation of 35 deg. Figure 26 compares beach
elevation to the percentage of time the significant wave height is greater than 1.1m.

The significant wave height data smoothed daily is show in the lower plot. The mean offshore wave height for the time series was 1.1 m with a standard deviation 0.43 m.

Figure 25. Comparison plots of beach elevation at Site B-1 and wave directionality. Beach elevation decreases during time periods where direction is dominated by westerly and northwesterly swells common of fall and winter. Failure events greater than 30m$^3$ are denoted by gray lines.
Figure 26. Comparison plots of beach elevation at Site B-1 and offshore wave height (555 m water depth). Failure events greater than 30m$^3$ are denoted by a gray line.
Discussion

The following results represent the range of capabilities of data derived from terrestrial LiDAR in monitoring coastal cliff processes. Conducting routine surveys allows for examination of temporal and spatial variations in erosion activity and beach elevation and can shed light on the dominant failure mechanisms and styles of erosion. Although our temporal coverage was short term we were able to identify and model subaerial processes and their spatial location on the cliff face and marine processes operating at the cliff base. Both end member styles of erosion were present to a varying degree at all sites and their relative importance shifted in time and space. Erosion patterns were seen to differ between geological formations. Erosion of the upper sandstone unit was localized and event driven, whereas erosion of the lower claystone/shale unit was more consistent and diffuse, spread out over the entire cliff face. The erosion patterns are consistent within each site, which suggest that material properties and stratigraphy are important controls on erosion.

The mean beach elevations taken during successive LIDAR surveys shown in Figure 27 demonstrate the link between beach elevation and width and the dominant erosional process. Site B has a lower beach elevation and is exposed to marine processes a larger portion of the time compared to the other sites. The over-steepened base of the cliff seen in the cliff profile is evidence of wave undercutting, this corroborates the lower beach elevations role in marine erosion as well as the total water elevation results which are discussed in the Appendix. Site A and C have higher beach elevations, talus accumulated at the base of the cliff, and profiles with a
gradual slopes at the base, but undercutting at zones of groundwater sapping. This indicates the relatively minor role of wave activity and the dominant role of subaerial erosion.

Figure 27. Mean beach elevation of surveys conducted at Site A, B, and C.
The processes that we believed to be dominant subaerially are groundwater sapping and thermal expansion and contraction. Our results show the possibility of a relationship between the activation of failure events and large changes in daily temperature and water introduced from precipitation events, however, due to the short term nature of this study we do not have enough data to show a significant correlation. Cross section data of all three sites reveal that zones of groundwater accumulation form unstable horizons that act as planes in which failures are activated upon. Extensive mapping of the geological units and the different material that comprises them shows that facies changes in permeability control where groundwater accumulates. Evidence of this is seen at the geological formation boundaries. The difference in permeability of the fine grained Delmar compared to the medium to coarse grained Torrey or the fine grained Ardath Shale to the medium grained Scripps creates the right conditions for water accumulation. Layers of sand interbedded in the Delmar and the Ardath also accumulate water and constrain where failure initiation occurs. The presence of aquitards can increase the pore water pressure, decrease the frictional strength (Ritter, 1986) and reduce the cohesive strength of the rock by dissolving chemical cements or softening the binding clays (Ritter, 1986; Hampton, 2002). The anthropogenic impact on water delivered to the cliffs sediments was evident at Site C. The cliff had multiple zones of groundwater saturation that were present year round and not linked to precipitation events. Surveys conducted at Blacks Beach in the same time frame as Torrey Pines show lower signal intensity returns from the scan data, which indicates a higher degree of moisture in the cliff
sediments. Anthropogenic additions to the groundwater table are important to consider in addition to precipitation. Future work should focus on analysis of pore pressures and analysis of groundwater flow to try and understand what triggers unstable conditions and how this might change given different climatic conditions.

