Title
The influence of tectonics, sea level, and sediment supply on coastal morphology in the Oceanside littoral cell, CA

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Publication Date
2010

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University of California, San Diego
2010
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ABSTRACT OF THE THESIS

The Influence of Tectonics, Sea Level, and Sediment Supply on Coastal Morphology in the Oceanside Littoral Cell, CA

by

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Master of Science in Earth Sciences
University of California, San Diego, 2010

Professor Neal Driscoll, Chair

Two studies, conducted within the Oceanside littoral cell, reveal how different earth processes (i.e. climatic, fluvial, and tectonic) affect and control both marine and subaerial morphology. The first study uses terrestrial LIDAR techniques to record changes in subaerial beach sediment due to seasonal transitions, on the San Luis Rey rivermouth in
Oceanside, CA. The study period spanned from winter to fall in 2008, so the majority of the data represents the transition from a winter to summer beach profile. A reversal in the seasonal accumulation trend (observed from April-May 2008) may be the result of two erosional wave events, with one occurring concurrently with increased precipitation and river discharge from the San Luis Rey River. The occurrence of two directionally favorable wave events, the second of which occurred during a pulse in precipitation and a slight increase in river discharge, appears to have caused sufficient beach erosion to reverse the seasonal accumulation trend.

The second study used high resolution CHIRP seismic reflection data, collected offshore, to provide new insights into tectonic control on coastal morphology and regional shelf width. Within the Oceanside littoral cell, a marked change in shelf width is observed and may be a result of faulting and folding in the region associated with splay faults off the Cristianitos Fault. There is an abrupt transition in the geology onshore, exposed in the sea cliffs. The tectonic feature responsible for the observed placement of adjacent geologic formations is proposed to be an oblique slip fault.
Sediment Response to Seasonal Transitions: Application to the Oceanside Littoral Cell
1.1 ABSTRACT

Change in beach sediment volume due to seasonal transitions is recorded using terrestrial LIDAR scanning techniques along the San Luis Rey rivermouth in Oceanside, CA. The rivermouth was scanned seven times during 2008 and quantitative volumetric differences between scans were calculated using I-Site 3-D modeling software. It is well known that in southern California, beach profiles ‘deflate’, or transport sediment offshore in response to waves generated by large winter storms. In the summer, beach profiles ‘inflate’, accumulating sediment on the subaerial beach-face in response to the lower energy, longer period swells of summer.

This study began in the winter season (January 2008) and ended in the beginning of fall (September 2008), so the majority of the data represents the seasonal transition from winter to summer. As expected, the beach sediment flux was positive throughout the study period with the exception of a reversal in the spring, which showed a loss of sediment (-569.07 m³). This reversal in the seasonal accumulation trend is thought to be influenced by two erosional wave events (one occurring concurrently with increased precipitation and river discharge from the San Luis Rey river) arriving from the Southwest at 230°. The loss of sediment on the beach-river mouth during an increase in river
discharge may have direct implications on the littoral cell sediment budget.

1.2 INTRODUCTION

Seasonal sediment flux of the beaches in southern California is an important cyclic process that affects the coastal environment (Inman et al., 1993; Winant et al., 1975). The beach profiles associated with the summer and winter seasons are examples of the equilibrium beach profile concept, which has proved to be an important tool for coastal engineers (Dean, 1991) and instrumental in modeling and observing changes to beach morphology (Hanson and Kraus, 1989; Larson and Krauss, 1994; Larson and Kraus, 1999; Romanczyk, 2005). This concept, introduced by Bruun (1954), states that beaches respond morphologically to changes in wave forcing, shifting their form to a constant shape that can be associated with a given type of incident wave (Inman et al., 1993). Therefore, the changes in beach profiles between seasons illustrate the response of the beach, by shifting its form, to changing wave conditions.

The equilibrium profile that the beaches of southern California shift to during the fall and winter, when forced by storm generated waves with high energy and high frequency, is characterized by the
transportation of subaerial sand offshore resulting in a narrow beach face strewn with cobbles. This process is referred to as seasonal ‘deflation’ of the beach. The shift in beach profile during the spring and summer, when forced by lower energy and longer period waves, results in the transport of sand from offshore back onto the beach face and results in a wide, sandy beach. Similarly, this process is referred to as the seasonal ‘inflation’ of the beach (Figure 1.1).

It is well documented that subaerial beach sand volume increases during the summer as sediment is transported onshore, and decreases as it is moved offshore during the winter by large storm waves (Shepard, 1950; Inman, 1953; Aubrey, 1979). This research examines the subaerial changes to a beach rivermouth in southern California during the seasonal accretionary period of 2008. Although the net volume change over the study period was positive, showing an accumulation of sediment, a net loss of material was observed between two surveys in spring. The reversal in trend will be the main focus of this chapter.
Figure 1.1. Change in subaerial beach profile from summer (top) to winter (bottom). Such a seasonal change is characteristic of many of the beaches in the Oceanside littoral cell (photos courtesy of Living with Coastal Change, 2009).

