Chapter 9
Influence of rock type and wave regime on varying rates of shoreline erosion, Santa Cruz Island, California

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Abstract

The evolution of island shoreline geometry is driven primarily by lithology and surrounding wave regime, with additional effects from internal rock structure, stream channels, groundwater seepage, and other hillslope processes on the island itself. Many of these driving factors are dynamic and interconnected, making it difficult to determine which are most dominant as island shape continues to change. This discussion combines aerial imagery and maps from previous studies, oceanographic data, and firsthand visual observation to make a simplified assessment of the role of rock type and wave regime on the shaping of Santa Cruz Island, in southern California, and to create four categories of shoreline erosions potential, ranging from low to very high. A comparison of island lithology, nearshore bathymetry, and surrounding wave regime will show that recent changes in island shape have been controlled first by the island's geologic history and structure, which differentially exposes rock type and determines orientation to nearby land masses and ocean bathymetry, secondly by waves, and lastly by the combined effect of rock discontinuities and other erosion processes. The coastline most vulnerable to high rates of erosion on Santa Cruz Island are those places where softer sedimentary rocks meet high incoming wave energy, both on its western coast, and on the northern side of the island's thin connecting neck. This vulnerability makes it likely that the island will slowly progress over time towards two distinct eastern and western Santa Cruz Islands.

Introduction

The geometry of island shorelines is driven primarily by tectonics, lithology and surrounding wave regime. While tectonic activity usually acts across geologic time scales, the hydrologic and mechanical action of wind and waves are constantly working either to erode cliffs or deposit sediment on beaches, re-shaping the coastline over a relatively short time-scale. Rates of cliff retreat on receding coastline vary greatly with rock type, but can be as high as 1 meter per year on Tertiary sedimentary rocks, and 10 meters per year on glacial drift deposits (Sunamura, 1992). In general, softer rock types with less shear strength will erode faster than those with higher strength, and stronger rocks will support much steeper cliff formation. Similarly, shoreline that is exposed to higher wave energy will erode faster, and be less subject to deposition of fine sediment. Knowledge of an island's lithology or wave regime can provide fairly straightforward explanations for individual coastal features, but the broader predictive power of either is low without a more detailed understanding of their local interaction, as well as knowledge of secondary factors. While models have been developed for the effect of wave regime on homogenous rock faces, theoretical analysis does not allow for variation within rock strength and structure (Belov et al., 1999). Case studies test the application of wave theory and geology as explanatory tools in complex real-world environments, and can potentially further understanding of the relative importance of competing drivers in coastal morphology. This discussion combines aerial imagery and maps from previous studies, oceanographic data, and firsthand visual observation to make a simplified assessment of the role of rock type and wave regime on the shaping of Santa Cruz Island, in southern California. The relative influence of rock type and wave regime on the current evolution of the Santa Cruz Island coastline is assessed, with attention paid to two main questions: (1) How do mechanisms and rate of retreat vary along the coast of Santa Cruz Island? (2) Is the middle portion of the island retreating faster than the east and west ends, with eventual evolution towards two separate islands?

Sections of shoreline are separated into four categories of erosion potential to delineate areas most likely to have high rates of retreat over the next century: low, moderate, high, and very high. A comparison of island lithology, nearshore bathymetry, and surrounding wave regime will show that recent changes in island shape have been controlled first by the island's geologic history and structure, which differentially exposes rock type and determines orientation to nearby land masses and ocean bathymetry, secondly by waves, and lastly by the combined effect of rock discontinuities and other erosion processes.

Background

Santa Cruz Island is the largest of the four northern Channel Islands (Figure 9.1) representing the south-westernmost expression of the Transverse Mountain Range (see Chapter 2 and Chapter 4). The island has a distinctive coastal geometry. As illustrated in Figure 9.1, a thin low-elevation "neck" connects the western mountains to the smaller eastern mountains. The island has a significantly longer north-south axis in the west, with the exception of a thin peninsula of land extending off its northwest corner.

Figure 9.1. Google Earth image of the northern Channel Islands in Southern California.

The shape of Santa Cruz Island changes significantly over geologic time scales. During the last glacial maximum (LGM), all northern Channel Islands were connected as one larger island, Santarosea, shown in Figure 9.2A. The current islands were separated as sea levels began to rise following the LGM (Agenbroad and Morris, 1999). The cross section in Figure 9.2B (from Chaytor et al., 2010) show changes in Santa Cruz Island's paleoshoreline, starting with the LGM and moving forward in time. Although much of the shoreline evolution displayed in these figures is due to changing sea levels and tectonic uplift (see Chapter 5), the bottom map demonstrates continued erosion of Santa Cruz Island's distinctive neck and western bay even during the more recent period of relative sea level stability. This indicates the presence of the other short-term drivers of shoreline geometry.

