Chapter 5
Marine Terraces on Eastern Santa Cruz Island: Sculpting an island by the land-sea intersection

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Abstract
Emergent marine terraces are a common landform along the California coastline. Marine terraces record a unique combination of stable sea level high stands preserved by a tectonically uplifting landmass. During a stable sea level period, high energy waves cut into and drive back sea cliffs resulting in a broad slightly seaward dipping wave cut platform. Wave cut platforms are preserved as marine terraces when sea level changes relative to the wave cut platform. Relative sea level change can be achieved by tectonic uplift or eustatic sea level fall. We discuss the processes that create, preserve, and alter marine terraces as well as present evidence for five periods of stable sea stands during the past ~400,000 years which correspond to periods of stable sea level and are superimposed on the tectonically rising Santa Cruz Island.

Introduction
The boundary between the North American and Pacific plates in southern California has undergone significant reorganization over the past ~40 Ma (Atwater, 1998; see Chapter 2). Due to the complex tectonic environment entire tectonic blocks located along this boundary have undergone substantial migration and rotation (Atwater, 1998; Kamerling and Luyenduk, 1985). These tectonic forces have shaped the topography of southern California, in part resulting in rapidly uplifting landmasses along the coast. The Santa Monica Mountains which extend westward to the northern Channel Islands are an example of such a rapidly uplifting landmass. In addition to tectonic forces, geomorphic processes also have a strong impact on the shape of the southern California coastlines. In cases where geomorphic denudation equals tectonic uplift, an equilibrium landscape is created. However, in cases where one process outpaces the other, a disequilibrium landscape is preserved. One such example of a disequilibrium landscape is the preservation of marine terraces along a tectonically active coastline.

Santa Cruz Island is an ideal setting for formation and preservation of marine terraces. The transpressional tectonic environment leads to rapid uplift and high energy waves from the Pacific Ocean provide the needed erosional forces to cut marine terraces during periods of stable sea level (see Chapter 4 and Chapter 8). Sizable portions of Santa Cruz Island are marine terraces (Figure 5.1) (Pinter et al., 1998; Scott and Pinter, 2003). The island consists of a core of Miocene volcanic and sedimentary rocks with marine terraces evidenced as large planar features along the eastern and western coasts (Weaver and Meyer, 1969; Scott and Pinter 2003; see Chapter 3). The relative coherency of the underlying bedrock influences the extent of the marine terraces; however sustained periods of stable sea level are required for high wave energy to cut platforms into bedrock regardless of composition (Bradley and Griggs, 1976).

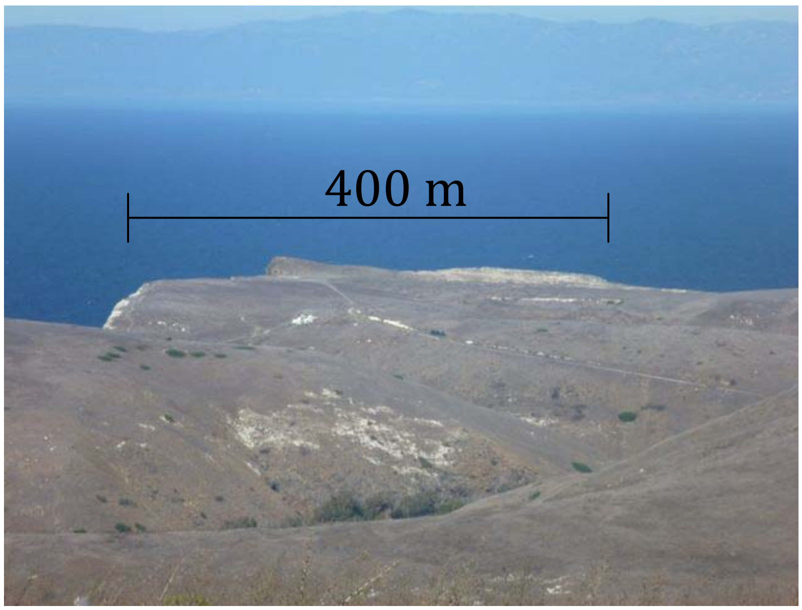

Figure 5.1. Photograph of the T3 terrace deposit at Cavern Point. At Cavern Point the T3 terrace has preserved shallow marine deposits mantling the wave cut platform (Figure 5). The approximate length of the scale bar is 400 meters.