When wave attack is more frequent talus gets reworked on shorter time scales and the cliff base gets re-exposed to wave activity faster. The beach elevation and talus volume time series taken at Site B shows this cycle of accretion and erosion at the base of the cliff. The beach elevation has a general trend of lower beach elevations during the winter and spring and higher beach elevations in the summer and early fall with some background variability. These trends follow seasonal trends in oceanographic conditions such as wave direction, wave height, wave period, and total water level. Reworking of material was most efficient when the peak wave direction was between 250 and 310 deg, directions common of the winter northwest groundswells and the spring and summer windswells and when the significant wave height was greater than the mean of 1.1 m (Figure 28). The amount of material reworked between successive surveys was controlled by changes in beach elevation. Reworking of talus was focused to the northwest side of the failure, which is due to the lower beach beach elevation. Although the southeast was elevated compared to the northwest, both locations showed a similar pattern in inflation and deflation. Our results indicate that in order to accurately model reworking both the talus volume and cliff input need to be quantified. We’ve found that just using the talus volume taken at each survey is not an accurate measure of sediment dispersal into the littoral
system. Figure 29 shows the beach elevation changes at Site B-1 compared with the total volume change including the cliff component and the talus volume. Deflations in the beach elevation correspond

![Graph showing various data](image)

**Figure 28.** Beach elevation (top), total volume change of talus between surveys (middle-top), percent time wave direction is in between 250 and 310 degrees (middle bottom), and the percent time the significant wave height is greater than 1.1m (bottom).
to increased reworking based off of the total volume change of the talus, whereas just
the volume of the talus does not show the same pattern, therefore, the cliff material
that gets introduced into the littoral system between surveys is a important variable in
accurately modeling sediment reworking. In addition, in all sites we found that when
talus is deposited at the base of the cliff it can create a positive feedback providing the
fronting cliff protection from wave attack allowing subaerial processes to dominate.
However, we saw that areas adjacent to the failure talus become scoured and have
accelerated wave based erosion compared to before the material was emplaced on the
beach subaerially.

Figure 29. Comparison plot of beach elevation at Site B-1 (top), total talus volume
change (middle), and talus volume (bottom).
The results of mapping the geological units and their respective sand contents show that there is large variability that depends on the paleo-depositional environment. Previous studies have overlooked this and assigned uniform sand content for the entire region. Most importantly, the value that is used as the LCD changes the littoral sediment yield as shown in our results. Studies that use 63 µm as the LCD overestimate the sediment that contributes to the littoral budget. As sediment delivery to the Oceanside littoral cell continues to decrease due to damming of upland watersheds, urbanization, and seacliff armoring, accurately quantifying the sediment entering the system becomes increasingly more important.
Conclusion

Seacliff erosion is a multi-variable process that involves the complex interplay between subaerial and marine processes along with the regional geology. We found the presence of both marine and subaerial processes in the study area and found that their importances changes through time. In a short-term study we were able to document how erosion on the cliff face and at the cliff base evolves through time and the connection with environmental conditions. Our results show that the dominant control that determines what process dominants in a given area is the beach elevation. Beach elevation plays a critical role in the reworking of talus and wave-based erosion and is controlled by wave direction, wave height, wave period, and tide. Using ground based LIDAR we were able to quantify how and when reworking dominates. This research gains important insight on the processes that lead to seacliff erosion and the role it plays in beach preservation, which can facilitate scientifically-based coastal management decision making. Estimates of cliff material that stays on the beach shows that previous estimates might have been too high and grain size variability in the cliffs need to be calculated for in sediment budget calculations. This involves accurately defining the LCD for the area of interest and quantifying the sand content found within the cliff forming sediments. Failure to use a LCD can lead to overestimations of material being delivered to the littoral system. This study presents a baseline to assess future patterns of erosion and erosional hotspots as sea level continues to rise into the future.
Appendix

Wave Runup

Various investigations (Hunt, 1959; Battjes, 1974; Guza and Thornton, 1982; Holman and Sallenger, 1985; Holman, 1986; Ruggiero et al., 2001; Stockdon et al., 2006) have determined empirical parameterizations of wave runup through an examination of wave setup and processes in the swash zone.