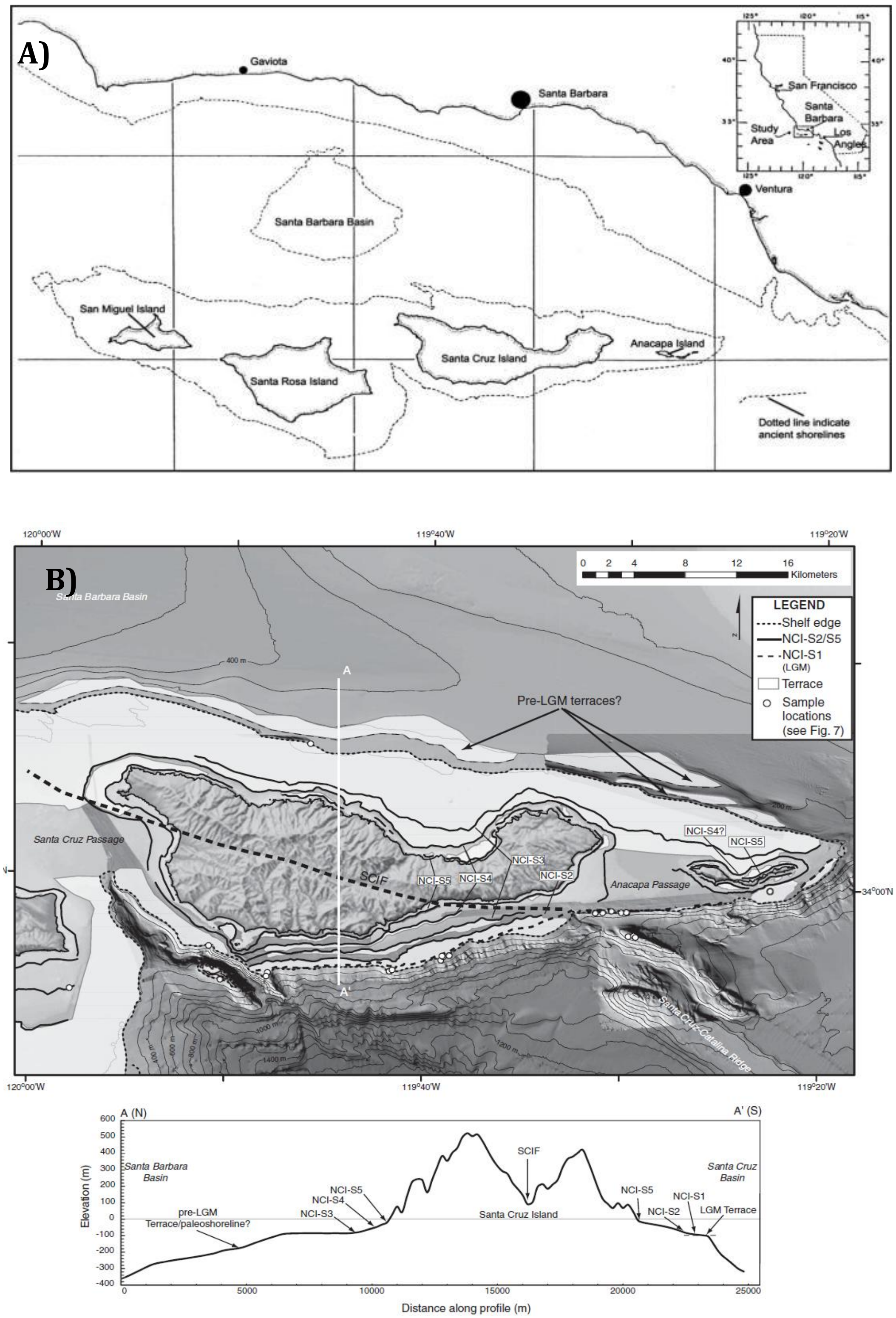

Figure 9.2. (A). Dotted lines show late Pleistocene shoreline, and presumed shape of the super- island of Santarosea. Taken from Agenbroad and Morris, 1999**.** (B).NCI S1-S5 represent paleoshoreline slope breaks, S5 created just prior to the modern shoreline. Map was intended to show uplift on Santa Cruz Island, but also shows development of middle neck. From Chaytor et al. 2010.

Rock Type and Resistive Strength

Several factors control rock strength, and in turn the rock's ability to withstand erosion by wind, waves, and other processes. Dickson et al. (2003) lists the following influences: structure and texture, mineral composition, bedding, jointing, water content, and state of stress. Structure, texture, and mineral composition are all inherent to the rock type itself, whereas jointing, water content, and state of stress are the result of tectonic activity and other external surface processes. These externally-driven discontinuities are very place-specific with complex interactions.

A simple model for rock strength takes the following form: $F_w = B\sigma_c$, where F_w is the strength of the rock mass, σ_c is the rock compressive strength, and B is a non-dimensional constant reflecting the presence of joints in the rock face (Budetta et al. 1999). Very little data has been collected on a local scale to describe the geometry and/or water content of discontinuities within homogenous rock types on Santa Cruz Island, so this discussion focuses only on those characteristics inherent to the rock itself. In the formula cited above, B would thus be equal to one. While this doesn't provide the ability to analyze small-scale differences in cliff retreat on Santa Cruz Island, relatively large differences in between classes of emergent rock masses there will likely mask the smaller effects of changing values for B. Below is a table showing rock compressive strength ranges for general categories, adapted from Afrouz (1992):

Table 9.1. Rock Strength classifications

Rock Strength	Rock Type Examples	Compressive Strength σ_c (MPa)	Toughness (psi)
Very High	Basalt, Dolerite, Quartzite, Gabro	> 200	> 59
High	Granite, Gneiss, Marble	100 - 200	16 - 59
Medium	Limestone, Sandstone, Shale, Slate	50 - 100	4 - 6
Low	Goal, Schist, Gypsum, Tuff, Siltstone	25 - 50	0.75 - 4
Very Low	Chalk, Rocksalt	< 25	< 0.75

Rock types on Santa Cruz Island are shown below in Figure 9.3, taken from Pinter and Sorlien (1991):