Background

The Channel Islands off the coast of central California are the southernmost expression of the western Transverse Ranges. The Transverse Ranges have rotated clockwise a minimum of 70° during the past 20 Ma in a broad region of dextral shear between the North American and Pacific plates (Kamerling and Luyendyk, 1985; Atwater, 1998; see Chpater 2). This block underwent rifting during initial rotation, erupting the Miocene volcanics that form the core of the eastern end of Santa Cruz Island. Rifting was followed by subsidence that lead to the deposition of basin deposits (Monterey Formation) as sea level rose during the early Miocene (see Chapter 3). This brief overview of the motion of the Transverse Ranges demonstrates the complex tectonic history, which has been extensively discussed in this volume (see Chapter 2 and Chapter 4). Currently, the Channel Islands are an extension of the Santa Monica Mountains that are extruding south of the Big Bend in the San Andreas fault (Atwater, 1998). Here the Transverse Ranges are bounded to the north by the Big Bend in the San Andreas Fault. This results in transpression of the Transverse Ranges and rapid uplift of the block, at rates of 0.7-1.5

mm/yr (Pinter et al., 2003; Chaytor et al., 2008; see Chapter 4). In addition to tectonic forces land-sea interactions have had a profound effect in the shaping of the island, producing substantial topographic features in the form of wave cut platforms on eastern Santa Cruz Island.

Wave cut platforms consist of a bedrock platform that has been planed into a gently seaward dipping platform by high energy wave regime (Figure 5.2) (Anderson and Menking, 1994; Rosenbloom and Anderson; Muhs et al, 2009). They are generated by sea cliff retreat (see Chapter 9, Bradley and Griggs 1976). The wave energy carves a shoreline angle into the retreating sea cliff. This angle is located at the maximum sea level height (Bradley and Griggs, 1976). In order to cut a platform sea level is required to remain relatively constant in relation to a landmass. Sea level can vary from 0-30 mm/yr (e.g. Fairbanks, 1989), and so wave cut platforms are most efficiently generated during sustained periods of high sea stand and are thus usually correlated to interglacial sea level maxima (Pinter et al, 1998). A caveat is that wave cut platforms may be cut anytime there is stable sea stand so during glacial maxima platform can be cut at lower elevations. These are often identified as paleoshorelines (Chaytor et al., 2008).

