Wave-cut or water-table platforms of rocky coasts and rivers?

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ABSTRACT

Despite evidence that weathering plays a role in forming intertidal, estuarine, and fluvial rock platforms, many publications uncritically refer to “wave-cut” or “stream-cut” rock platforms. The alternative explanations of chemical weathering and physical water erosion of rock platforms have been debated since 1839. Our new approach to this long-standing problem introduces data from fluvial as well as coastal rock platforms and documents the saprock-bedrock division of weathering profiles. We report local field evidence for a dominant role of differential weathering of sedimentary beds in an intertidal rock platform at Sunset Bay and a riverside platform near Days Creek, both in southwest Oregon, USA. Despite continuing tectonic uplift, both rock platforms remain within the zone of modern water table and intertidal fluctuation. Above this zone of frequent wet/dry cycling, rock is weakened by subaerial weathering, as documented by decreased rock hardness from the application of a Schmidt hammer, high slaking quantified by wetting-drying experiments, Munsell color indication of elevated oxidation of fine fractures, and peripheral loosening of calcareous fossils. At these sites, the shape and elevation of rock platforms in coastal and fluvial settings appear to reflect differences in strength between bedrock and saprock within the zone of water table fluctuation. In our study sites, waves and floods do not “cut” rock but remove clasts already weakened by weathering to expose the local water table as a bedrock surface. Other local agents of rock removal include salt weathering, eolian abrasion, landslides, debris flows, and fungal, plant, and molluscan bioerosion.

INTRODUCTION

One of the longest running debates in geomorphology concerns whether intertidal rock platforms were created by wave erosion or differential weathering. Henry de la Beche (1839, p. 439) acknowledged the distinction, but emphasized wave action:

> In many situations common atmospheric influences so combine with the action of the breakers to produce the destruction of the cliffs, that it may be difficult to say whether the loss of land may be due more to the one than the other: in most cases however, the breakers cause nearly the whole loss, leaving isolated rocks to show, to a certain extent, the destruction they have caused.

Ramsay (1846, p. 327) agreed with primacy of wave erosion:

> The line of greatest waste on any coast, is the average level of the breakers. The effect of such waste is obviously to wear back the coast, the line of denudation being a level corresponding to the average height of the sea.

James Dwight Dana, during his United States Exploring Expedition of 1838–1842, was first to note rock platforms as a distinct landform worthy of attention. He also advocated wave action (1849, p. 109):

> The water in these cases, has worn away the cliffs, leaving the basement untouched. A surging wave, as it comes upon a coast, gradually rears itself on the shallowing shores; finally, the waters at top, through their greater velocity, plunge with violence on the barrier before it.

But later in the same volume (Dana, 1849, p. 442), a different idea emerges:

> The existence of this platform is owing to this protection of the sea from wear and decomposition. Above, the material has disintegrated, and been washed away by the action of streamlets and the waves; but beneath the water these effects do not take place.

Bell and Clarke (1909, p. 30) developed this latter idea further, suggesting a “cooperation of subaerial weathering, which causes the retreat of the cliffs, with marine weathering, which removes the waste so formed.” At the crux of the debate is the relative contribution of terrestrial (largely biochemical) and marine (largely physical) weathering to observed rock platform levels.

The wave erosion explanation has been popular, as indicated by widespread use of the term “wave-cut platform” (e.g., Regarda et al., 2010; A GeoRef search between 1 Jan. 2006 and 1 Apr. 2011 yielded 113 citations for “wave-cut”) and application of wave energy models (Trenhaile, 2008, 2010). Wave erosion also has been confirmed with observations of storm waves (Bartrum, 1924, 1935), varied platform saturation levels (Trenhaile and Mercan, 1984; Trenhaile and Porter, 2007), and erratic distribution of rock strength from Schmidt hammer tests (Kennedy et al., 2011). In contrast, the alternative idea that coastal rock platforms were created by weathering is supported by observation of weathering in flanking cliffs (Bartrum, 1916; Berryman, 1993), diminished energy of waves on platforms (Stephenson and Kirk, 2000a), patterns of differential rock strength by Schmidt hammer (Stephenson and Kirk, 2000b; Kennedy and Beban, 2005), and rock platforms in estuaries and bays protected from ocean waves (Hills, 1949; Kennedy and Paulik, 2006). Furthermore, waves have been observed to destroy (rather than construct) the outer edges of rock platforms by guttering and potholing (de la Beche, 1839; Hills, 1949; Kennedy et al., 2011). Because of this long-running dispute, the term “shore platform” has been urged as a non-genetic alternative to “wave-cut” or “water-layer weathered” (Hills, 1949; Trenhaile, 1987).

