EXERCISE 6

COASTAL TERRACES, SEA LEVEL, AND ACTIVE TECTONICS

Supplies Needed

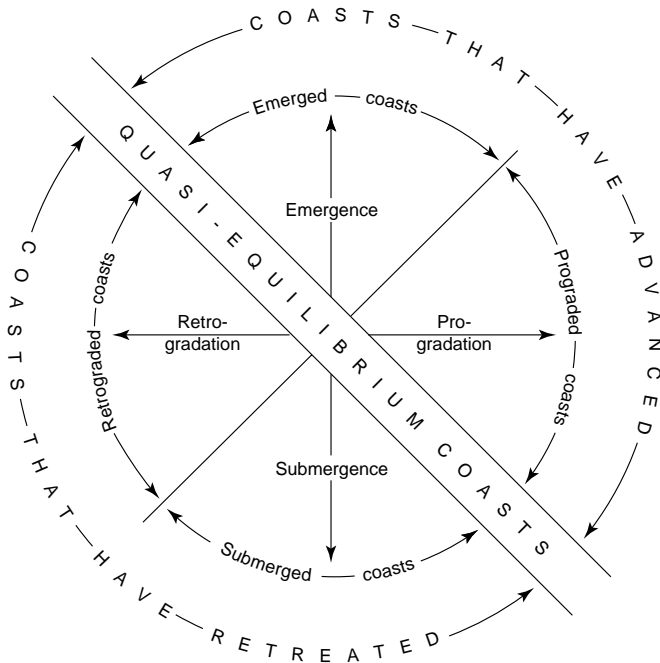• calculator
• striaght-edge ruler
• graph paper

PURPOSE

Coastlines are one of the major geomorphic systems of the Earth. In addition, sea level is important to studies of active tectonics because it is a unique horizontal datum – a widespread plane of equal elevation. Because coastal landforms are created at or near sea level, finding old coastal features some distance above the modern coastline indicates tectonic deformation of the surface in the time since those features formed. Some of the most useful landforms for studies of active tectonics are coastal terraces, including both erosional terraces and uplifted coral reefs. These landforms are prominent along many coastlines, and they can be useful tools for measuring rates and patterns of tectonic uplift.

INTRODUCTION

Coastlines have been called battlefields in the war between ocean and land. Oceanic processes, including wave action and attack by chemical and biological action, fight to erode the coast and push the shore inland. The land resists the ocean's attack with the strength of coastal rock and with sand transported to the coast by rivers. Where a sandy beach protects the shore, most of the ocean's energy is consumed moving the sand around. If the supply of sediment exceeds the erosional energy of the ocean, the shore will advance ("prograde") oceanward. Tectonic uplift is another ally of the land, slowly lifting the coast. The third major force in the battle for coastlines is the worldwide position of sea level. Fluctuations of 125 m or more have accompanied the growth and decline of the great ice sheets of the Pleistocene.

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The coastlines of the Earth can be classified by the relative strength of two variables (Figure 6.1): 1) sediment supply (from sediment-rich to sediment-poor), and 2) the relative position of the land relative to sea level (including the combined effects of tectonics and sea level). As Figure 6.1 below shows, coastlines advance in response to tectonic uplift or falling sea level *(emergence)* or to sediment supply in excess of erosion *(progradation).* Coastlines retreat in response to tectonic subsidence or rising sea level *(submergence)* or to erosion in excess of sediment supply *(retrogradation,* or *shoreline retreat).*

Figure 6.1. Process-oriented classification of coastlines. (After Valentin, 1970; cited in Bloom, 1991)

To isolate just one of the variables illustrated in Figure 6.1, consider coastlines that have an abundant supply of sediment. The most familiar characteristic of sediment-rich coasts is a *beach.* Tides and waves maintain a dynamic equilibrium on beaches. Storms can temporarily shift the equilibrium in favor of the ocean, stripping away large volumes of sand, but a return to low-wave-energy conditions will return sand to the beach. As mentioned earlier, sand effectively armors the shore against wave attack and erosion.