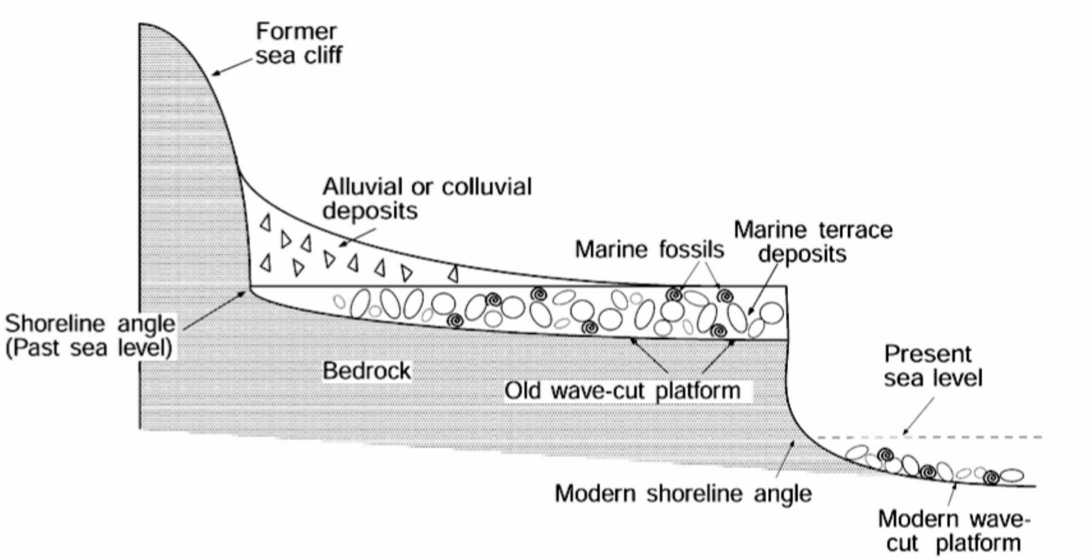

Figure 5.2. Conceptual model of high wave energy near shore morphology from Muhs et al, 2009. The high energy wave regime cuts into the modern sea cliff carving a wave cut platform which dips gently seaward. Hightide is marked by the modern shoreline angle. The wave cut platform is mantled by shallow marine deposits. If the wave cut platform is removed from interaction with the high energy wave regime the marine deposits can be preserved. Shoreline angles are used to determine the location and elevation of preserved wave cut platforms.

It is important to consider the lithology of the bedrock when evaluating wave cut platforms. Softer, sedimentary beds will fail more easily than crystalline rocks resulting in relatively larger wave cut platforms for the same duration and wave energy (see Chapter 9), although duration of sea stand is perhaps the best explanation for variation of platform width (Bradley and Griggs, 1976).

Wave-cut platforms can be preserved as marine terraces if they are removed from interaction with the high energy wave regime. This is achieved through tectonic uplift of the landmass or sea level retreat associated with eustatic sea level fall. A major factor determining sea level is the amount of water stored in polar ice sheets. Sea level varies inversely with the volume of water stored in the polar ice caps. During global glaciation eustatic sea level falls and during interglacials sea level rises. Eustatic changes can result in rapid abandonment or reoccupation of a wave cut platform. Tectonic forces are required to raise the marine terrace so that when sea level subsequently rises the marine terrace is preserved above current sea level. Marine or alluvial deposits can be preserved on uplifted terraces during the abandonment and subsequent uplift of the marine terrace.

There is a caveat to the marine terrace preservation process. A wave cut platform cut during a low stand when sea level rises the platform may be drowned is sea level rises. If the distance between the wave cut platform and the base of the wave action is large enough waves be unable to effectively mix the bottom sediment (Chaytor et al., 2008). If the shoreline angle of the submerged platform is preserved submerged marine terraces can be identified.

Degradation of marine terraces comes from two main sources 1) erosion of paleo-sea cliffs (Figure 5.3) and 2) incision by stream channels (Figure 5.4). Sea cliffs have oversteepened faces often reaching near 90° (Anderson et al. 1999; see Chapter 9). As waves cut into the base of the sea cliff the cliffs are driven back at an angle nearly perpendicular to the wave cut platform. Sea cliffs are a disequilibrium feature and will erode into a more gently slopping colluvium covered terrace (Scott and Pinter, 2003). Also marine terraces are coastal features and as such they are incised by streams channels trying to reach equilibrium on their way to the ocean (Rosenbloom and Anderson, 1994). As stream channels cut down through the tectonically rising landmass the sides of the channel oversteepen and become unstable. This leads to mass wasting of the terrace adjacent to the stream channels. Landslides are only a temporary blockage for the stream channels and the incising streams remove rapidly the debris (Rosenbloom and Anderson, 1994). Mass wasting due to stream channel incision has a smaller effect on islands as the stream length and power are limited by the area of the island. The maximum stream length is approximately the half-width of the island, limiting stream power ultimately leading to better preserved terraces on islands (Anderson et al, 1999).