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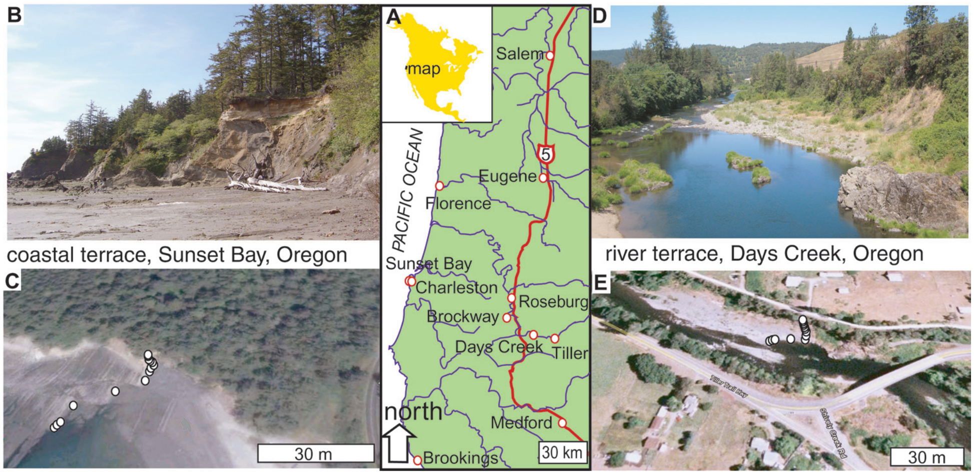

Figure 1. Study sites in southwest Oregon: (A) map; (B) view from the east of the cliff and intertidal rock platform at Sunset Bay; (C) satellite image of sampling sites at Sunset Bay; (D) view from the south of cliff and alluvial rock platform at Days Creek; (E) satellite image of sampling sites at Days Creek.

Here we take a new approach to the problem by simultaneously studying a rock platform beside a stream and the sea, and also by applying new concepts of weathering profiles. Both coastal and streamside cliffs show four distinct layers, recently recognized by Graham et al. (2010): (1) bedrock—hard unweathered rock; (2) saprock—rock with limited oxidative weathering along fractures; (3) saprolite—soft, oxidized, deeply weathered rock; and (4) solum—densely rooted, oxidized, and organic soil profile. The boundary between bedrock and saprock is at the limit of oxidative weathering and fungal hyphal penetration, generally at the water table or river level in alluvial settings. The rock platform beside a river is called a "strath" (Bucher, 1932) or "beveled bedrock platform" (Montgomery, 2004). Strath terraces are former rock platforms elevated well above current stream level because of relative base-level fall, and if covered with alluvium are called fill terraces (Bucher, 1932; Bull, 1979; Montgomery, 2004), comparable with marine terraces overlain by raised beaches or alluvium (Bockheim et al., 1996; Anderson et al., 1999). Such fluvial rock platforms and terraces are widely regarded as "stream-cut" (Bucher, 1932) or "fluvially eroded" (Reusser et al., 2004), which implies that they were created by physical abrasion of pebbles and other tools carried by the stream (Gilbert, 1877; Stock et al., 2005). Strath terrace widening by physical stream abrasion in some places and armoring in others has been attributed to prolonged climatic stability (Fuller et al., 2010; Stark et al., 2010) and to meander migration and cutoff (Finnegan and Dietrich, 2011). In contrast, a role for chemical weathering is supported by observation that strath terraces are flanked on one side by a deep channel and potholes and on the other side by a weathered cliff or soft rock (Montgomery, 2004). Fluvial and pedogenic concepts bring new and instructive perspectives on the perennial problem of the origin of rock platforms.

This paper presents studies of both coastal and fluvial rock platforms from a single region of comparable climatic, water table, and tectonic setting. At each site, a variety of proxies for rock strength and degree of weathering were gathered to answer the following two questions:

1. Are rock platforms cut entirely by focusing of wave and flood energy?
2. Do they reflect differences in rock hardness created by different degrees of weathering?