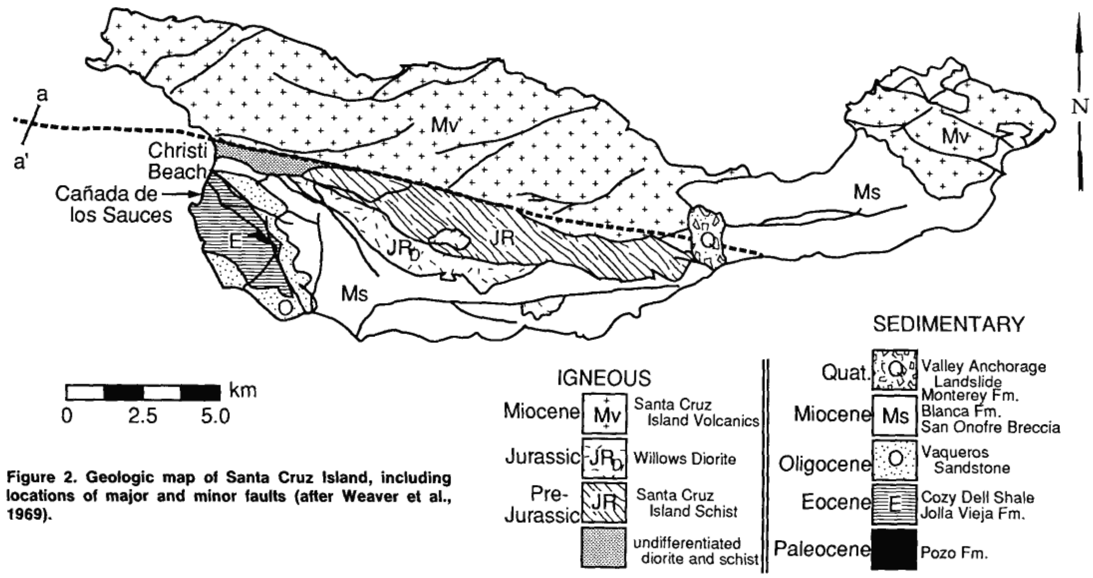

Figure 9.3. Geologic map of Santa Cruz Island, showing major rock type classifications and the Santa Cruz Island fault.

The lithology of Santa Cruz Island is comprised largely of two rock types (see Chapter 3). The above map shows that much of the northern half of the island is composed of Santa Cruz Island volcanics, with an important exception at the neck. Referring back to Table 1, these rocks will generally have greater than 200 MPa compressive strength, giving them a σ_c > 200. In contrast, the neck of the island is composed almost entirely of the Miocene-aged Monterey Formation; a siliceous shale. Referring to Table 1, the compressive strength of shale ranges from 50 to 100 MPa, at least half that of the volcanics. The neck also contains a small amount of Breccia. Breccia compressive strength can take a wide range of values depending upon source rock and weathering. It has been measured in laboratory tests at anywhere from 2 to 95 MPa (Birid 2006, Tawake 2008). Even at the high end of this range, however, its strength is typically half that of cohesive basalt. This difference can decrease when significant jointing and faulting weaken the basalt, as was noted by Dickson et al. (2003). Not only does the Monterrey formation shale and San Onofre Breccia of the middle neck have low compressive strength, it also has well-developed internal discontinuities that promote the development of mass movements, particularly when the strata dip towards the ocean. The southwestern portion of the island is composed almost entirely of breccias, sandstones, schist, and shale (shown above in figure 3). Referring again back to table 1, most of these rock types fall within the 50 – 100 MPa range for compressive strength, again at least half that of basalt. These differences in strength play a large role in differential rates of cliff retreat along the island's coastline.

Wave Action and Cliff Retreat

Waves and nearshore currents can act as either constructive or destructive forces. As destructive forces, waves put pressure upon coastal cliff faces or carry away beach sediments, causing eventual shoreline retreat from cliff failure or beach erosion. Benumof et al. (2000) list the following as important drivers behind the force of waves: (1) The water level as related to tidal variation, (2) Beach sediment type and size, (3) Shoreface morphology, and (4) Deep-water wave characteristics. Mathematically, the destructive force of waves is given in Budetta et al. (1999) as $F_W = A\rho g H$, where *A* is a non-dimensional constant reflecting the effect of beach sediment acting as an abrasive, *ρ* is water density, *g* is gravity, and *H* is wave height. As suggested by Benumof and discussed in Burley and Suddeth (this volume), this height *H* is in turn dependent upon swell characteristics, currents, wind, and approaching bathymetry. A more detailed description of wave energy can also be found in Burley and Suddeth (this volume).

Much of Santa Cruz Island is surrounded by steep cliffs, defined for purposes of GIS analysis as coastline with a greater than 40 degree gradient over the first 10 meters from shore. As waves assail a cliff face, a notch is slowly carved out of the rock. Caves like the one pictured below are exaggerated expressions of this process.

Notes: This cave has been eroded into Santa Cruz Island volcanic rock, on the northern side of Potato Harbor. Picture taken by Robyn Suddeth

Eventually, cohesion, or shear strength of the rock is too low to withstand the pressure of its own weight, and rock fall occurs. Belov et al. (1999) describe the rate of development of a cliff notch as a function of wave energy at the cliff base, the resistance of the cliff mass, and the abrasive action of sediments within the wave system at the base of the cliff.

As constructive forces, waves and nearshore currents can act to transport sediment from erosion zones to zones of deposition, assisting in the construction of beaches or underwater platforms that further diminish the destructive force of incoming waves and encourage additional aggradation.