The Atlantic coast of the U.S. illustrates many of the complexities of a sediment-rich coastline. Sediment supply from rivers creates the prominent spits and barrier islands that characterize much of the coast from Fire Island, New York to Miami Beach, Florida. Barrier islands have been interpreted to be features of submergent coasts, formed as global sea level advanced in response to melting of the last Pleistocene ice sheets. Over longer periods, however, the North American coast is very slowly rising relative to the ocean in response to erosion of the land *(isostatic compensation).* Thus over glacial-to-interglacial time periods the Atlantic coast is submergent, but over longer periods it is emergent.

Landforms of sediment-rich coasts can be useful in studies of active tectonics (see for example Winker and Howard, 1977), but sediment-poor coasts generate the landforms that are most useful. The coastal landforms that are most widely used in studies of active tectonics are *coastal terraces.* Coastal terraces include two varieties: 1) erosional terraces, and 2) uplifted coral reefs. Both varieties form in close association with sea level, but erosional terraces form by wave erosion and shoreline retreat, while coral reefs form by biological activity and shoreline advance. Both erosional terraces and uplifted coral reefs reflect the complex history of glacial-to-interglacial sea-level fluctuation and long-term uplift of the land. The exercise that follows uses erosional terraces as an example, but uplifted coral reefs also are widely studied to decipher sea-level and tectonic history.

EROSIONAL COASTAL TERRACES

Erosional terraces are the characteristic landform of much of the Pacific coast of North America. In these areas, the shoreline is relatively unprotected by sediment and is exposed to marine erosion during part or all of the year. Mechanical erosion by breaking waves, as well as chemical erosion by salt and erosion by organisms that burrow into the rock, carve a broad platform just off the shore called a *wave-cut platform.*   As erosion attacks the land and the wave-cut platform widens, breaking waves often cut a steep *sea cliff* into the shore.   The line where the wave-cut platform meets the sea cliff is called the *shoreline angle,* and the shoreline angle is the single best marker of the position of sea level at which an erosional terrace formed.   Figure 6.2 shows the features of an actively-forming erosional terrace.
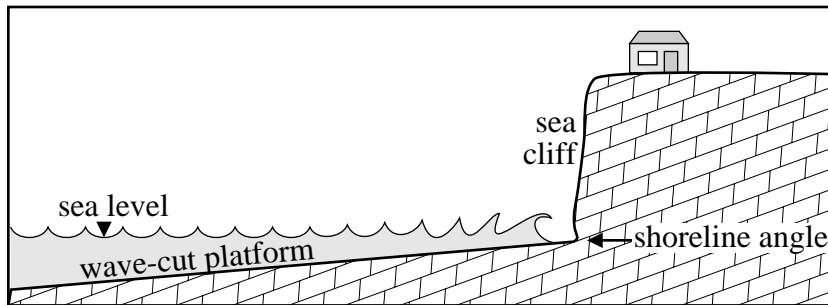

Figure 6.2. Characteristic features of an actively-forming erosional terrace.

SEA LEVEL

The ocean surface is Earth's best approximation of a perfect horizontal datum. Averaged over periods from a few hours up to a few years, sea level becomes an increasingly precise measurement of a surface of equal gravity potential. Although av-erage sea level around the Earth has changed little in about the last 5,000 years, it fluctuated
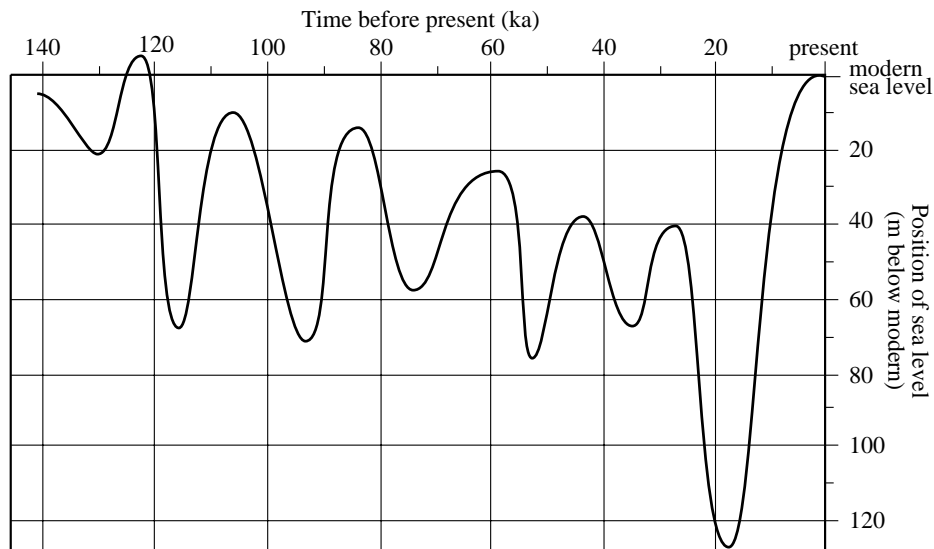