1.3 STUDY AREA
Littoral cells are constructs to simplify balancing the sediment budget along coastal regions; each cell is assumed to have a closed sediment budget bounded on each end by either a headland or a sediment sink. Several sources provide sediment to littoral cells. In southern California event-dominated rivers episodically deliver sediment to the nearshore region (Inman and Jenkins, 1999) and the collapse and gully erosion of the sea cliffs backing the beach also appears to be an important source (Haas, 2005; Young and Ashford, 2006). Transport processes move the sediment south in the Oceanside Littoral Cell, where it is intercepted and captured by the Scripps submarine canyon (Inman and Brush, 1973). Recent research by LeDantec et al. (2009) suggests that some sediment bypasses the Scripps Canyon as evidenced by a thick depocenter between the La Jolla and Scripps canyon heads.
The Oceanside littoral cell is bounded to the north by Dana Point and terminates to the south with the La Jolla submarine canyon (Figure 1.2). For the majority of the cell, the beaches consist of semi-continuous stretches of sand or cobbles backed by sea cliffs of varying height.
reaching up to a maximum of 300 feet (Masters, 2006). Within the confines of the Oceanside littoral cell, eight streams drain the Peninsular ranges and deliver terrigenous sediment to the ocean. The geology of the Peninsular ranges consists of Jurassic and Cretaceous granitic plutons overlain by a thin layer of post-Cretaceous sediment (Inman and Jenkins, 1999). Of the eight rivers draining these granitic plutons, the Santa Margarita and San Luis Rey rivers are the two largest, and supply the majority of the sediment flux from rivers (Masters, 2006). The San Luis Rey River flows from the Palomar and Hot Springs Mountains of North San Diego County, through the city of Oceanside, and discharges into the ocean immediately south of the Oceanside Harbor. It has a drainage area of 1,440 km² with a headwater elevation of 2,140 m (Inman and Jenkins, 1999).

The drainage basin of the San Luis Rey River is classified as moderately developed according to Inman and Jenkins (1999), who developed a drainage basin classification nomenclature. Moderately developed basins are identified as having one or more water retention structures, mostly on secondary streams (Inman and Jenkins, 1999). Immediately bounding the San Luis Rey rivermouth to the north is a rock groin (Figure 1.3), associated with the Oceanside small craft harbor.
(Inman and Jenkins, 1985; Army Corps, 1990). “Groin” is a broad term used to define any structure orthogonal to the shoreline with the potential to obstruct sediment transport alongshore (Perdomo, 2004).

The groin bounding the study area was first constructed in 1961 as a 120 meter long rock-rubble mound structure, which extended 90 m into the Pacific Ocean, oriented approximately SW at 230°, shown in Figure 1.4.

The groin was significantly lengthened in 1968, when it was extended by 158 m, bringing the total length of the structure to approximately 280 m (Perdomo, 2004).
Figure 1.3. Aerial view of the study area, the beach rivermouth of the San Luis Rey River (California coastline, 2008).
Figure 1.4. Orientation of the rock groin bounding the San Luis Rey Rivermouth to the north (modified from U.S. Army Corps of Engineers (USACE), Los Angeles District, 1991b).
1.4 EQUIPMENT

This research used an I-Site 4400 LIDAR (Light Detection And Ranging) laser scanner to collect high-density topographic point cloud data. The laser scanner was secured onto a durable off-road wagon (Figure 1.5), which allowed the equipment to be easily transported on a sandy beach environment. Other instruments used during data collection include a Hammerhead portable PC controller to manage and store received data, a Trimble 5800 RTK GPS device, and a cell phone used to connect the mobile unit to the VRS (virtual reference station). The California Virtual Reference Station (CALVRS) was used to obtain field corrections for the RTK GPS. The San Luis Rey Rivermouth was quantified using a series of 360° topographic scans at approximately 6 minutes per scan.

The scanner must be level to obtain accurate data. There is a built in tilt/level compensator, able to self-correct within a 3° range, which served to auto-level the scanner after approximate manual leveling in the field was performed (Olsen et al., 2009). Built into the scanner is a 37 mega pixel scan-line digital camera with the capability of capturing a 360° panoramic image while simultaneously collecting point data, by assigning an RGB value to each returned point in the data set (Dingler, 2007). The application of the I-Site 4400 LIDAR scanner for topographic
scanning yields an accuracy of approximately 5 cm, with increasing accuracy in a laboratory setting (I- Site, 2007). Combined with the RTK GPS accuracy of 2.2 cm (Trimble, 2008), the maximum error of the equipment is 7.2 cm for each topographic point (Olsen et al., 2009). The self-leveling capabilities of the scanner, along with the 37 mega pixel digital camera, a GPS mount on the top of the scanner itself, its durable construction, and the use of a Virtual Reference Station (VRS) system all contribute to an instrument system suited to rapidly collect quantitative data in a challenging coastal environment.
1.5 METHODS

Studies have historically examined the seasonal change in beach profile on and offshore using reference rods, fathometers, acoustic depth sounders, GPS, and boats (Winant et al., 1975; Aubrey, 1979). This research takes a new approach, quantifying the change in subaerial sediment of the San Luis Rey rivermouth over a nine-month study period in 2008, using a LIDAR terrestrial laser scanner. The purpose of observing changes in the San Luis Rey rivermouth profile over time is to quantify the seasonal change in subaerial beach sediment and morphology.
The rivermouth was surveyed seven times over a nine-month study period, beginning January 29, 2008 through September 26, 2008, using a LIDAR terrestrial laser scanner. The scanner used in this research utilizes the time of flight of a pulsing laser to obtain point cloud topography. It sends out a 905 nm diode laser pulse, which is reflected off the target and is then received back at the instrument as a topographic point.