The effective wave regime around Santa Cruz Island is dominated by an incoming Northwest swell in the winter months, when storm and wave energy is highest, and by a Southern swell in the summer time. (For more detail please see Chapter 8, this volume). The following 2 figures show direction and magnitude of incoming waves for the more high-wave-energy winter months, as well as refraction and defraction patterns around the island (see Chapter 8, this volume, for an explanation of these processes). Winter wave pressures have been broken into four categories in figure 4b, ranging from 0 to 100 kN/m.

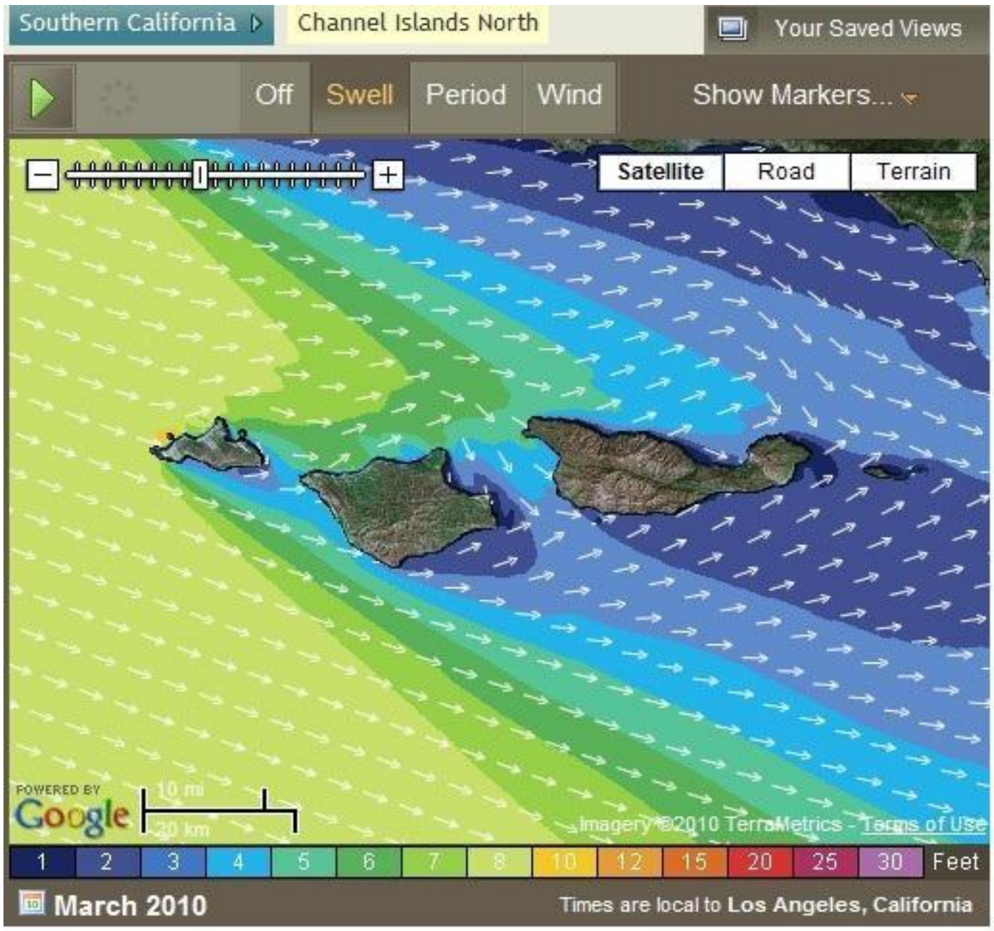

Figure 9.4a Wave Regime around Santa Cruz Island, California, obtained from SCRIPPS. Arrows represent direction, and colors represent wave height.

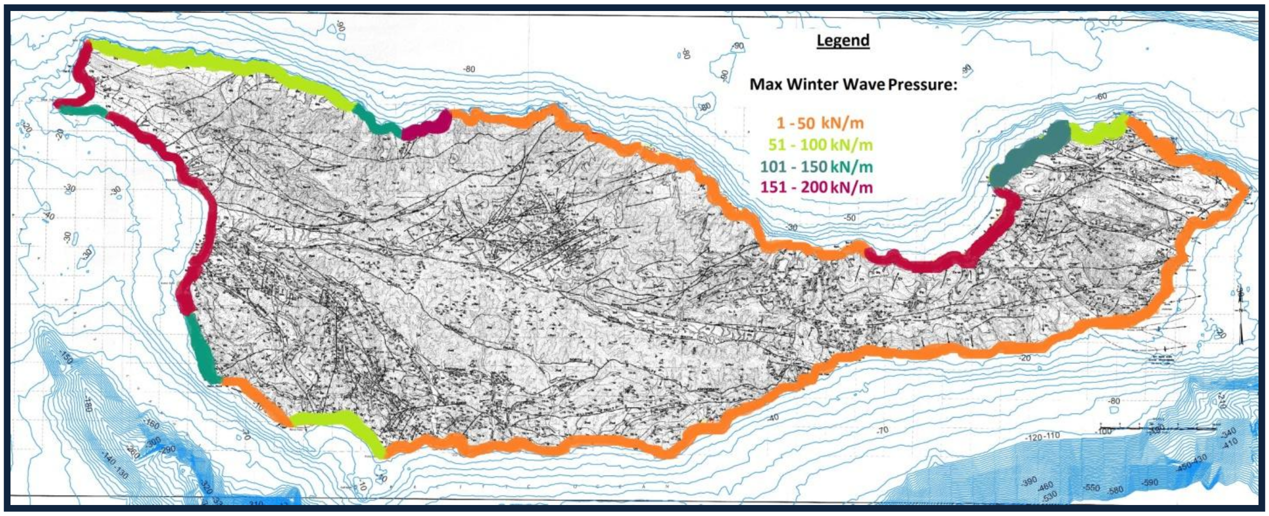

Figure 9.4b Bathymetry and Wave Pressures around Santa Cruz Island. Derived with data taken from Chapter 8.