Figure 6.3. History of fluctuating sea level during the last 140,000 years.

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immensely during the previous 2,000,000 years or so. Figure 6.3 is a curve that shows sea-level history during the last 140,000 years. It was inferred from uplifted coral reefs in New Guinea (Bloom et al, 1974; Pinter and Gardner, 1989).   You will also use another sea-level curve (Figure 6.8) that was inferred from isotopic chemistry of fossil microorganisms. Figure 6.8 shows a longer interval of time than Figure 6.3, but the position of sea level is not precisely calibrated.

Pleistocene fluctuations in sea level primarily reflect the growth and decay of the great ice sheets that repeatedly covered much of North America and Europe. These ice sheets reached thicknesses of several thousand meters, storing up to 100 billion cubic meters of water on the continents and depleting the world's oceans proportionally. At the time of the last glacial maximum about 18,000 years ago, global sea level was approximately 125 m lower than it is today, and vast areas that are now under water were then dry land. During the last two million years, continental ice sheets grew and then melted eight to twelve times or more, and sea level has risen and fallen in synch.

Coastlines tend to record long-term fluctuations in sea level where tectonic activity slowly lifts the land up relative to the ocean. Such coasts often record multiple cycles of rising and falling oceans preserved over tens to hundreds of thousands of years. Broad wave-cut platforms are cut when sea level is near its highest position in each cycle, such as today. When sea level is rising or falling, the position of the coast is changing too rapidly to carve this distinctive set of landforms. On many uplifting coastlines, the wave-cut platform carved during the *previous* sea-level high-stand is preserved as a bench located above the modern sea cliff (Figure 6.4). These benches are known as *uplifted coastal terraces,* and staircases of as many as a dozen of such terraces are found along tectonically-
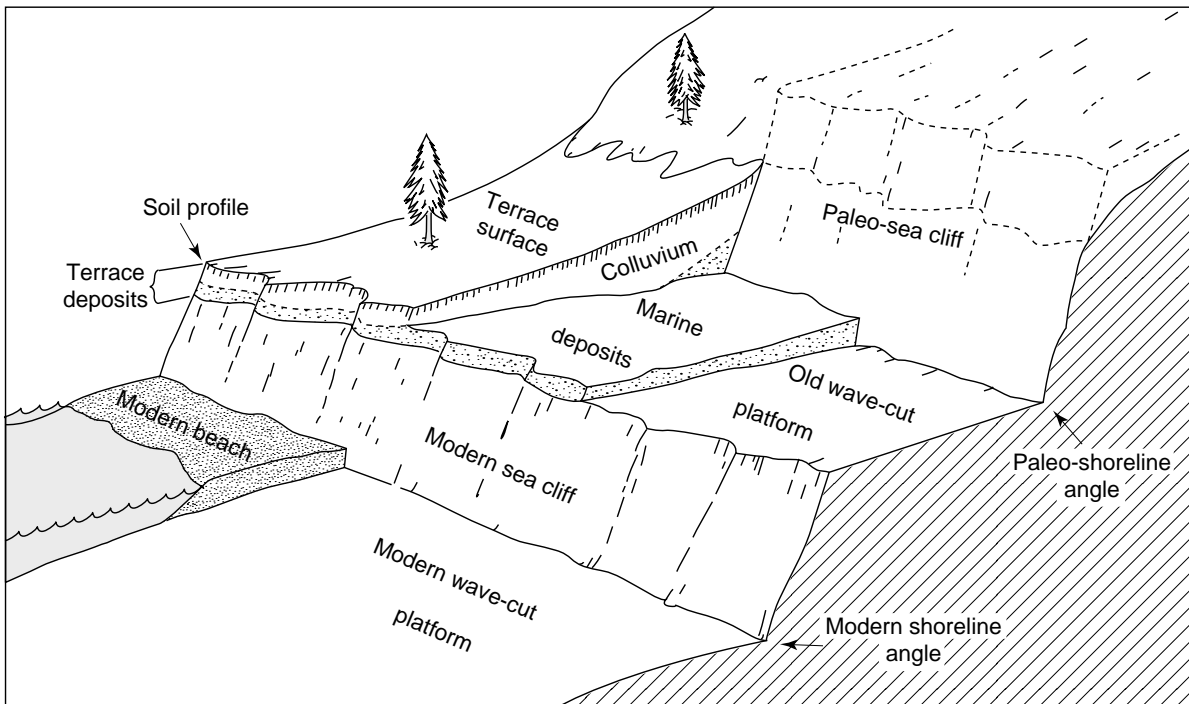