Short-range scans were used as opposed to long-range scans for their ability to collect data closer to the scanner origin, allowing for a more dense set of data points. Available as an automatic scanning option available on the scanner instrument, short-range scans allow data to be collected beginning 2.25 m away from the scanner position, while the long-range scanning option begins data collection at 10 m. Figure 1.6 shows the difference between the two scanning options. By employing multiple 360° short-range scans, the rivermouth is quantified as a 3-D topographic point cloud.

Scanning low lying environments (such as the rivermouth) with the LIDAR scanner gives good resolution immediately surrounding the instrument, however the resolution diminishes with distance from the scanner due to the grazing angle of the laser (seen in Figure 1.5). The grazing angle of the scanner is 0.108°, and as the point cloud distance increases away from the scanner origin, the further apart each
topographic point in that cloud will be (Olsen et al., 2009). To obtain desired coverage of the rivermouth, multiple closely spaced scans were acquired for each survey. Figure 1.7 shows examples of poor and ideal data coverage necessary for proper analysis.
Figure 1.6. Difference between data density for long-range (top) and short-range (bottom) scans. Both images represent one individual scan with the white areas representing dense clusters of data points. The center of each black circle (the shadow zone) is the origin of the laser scanner, which collects data 360°.
Figure 1.7. Comparison of topographic point cloud data for different scan densities. The top image shows significant gaps, or empty space, between data points and contains approximately 724,000 points. The bottom panel shows a well-populated data set without significant space between topographic points, containing approximately 3,600,000 data points.
The rivermouth profile was captured with the LIDAR scanner monthly (with the exception of two months when the scanner was unavailable due to other commitments). Each scan was georeferenced using real-time kinematic GPS, and were coregistered using the I-Site software. This allows the scans to be accurately aligned, giving a complete topographic representation of the rivermouth morphology. To account for the natural variability of the tides, each of the scanning periods were scheduled for a consistent tide height of 2 feet. Since the LIDAR data is essentially a ‘snapshot’ of the topography at that point in time, taking the monthly scans at a constant tide height allows for a similar area to be imaged. Surveys of the rivermouth were not possible after September 2008 due to restricted beach access. Construction of the Pacific Street bridge over the San Luis Rey River in Oceanside, CA blocked off the beach access point for the LIDAR equipment, preventing further scanning. Post-construction surveys of the rivermouth would not be representative of natural conditions due to the anthropogenic changes in beach morphology.

1.6 DATA PROCESSING AND VOLUME CALCULATION

The data were processed and quantitative volumetric comparisons of the rivermouth were determined using I-Site 3-D
visualization software. After the data has been downloaded off the
Hammerhead portable field computer and imported into the software,
raw point cloud data received at each scan is registered with its
corresponding GPS point. This allows the points to be accurately
aligned in space, creating a precise 3-D topographic model. The first
filter applied to the data is a limiting polygon around the extent of the
rivermouth. This automatically deletes any point outside the polygon,
and is an efficient way of reducing the data to one specific study area.
Each scan in the 3-D model is then filtered by range (100 meters), which
excludes outlying and inaccurate points captured by the LIDAR
scanner beyond that limit. Next, the data is manually reduced using a
variety of techniques including examining cross sections, zoom tools,
and different view modes. This is done to eliminate obtrusive transient
points not pertaining to the rivermouth morphology that might have
been included in the scan (birds, sunbathers, etc...).

After the filtering of the data is complete, a topographic fusion
triangulation is applied to the 3-D point cloud, which creates a surface
by connecting all the points with triangles. The filtering is necessary not
only to eliminate undesirable and inaccurate data, but also to reduce
the number of points in the model before a topographic triangulation
can be run. If the number of data points remains too high, a minimum
separation filter (between each individual point) can be applied to the data.

Quantitative changes in rivermouth sediments are calculated by comparing a triangulated surface to another triangulated surface of an earlier survey date. The newer surface is then automatically colored by distance from the older surface, with blue being areas of sediment accumulation, orange being the areas of erosion, and green being areas of no overlap between the two surfaces, preventing any volumetric comparison. There are some visibly prominent edge coloring effects that appear as intense blue or oranges areas, suggesting extreme erosion/accumulation. These occur only on the periphery of the surfaces and are artifacts of the coloring algorithm. This false coloring is an inherent error in the 3-D modeling I-Site software. When the new surface is colored by distance from the old surface, the software tries to tie in points outside the surface to the edge triangles, making an obvious falsely colored artifact. They do not affect the volume change calculations, which are performed before the new surface is colored against the older surface.
1.7 RESULTS

This study reveals the elevations changes along the beach at the rivermouth of the San Luis Rey River over the seasonal transitions in 2008. Volumetric changes in beach sand between surveys were obtained and compared over the nine-month survey period (January 2008-September 2008). Triangulated topographic surfaces that reveal areas of sediment erosion and accumulation are shown in Figures 1.9 and 1.10. As seen in Table 1.1, the net volume flux of beach sediment was positive over the nine-month survey window, with the total accumulation of subaerial sediment being 4,220.62 m\(^3\). This accumulation trend was expected as the majority of the study took place from winter through the summer season, which is characterized in southern California by beach inflation (Yates et al., 2008).

