Landscapes from the Waves—Marine Terraces of California

Many coastlines around the world have stair-step landforms, known as marine terraces. Marine terraces make up a large part of coastal California's landscape—from San Diego to Crescent City. Find out how these landscapes form, why marine terraces are of interest to scientists, and where you can explore these landscapes.

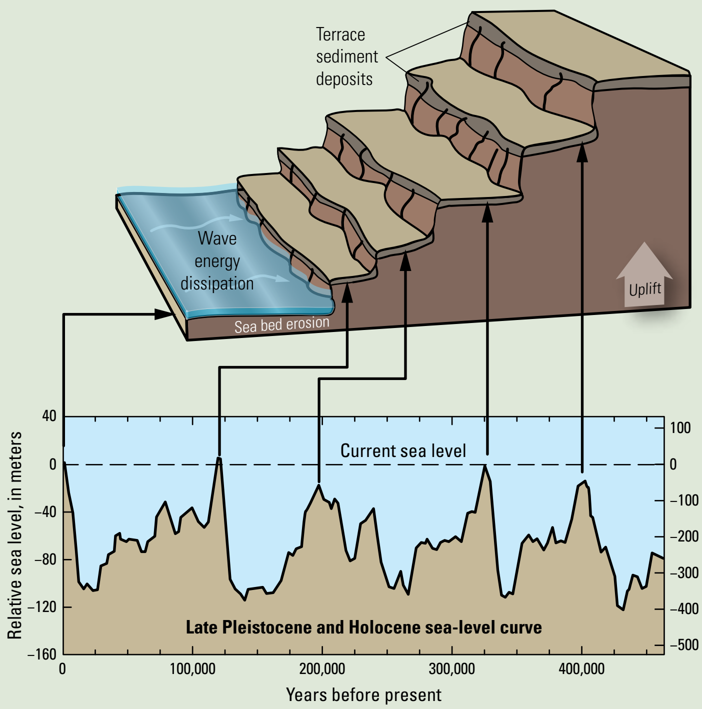
San Clemente Island of the Channel Islands in southern California. The stair-step-like flat surfaces are marine terraces of different ages. Photograph by Dan Muhs, USGS.

How Marine Terraces Form

Marine terraces result from the interaction of two geologic processes: uplift of the land surface and the natural rise and fall of sea level over hundreds of thousands of years. As sea level rises, waves move underwater sediment—sand and gravel—back and forth against bedrock, acting like sandpaper to hone bedrock into flat, broad platforms.

When sea level falls, wave-cut surfaces are exposed above water. Earthquakes on California's coastal faults, along with other processes that deform the Earth's crust, cause uplift of the land surface. When uplift is fast enough, it causes wave-cut surfaces to be preserved as marine terraces above the influence of the ocean. Where land is not uplifted high enough, wave-cut surfaces will be flooded by the rising sea. It is important to note that high marine terraces seen along the coast do not represent past shorelines at that elevation, rather, they record ongoing uplift that occurs simultaneously with fluctuating sea level. The crust steadily moves upwards and high sea-level stands erode notches into the uplifting terrain.

Marine terrace deposits on Santa Rosa Island, one of the Channel Islands in southern California. The geologist pictured here is standing on bedrock (the tilted rock layers). Just above the geologist's head is an old wave-cut surface, which is covered by a layer of rounded cobbles that were once shoreline sediments. The movement of sediment by wave action acts like sandpaper on the bedrock to create the wave-cut surface. Above the cobbles are sandy deposits from former beach and river settings that covered the wave-cut surface after it formed.
Photograph by Dan Muhs, USGS.

