The serpentine outcrops of Goiás state have already yielded a rich harvest of metal-tolerant plants from an extraordinarily wide variety of plant families. Much remains to be done, not only at other seasons of the year, but also in areas not yet surveyed. Further progress will be made during the next few years.

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Depositional History of Hollows on Steep Hillslopes, Coastal Oregon and Washington

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Radiocarbon dates from 18 colluvial deposits in steep hillslope hollows in the coastal mountains of Oregon and Washington were used to evaluate long-term hillslope history and regional variations in erosion rates. Dates from multiple stratigraphic levels at 11 sites document that the deposits progressively thicken over time and record continual erosion of the surrounding slopes. Calculated erosion rates are greater at the drier Oregon sites than at the Washington sites, although much variability is present in each area. Basal radiocarbon dates from hollows in each area are clustered in time, suggesting periods of widespread landsliding. In Washington, the clustering of dates corresponds to a warmer and drier period in the early Holocene, 10000 to 7000 B.P., suggesting landsliding associated with a higher fire frequency than today. In Oregon, a clustering of basal dates at 7500 to 4000 B.P. suggests a period of widespread landsliding that occurred later than in Washington, possibly associated with changes in the frequency of fires or intense storms.

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Hollows are the portion of hillslopes with contours concave from the slope, as originally defined by Hack & Goodlett (1960) and Hack (1965) for their study areas in the Appalachian Mountains. Hollows are a dominant feature of hillslopes in many landscapes, and play an important geomorphic role in modulating the flux of colluvial debris from slopes to stream channels. Topographic convergence into hollows results in long-term deposition of colluvium, and as the deposits thicken they become less stable, generally leading to failure by landsliding (Dietrich & Dunne 1978, Okunishi & Iida 1981). Hollows thus undergo a cycle of alternating accumulation and evacuation of colluvium (Figure **1**). Landslides in these deposits are the primary source of debris flows in many landscapes (Figure **2**), and constitute a significant geologic hazard as well as an important sediment source (see review in Reneau & Dietrich 1987). The age of colluvial deposit in a hollow approximately records the time of a previous landslide, and offers insight on landslide recurrence intervals and the effects of climatic changes on hillslope processes (Reneau et al. 1986, 1989, in press).

The rate at which bedrock is disrupted, converted to colluvium, and transported down hillslopes often limits the sediment supply to streams and the rate at which landscapes can evolve. Important processes include disruption of bedrock by growth of tree roots and toppling of trees during windstorms (e.g., Denny & Goodlett 1956) (Figure **3A, B**), burrowing by animals (e.g., Imeson 1976, Thorn 1978) (Figure **3C**), and downslope raveling of loose debris after fires (e.g., Anderson et al. 1959, Krammes 1960). These processes are generally very slow or discontinuous, varying in time and space, and are thus difficult to measure accurately despite their fundamental geomorphic importance. Hollows, acting as traps for debris transported down hillslopes, provide one of the few means to obtain local rates of hillslope erosion that are averaged over long time spans (Dietrich & Dorn 1984, Reneau et al. 1989). They can thus yield unique information on the rates of landscape change.

The purpose of this study was to obtain chronologic data from hollows in the Oregon Coast Range and in the Olympic Mountains of western Washington (Figure **4**, *top*), and to use these data to evaluate long-term hillslope history and regional variations in erosion rates. The study sites were chosen to complement a previous study area in the central California Coast Range (Figure **4**, *top*) (Reneau et al. 1986, in press), with the goal of comparing hillslopes with similar bedrock but a significant range in annual rainfall. The western Olympic Peninsula is one of the wettest areas in the conterminous United States, with an average annual rainfall of ~3500 mm/yr supporting a dense coniferous forest. Rainfall of ~2500 mm/yr in the western Oregon Coast Range also supports a dense coniferous forest. The study area in California is much drier: a mixed hardwood forest at the primary sites receives ~800 mm/yr of rain. Bedrock in all three areas is primarily sandstone and shale, although relatively undeformed strata in Oregon contrasts with variably folded and faulted strata in Washington and California.

In this paper the authors summarize results of the dating and analysis of hollows in coastal Oregon and Washington, and compare the depositional history of these areas with that of the California study area. Depositional rates of colluvium have been used to calculate long-term hillslope erosion rates on the surrounding slopes, allowing a quantitative comparison of the relative rates of erosion among the three areas. In addition, dating from multiple stratigraphic levels documents changes in depositional rates of colluvium in selected deposits over time. A more detailed discussion of the results from the Washington study area is presented in Reneau et al. (1989), and detailed results from Oregon are presented in Reneau (1988).

Methods

The depositional history of hollows in each area was quantified using radiocarbon dating of charcoal fragments contained within the colluvium, including both conventional radiocarbon dating of large (2 to 10 g) samples of charcoal and accelerator mass spectrometry dating of small (65 to 1100 mg) samples. All samples in Oregon and Washington were collected from roadcut exposures where cross sections through colluvial deposits were well displayed (Figure **5**), and where the topography of the contributing drainage basin was distinct.