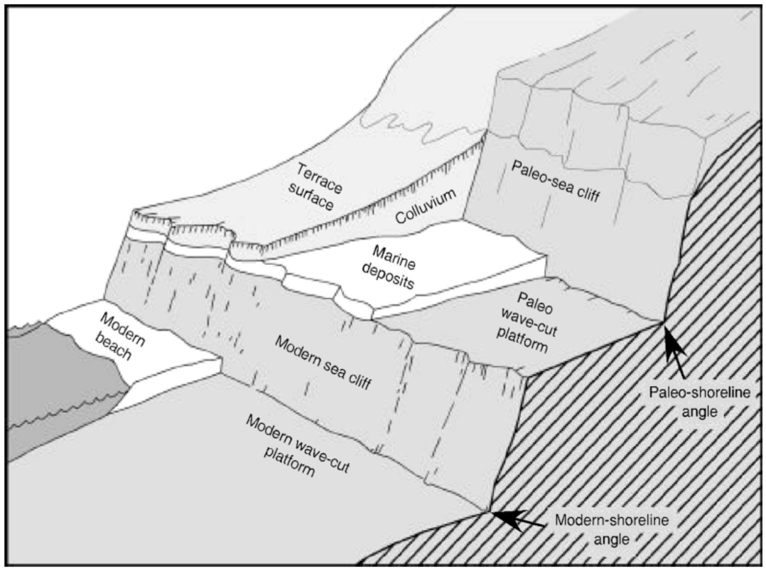

Figure 5.3. Conceptual model of a preserved marine terrace. The paleo-sea cliff in the foreground is representative of a well preserved marine terrace. The colluvium covered terrace surface in the background demonstrates an equilibrium marine terrace landscape achieved by erosion of the oversteepened paleo-sea cliff. From Scott and Pinter (2003).

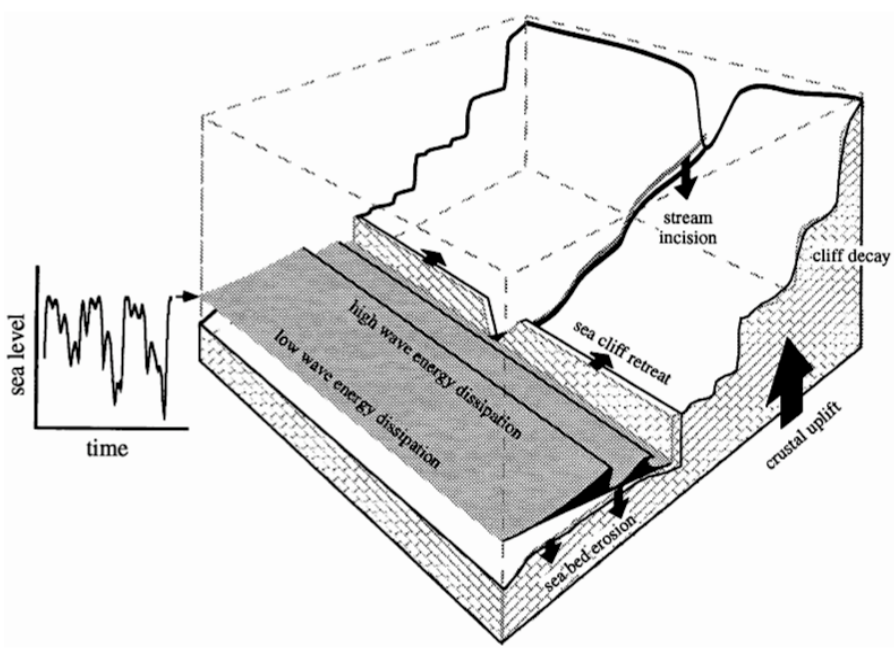

Figure 5.4. Conceptual model of stream incision on a marine terraced landscape. Variations in sealevel superimposed on an uplifting landmass carves marine terraces that are then incised by stream channels attempting to reach equilibrium on their way to the sea. This can lead to oversteepening of channel walls that leads to mass wasting of the marine terrace. From Anderson et al. (1999).