OREGON FIELD SITES

Oregon sites have two distinct advantages for the study of rock platform genesis and history. First, Oregon has many steeply dipping sedimentary sequences so that the same bed with the same geomechanical and geochemical properties can be traced though the rock platform to cliffs flanking both coasts and streams (Fig. 1). Second, Oregon is tectonically uplifted at known rates from offshore subduction of the Juan de Fuca Plate (Burgette et al., 2009). Our two sites were selected within a similar region for climate, vegetation, soil, and rock type in the interests of experimental design to minimize these potentially confounding variables in platform development:

1. On the coast at Sunset Bay (Armentrout, 1981), in Cape Arago State Park (N43.33573° W124.373586°) near a tide gauge (at Charleston, Oregon, USA: http:/tidesandcurrents.noaa.gov [accessed 17 June 2010]).
2. Along the South Umpqua River at Days Creek (Imlay et al., 1959), near Canyonville, Oregon, USA (N42.973282° W123.172986°) between two river gauges (USGS, Tiller and Brockway, Oregon, USA: http://waterdata.usgs.gov [accessed 19 June 2010]).

Modern soils on the Pleistocene terraces at Sunset Bay and Days Creek are described by Haagen (1989) and Johnson et al. (2003), respectively. Bedrock dip was measured at 57°E on magnetic azimuth 001° at Sunset Bay and 62°E at azimuth 92° at Days Creek. The surface of the flat part of the Sunset Bay platform slopes 2.5° seaward, and the Days Creek rock platform slopes 3.3° to the river. Raw measurements of shale and sandstone at these localities, and a statistical summary of differences between cliffs and platforms, are included in the GSA supplemental data repository[1].

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[1] GSA Data Repository item 2012153, statistical tests and sample data, is online at www.geosociety.org/pubs/ft2012.htm. You can also request a copy from *GSA Today*, P.O. Box 9140, Boulder, CO 80301-9140, USA; gsatoday@geosociety.org.

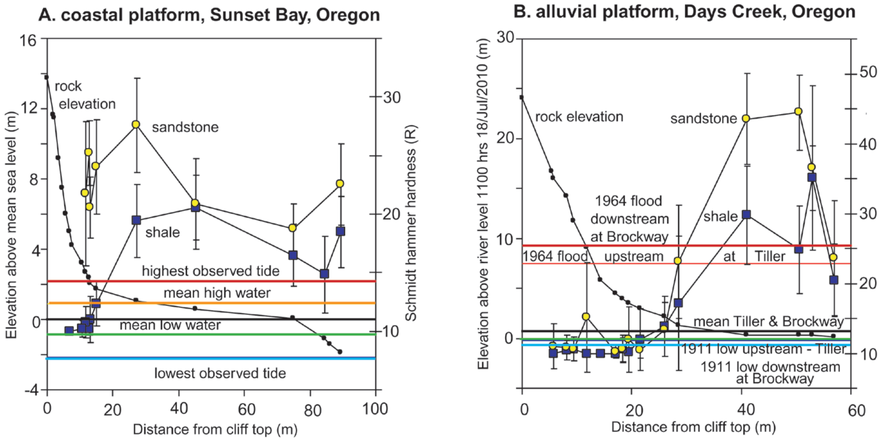

Figure 2. Schmidt hammer measurements (secondary axis) and topographic profile (primary axis) at Sunset Bay (A) and Days Creek (B), Oregon. Colored lines show historic flood and tide levels.

Water table levels on the same geomorphic terrace near Sunset Bay are intersected at an elevation of 49.1 m by the Stictland bore (N43.217123° W124.372686°), drilled from an elevation of 58.2 m (Beaulieu and Hughes, 1975), so that at 2.05 km from the shore, the general slope of the water table is 2.2° seaward. Near Coquille, on a similar fluvial terrace as at Days Creek, the L. Rose bore (N43.18884° W124.101236°), at an elevation of 43.2 m, has the water table at an elevation of 42.9 m (Beaulieu and Hughes, 1975), so that at 560 m from the nearest stream, the general slope of the water table is 2.5°.