Figure 6.4. An uplifted marine terrace and associated features. (After Weber, 1983)

active coasts. You should understand that each terrace and the sea cliff above it represent the position of the shore at some time in the past. The shoreline angle measures the highest position of sea level for each interval of time. A layer of marine sediment (the last beach to cover the platform) commonly mantles the terraces, and that layer is in turn covered by a wedge of colluvium (gravity-laid debris eroded from the old sea cliff).

COASTAL TERRACES OF SAN CLEMENTE ISLAND

San Clemente Island lies 100 km off the coast of Southern California between San Diego and Los Angeles. The island is about 33 km long and a maximum of 5 km wide, forming a steep ridge more than 600 m (2000 ft) at its crest. A portion of San Clemente is illustrated in Figure 6.5 and in Figure 6.6. The island is asymmetrical, the southwest-facing slope being relatively gentle and the northeast-facing slope much steeper. This asymmetry is interpreted to reflect activity on the San Clemente fault, a right-lateral strike-slip fault which runs just off the northeast shore of the island. That fault is part of the greater San Andreas fault system, carrying a small portion of the slip between the Pacific and North American plates (see Regional Focus A).

San Clemente Island is one of the most famous locations for erosional coastal terraces in the world. At least ten different terraces cut the southwest face of the island, rising like a giant staircase from the Pacific shore (Muhs, 1983). The terraces are cut by deep river gorges and locally are covered by alluvial-fan and wind-laid deposits, but the same terrace levels can be traced along much of the length of the island. The terraces locally are covered by colluvium and by a veneer of marine sediment as illustrated in Figure 6.4 (Crittenden and Muhs, 1986). All in all, the number of terraces on San Clemente, their continuity, and their preservation are exceeded at no other site in the world.

Mapping the San Clemente Terraces and Measuring their Shoreline Angles

1) On a piece of graph paper, construct a topographic profile between points A and A' on Figure 6.5. The instructions for constructing topographic profiles were outlined in Exercise 3. Note that the topographic contours in Figure 6.5 are in feet, so that the vertical axis on the profile also will need to be in feet. In addition, you'll find that a vertical exaggeration of about five (VE=5) will nicely accentuate the terraces.

2) The lowest terrace, labeled T1, is difficult to discern on the topographic map because its elevation (5 m) is less than the contour interval of the map. Label the next terrace (the lowest one that shows on your profile) as T2, and label higher terraces sequentially from there.

3) Add the wave-cut platforms to each of the terraces on your profile. In order to do this, you'll need to know the thickness of sediment (colluvium plus marine material) on each platform. Column 2 in Table 6.1 gives this information at a number of drill-hole sites illustrated as dark dots on Profile A-A' on Figure 6.5. Assume that the wave-cut platforms are horizontal, and draw them at the appropriate elevations on your profile.

4) Add the paleo-sea cliffs to each of the terraces on your profile. The sea cliff commonly intersects the ground surface at the steepest point on the slope above an

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uplifted wave-cut platform and dips steeply downward at 60° or more. On a vertically-exaggerated profile, paleo-sea cliffs can appear close to vertical. The intersection of a sea cliff and the wave-cut platform below is the shoreline angle of that terrace.

5) Measure the elevation of each shoreline angle (in ft), and enter it into Column 3 of Table 6.1. Convert the shoreline-angle elevations into meters (1 ft = 0.305 m), and enter that information in Column 4.