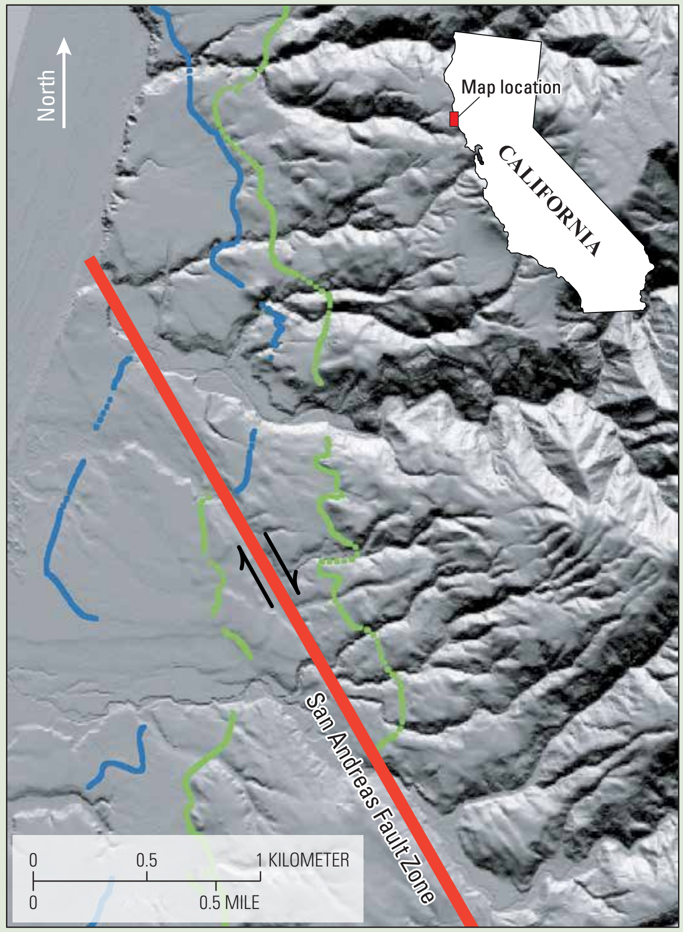


Schematic drawing showing the features and formation of a terraced coastline. The graph shows how global sea level has changed over the past 450,000 years relative to today. Ocean-wave action during high sea-level stands in the past eroded wave-cut platforms into bedrock at sea level. These platforms were then uplifted by recurring movement on nearby faults, thereby preserving the marine terraces from further erosive wave action. Older terraces are higher and farther from today's coastline.

Coastal Faults and Uplift

Uplift of the land surface near the California coast is the result of movement along nearby faults, accompanied in some areas by crustal warping and folding. Scientists estimate uplift rates using the elevation of ancient shorelines (distance above current sea level), ages of the marine terraces, and estimated heights of past sea level. In some locations, such as near Point Arena in northern California, marine terraces that formed across the San Andreas Fault can provide information concerning slip rates on the fault. Continued horizontal movement on the fault has offset the uplifted ancient shorelines such that shorelines of older terraces are displaced farther than younger ones. Scientists use this information to estimate the horizontal slip rate of the San Andreas Fault through time, to better understand earthquake recurrence intervals.

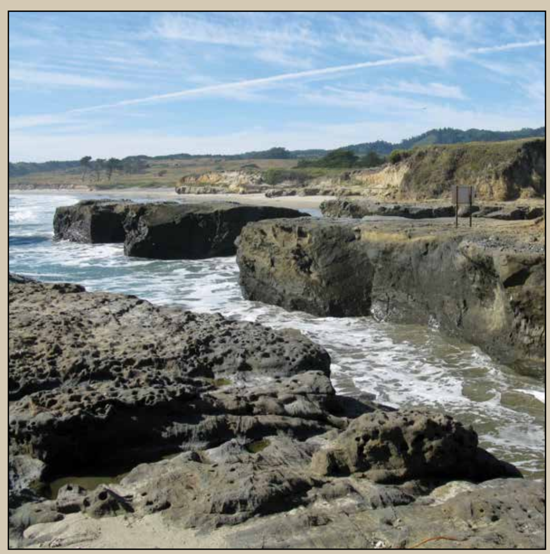
Marine terraces are some of the most visible landforms in Channel Islands National Park in southern California, giving all five islands within the park a stair-step-like appearance. The lowest—and therefore, youngest—marine terrace along many of the islands' coasts dates to the last major interglacial period, which occurred about 120,000 years ago when sea level was 20 to 26 feet (6 to 8 meters) higher than today. On Anacapa, Santa Barbara, and Santa Cruz Islands, this young marine terrace has not been uplifted much above the elevation at which it formed. On San Miguel and Santa Rosa Islands, however, the youngest marine terrace has been uplifted to higher elevation, indicating a greater rate of tectonic uplift on these two islands. Some of the highest marine terraces in Channel Islands National Park are 1 million years old, such as on San Miguel Island, and as much as 2 million years old on Santa Cruz Island. Marine terrace deposits on the Channel Islands contain abundant fossil marine invertebrates—most of them species that are still living today—that provide scientists information about Pacific Ocean temperatures off the southern California coast during the recent geologic past.