Sediment flux varied significantly from month to month (Table 1.1). Changes in sediment volume between surveys were all positive, reflecting the seasonal trend, with one exception. The period between surveys 4/24/2008 and 5/30/2008 showed a loss of 569.07 m\(^3\) of sediment. The southwest region of the rivermouth was the site of the most intense erosion during this time (orange-shaded region on Figure 1.9). The fact that this area is the most intensely eroded may indicate
that the reversal in the seasonal accumulation trend, seen in Figure 1.8, is the result of the arrival direction of the incident waves coupled with the erosional effects of river discharge. In this specific study area, the southwest area of the beach is the most exposed to wave action, with most of beach face in the northern part being sheltered by the presence of the groin.

Table 1.1. Summary of volumetric change between individual survey dates and net volume change throughout the study period.

<table>
<thead>
<tr>
<th>Survey date</th>
<th>Season</th>
<th>Volumetric change (M^3)</th>
<th>Net Volume Change (M^3)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1/12/08</td>
<td>Winter</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td>2/28/08</td>
<td></td>
<td>399.34</td>
<td>399.34</td>
</tr>
<tr>
<td>4/24/08</td>
<td>Spring</td>
<td>845.57</td>
<td>1244.91</td>
</tr>
<tr>
<td>5/30/08</td>
<td></td>
<td>-569.07</td>
<td>675.84</td>
</tr>
<tr>
<td>7/16/08</td>
<td>Summer</td>
<td>2,301.30</td>
<td>2,977.14</td>
</tr>
<tr>
<td>8/26/08</td>
<td></td>
<td>146.605</td>
<td>3,123.75</td>
</tr>
<tr>
<td>9/26/08</td>
<td>Fall</td>
<td>1,096.87</td>
<td>4,220.62</td>
</tr>
</tbody>
</table>
Figure 1.8. The accumulation trend of beach sand volume from January to September 2008. These results corroborate the well-known seasonal sediment accumulation from winter to summer along beaches in Southern California. Note the reversal of the trend and sediment erosion between April and May, 2008.
Figure 1.9. Blue areas show sediment accumulation, orange areas show erosion, and green areas are regions of no overlap between the two surfaces, and are omitted from any volumetric comparison. Edge effects are observed along the edges of the surfaces where no overlap occurs, and are identified as the brightly colored blue or orange colors. These are artifacts of the differencing algorithm and are not used in the volume calculations. This image shows the change in sediment volume of the study area between 1/29/2008 and 2/24/2008, a gain of 399.34 m$^3$. 
Figure 1.10. The change in sediment volume between April 24, 2008 and May 30, 2008 is shown. Note the area of erosion (orange shade) is predominantly focused along the beachfront. Two wave events with significant height and an azimuth of approximately $230^\circ$ occurred during this time period. The wave direction is orthogonal to the beach and parallel to the groin orientation immediately north of the rivermouth.

1.8 DISCUSSION

The wave properties for the entire study period are shown in Figure 1.11. The data for this figure were acquired by from CDIP buoy 45
(SCRIPPS, 2008), which is maintained and operated by the Coastal Data Information Program, Integrative Oceanography Division, operated by the Scripps Institution of Oceanography. For the total water level calculation, tidal data was acquired from NOAA tidal station 9410170 (NOAA, 2009). Total water level is defined as the sum of the tidal level and water run-up level, and was calculated using the methods outlined in Olsen et al., 2009.

The gray shaded box depicts the time between the surveys in April and May 2008, during which the net volume loss occurred. During this time period, there were two wave events that arrived from the southwest, ~230°. These waves events had periods from 12-17 seconds and significant wave heights reaching 1.6 through 1.8 meters (Figure 1.11). The total water level during both of these events exceeded 2.5 meters. It has been shown that beach profiles respond to variations in wave properties, such as direction, height, and period (Inman, 1953; Aubrey, 1979; Pawka, 1976; Clarke et al., 1984). This erosional event and the associated reversal of trend during a longer period of accumulation may be caused by the change in wave orientation, height, and water level.

There are ten other wave events that arrived during the study period with significant wave heights ($H_s$) greater or equal to 1.25 m with
corresponding total water levels reaching at least 2 m. The direction of wave arrival appears to be bimodal (Figure 1.11) with three of the events from the south-southwest (~190-200°) and seven from the west (~270-290°). During the time period between surveys 4/24/2008 and 5/30/2008, two wave events arriving from 230° occurred. This direction of wave arrival is orthogonal to the beach and parallel to the rock groin, allowing the waves to approach the beach unimpeded. The study area is fully exposed to the erosion potential of the incoming waves traveling with this angle of incidence, compared to a wave event arriving at ~270-290° which would be intercepted by the groin and the majority of the study area would be protected, or a wave event arriving from ~190-200°, an angle that is sub-parallel to that of the beach.
Figure 1.11. The wave conditions during the reversal (April-May) are indicated by the gray shaded box. The two red lines are the wave events that arrive from 230°, have significant wave height greater or equal to 1.25 m, and total water levels of 2.5 m or higher. The blue band across the wave direction plot denotes an arrival angle of ~ 230°.
With the presence of the groin bounding the study area to the north, river dispersal is restricted by the groin to the north and can only flow to the west, out to sea, south parallel to the beach, or some azimuth in between. The dominant longshore current in the Oceanside Littoral Cell is southward. Figures 1.12 and 1.13 illustrate daily total precipitation and daily mean discharge from the San Luis Rey rivermouth, respectively (USGS, 2009). These figures show that the second wave event from the southwest (230°; Figure 1.11) occurred during a storm event in the county with increased precipitation and related discharge. Given the surveys were conducted on 4/24/2008 and 5/30/2008, it is difficult to fingerprint the actual event responsible for the erosion, but the two events with a southwest orientation (~230°) appear to have the optimum trajectory to cause the observed change.