Both rock platforms have a flanking cliff and terrace, which represents an uplifted rock platform of the past overlain by coastal and alluvial sands and gravels, and local accumulations of sea shells (Beaulieu and Hughes, 1975). The Whiskey Run terrace, 13.5 m above the intertidal rock platform at Sunset Bay, has been mapped throughout the southern Oregon coast and dated at 80 ka near Cape Blanco, 57 km south of Sunset Bay (Bockheim et al., 1996). Thus, the long-term uplift rate at Sunset Bay was 0.17 mm a^{-1}, comparable with Oregon long-term coastal stream incision rates of 0.2 mm a^{-1} (Personius, 1995). Since the last great earthquake 312 years ago, geodetic uplift has been 4 mm a^{-1} for the area around Coos Bay, and this rate exceeds location-specific sea-level rise of 2.3 ± 0.2 mm a^{-1} (Burgette et al., 2009). Interseismic uplift since the last great earthquake in AD 1700 has thus raised this part of the coast 53 cm above sea level. Uplift due to short-term strain is rapid, but it is undone by subsidence during great earthquakes so that long-term uplift is only 5% of the short-term uplift rate.

The age of the bedrock terrace 16.7 m above the river-level platform at Days Creek is unknown, but is probably also ca. 80 ka, because long-term rates of stream incision for this part of the Umpqua River are 0.2 mm a^{-1} (Personius, 1995). In contrast, short-term interseismic geodetic uplift rates are only 1.5 mm a^{-1} this far inland on the North America plate (Burgette et al., 2009).

COMPARISONS OF ROCK PLATFORMS AND CLIFFS

If rock platforms were cut by waves alone there would be no difference in weathering or strength of the platform and cliff, but if the platform reflects weathering differences such as bedrock and saprock, there would be differences between platform and cliff. The following observations and experiments were designed to test these alternatives.

Fossil Weathering

Fossil collecting was an initial indication of differences in rock hardness in the platform versus cliff. At both localities, fossils break out in the round from their gray shaley matrix in the cliff, but hammering more often breaks through the fossil within indurated matrix of the rock platform. The fossils are calcitic and aragonitic shells more readily weathered than their illitic, quartzo-feldspathic matrix. Fossil shells were partially dissolved by weathering to form large, wide spaces along fine cracks in the cliff but not in the platform. Sunset Bay exposes the middle Eocene (Lutetian) Coaledo Formation, including sandstones with turritellid gastropods and venericardid bivalves and shales with siderite nodules containing crabs and nautiloids (Armentrout, 1981). The river platform at Days Creek exposes sandstone and shale of the Early Cretaceous (Hauterivian) Days Creek Formation, including sandstones with marine scallops and belemnites and shales with siderite nodules containing ammonites (Imlay et al., 1959).

Schmidt Hardness

Differences observed during fossil hunting between the hardness of the fossil matrix of cliff and adjacent platforms were quantified by vertical field application of a Schmidt hammer, which measures recoil from impact of a spring-loaded piston. At least 25 measurements were taken at each station as recommended by Niedzielski et al. (2009). Schmidt hardness (R) of the instrument (type N Original) was calibrated for impact recoil (N) in newtons mm^{-2} by the manufacturer (Proseq SA, Switzerland), according to the formula: $N = 1.8R - 13.8$. These results quantify observed fossil adhesion. Fossil collecting in samples with R values greater than 30 requires vigorous hammer blows and care to avoid rebound, whereas light picking breaks out fossils from matrix of lower R value.

At both Sunset Bay and Days Creek, rock hardness recorded by the Schmidt hammer declines abruptly at the break in slope between the rock platform and the nearby cliff (Fig. 2). Platform hardness is high and variable, but cliff hardness is uniformly low. This also applies to sandstones where they form erosion-resistant ribs well above the level of the platform, thus forming subsidiary cliffs.

Schmidt hardness did not decline due to softness of the exterior of the rock because the piston seldom left a clear mark