Table 6.1. Summary of coastal-terrace information from San Clemente Island.

1 Terrace	2 Depth to wave-cut platform (m)	3 Shoreline-angle elev. (ft)	4 Shoreline-angle elev. (m)	5 Estimated age (ka) (Questions 7, 11)
T1	0	16*	5	
T2	7			125
T3	9			
T4	11			
T5	10			
T6	15			

* see Instruction 2 above

COASTAL TERRACES, UPLIFT, AND SEA-LEVEL HISTORY

There is a *Catch 22* in studying uplifted marine terraces. You would like to know two things: 1) the ages of the terraces and 2) the long-term uplift rate in the area, but you need the age to calculate the uplift rate, and you need the uplift rate to calculate the age. The general equation for uplifted marine features is:

$$U = \frac{z - z_0 - SL}{t} \tag{6.1}$$

where U is average uplift rate, z is modern elevation of the feature, z_0 is the elevation at which the feature formed relative to sea level at the time (depths are negative), SL is sea level at the time (see Figure 6.3), and t is the age of the feature. Equation 6.1 is a simple "rate equals distance divided by time" formula – uplift rate is the distance uplifted (present terrace elevation minus the elevation at which it formed) divided by the time interval.

Example 6.1:

Find the uplift rate at a site where you collected a 30,000 year old shell sample at an elevation of 14 m above modern sea level. The sample was found in original growth position (not transported or otherwise disturbed), and a paleontologist estimates that the organism lived about 5 m below mean sea level.

You will use Equation 6.1 to find uplift rate (U). The information above tells you that $z=14$ m, $z_0=-5$ m, and $t=30,000$ years$=30$ ka. In order to find SL, use Figure 6.3. At time $t=30$ ka, sea level was about 40 m below modern sea level ($SL=-25$ m). Plugging this information into Equation 6.1:

$$U = \frac{14 \text{ m} + 5 \text{ m} + 40 \text{ m}}{30 \text{ ka}}$$

$$U = 2.0 \text{ m/ka}.$$

Working with coastal terraces, Equation 6.1 becomes even simpler because terrace shoreline angles always form at $z_0=0$, so that this term drops out of the equation. Furthermore, as discussed earlier, coastal terraces form at local peaks in the sea-level curve, when sea level was at a temporary maximum. As a result, there are a limited number of ages at which coastal terraces could form (the peaks in Figures 6.3 and 6.8).

Analysis of uplifted coastal terraces is facilitated by a graphical rendering of Equation 6.1 that combines sea-level history, elevations, and uplift all in a single figure (Figure 6.7). In the example illustrated in Figure 6.7, one terrace formed at 85 ka and the other at 125 ka. The two terrace shoreline angles are now found at elevations of 66 and 131 m above sea level, respectively. On a graph like Figure 6.7, uplift rate is the *slope* of the line that connects the point at which each terrace formed with its position at $t=0$. The slopes of both of these lines are 1.0 m/ka. Being in the same location, the uplift for both terrace must be the same, so the two lines must be parallel. You also can use Equation 6.1 to verify this result.
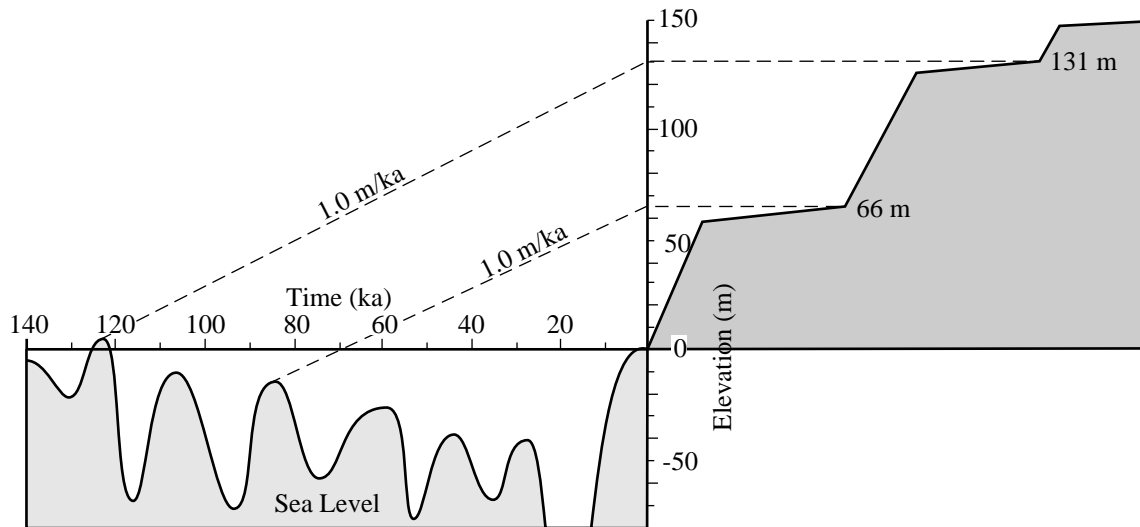