Description

Terraces are well documented on the western end of Santa Cruz Island (Scott and Pinter, 2003). Pinter et al (1998) identified 3 terraces of different ages on the western end of the island. A DEM study of the eastern end of the islands identified the remnants of the same 3 terraces using the location of preserved shoreline angles (Figure 5.5) (Scott and Pinter, 2003). Both absolute dating techniques and relative altitudinal spacing were used to determine the ages of the terraces. Young terraces can be dated using U-series analysis of solitary corals (up to 125 ky high stand) or for very young terraces ^{14}C dating of shell material can be used (Scott and Anderson, 2003; Chaytor et al., 2008). Relative altitudinal spacing relies on elevation of marine terraces and sea level curves to date terraces. As the island (or any landmass) is tectonically uplifting each subsequent high stand cuts a platform at lower elevation than the older terrace. Relative terrace age increases inland; the highest topographically is the oldest terrace. The lowest and therefore youngest emergent terrace is located adjacent to the current shoreline. The age of the youngest terrace (T1) was calculated from U-series analysis of solitary corals on several sites on the western end of the island (Scott and Pinter, 2003). The age of this terrace is ~125ka and with the inner angle 18m above sea level. This age correlates to the marine isotope stage (MIS) 5e, which corresponds to an interglacial period of eustatic high stand (Figure 5.6). The second terrace (T2) was dated using relative altitudinal spacing and late quaternary sea level history (Pinter et al, 1998). T2 is approximately 50m above sea level. This terrace has an age of at least 320ka and corresponds to MIS 9, also an interglacial period with eustatic high seas. The largest, highest, and oldest terrace (T3) is at least 400ka. This terrace ranges in height from approximately 90-200m above current sea level (Scott and Pinter, 2003). Due to tectonic and geomorphic processes this terrace also has the most variability in height due to the folding and faulting of the island from the transpressional tectonic environment.