Guza and Thornton (1982) found a linear relationship independent of beach slope in an investigation of swash dynamics at Torrey Pines State Beach. They found the significant vertical runup elevation, \( R_s \), was related to the significant wave height, \( H_s \), by the following expression:

\[
R_s = 0.71H_s + 0.035 \text{ (meters)}
\]  

(5)

In an investigation of an intermediate sloped beach in Duck, North Carolina, Holman (1986) expressed the 2% exceedance value of the runup maxima, \( R_{2\%} \), as

\[
R_{2\%} = H_o(0.83\xi_0 + 0.2)
\]

(6)

where \( \xi_0 \) is the Iribarren number defined as \( \xi_0 = \beta/(H_o/L_o)^{1/2} \) and \( \beta \) is the local beach slope, \( H_o \) is the deep water significant wave height, and \( L_o \) is the deep water wavelength, a function expressed as \( L_o = (g/2\pi)T^2 \) where \( g \) is the acceleration due to gravity and \( T \) is the wave period. Conditions during which 2% of wave runup
maxima reach or exceed the elevation of the cliff/beach face junction were also calculated by Ruggiero et al. (2001) using the Duck, North Carolina runup data of Holman (Holman, 1986) and additional runup data from the Oregon coast. They found the following relationship:

\[ R_{2\%} = 0.27(\beta H_0 L_0)^{1/2} \]  

(7)

Taking data from dissipative to reflective beaches worldwide Stockdon et al. (2006) devised a parameterization for maximum runup elevation using wave height, H, deep-water wave length, L_0, wave period, T, and beach steepness, \( \beta \) in the following expression:

\[
R_{\text{Stockdon}} = 1.1(0.35\beta (H_0 L_0)^{1/2} + \frac{[H_0 L_0 (0.563\beta^2 + 0.004)]^{1/2}}{2})
\]

(8)

**Total Water Level**

Wave runup equations 5-8 were combined with measured tidal data to calculate TWL. According to the property erosion model in Figure 7, erosion is more likely when the total water level elevation exceeds the elevation of the cliff base. Significant wave height, peak period, and peak directional data were obtained from the CDIP station 100 buoy located offshore of Torrey Pines State Reserve at a depth of 555 m (CDIP). Gaps in the data were filled with data from the CDIP station 093 buoy located offshore of Mission Bay at a depth of 198 m (CDIP). In order to
get accurate depictions of the wave height, transformation of the wave field to shallow water is necessary. Simple linear interpolations cannot be used due to the complex morphology of the La Jolla Submarine Canyon. The boundary constraints needed for the transformations were out of the scope of this study, however, we present TWL data taken from offshore buoy data in order to reflect the general patterns of the oceanographic conditions at the time.

The mean TWL elevations using wave runup equations 1-4 for different foreshore slope values ($\beta=0.02, 0.03, 0.04, 0.05$) is shown in Table A-1. Guza and Thornton’s wave runup equation is independent of beach slope therefore it has a constant mean TWL elevation. The mean TWL elevations of Ruggiero et al. (2001) and Stockdon et al. (2006) begin to converge at a foreshore slope value of 0.04, whereas Holman’s (1986) wave runup equation yields a lower mean TWL elevation. Total water level curves for the four different wave runup equations for the time series are shown in Figure A-1. A foreshore slope value of 0.04 was used.  Plots all four curves are plotted on the same graph for the time period of October 2007 to April 2008 (Figure A-2). The curves for Stockdon (2006) and Ruggiero (2001) are almost indistinguishable from each other. The curve for Holman (1986) follows the same patterns as Stockdon (2006) and Ruggiero (2001), but has on overall lower elevation. The curve for Guza and Thornton (1982) does not exhibit the same general pattern and is consistently lower in elevation compared to the other curves.
Table A-1. Comparison of mean TWL equation derived for different foreshore slopes ($\beta$) using wave runup equations 5-8.