Several important patterns are shown in figures 4a and 4b. First, the larger winter waves (NW swell) hit the north and northwestern sides of the island most directly, with significant diffraction and refraction occurring around Santa Rosa Island and Santa Cruz's western peninsula. This results in a transition along the island's southern coast from a regime dominated by the higher energy NW swell to one dominated by the much smaller southern swell. This particular feature may help to explain why the island neck seems to be eroding more severely on its northern side, and may also explain the transition from convex to concave shoreline along the island's west-facing coast. Second, these visuals show very few occurrences of wave impact orthogonal to the shoreline, with one noticeable exception seeming to occur off the northern neck of the island, where wave energy is aimed directly at its northeast bay. Areas of dense offshore contour lines in figure 4b show very steep approaching bathymetry. During most oceanographic conditions, these are likely to be places where waves do not "feel" bottom early enough to break, and instead are reflected off of the cliff face. This results in less energy being transferred onto the cliff face from the wave, because potential energy is never transferred to kinetic as it is in a breaking wave (see Chapter 8). However, during less frequent events, when much larger waves approach these cliffs, the abrupt bottom effects of this steep bathymetry may result in much larger breaking waves than places of lower gradient bathymetry. Significant erosion occurs on these cliffs during these less frequent events during which waves with very long wavelengths have a relatively large impact over a short time span. This is in contrast to the island's bays and beaches, where a wider nearshore bench (low-gradient bathymetry) causes waves to break regularly, resulting in less severe (wave energy is dissipated as it is disturbed by bottom roughness), yet constant erosive action (See Chapter 8).

The Combined Effect of Rock Type and Wave Energy on Cliff Retreat

Sunamura (1992) provides a mathematical formula for the long-term average rate of cliff erosion, *R*: $R = Kln\left(\frac{F_W}{F_R}\right)$, where *K* is a velocity constant with units wavelength/period (determined empirically as an average over the time period of interest), F_w is the average destructive force of waves, and F_R is the average strength of the rock mass. Expressed verbally, if the average destructive force of waves over time is less than the average strength of the rock mass, the coastline will progress seaward rather than being eroded inward. Further, a unit increase or decrease in average assailing wave force will have a smaller impact on rate of cliff retreat than a unit increase in average rock resistance. This formula suggests, then, that cliff retreat is more sensitive to changes in the average strength of rock mass than to changes in the average destructive force of waves.

Secondary Mechanisms of Shoreline Erosion and/or Accretion

Not all shoreline on Santa Cruz Island is surrounded by vertical cliff. Fluvial and other erosional processes at work on the island itself combine with weaker rock type and/or wave energy to create beaches and bays, backed by more gently sloping hills (defined for the purpose of GIS analysis later as less than 20 degrees of gradient within the first 10 meters from shore). In the thin island neck, major landslides within the Monterey Formation have given way to Chinese Harbor on the island's northern side, and to moderate cliffs backed by gentle slopes on the south (see Chapter 6), where wave energy is not as severe. Drainage systems provide sediment for beaches all around the island, in some places helping to dissipate incoming wave energy and protect the coastline from rapid erosion. Lastly, offshore factors like neighboring islands, kelp forests, and longshore sediment transport can dissipate incoming wave energy and in some cases lead to aggradation (Chapter 8).

Discussion: Shaping the Santa Cruz Island coastline

A Classification Scheme

Wave pressures are segregated into four categories ranging from 0 to 100 kN/m, and rock types into two categories of compressive strength, to yield eight combinations of wave energy and rock strength on Santa Cruz Island:

Table 9.2. Rock strength for a given wave energy.

Maximum Winter Wave Pressure (kN/m)	Rock Compressive Strength Strong: >200 MPa Weak: <100 Mpa
0 – 50	Strong (Santa Cruz Island Volcanics)
0 – 50	Weak (Monterey Formation, all
51 – 100	Strong
51 – 100	Weak
101 – 150	Strong
101 – 150	Weak
151 – 200	Strong
151 – 200	Weak

These combinations are displayed visually in Figure 9.5 below:

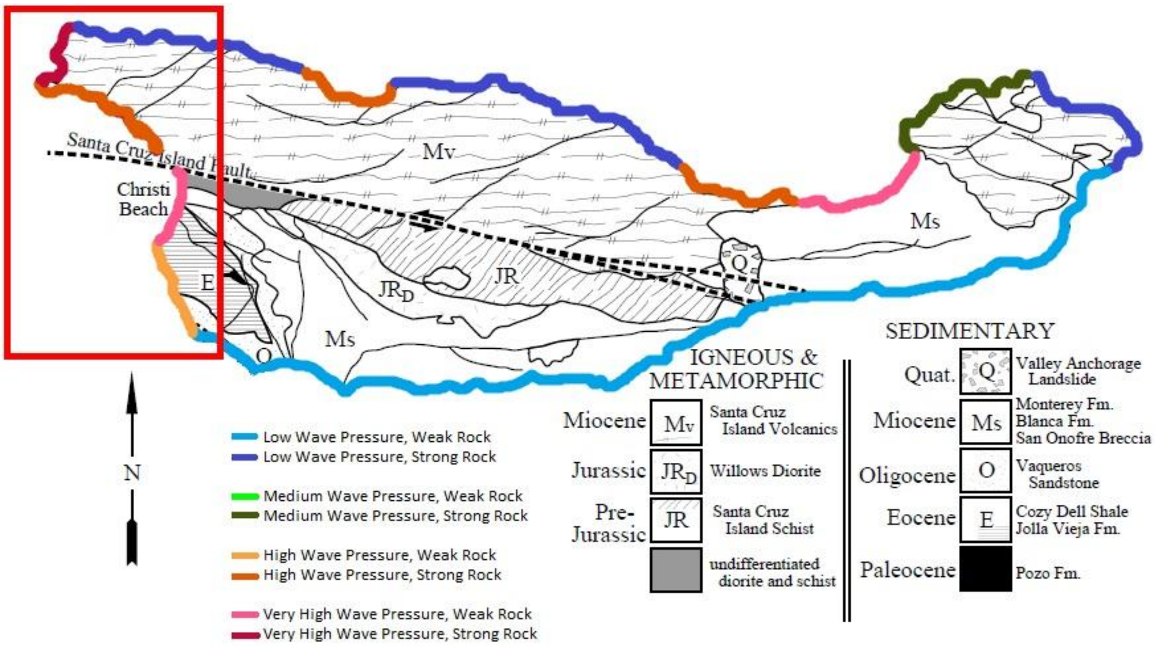

Figure 9.5. Rock Type and Wave Pressure, Santa Cruz Island. Base map taken from Pinter and Sorlien (1991).

The western end of the island (red box in Figure 5) is likely a demonstration of rock type dominance over wave energy (holding tectonic activity and other processes constant) in rate of cliff retreat, as expected from Sunamura's formula: $R = K ln\left(\frac{F_W}{F_R}\right)$. The stronger northern volcanics and weaker southern shales and sandstones, separated by the Santa Cruz Island Fault, are exposed to a similar wave pressure regime. However the southern portion of the island seems to be eroding along the fault line at a faster pace than its northern counterpart.

Given this affirmation of the relative importance of rock strength when compared to wave forces, we simplify the eight combinations of wave pressure and rock type into four categories of shoreline erosion potential on Santa Cruz Island (Figure 6). The word potential is used to indicate the presence of other interacting drivers of shoreline retreat or advance, including tectonic activity and mass movements resulting from surface processes, that may further influence relative rates of shoreline retreat or advance but are not included in this simplified classification scheme.

Shoreline Erosion Potential	Maximum Winter Wave Pressure (kN/m)	Rock Strength (Strong = SCI Volcanics, Weak = all others)
Low	0 – 100	Strong
Moderate	0 – 100 101 – 200	Weak Strong
High	101 – 150	Weak
Very High	151 – 100	Weak

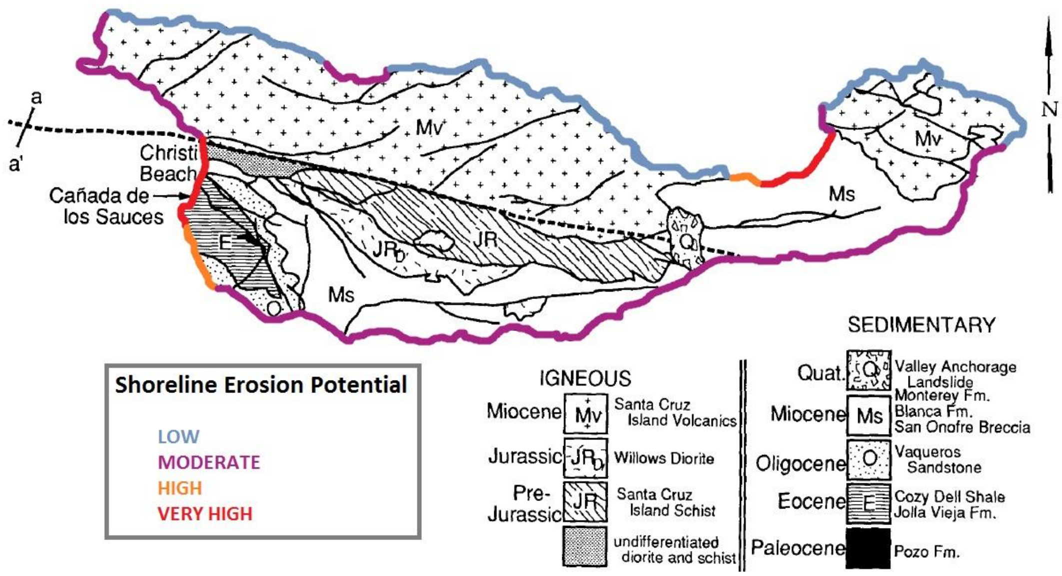

Figure 9.6 Differential shoreline erosion on Santa Cruz Island, California

Where rock strength is high and wave energy moderate or low, the combined result is fairly steep cliffs with a low potential for erosion. This can be seen in figure 7, where dark purple lines along the Santa Cruz Island Volcanics indicate gradients greater than 40 degrees over the first 10 meters inland.