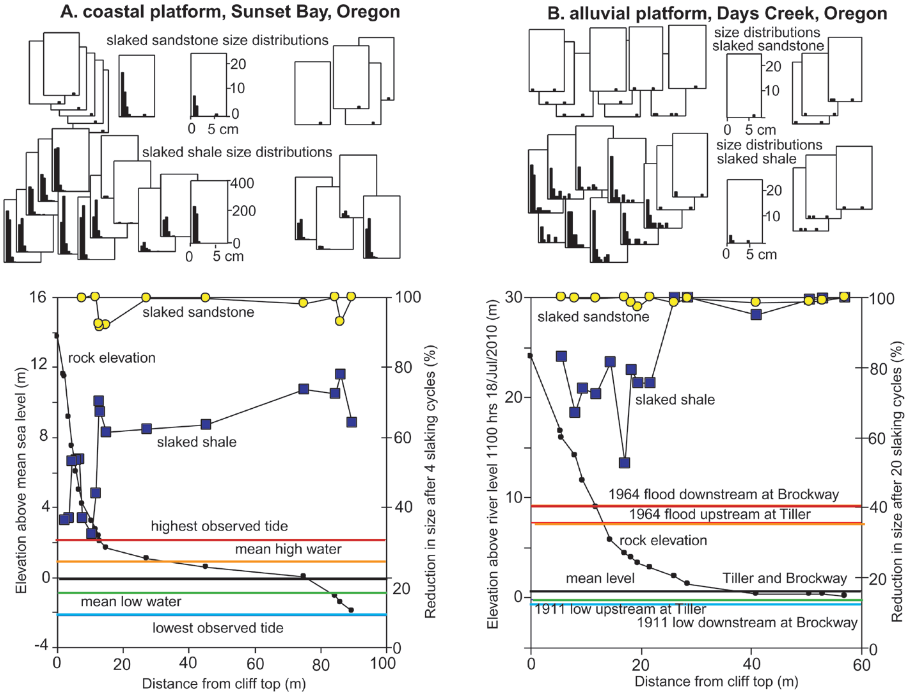

Figure 3. Reduction in size after slaking experiments (secondary axis and size distributions) and topographic profile (primary axis) at Sunset Bay (A) and Days Creek (B), Oregon. Colored lines show historic flood and tide levels.

on the rock. Rather, lack of hardness was due to fractures that absorbed recoil, and hollow echoes suggested that some factures were subparallel to the surface. Near the tops of the cliffs, fractures vertical to the surface were so numerous that the 1-cm-diameter piston straddled them, and these fractures absorbed much of the impact.

Slaking

Another indication of differential strength between platform and cliff is slaking: the tendency of shaley rocks to flake into pieces with wetting and drying (Trenhaile, 1987). In the interests of time and comparison between distinct fluvial and intertidal regimes, an aggressive laboratory experiment of complete wetting and drying was chosen, rather than replicating tides of cold salt water or river flood cycles (Kanyaya and Trenhaile, 2005). Pieces of rock 5–7 cm across were each immersed in 100 ml of Eugene (Oregon, USA) tap water at room temperature for 24 hours and then dried completely for 24 hours. Sunset Bay shales collapsed into more than 600 pieces after only 4 cycles of this treatment, whereas indurated shales of Days Creek required 20 cycles before they broke down.

Grain size histograms (Fig. 3) show that a large proportion of the shales broke down to grains less than silt size, as easy to move by moderate wind or rain as by waves and floods. Sandstones from both localities were less prone to fragmentation, remaining unaltered or sloughing off only one or two small rock splinters. This observation explains weather-resistant sandstone ribs above the shale platform at both localities: Such lithology-dependent resistance to weathering is commonly observed along rocky coasts (Trenhaile, 1987; Naylor and Stephenson, 2010).

Bulk Density

Bulk density of rock specimens can be another indication of mass depletion in weatherable minerals, and it was measured by the clod method (Retallack, 1997), in which paraffin-coated specimens ~1.5 cm in size were weighed in and out of water with a temperature of 4 °C. All the rock specimens were remarkably uniform across both transects, with mean and standard deviation of 2.21 ± 0.04 g cm^{-3} for 17 Sunset Bay shales, 2.17 ± 0.10 g cm^{-3} for 12 Sunset Bay sandstones, 2.56 ± 0.02 $g.cm^{-3}$ for 15 Days Creek shales, and 2.56 ± 0.08 g cm^{-3} for 13 Days Creek sandstones. These errors are close to that for 11 replicates of an independent sandstone standard from the Ediacara Member of South Australia run at the same time: 2.45 ± 0.02 g cm^{-3}. Despite a statistically significant difference in bulk density of shale in cliff and platform at Days Creek (see supplemental data [footnote 1]), the difference is slight, and well short of rock weakening by geochemical mass transfer of base cations or redox sensitive elements found in saprolites of deep-weathering profiles (Brimhall et al., 1992).