Figure 6.7. Uplift of terraces formed at 85 and 125 ka at a constant rate of 1.0 m/ka.

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6) On San Clemente Island, the T2 terrace has been dated at 125 ka using uranium-series analysis of corals collected from the wave-cut platform. Using Figure 6.7 as an example, plot the position at which T2 was formed and the present elevation of its shoreline angle (at t=0) on Figure 6.8. Connect these two points. What has the average uplift rate been on San Clemente Island during the last 125,000 years?
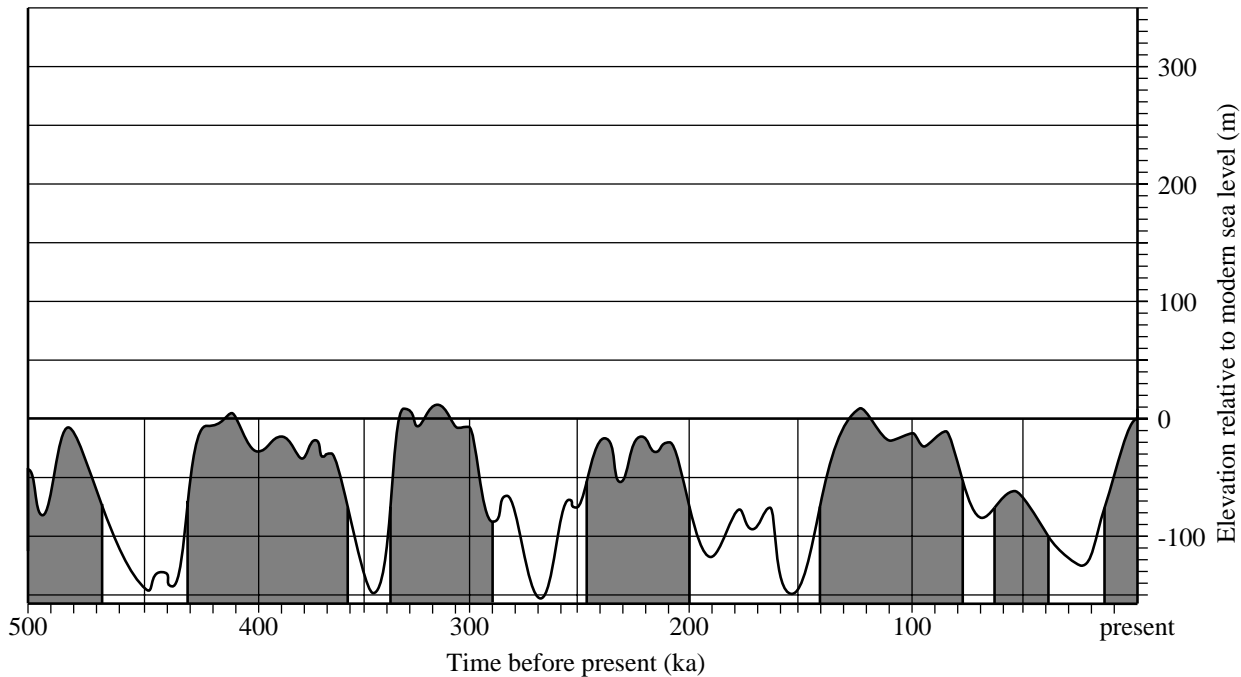

Figure 6.8. Uplift diagram for San Clemente Island terraces. (Sea-level curve after Shackleton and Opdyke, 1973)

7) Assume that the uplift rate that you calculated in the previous question has been constant during at least the last 500,000 years. Use Figure 6.8 to estimate the ages of the T1 and the T3 terraces on San Clemente Island. Follow the example shown in Figure 6.7. Enter your results in Column 5 of Table 6.1.