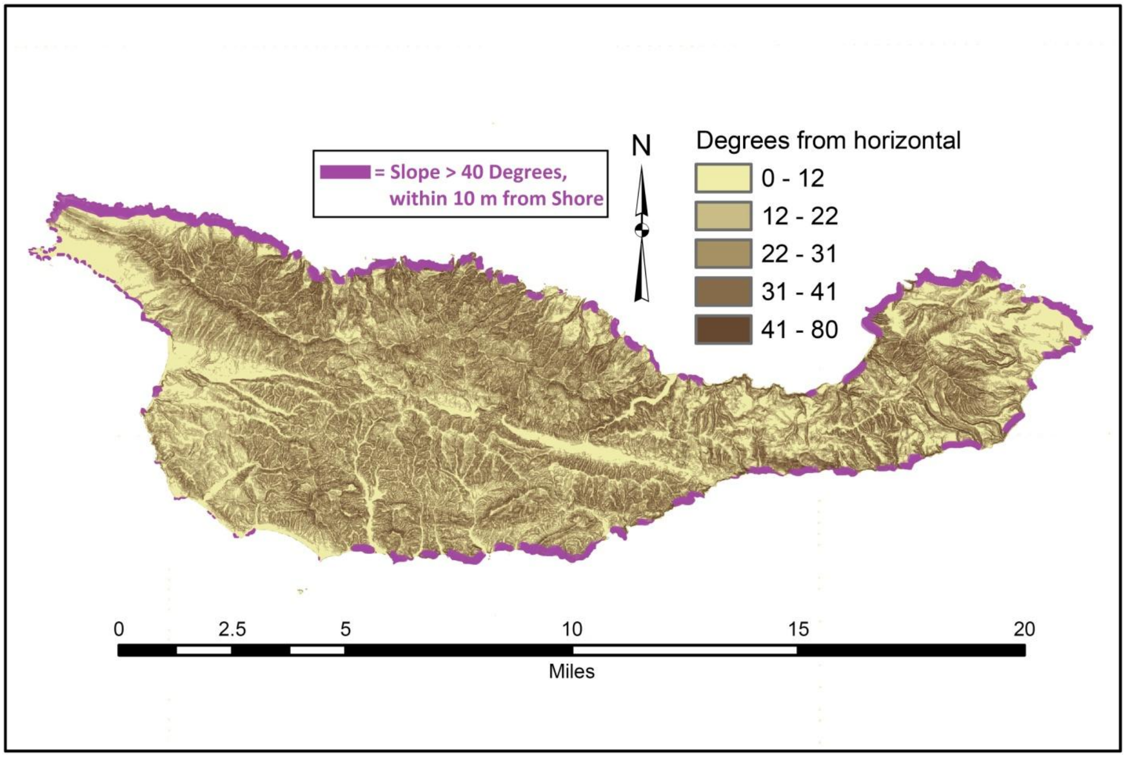

Figure 9.7 Cliffs around Santa Cruz Island, defined by coastline with greater than 40 degree gradient over the first 10 meters inland.

Highest erosion potential on Santa Cruz Island occurs where high incoming wave energy coincides with sedimentary rock. This combination can also exacerbate landsliding as weaker rocks are degraded both at the base of the hillslope from wave pressure, and from within due to water seepage, recent grazing, and other surface processes acting upon well-developed internal discontinuities. This is especially true on the Island's middle neck. This is perhaps one area where a simplified classification scheme based only upon rock type and wave energy misses a significant factor in erosion potential on Santa Cruz Island: discontinuities and surface morphology are not taken into account, which likely make it more vulnerable than indicated by the given "moderate" rating.

The classification scheme presented here can be compared to a similar "Coastal Vulnerability Index" created by the United States Geological Survey (Pendelton et al. 2005) for the Channel Islands. This index is described by the following formula:

$$\text{CVI} = \sqrt{\frac{a*b*c*d*e*f}{6}}$$

Where *a* = geomorphology (cliffs, sand and gravel beaches, alluvial fans, and other categories), *b* = shoreline erosion / accretion rate, *c* = coastal slope, *d* = relative sea-level rise rate, *e* = mean significant wave height, and *f* = mean tide range.

In contrast to Sunamura's (1992) equation for rate of cliff retreat used to inform this analysis, the USGS index gives an equivalent weight to all six factors, including wave height and shoreline geomorphology. Only two of these are shown by the USGS analysis to vary significantly around the Santa Cruz Island shoreline: geomorphology and coastal slope. Also, shoreline erosion is considered a part of the index, rather than being the variable of interest. Results from the USGS report are pictured below (Figure 8):