Oxidation Colors

Additional evidence of weathering comes from observations of color using a Munsell chart (Munsell Color, 1975). The scale used here, with hue 5YR taken as 5 and 5Y as 15, has redder hues the lower the number. Except for the uppermost meter of the cliffs, all of the rocks are a little weathered and gray, with reddish hues restricted to fractures in both sandstones and shales (see supplemental data tables [footonote 1]). Truly red fractures are found only near the top of the cliffs. Other specimens have fractures oxidized to yellowish and brownish red only (Fig. 4).

Subaerial oxidative weathering to red hematite and brown goethite is thus restricted to fractures and increases toward the top of the cliff above the rock platform. The uppermost meter of each cliff is a mottled red saprolite, but most of the cliff is saprock. Graham et al. (2010) make a convincing case that vascular plant roots and fungal hyphae aid weathering of such deep cracks in weakened rock (saprock) beneath chemically altered rock (saprolite). Cracks in rock platforms have been used as evidence

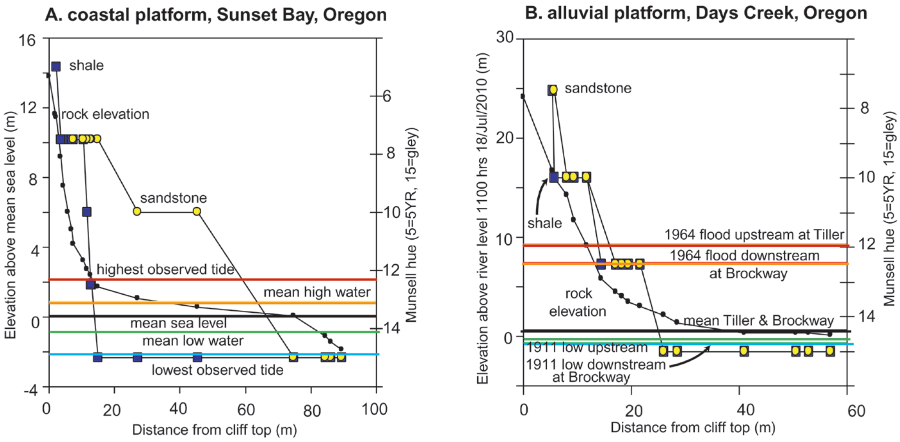

Figure 4. Munsell color (secondary axis) and topographic profile (primary axis) at Sunset Bay (A) and Days Creek (B), Oregon. Colored lines show historic flood and tide levels.

against a role for weathering in platform genesis because of observed variation in saturation (Trenhaile and Mercan, 1984), as expected in zones of water table and intertidal fluctuation (Ollier and Pain, 1996). More to the point of rock strength is the degree of weathering of the cracks, and the colors presented here are evidence that cracks in rock platforms never dried sufficiently to allow oxidized weathering rinds like those in cracks on the flanking cliff.

CONCLUSIONS

This study has revealed a sharp discontinuity in rock strength and oxidation of fractures, but not overall color or bulk density, between the saprock cliff and bedrock platform (Fig. 5). The discontinuity between saprock and bedrock is at the break in slope between the rock platform and the cliff, and the discontinuity is also a seepage point, moist with water or white with powdery salt efflorescences. It approximates the mean water table, above which oxidative weathering in fractures by plant roots and fungal hyphae are permitted. The slope of the rock platform from this break in slope toward mean sea or stream level (2.2° for Sunset Bay and 3.3° for Days Creek) is similar to the accommodation of water table to topography (2.2° to 2.5° calculated from well data of Beaulieu and Hughes, 1975) and well within tidal and river fluctuation (mean ± 0.9 m between mean low and mean high tide at Charleston, and mean ± 1.3 m between mean January and mean August river level at Tiller). Both fluvial and coastal rock platforms are exhuming the surface below which local water table fluctuation inhibited subaerial weathering. Below this level is hard bedrock and no evidence of weathering. Above this level, loose blocks of rock movable by waves and flood are created by a variety of subaerial processes: fungal hyphae, roots of grasses, blackberries and poison oak, honeycomb weathering, salt efflorescences, slaked shale fragments, slump blocks, and debris flows.