8) Why wouldn't Figure 6.8 be useful for estimating the ages of the highest terraces in the San Clemente sequence?

RELATIVE SPACING OF COASTAL TERRACES

You may have noticed that the assumption casually slipped into Question 7 – that an upli rate measured in the last 125 ka has been constant during 500 ka or more – is a very sweepi claim. While it is true that uniform uplift has been demonstrated in many areas, uplift rates in oth locations have varied substantially during the Quaternary (Bishop, 1991; Rockwell et al, 1988). I addition, the method outlined for Questions 6 and 7 requires that at least one terrace in a sequence can be dated using some radiometric or other numerical technique. The *relative-spacing method* an alternative technique for determining terrace ages in sequences in which several different terraces are preserved, but numerical age control may not be present. In addition, the method tests whether the assumption of uniform uplift over time is valid or not.

The relative-spacing method requires that several terraces be present is a sequence and that shoreline-angle elevations be known with fair accuracy. This technique takes advantage of the fact that terraces seem to form only at peaks in the sea-level curve, so there are a finite number of ages to which any given terrace can correspond. If and only if there has been a constant rate of uplift, then terrace elevations can be used to infer terrace ages. The relative-spacing technique involves constructing a plot of total uplift versus time for all terraces in a sequence. Example 6.2 illustrates how the technique is used to test a hypothesis of terrace ages.

Example 6.2:

A sequence of four terraces have the following shoreline-angle elevations. Use the relative-spacing technique to test the hypothesis that the four terraces formed at the times shown:

	T1: 25 m;	T2: 55 m;	T3: 100 ka;	T4: 150 m
Hypothesis:	**t=60 ka**	**t=85 ka**	**t=107 ka**	**t=125 ka**

First of all, note that all four of the ages in the hypothesis above correspond to sea-level maxima on Figure 6.3. The next step in this technique is to calculate total uplift for each of the terraces, given the ages in the hypothesis. Completing a simple table is very helpful here.

Terrace	z (m)	t (ka)	SL at t (m)	uplift (m)
T1	2	60	- 28	
T2	29	85	- 14	
T3	75	107	- 10	
T4	183	125	+ 6	

The first three columns above reiterate the hypothesis to be tested, and the fourth column lists the positions of sea level (Figure 6.3) at the times specified. The fifth column in the table is total uplift *(not* uplift *rate)*, which is simply the difference between the modern elevation of a terrace and the elevation at which it formed:

$$\text{uplift} = z - \text{SL} \qquad (6.2)$$

You should see that Equation 6.2 is just a highly simplified version of Equation 6.1 in which has been removed (because shoreline angles form exactly at sea level) and in which time (t) is not considered. Completing the table:

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Terrace	z (m)	t (ka)	SL at t (m)	uplift (m)
T1	2	60	- 28	30
T2	29	85	- 14	43
T3	75	107	- 10	85
T4	183	125	+ 6	177

The next step in the relative-spacing technique is to plot uplift versus terrace age (t) for all the terraces in the sequence as shown below:
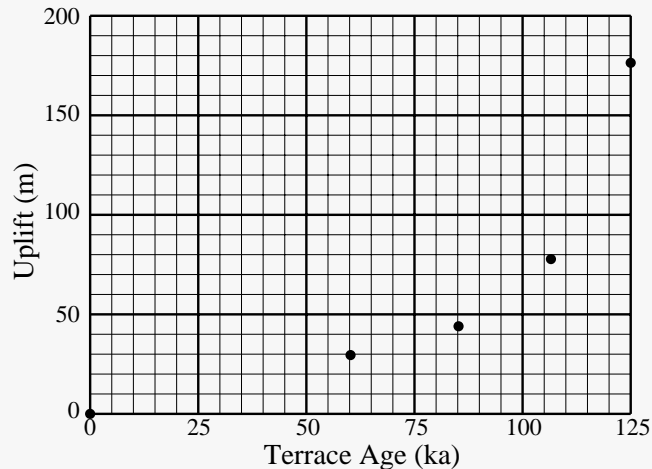
The fact that the four points on the plot above do not fall on a straight line could indicate either one or both of the following: 1) that the hypothesized ages do not work, or 2) that uplift has not been uniform over time at this site.