The second event has greater wave height and higher water level and as it occurs shortly after the first event (28 days), perhaps the first event preconditioned the region for additional erosion during the second event. It is possible that river levels increased due to the precipitation event (Figure 1.12) and associate increase in river discharge. An increase in river levels would promote the sapping of water through the beach, and facilitate grain erosion through
additional lift due to fluid weeping out along the beachfront. Even with numerous surveys during the course of the year in this region, we have temporal aliasing that makes it difficult to understand the exact relationship between process and product. It is clear from this study, that numerous surveys before and after events are required to determine the processes that mobilize sediment.
Figure 1.12. Daily Precipitation data acquired from Guejito Creek in San Pasqual, CA (USGS, 2009). The gray shaded box delineates the period when the reversal in sediment accumulation occurred. Note the spike in precipitation during this time period. Dashed vertical lines represent time of each survey.
Figure 1.13. Daily mean discharge for the San Luis Rey River measured in Oceanside, CA (USGS, 2009). The gray shaded box highlights the period when the sediment erosion occurred. Notice the increase in discharge in response to the precipitation. Dashed vertical lines represent time of each survey.

The wave height, period and water level can all play a role in sediment transport in nearshore regions (Figure 1.10). As seen during a previous survey comparison (Figure 1.9), incident wave events caused localized erosion, but did not cause a net loss in beach sediment during the period of seasonal accumulation. The occurrence of two directionally favorable wave events, the second of which occurred during a pulse in precipitation and a slight increase in river discharge,
appears to have caused sufficient beach erosion to reverse the seasonal accumulation trend.

The loss of 569.07 m$^3$ of beach sediment between the surveys on 4/24/2008 and 5/30/2008 is small when compared to the seasonal inflation and deflation of the beach or the annual sediment budget for the Oceanside Littoral Cell, but it provides insight into the processes of sediment transport in the nearshore region. By examining the wave characteristics alone it would be difficult to predict which event would cause significant erosion and the observed reversal of trend. Based on LIDAR surveys (Oslen et al., 2009; Young and Ashford, 2006) and grain size analyses (Haas, 2005), it appears the sea cliffs are an important source of sediment for nearshore regions in the Oceanside Littoral Cell. Studying beach process will also help elucidate how this sediment is dispersed in the region (Yates et al., 2008).

1.9 CONCLUSION

Seasonal change to the subaerial beach rivermouth of the San Luis Rey River in Oceanside, CA was measured using terrestrial LIDAR scanning techniques. A net increase in volume of beach sediment was quantified over the nine-month survey window, with the total accumulation of subaerial sediment being 4,220.62 m$^3$. This positive
accumulation trend corroborates the well known seasonal beach profile dynamics of southern California, which is characterized by net transport of sediment onto the beach during the transition from winter to summer. Despite the long-term inflation of the beach, there was a period between surveys in the spring of 2008, which experienced a loss of 569.07 m$^3$ of beach sediment.

The data presented in this paper illustrates the variability, timing, and intricacy of the seasonal inflation and deflation of southern California beaches. During these yearly equilibrium shifts in beach profile, changes in wave conditions and orientation may cause erosional events. Nevertheless, these erosional events during inflation or depositional events usually do not cause a long-term reversal in the trend as observed between April and May of 2008. Such events may be important in explaining some of the year to year variability in the magnitude of beach elevation changes. The processes that impact the seasonal variation in beach elevation remain poorly understood and this research clearly demonstrates that numerous surveys are required to document the events that transport sediment in the nearshore region. The terrestrial LIDAR scanning technique used in this research only addresses the flux of subaerial sediment.
1.10 REFERENCES


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Sub-surface Structure of the Inner California Borderlands Continental Shelf: Dana Point to Oceanside Harbor
2.1 ABSTRACT

High resolution CHIRP seismic imaging of the inner shelf off the northern portion of the Oceanside littoral cell has yielded new insights into tectonic control of local coastal morphology and regional shelf width. Here we propose that differences in shelf width within the Oceanside littoral cell (a broad northern shelf up to 9.6 km and a narrow shelf to the south within 3-5 km) are a result of faulting and folding in the region associated with splays of the Cristianitos Fault. Fault-fold structures are observed in the seismic data north of San Mateo Point, where the exposed shoreline geology abruptly transitions from the well lithified, competent San Mateo sandstone to the south, to the younger marine siltstone/sandstone of the Capistrano Formation to the north. Subsurface structure associated with the Cristianitos Fault zone is also present. The tectonic feature responsible for the observed placement of adjacent geologic formations is proposed to be an oblique slip fault, a northern splay of the Cristianitos fault zone, with a similar sense of motion (the west block down-dropped to place the younger Capistrano Formation next to the older facies of the San Mateo).
2.2 INTRODUCTION

The California Continental Borderlands can be described as a tectonically active region within the geologically young continental margin of southern California (Inman and Nordstrom, 1971). The tectonic expression beneath the eastern Gulf of Santa Catalina between Dana Point and Oceanside is historically complex, and has been examined by numerous studies. A low-angle, east dipping, normal detachment fault underlies the Newport-Inglewood fault zone and is described as the Oceanside detachment (Crouch and Suppe, 1993; Bohannon and Geist, 1998). This rifting pre-dates the present transpressive regime (e.g., Ingersoll and Rumelhart, 1999) and defines the boundary between the Catalina Schist (footwall) and the sedimentary rocks of the Peninsular ranges (hanging wall).