The platform profiles are graded to mean water table and sea level despite short-term (10^3 yr) interseismic uplift rates of as much as 4 mm a^{-1} (Burgette et al., 2009) and long-term (10^5 yr) uplift rates of as much as 0.2 mm a^{-1} (Personius, 1995). As in other tectonically uplifted regions (Berryman, 1993; Kennedy and Beban, 2005), long-term uplift or sea-level change over tens of thousands of years exceeds the rate of upland migration of platforms, so that a new platform is initiated at a water table exposure and an old platform is stranded as an elevated terrace (Bockheim et al., 1996). In both river and coastal cases, the modern rock platforms are efficiently maintained, without steep slopes predicted from relative sea-level change (by Trenhaile, 2010). These observations suggest a role for bioturbation, wind erosion, and mass wasting in creating moveable rocks above the solid bedrock of the platforms. Between storms and floods, we have observed over the past 30 years that these movable rocks are stripped or deposited, depending on the magnitude of the event. Within meandering streams, these different conditions are seen on different banks, the depositional point-bar versus the erosional cut-bank. The cut-bank is largely responsible for exhuming alluvial water tables (Stark et al., 2010).

The rock platforms examined are close to base level, conventionally defined as two slightly different levels: both the lowest level to which streams can cut and also levels of lakes or seas into which rivers flow (Leopold and Bull, 1979). Streams flowing into lakes or the sea have meters of channel excavation below mean river or sea level (Bockheim et al., 1996). Like other rock platforms beside rivers (Montgomery, 2004; Stock et al., 2005), the rock platform near Days Creek (Fig. 1) is a meter or more above the channel thalweg. Thus, rock platforms are above the lowest level to which flooded streams cut by physical abrasion. Similarly, intertidal rock platforms rise above mean sea level and above the zone of intense wave energy at the outer edge of the platform (Stephenson and Kirk, 2000a; Kennedy et al., 2011). Furthermore, the rock platforms observed are not completely level, but slightly sloping and irregular (Figs. 2–4), unlike lake or sea levels, the second criterion of base level.

Floods and storm surges do much to clear rock platforms of debris from slumping and eolian abrasion, as we have observed firsthand at our sites over the past 30 years. Floods and storms, however, do not create the underlying discontinuity in rock strength revealed here within the zone of water table and intertidal fluctuation. Differences in rock hardness and weathering between cliffs and rock platforms support the idea that rock platforms in Oregon were water table platforms, and the uplifted rock surfaces behind them were paleo–water-table terraces stranded by a tectonic regime of long-term tectonic uplift. Similarly, coastal platforms became coastal terraces in tectonically active New Zealand when long-term uplift and lowered water table allowed undercutting at the outer edge (Berryman, 1993; Kennedy and Beban, 2005). Uncritical use of

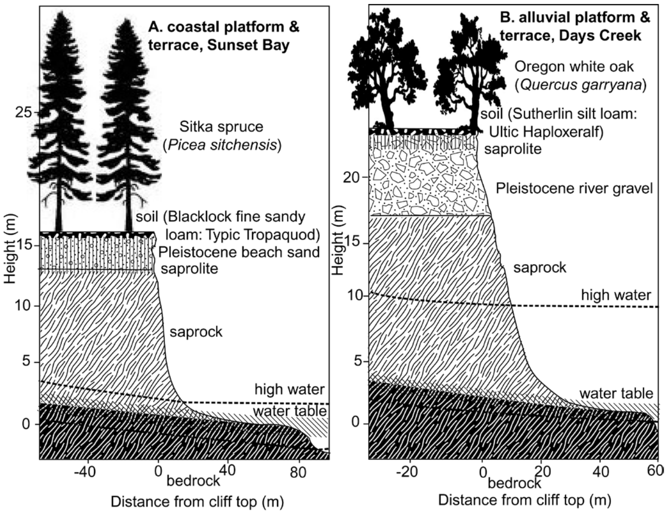

Figure 5. Cartoon of saprock-bedrock boundary at water table in coastal rock platform at Sunset Bay (A) and alluvial rock platform at Days Creek (B), Oregon.

the terms "wave-cut" and "stream-cut" is not recommended, because determining the relative role of physical and biochemical erosion in the formation of Holocene rock platforms and Pleistocene terraces is a non-trivial scientific problem. Our study indicates that some rock platforms are water tables exhumed from overlying weathered saprock.

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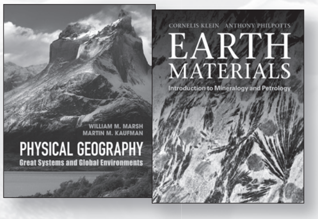

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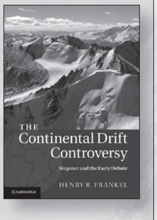

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