Ancient shorelines near Point Arena have been horizontally offset across the San Andreas Fault Zone (red line). The green lines on the map trace the uplifted shoreline of a 120,000-year-old marine terrace and the blue lines trace that of an 80,000-year-old marine terrace. Recurring horizontal fault movement has shifted the green shorelines about 1.6 miles (2.5 kilometers, km) apart and the blue shorelines about 1 mile (1.5 km) apart across the San Andreas Fault.

How Do We Know Bedrock Was Once at Sea Level? Fossils.

The California coast is home to a group of clams (from the family Pholadidae) that drill into rocks, wood, and sediments in the intertidal zone—the area between high and low tide levels. When fossils of these clams are found on a bedrock surface away from the ocean, geologists can be sure that the surface was once at sea level. Fossils of other clams, corals, and marine snails are also sometimes found in sediments deposited just above the wave-cut surface, serving as additional evidence that they formed near sea level. When hiking along cliffs and past roadcuts near the coast, you may see these fossils. Rocks with holes are common on today's beaches along the California coast—in many cases, these represent the remnant homes of pholad clams.

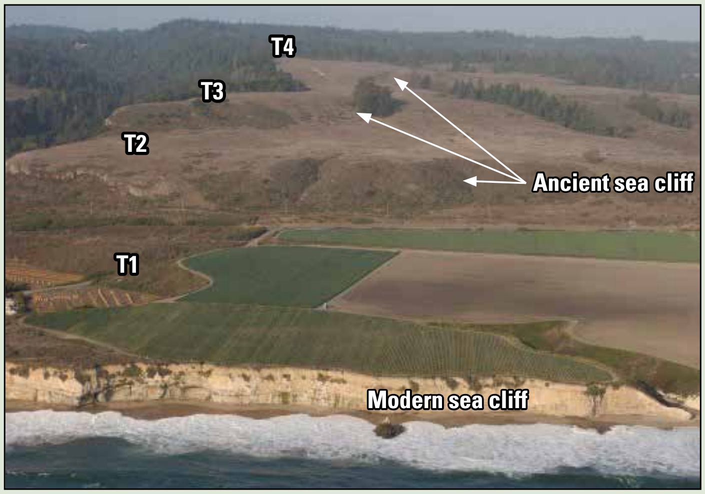


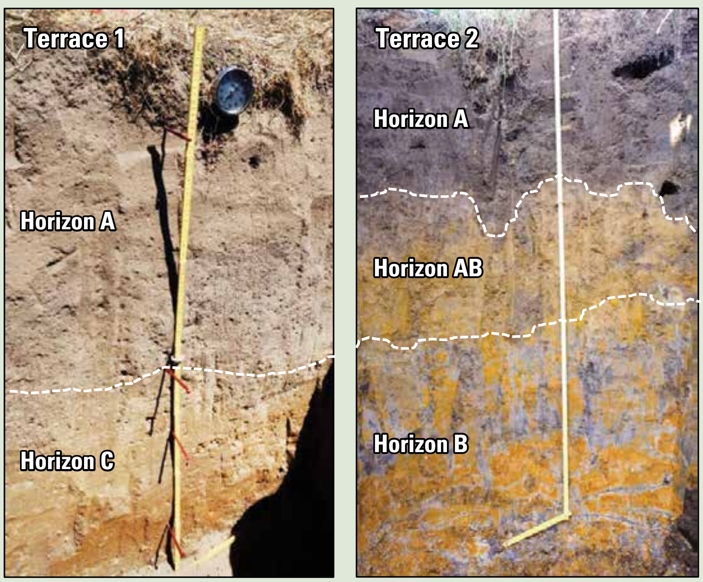
At Año Nuevo State Park, located along Highway 1 north of Santa Cruz, fossil clams from the family Pholadidae are preserved in bedrock (left). Clams are 1 to 2 inches (2.5 to 5 centimeters) in size. Right, an uplifted wave-cut platform with holes drilled by pholad clams (foreground). Photographs by Dan Muhs, USGS.