Uplift of the San Joaquin Hills (immediately north of Dana Point) at rates of 0.21-0.27 m/ky has attributed to compressive shortening along the dextral strike slip Newport-Inglewood fault (Grant et al., 1999). Rivero et al. (2000) suggest the underlying Oceanside detachment has been reactivated as a blind thrust system with the potential for ruptures on the order of M7.1-7.6. A complex zone of folding and thrust faulting west of the Newport-Inglewood Fault zone (in the northern portion of the Oceanside Littoral cell) is described by Fischer and Mills, 1991. The
structures they identify on the continental slope include numerous fold belts and thrust faults, which they identify as the San Mateo Fault Zone. This style of tectonics is representative of local compression. Ryan et al. (2009) present a schematic model of block rotation which describes a small block bounded to the east by the Newport-Inglewood-Rose Canyon Fault and to the west by the Coronado Bank Fault.

Most investigations in this coastal region of the Gulf of Santa Catalina focus on the continental slope and farther offshore. The continental shelf off the Inner California Continental Borderlands is characteristically narrow, averaging ~3 km (Schiff, 2000). There is a distinct change in shelf width within the Oceanside littoral cell, bisected by the Carlsbad submarine canyon. For the majority of the shelf from Dana Point to the Carlsbad canyon (the northern portion of the Oceanside Littoral cell), the width exceeds 5 km, extending up to ~9.6 km offshore of Horno Canyon (Fischer and Mills, 1991). The width of the shelf from the Carlsbad canyon to the La Jolla submarine canyon (the southern portion of the Oceanside Littoral cell) narrows, averaging from 3 – 5 km (Figure 2.1). Hogarth et al. (2007), identifies the anomalously wide portion of the southern shelf to be a pop-up structure due to a left jog in the dextral Rose Canyon Fault.
Figure 2.1. Location map shows the variation in shelf width, being up to ~9.6 km offshore of the northern margin and decreasing to 3 – 5 km along the southern portion of the Oceanside littoral cell.
2.3 REGIONAL FAULT ZONES

The offshore portion of the Newport-Inglewood Fault Zone (NIFZ) is one fault in a series of northwest-southeast trending en-echelon fault zones that characterize the California borderlands in the Gulf of Santa Catalina (Fischer and Mills, 1991; Wright, 1991). The NIFZ is the easternmost fault zone, and the Coronado Bank, Palos Verde Hills, San Diego Trough, and San Clemente fault zones (respectively) extend west into the borderlands. These series of faults constitute the western boundary for the zone of seismic accommodation due to the translation between the Pacific and North American plates (Walls et al., 1998; Fialko, 2006).

The Newport-Inglewood Fault Zone is the major identified source of tectonic activity on the inner continental shelf between Dana Point and Oceanside Harbor. Near vertical strike slip faulting with a right-lateral sense of motion is the dominant mode of tectonic translation (Wright, 1991). The NIFZ between Dana Point and Oceanside is geomorphically expressed within a broad zone (0.4 - 0.5 km) of associated splays and step-over structures (constraining and releasing bends), with an approximately 2 km left step offshore of Las Pulgas.
canyon (Fischer and Mills, 1991). The transition from the Rose Canyon to Newport-Inglewood Fault occurs south of the study area, in the vicinity of Carlsbad Canyon. The northern trending Rose Canyon Fault oversteps to the northwest trending Newport-Inglewood fault zone, requiring a left bend. This change in fault trend is accommodated by an antiform with associated folding that is observed at mid-slope depths extending to the northwest for ~ 15 km (Ryan et al., 2009). A right-lateral slip rate of 1.3 mm/yr to 2.1 mm/yr was estimated by Fischer and Mills, 1991 in light of the observation that the there is ~7 km of offset between correlative features. Grant and Shearer (2004) proposed a similar slip rate of 0.5 mm/yr to 2.0 mm/yr. The only major earthquake occurring along the NIFZ was the M 6.3 Long Beach earthquake in 1933 (e.g., Trifunac, 2003), which ruptured along the onshore strand of the fault in the LA Basin.

The main onshore tectonic feature in the northern Oceanside littoral cell is the Cristianitos Fault, a west dipping oblique slip fault with multiple splays trending approximately north-south (Ehlig, 1979). The fault has been inactive for the last ~ 125,000 years based on the presence of an undisturbed overlying marine terrace that mantles the Monterey Formation to the south and the San Mateo Formation to the
north. Mapping by Sorenson et al. (2009 – unpublished UCSD Senior Project) identified a southern splay of the Cristianitos Fault zone, which is ~2.5 km south of the main fault trace and identified a new fault ~ 4 km south of the Cristianitos Fault.

Seismic imaging of the continental shelf from Dana Point to Oceanside Harbor was conducted to investigate the tectonic control and relation of the shelf width, coastal morphology and local geology. A shallow transpressive structure along the transgressive surface is observed above the Cristianitos Fault zone. The trend of the relief on the transgressive surface is approximately north-northeast and coincides with the widest point of the shelf (~ 9.6 km) to the southwest, and the San Mateo point promontory to the northeast.