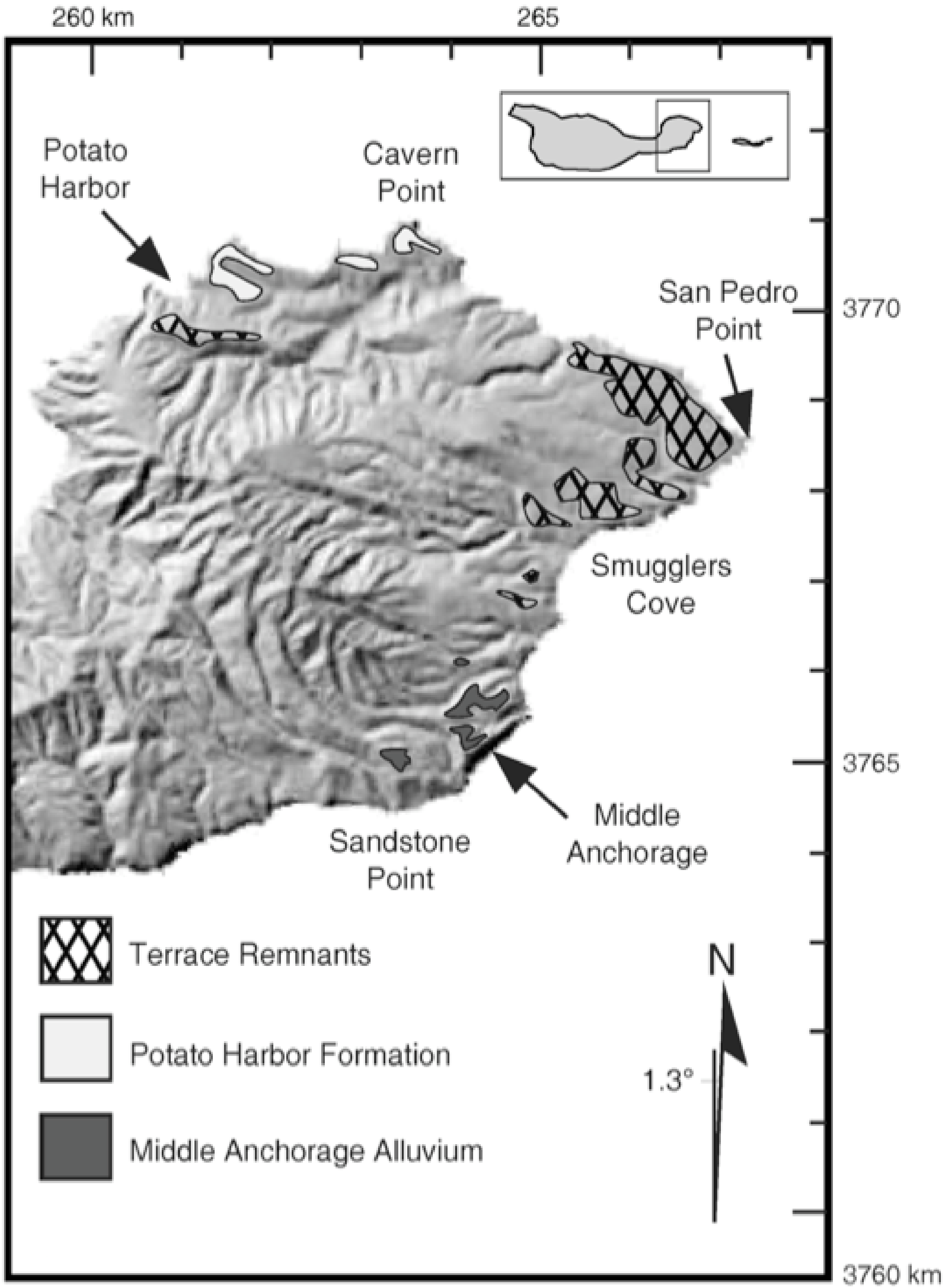

Figure 5.5. Map of eastern Santa Cruz Island. Terrace that have had marine deposits removed , labeled as terrace remnants, are show as crosshatched areas. The Potato Harbor formation is indicated in white and Middle Anchorage Alluvium is shown as dark grey. These terraces are T3 terraces. T2 and T1 terraces are located seaward of the T3 deposits.