Soils

Marine Terrace Soil Chronosequences

As marine terraces are uplifted above the influence of the sea, they are colonized by terrestrial plants and animals. Gradually, soils develop on the wave-cut surfaces and the soil profiles continue to change with the passage of time. Thus, a stair-step progression of marine terraces will show a predictable sequence of soils with the oldest, more depleted soils on the highest terraces and the youngest, more fertile soils on the lowest terraces. This group of soils, progressing from old to young, is called a soil chronosequence.





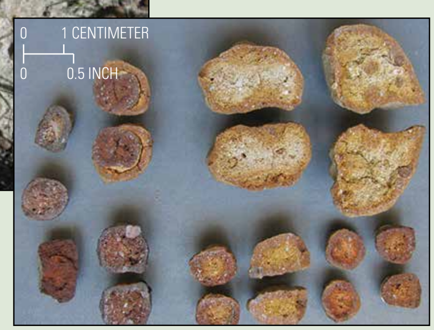
Wilder Ranch State Park near Santa Cruz is a good example of the stair-step landscapes and soil chronosequences that are typical of uplifted marine terraces (top). Terraces are labeled with a T (numbers increase away from the modern shoreline); the base of ancient sea cliffs indicate past shorelines. Photograph © 2015 Kenneth and Gabrielle Adelman, California Coastal Records Project, californiacoastline.org. Soil pits in terrace 1 (left) and terrace 2 (right) are approximately 5 feet (150 centimeters) deep. Both soils started as similar sandy marine sediments. The younger soil on terrace 1 has experienced less time for soil development and has just two main soil horizons. Terrace 2 has been exposed for longer and has developed four main soil horizons, three of which are visible here (soil horizon C is beneath the soil pit). Photographs by Marjorie Schulz, USGS.

The formation of soil, referred to as pedogenesis, occurs over thousands of years and is characterized by a progressive change in mineral composition and soil structure. The longer a terrace surface is exposed, the older and more nutrient-depleted the soil becomes. Young soils are more similar to the starting material, making them nutrient-rich and therefore commonly used for agriculture. Older soils are more weathered—the primary minerals have dissolved and been replaced by secondary clay minerals. Older soils generally have low organic content, are nutrient-poor, and are commonly not productive enough for row crops.

Marine terrace soil chronosequences along the California coast are of interest to scientists because they allow measurements of many aspects of soil development over time, such as changes in nutrients (caused by mineral weathering), soil hydrology (water content), organic matter, and biology. In addition, California has a distinct rainfall gradient from north to south—San Diego is much drier than Eureka—that allows scientists to compare soil processes in dry versus wet ecosystems. The study of terrace soil chronosequences along this rainfall gradient aids our understanding of how soil processes and ecosystems will respond to climatic changes.

Soil Nodules

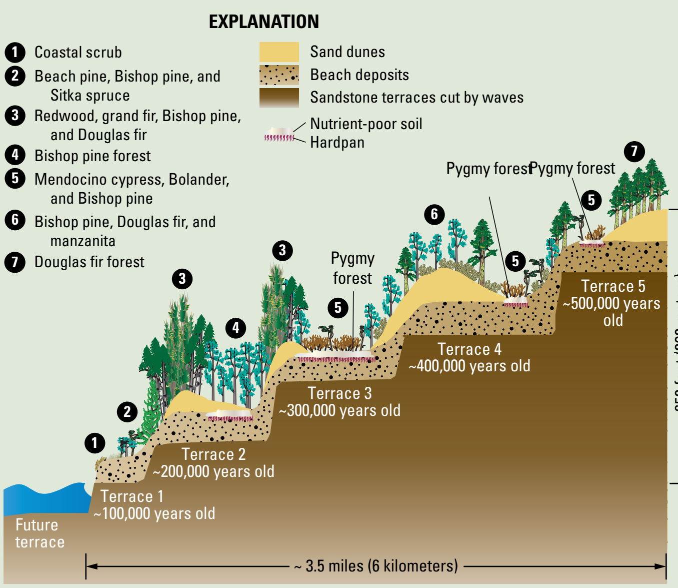
Because iron is an important plant nutrient, scientists seek to understand how it migrates and concentrates in soils. Many terrace soils along the California coast contain iron nodules, which are hard, oval shaped, and usually dark orange or brown in color. Their appearance causes nodules to sometimes be mistaken for small meteorites; however, the nodules actually form within soils. Some soil surfaces in southern California and on the Channel Islands are covered by nodules because any smaller soil particles have been eroded away, leaving the larger, denser nodules behind. Soil nodule abundance decreases northward along the California coast towards wetter climates, indicating that soil nodules either form more easily or are perhaps better preserved in the drier soils of central and southern California. If you look closely at soil mounds around gopher holes, you may be able to find a soil nodule. How soil nodules form in these soils is currently under discussion. Nodules were originally thought to form from the effect of wetting and drying cycles on iron in the soil, however, more recent study shows microbial activity (fungal and bacterial) may also be important in nodule formation.