9) Assume that the ages for the four terraces listed in Example 6.1 are correct. Is the relative spacing of these terraces consistent with a change in uplift rate during the formation of this sequence?

What is the modern uplift rate?

What was the uplift rate before the change?

When did the change in uplift rates occur?

10) Use the relative-spacing technique for the terraces you profiled and measured on San Clemente Island to test your T1, T2, and T3 terrace dates. A data table and an uplift-vs.-time plot are provided below. Are these dates consistent with a single, constant rate of uplift during the time that these three terraces formed?

Terrace	z (m)	t (ka)	SL at t (m)	uplift (m)
T1	5			
T2		125		
T3				
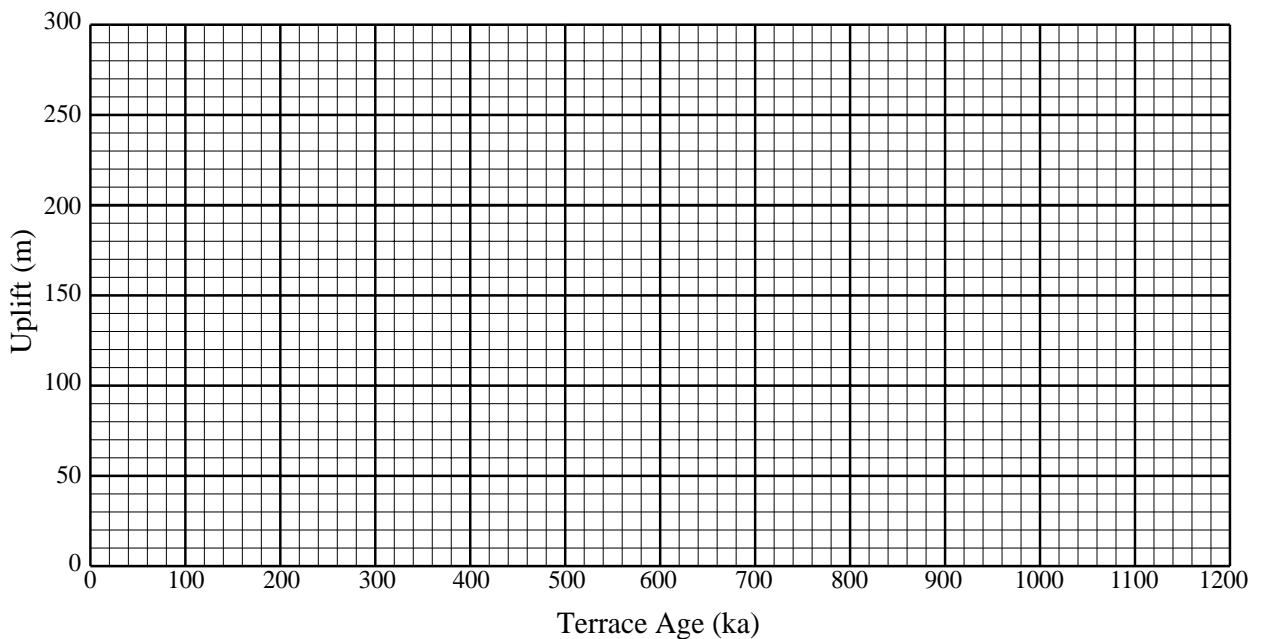
11) Now assume that all of the terraces that you profiled on San Clemente Island formed near modern sea level (SL=0; therefore uplift=z). As you can see from Figure 6.8, most interglacial high stands did fall near modern sea level. Given the present-day elevations of the higher San Clemente terraces, estimate the ages from the graph above. Enter this information in Table 6.1. What is the main assumption that these age estimates require?

Terrace	z (m)	t (ka)	SL at t (m)	uplift (m)
T4			0	
T5			0	
T6			0	

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