2.4 METHODS

The CHIRP (Compressed High Intensity Radar Pulse) seismic reflection data presented in this study was collected during three research cruises aboard the R.V. Sproul (October 2008, December 2008, and December 2009). Approximately 165 line-km of seismic data were collected from Dana Point to Oceanside Harbor (Figure 2.2). The Edgetech subsurface profiler was towed behind the vessel at a speed of 3.5-4 knots at a depth of 1 meter. A 1-6 kHz swept frequency, digital
acoustic signal is emitted by the instrument to image the nearshore subsurface stratigraphy at high resolution. As the signal penetrates the marine sediment and encounters material with different density and velocity (acoustic impedance), some of the energy is transmitted and some is reflected back to the instrument. The amplitude of the reflectors is controlled by the acoustic impedance contrast between layers.

The recording system merges GPS data with each shot for accurate location of the seismic profiles.

Figure 2.2. Approximately 165 line-km of sub-surface seismic profiles were collected between 2008 and 2009 in the northern portion of the Oceanside littoral cell. Gray lines represent ship track grid.
2.5 RESULTS

Throughout the data volume, the transgressive surface associated with the most recent postglacial sea level rise is distinctly imaged. This surface is noted by the truncation of dipping acoustic reflectors beneath the erosive surface (Figure 2.3B). Sorenson et al., 2009 (unpublished UCSD Senior Project) use the exposure of the Monterey formation south of the San Onofre Nuclear Generating Station (SONGS) to infer an extension of a mapped fault trace. The dip of this formation correlates with the northwest-southeast dipping reflectors underlying the transgressive surface. Three distinct sediment packages are identified in the seismic profiles. Sediment package 1 (shaded orange) is observed to overlie the transgressive surface. This basal package is interpreted to be a lag deposit, infilling the lows and wave-cut notches created by still stands in the sea level rise that might re-excavate terraces cut during the falling limb of sea level (e.g., stage 3). The thickness of the overlying unit that mantles the transgressive surface varies in large part due to the relief on the surface.

Sediment package 2 (shaded red) exhibits gently dipping lateral reflectors and is interpreted as a mid-shelf lag deposit, being transported seaward as sea level rose and eroded the nearshore
deposits. The distinct lateral reflectors are suggestive of event horizons, placing coarser material over the finer-grained midshelf deposits.

Sediment package 3 (shaded blue) is interpreted as the most recent, late Holocene sedimentation. The acoustic character of this package is transparent and quite distinct from units 1 and 2. There are no major lateral or horizontal reflectors within this unit, which appears to be more uniform, well sorted, modern marine deposition (Figure 2.4B).

Figure 2.3. Uninterpreted (A) and interpreted (B) seismic dip line 10. The nearshore dipping and folding beds are evidence for north-south compression, recording the transpressive tectonic environment before the transgressive surface.
Figure 2.4. (A) is the uninterpreted and (B) is the interpreted seismic dip line 06. See Figure 2.2 for location of the profile. The orange shaded, basal sediment package 1, the overlying sediment package 2 (shaded red), and the most recent Holocene sediment package 3 (shaded blue). The red arrows indicate the onlap of a sediment package and are correlative features between seismic profiles.
Figure 2.5. Seismic profile strike line 18. Relief and sedimentation on transgressive surface to the south is notably different than more planar character of the transgressive surface to the north. Note the thickness variations over transgressive relief shaded brown. This is interpreted to be a relic beach structure.
Figure 2.6. Seismic strike line 18a, showing antiform folding within the Cristianitos Fault zone. The fault zone extent is identified to the north by the onlap of sediment package 2, and to the south by the truncation of the underlying dipping strata.

There is apparent relief on the transgressive surface seen in strike line 18 (Fig. 2.5), above which is a feature exhibiting high impedance and is proposed to be a relict beach structure (shaded brown). The onlap of acoustic reflectors as well as observed differences in sediment thickness and lateral variability (Figure 2.4B).
coincident with the extent of transgressive surface relief, suggests relief-controlled sediment deposition. Sediment packages 2 and 3 display a conforming, successive overlap of the underlying stratigraphy. The trend of relief on the transgressive surface is generally north-northeast and is imaged from San Mateo point to the intersection of the shelf to the southwest (Figure 2.7). The extent of this highstand relief is ~ 15 meters above the surrounding region and is up to approximately 4 km in width.

High resolution sub-surface imaging offshore allows specific structure within the Cristianitos Fault zone (CFZ) to be identified. Previous publications (e.g., Kennedy and Tan, 2007) identify offshore extensions of the Cristianitos Fault as general, broad zones of faulting. The data in this study identifies specific structure within this broad zone of faulting. Antiform and synform folding is clearly shown in the seismic profiles crossing the fault zone, indicative of a transpressive tectonic environment (Figure 2.6B). The northwest extent of the CFZ is interpreted as the ceasing of observed folding, which coincides with the onlap of sediment package 2. This onlap can be correlated between seismic profiles. The southeast extent is identified by the truncation of two dipping stratigraphic reflectors, which can also be correlated throughout the data volume.
The deformation attributed to the Cristianitos Fault is observed exclusively below the transgressive surface, as expected. This fault is reported to be inactive (most recent faulting occurred ~ 125,000 years ago), and with the last post-glacial sea level rise beginning approximately 20 k.a. (Fairbanks, 1989), the transgressive surface would be expected to truncate fault structures at depth (which were previously subaerially exposed), and be overlain with more recent, Holocene sedimentation. There is conclusive evidence throughout the seismic profiles against faulting during the Holocene. There is no observed offset of the overlying Holocene sediment packages, which would be expected if deformation was ongoing.