Soil nodules revealed on the surface of a gopher mound after a rainstorm (left). Cutting soil nodules in half reveals their complex histories of iron cementation (right). USGS photographs by David Stonestrom (left) and Marjorie Schulz (right).

Pygmy Forests on the Ecological Staircase

Because old marine terrace soils are nutrient-poor, the lack of nutrients can affect vegetation growing on these soils. The difference in nutrient availability causes distinct plant ecosystems to grow on terraces of different ages, resulting in an ecological staircase superimposed on the sequence of terraces. Extraordinary examples of this can be observed in several northern California parks, including Jug Handle State Natural Reserve, Russian Gulch State Park, Salt Point State Park, and Van Damme State Park. In these places, older marine terraces have a combination of highly weathered soil, low nutrient levels, and poor drainage owing to the formation of a dense soil layer, called a hardpan. Together, these soil conditions cause stunted growth in the local forest—creating a pygmy forest. The pygmy forest is home to hardy plants that are of interest to scientists who study the characteristics that allow the plants to survive in such an unforgiving environment.



Cross sectional view of marine terraces illustrating the ecological staircase in Mendocino County. Modified from a figure by Michael Kauffmann, available at http://blog.conifercountry.com/2014/07/the-ecological-staircases-of-mendocino-county/.

Dynamic Landscapes

Born of the erosive action of ocean waves, uplifted above the influence of the sea, and then subjected to varying climatic and environmental conditions, marine terraces represent a dynamic landscape—one at the intersection of tectonics, sea level fluctuation, and the effect of climate. As a result, marine terraces provide ample opportunity to study these processes through time, leading to a better understanding of seismic hazards, past climates, and soil development. By conducting this research, the U.S. Geological Survey is leading the way to make better informed decisions about our dynamic planet.

Acknowledgements

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Where to Find Marine Terraces

Publicly accessible lands in California that have good views of marine terraces.

1. Prairie Creek Redwoods State Park
2. Patrick's Point State Park
3. Trinidad State Beach
4. King Range National Conservation Area
5. MacKerricher State Park
6. Jug Handle State Natural Reserve
7. Point Cabrillo Light Station State Historical Park
8. Russian Gulch State Park
9. Mendocino Headlands State Park
10. Van Damme State Park
11. Manchester State Park
12. Point Arena-Stornetta, Calif. Coastal National Monument
13. Gualala Point Regional Park
14. Salt Point State Park
15. Fort Ross State Historic Park
16. Sonoma Coast State Park
17. Point Reyes National Seashore
18. Golden Gate National Recreation Area
19. McNee Ranch State Park
20. San Gregorio State Beach
21. Pomponio State Beach
22. Pescadero Marsh Natural Preserve
23. Año Nuevo State Park
24. Cotoni-Coast Dairies, Calif. Coastal National Monument
25. Wilder Ranch State Park
26. Natural Bridges State Beach
27. Seacliff State Beach
28. Manresa State Beach
29. Sunset State Beach
30. Garrapata State Park
31. Andrew Molera State Park
32. Hearst San Simeon State Park
33. Fiscalini Ranch Preserve
34. Harmony Headlands State Park
35. Montaña de Oro State Park
36. Jalama Beach County Park
37. Gaviota State Park
38. El Capitán State Beach
39. Point Mugu State Park
40. Point Dume State Beach
41. Channel Islands National Park
42. Torrey Pines State Natural Reserve
43. Cabrillo National Monument

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