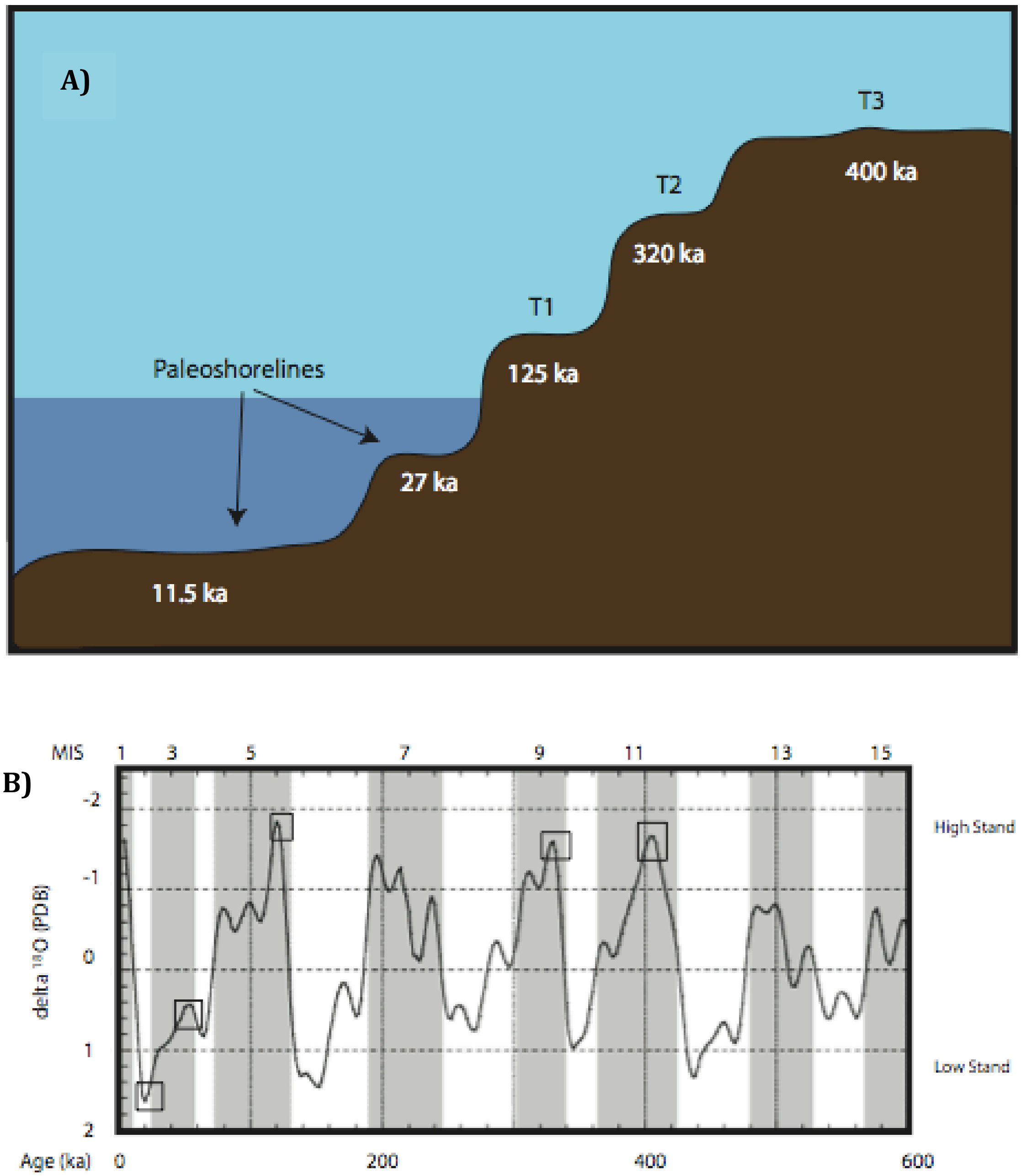

Figure 5.6. [A] Diagram of current terrace and paleoshoreline locations with corresponding ages. **[B]** SPECMAP sea level curve to 600 ka. The ages corresponding to the creation of the wave cut platforms are indicated with boxes. SPECMAP: (htpp://www-odp.tamu.edu/publications/182_SR/015/015_f4.htm)

Early work on eastern Santa Cruz Island by Weaver and Meyer (1969) identified Pleistocene sandy limestone deposits on what would later be determined the T3 terrace (Scott and Pinter, 2003). Erosional processes have removed much of the shallow marine deposits on this largest and oldest terrace in most locations. However, marine deposits have been found near both Potato Harbor and Middle Anchorage. T3 at Potato Harbor is overlain by fossiliferous sands of the Potato Harbor Formation indicating coastal origins (Scott and Pinter, 2003). The Potato Harbor formation unconformably lies above the Santa Cruz Island Volcanics, and is up to 85 feet thick with diagenetic alterations and biomicrosparite deposits throughout the section (Figure 5.7).