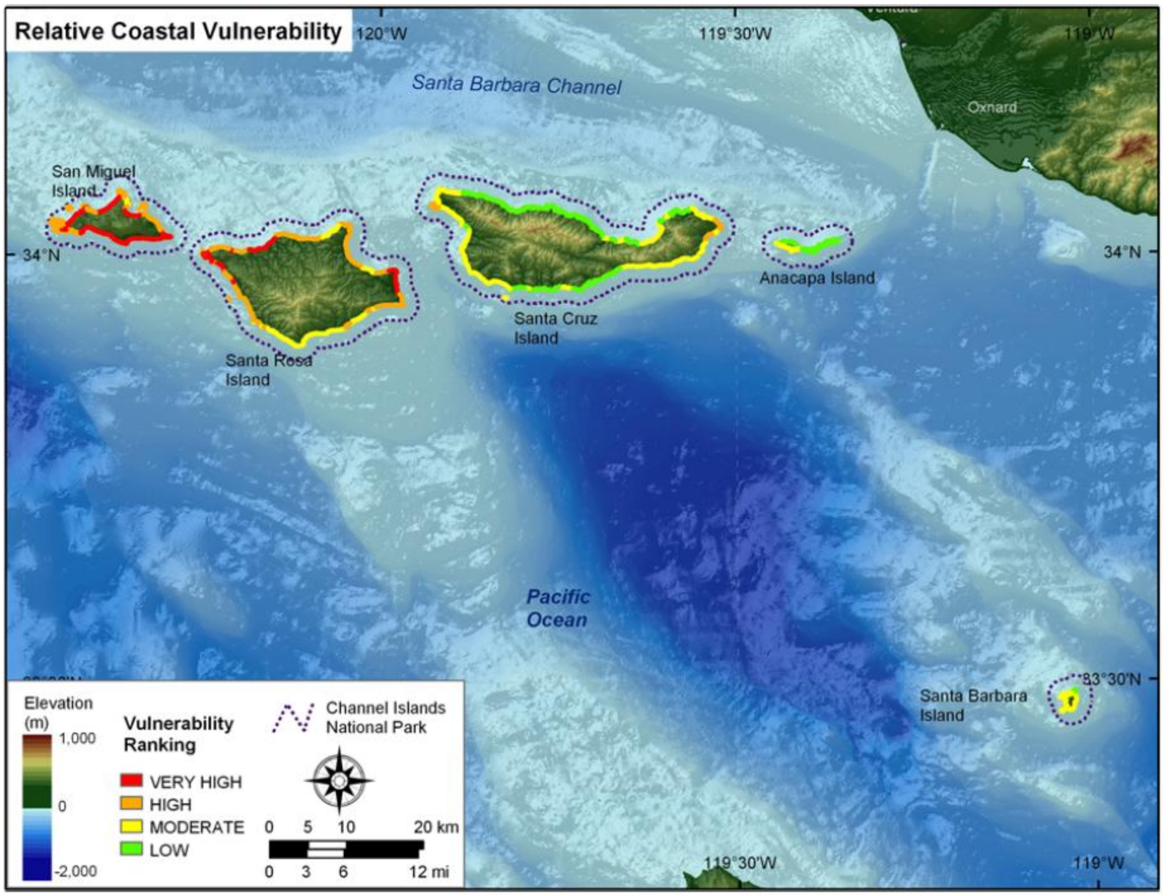

Figure 9.8 USGS Coastal Vulnerability Assessment for Channel Islands National Park. Taken directly from Pendelton et al. 2005

The above map demonstrates general agreement with this paper's assessment of relative vulnerabilities along the Santa Cruz Island coastline, with several notable exceptions. While the western coast and northeast neck display expected high vulnerability due to the incoming NW swell, no differentiation is seen on the western side of the island between volcanic and sedimentary rock types. This is because the USGS index does not account directly for rock type. Also, the eastern neck and small portion of the eastern mountains are both assigned to a higher vulnerability category than the western portion of southern shoreline. This is due to the the "coastal geomorphology" term in the USGS index, and most likely reflects the internal discontinuities and landslide activity of that portion of the island discussed above.

Improvements could be made to both approaches. The USGS index should include a variable for rock strength, and might be improved with weighted coefficients that reflect the stronger influence of some factors over others. The erosion classification scheme presented in this analysis would benefit from a more advanced understanding of *B* in the equation for rock strength: $F_w = B\sigma_c$. Recall that *B* was set to 1 for this analysis. Weighting rocks of equivalent type by the presence and orientation of internal discontinuities would more realistically define categories of relative rock strength on Santa Cruz Island. This would allow for an improved assessment of erosion potential and more mechanistically reflect differences within homogenous rock types that are captured by the "coastal geomorphology" term in the USGS vulnerability index. However, the simple classification developed here does provide enough information to begin an explanation for the modern shaping of the island's coastline, and to offer clues to its future trajectory.

Caveats

Several other factors may also affect patterns of erosion and/or beach development on Santa Cruz Island. The most important of which, ignored in the above discussion, is ongoing uplift and faulting (see Chapter 5). These processes can either accelerate or decelerate rates of shoreline retreat, depending on their influence on discontinuities within rock masses and on rate of uplift of shallow marine terraces, respectively. Often, as is the case with Potato Harbor, inlets will develop along a fault or joint, at the transition between rocks of differing strength or where a joint creates a point of weakness in homogenous rock (see picture below). The location of these faults and joints then becomes an important factor in shore geometry, although more so at a local rather than island-wide scale.

Notes: Picture taken from western edge of Potato Harbor, looking across at contact between basalt (bottom) and sedimentary (top) rocks. Potato Harbor was created by erosion into the softer sedimentary rock, where it replaces the basalt at sea level. Picture taken by Robyn Suddeth.

Finally, as already mentioned, groundwater seepage, drainage patterns, and orientation of rock bedding are internal island factors that play a role in sediment supply to the coast, and landslide occurrence, which in turn affects relative rates of erosion.

Conclusion

Coastal geometry on Santa Cruz Island supports theoretical descriptions of cliff retreat, beach formation, and other mechanisms that drive coastal morphology. Rock type is the dominant control, with wave regime playing a secondary role. The middle neck of the island has the highest rate of erosion, both from internal landsliding and from increased vulnerability to wave energy. This is due mainly to rock type – the Monterey Formation shale that comprises much of the island's middle neck has a much lower compressive strength than the volcanics that dominate the island's eastern and northwestern mountains. Wave energy around the island is highest on its northwestern edge, where surrounding islands and protruding coastline have not significantly deflected the winter NW swell. Other important factors of cliff and shoreline retreat include tectonic activity and resulting rock structure, and island fluvial processes. Places of highest vulnerability on Santa Cruz Island are its northern neck, and west-facing sedimentary rocks. It seems likely the island will eventually be separated into two distinct islands, as landsliding and wave action continue to erode the middle neck from both sides, and that the sedimentary cliffs of the southwest shore will retreat at a faster rate than the northwest volcanics. Rate of erosion on Santa Cruz Island can be broadly differentiated with a simple analysis of rock type and incoming wave energy, but would benefit from inclusion of internal rock properties to more realistically define relative rock strength.

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