2.6 DISCUSSION

The trend of the relief on the transgressive surface is an expression of adjacent geologic formations. The lithology underlying the extent of observed transgressive surface relief is inferred from shoreline exposure of the geologic formations in the sea cliffs. The exposed geology onshore transitions abruptly from the San Mateo sandstone to the south, to the siltstone of the Capistrano Formation immediately north of San Mateo Point (Figure 2.7). Based on exposed shoreline geology, the more competent, coarse-grained San Mateo sandstone underlies the extent of the transgressive surface relief. This formation is described to be a dense, well-lithified sandstone and is
the formation that the San Onofre Nuclear Generating Station is built upon (McNey, 1979). Where the inferred underlying lithology of the transgressive surface transitions to the Capistrano Formation (north of San Mateo Point) sub-surface dipping and folded reflectors are observed within the seismic reflection data (Figures 2.3 and 2.4). This nearshore folding is an expression of the transpressive tectonic regime.

The spatial correlation of the relief on the transgressive surface with San Mateo Point and the widest part of the continental shelf (~9.6 km) is due to uplift and deformation and possibly to the emplacement of adjacent geologic formations with different erosive properties. Figure 2.7 shows the relationship between these features and the exposed shoreline geology. The placement of the Capistrano Formation (to the north) and San Mateo Formation (to the south) adjacent to each other may be responsible for the trend of the San Mateo promontory, the highstand relief in the seismic profiles, and the ~9.6 km wide shelf. We propose that the tectonic feature responsible for this abrupt change in shoreline exposure is a strike-slip fault parallel to the Cristianitos fault, with a down-to-the-west throw, placing younger facies next to older formations. Figure 2.8 shows a schematic cross section depicting the spatial relationships between the exposed shoreline geologic units, and the inferred fault. The cross-
section shows the spatial relationship between geologic units from south to north (right to left), and the tectonic features identified along the shoreline exposures (modified from unpublished data, Sorenson et al., 2009; Young et al., 2010).
Figure 2.7. The extent of the highstand relief on the transgressive surface (identified in the seismic profiles) and the coincidence of the trend with the San Mateo promontory and widest part of the continental shelf. A new splay off the Cristianitos Fault to the north appears to control the abrupt transition from the San Mateo to Capistrano formations and is dashed where projected onshore and offshore.
Figure 2.8. Stratigraphic column depicting age and stratigraphic relationships between the geologic units (after McNey, 1979). Below is a cross section (not to scale) of the observed placement of geologic formations along the beach (modified from Sorenson et al., 2009).
Figure 2.9. Location of identified northern splay of the Cristianitos Fault. This figure shows the Capistrano Embayment, a structural trough formed from the down-dropped western block of the Cristianitos Fault. Figure modified from Figure 1 in Ehlig, 1979.
2.7 CONCLUSION

High resolution seismic imaging of the inner shelf in the northern portion of the Oceanside littoral cell has yielded a new perspective on tectonic control of the shelf width and observed coastal morphology in the region. Fault deformation and the differential erosion of different geologic formations across the fault may explain the San Mateo promontory, the relief on the transgressive surface imaged in the seismic profiles, and the width of the shelf (~ 9.6 km). The tectonic feature responsible for the observed arrangement of geologic formations is proposed to be an oblique slip fault, a northern splay of the Cristianitos Fault zone, with the west block down-dropped to place the younger Capistrano Formation next to the older facies of the San Mateo.

Change in shelf width within the Oceanside littoral cell (broad northern shelf up to 9.6 km and narrow shelf to the south within 3-5 km) may be a consequence of these strike-slip faults. This study provides conclusive evidence against Holocene fault activity within the study area. The three sediment packages overlying the transgressive
surface do not exhibit structure associated with tectonic deformation.

The results of this study provide offshore observations that can be tested through future onshore investigation.

2.8 REFERENCES


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Conclusions
The results of the two studies described in this thesis provide new perspectives into known processes as well as a new understanding of tectonic control on coastal morphology and continental shelf width. Using LIDAR terrestrial scanning techniques, the seasonal transition from a winter to summer beach profile was quantified. A net increase in beach sediment volume was observed over the nine-month survey window, with the total accumulation of subaerial sediment being 4,220.62 m$^3$. A reversal in this seasonal accumulation trend occurred between April and May, 2008 as ~570 m$^3$ of sediment was eroded from the beach. It is proposed that this loss of material was influenced by the incident wave properties during this short period of time, in concert with increased precipitation and river discharge. During these seasonal equilibrium shifts in beach profile, changes not only in wave conditions, but also properties such as river discharge and precipitation can have direct consequences on the seasonal accumulation of subaerial beach sediment.

The collection of ~165 line-km of CHIRP seismic reflection data has yielded new understanding into tectonic control of the width of the continental shelf and observed nearshore morphology within the northern extent of the Oceanside littoral cell. Correlating the observed structure within the seismic profiles with the exposed shoreline geology
provides the basis for the proposal of an oblique-slip fault trending approximately north–south, with the west block down-dropped. This fault is inferred to be a northern splay of the Cristianitos Fault zone, trending onshore immediately north of San Mateo Point. Additionally, this study provides conclusive evidence against Holocene fault activity within the study area. The results of this study provide offshore observations that can be tested through future onshore investigation.