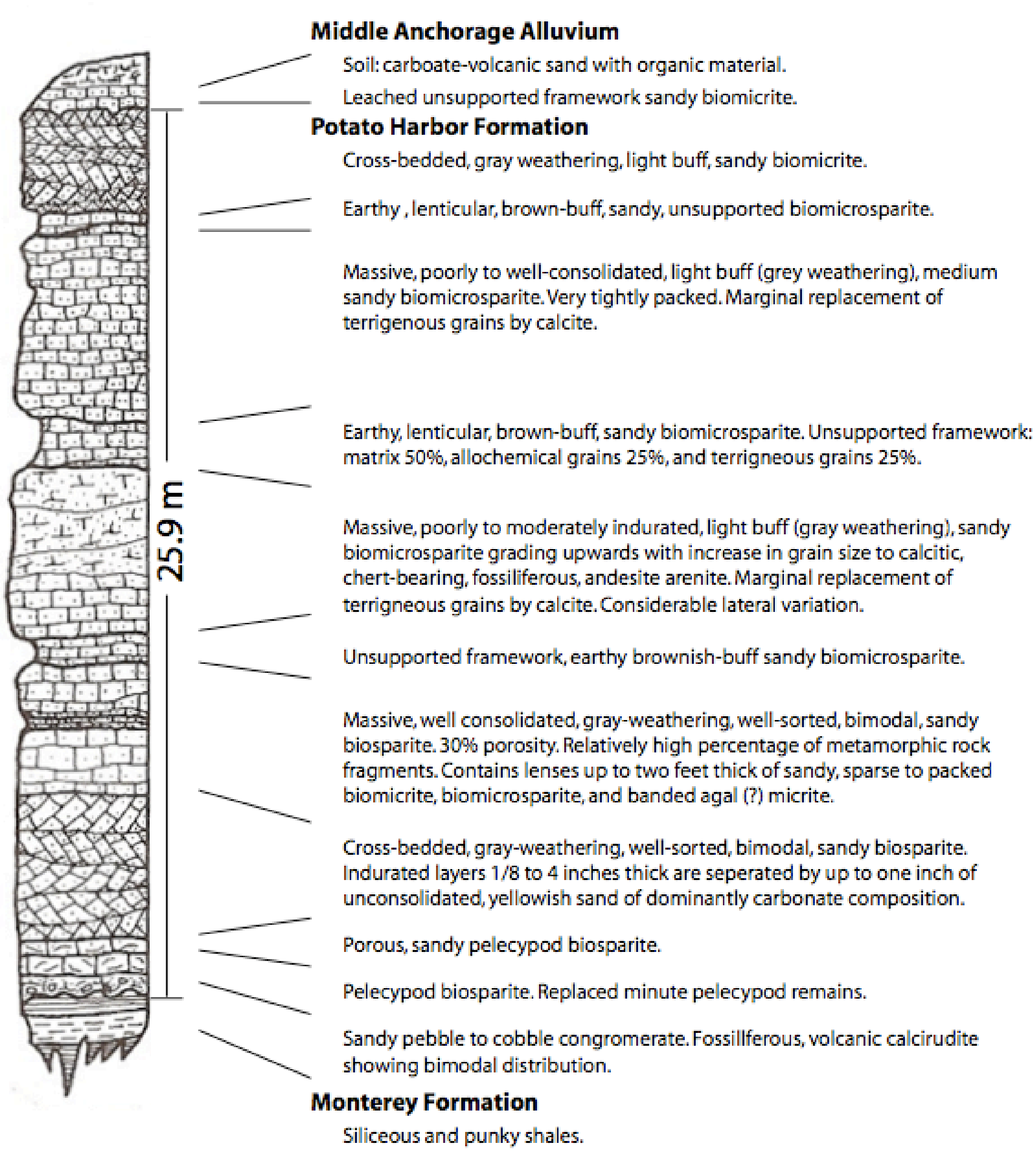

Figure 5.7. Stratigraphic column of the Potato Harbor formation. This formation is predominantly sandy limestone that unconformably overlies the Monterey formation. From Weaver and Meyer (1969).

T3 near Middle Anchorage on southeastern Santa Cruz Island is overlain by the Middle Anchorage Alluvium and although there are terrestrial sources for the alluvium, gastropod bore holes indicative of a costal environment are present (Weaver and Meyer, 1969).

Two submerged terraces or paleoshoreline have been identified and dated by Chaytor et al. (2008). Data sets compiling multibeam bathymetry and side-scan sonar with DELTA submersible dives were used to identify and map the submerged paleoshorelines. The lowest paleoshoreline is a large shelf surrounding the northern Channel Islands. This shelf has been dated using ^{14}C resulting in an age of 11,500. This age corresponds to the Last Glacial Maximum (LGM). This platform was cut during a period of stable low stand and has been preserved as it was submerged and removed from interaction with the high energy wave regime. The shallower paleoshoreline was dated using the same techniques and has an age of 27 ka. Interestingly this is the only preserved wave cut platform that does not correspond to a high or low stand, but simply a period of prolonged stable eustatic sea level (Figure 5.6). Both of the paloeshorelines have been resubmerged as sea level has been rising after the LGM. As Santa Cruz Island continues to uplift it is expected that these paleoshoreline will be reoccupied and removed, rather than be preserved as marine terraces.

Conclusion

Through the use of U-series, ^{14}C, and relative altitudinal dating techniques 5 preserved wave cut platforms have been identified on eastern Santa Cruz Island (Scott and Pinter, 2003; Pinter et al, 1998; Chaytor et al, 2008). The terraces range in age from 11.5 -400 ka and correspond to periods of eustatic stable sea level. The older (125-400 ka) preserved marine terraces were cut during periods of stable high stand (Pinter et al, 1998). The submerged paloeshorelines (11.5-27 ky) were cut during periods of stable sea level, however the stable sea level did not correspond to high stands resulting in the drowning of the platforms during the current sea level rise (Chaytor et al, 2008). Marine terrace ages and elevations in relation to eustatic sea level can be used as strain markers to determine vertical deformation and rates of surface uplift (see Chapter 4 for discussion in relation to Santa Cruz Island).

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