<table>
<thead>
<tr>
<th></th>
<th>$\beta=0.02$</th>
<th>$\beta=0.03$</th>
<th>$\beta=0.04$</th>
<th>$\beta=0.05$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Guza and Thornton</td>
<td>1.59</td>
<td>1.59</td>
<td>1.59</td>
<td>1.59</td>
</tr>
<tr>
<td>(1982)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Holman (1986)</td>
<td>1.88</td>
<td>2.33</td>
<td>2.77</td>
<td>3.21</td>
</tr>
<tr>
<td>Ruggiero et al.</td>
<td>2.81</td>
<td>3.27</td>
<td>3.66</td>
<td>4.00</td>
</tr>
<tr>
<td>(2001)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Stockdon et al.</td>
<td>3.09</td>
<td>3.36</td>
<td>3.65</td>
<td>3.96</td>
</tr>
<tr>
<td>(2006)</td>
<td></td>
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</table>
Figure A-1. Total water level curves for A.) Guza and Thornton, 1982; B.) Holman and Sallenger, 1985; C.) Ruggiero et al., 2001; D.) Stockdon et al., 2005 using a foreshore slope value of 0.04. Data in the gray box is plotted together in Figure A-2.
Total water level was used in the analysis of failure reworking at Site B-1. Figure A-3 compares beach elevation with the percentage of time the total water level is greater than 1.4 m, the mean of the beach elevation plus one standard deviation. The middle plot is the TWL calculated with Guza and Thornton’s (1982) wave runup
equation. The lower plot is the TWL calculated with the wave runup equations of Holman (1986), Ruggiero (2001), and Stockdon (2006). Note different scales between graphs and variations between curves. The TWL curve of Guza and Thornton (1982) along with significant wave height and direction are compared to the beach elevation at Site B-1 in Figure A-4. The percent of time that the TWL was greater than the mean beach elevation plus $1\sigma$, the wave direction was between 250 and 310 degrees, and the significant wave height was greater than the mean of the time series are used as comparative measures for wave activity. Total water level is in general agreement with the patterns of the oceanographic conditions and the beach elevation. TWL is inversely related to the beach elevation and is directly related to the significant wave height. Differences in the significant wave height curve and the TWL curve are due tidal influence.

Not all wave runup equations were accurate for the study area, due to the fact that different model predictions that try to estimate wave runup take into account different input variables. The variability in the mean elevations of TWL in Table A-1 reflect the disparity in modeling wave runup on natural beaches, most likely for the following reasons: First, the randomness in direction and frequency of ocean waves must be reported as statistical measures, often described by the peak period, $T_p$, and
Figure A-3. Beach elevation at Site B (top) derived from LIDAR data. Percent of time TWL is greater than the mean beach elevation plus 1\(\sigma\) (1.4 m) at the northwest location using Guza and Thornton (1982) wave runup equation independent of foreshore slope (middle) and using wave runup equations from Holman (1986), Ruggiero et al. (2001), and Stockdon et al. (2005) using a foreshore slope of 0.04. Failure events greater than 30m\(^3\) are denoted by a gray line.
the significant wave height, $H_s$, (defined as the mean of the largest 1/3 of waves recorded during the sampling period). Second, wave-height measurements can be expressed in deep water ($H_0$) or at the break point ($H_b$). Third, and most importantly, the beach morphology is dynamic and beach slope changes spatially and temporally, thereby making it difficult to assign a single beach slope value. For instance, Guza
and Thornton (1982) found the beach slope in the study area to vary from 0.03 in the spring to 0.05 in the fall on the beach face and a more constant ~0.02 in the surf zone and offshore. In our field investigations, we also observed a steeper beach face in the late summer and early fall. Our observations help put constraints on the different wave runup models and allow us to determine the one that is most applicable to the region. We believe the wave runup equation of Guza and Thornton (1982) is best suited for this study due to the fact that the empirical relationship was derived for the beaches in the study area, is independent of beach slope, and is more consistent with changes in beach elevation. This doesn’t preclude that other models are not better suited for other coastlines, but it does indicate the caution needs to be taken when choosing a wave runup equation for TWL modeling purposes since they can potentially overestimate or underestimate the water elevation. In addition, the relative importance of beach face and overall surf zone slopes to run-up processes are not well understood and precaution is advised when using TWL models, especially future predictions since the morphology of the beach face is unknown.
References


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Griggs, G.B., 1999, California’s coastline; El Nino, erosion and protection, in Ewing, L.C., and Sherman, D.J., eds., California’s Coastal Natural Hazards: University of Southern California Sea Grant Program, CSBPA Conference, p. 36-55.