Mass depositional rates of colluvium were calculated for specific cross sections in each deposit using the radiocarbon dates and data on colluvial density and deposit size. The bulk density of colluvium increases with depth due to consolidation, and mass depositional rates are thus more accurate than volumetric depositional rates to quantify the history of each deposit (Reneau et al. 1989). Measurements of the density of colluvium in multiple deposits were used to develop separate equations relating density and depth for Oregon and Washington. The mass of each

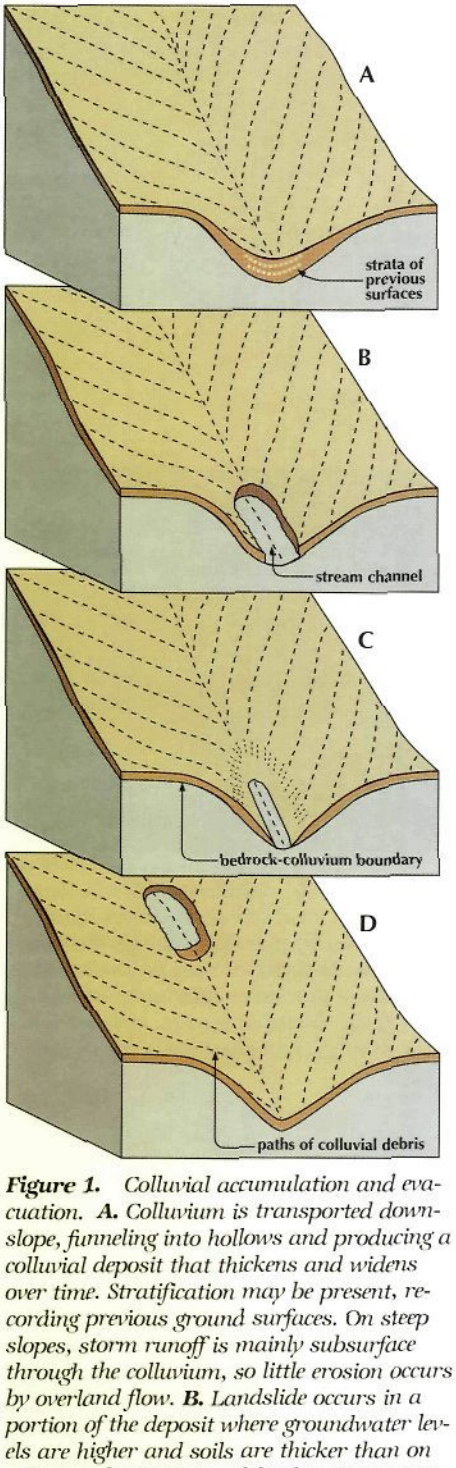

Figure 1. *Colluvial accumulation and evacuation.* ***A.*** *Colluvium is transported downslope, funneling into hollows and producing a colluvial deposit that thickens and widens over time. Stratification may be present, recording previous ground surfaces. On steep slopes, storm runoff is mainly subsurface through the colluvium, so little erosion occurs by overland flow.* ***B.*** *Landslide occurs in a portion of the deposit where groundwater levels are higher and soils are thicker than on adjacent slopes. Some of the deposit may remain uneroded beneath the failure plane. A stream channel often extends upslope into the scar.* ***C.*** *The landslide scarp slowly degrades. Runoff cannot remove all the colluvium accumulated from erosion of the scarp and adjacent slopes, and the channel gradually disappears as colluvium thickens and becomes vegetated.* ***D.*** *The next landslide may occur elsewhere in the hollow where colluvium had continued to thicken. Different parts of a hollow may thus have distinct histories.*

horizon between dated stratigraphic levels was then calculated by combining these equations with equations describing the cross-sectional shape of each deposit.

Depositional rates of colluvium at each cross section, calculated from horizon mass and the radiocarbon dates, were used to calculate long-term erosion rates on the surrounding slopes. These calculations required field measurements of the local hillslope topography to define the source area for the colluvium. The procedure for calculating erosion rates, described in Reneau et al. (1989), does not assume that all colluvium transported into a hollow is "trapped," but instead acknowledges that the same processes transporting debris into a hollow continue moving some fraction downslope. Net deposition occurs because more debris is funneled into hollows than can be transported out. With the assumption that the amount transported down the axis of a hollow does not change over short distances, the deposited mass equals the amount added from the adjacent side slopes. The accumulated colluvium can then be spread over the contributing slopes and expressed as an equivalent vertical lowering of the bedrock surface. Possible errors in calculated erosion rates of ~25% are estimated from uncertainties in measuring density, deposit shape, and local topography (Reneau et al. 1989).

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Figure 2. *Landslide scars in clearcut at head of hollow, Smith River basin, Oregon Coast Range. Such failures in clearcuts may be similar to those that occur after natural wildfires, caused in part by reduced soil strength accompanying root decay.*

Results

Radiocarbon Dating

Twenty-one radiocarbon dates were obtained from nine sites in Washington (Figure **4**, *middle*), including dates from multiple stratigraphic levels in five deposits. Twenty-four dates were obtained from deposits in nine Oregon hollows (Figure **4**, *bottom*), including multiple levels in six of these. Cross sections of four of the dated deposits are shown in Figure **6**. Most sites contain a Holocene record—<10000 years (Table **1**)—although several extend into the latest Pleistocene and one dated deposit in Oregon is older than 40000 B.P.(radiocarbon years before present). Basal ages in each area are clustered: most Washington dates are between 10000 and 7000 B.P., and most Oregon dates are between 7500 and 4000 B.P. (Figure **7**). A similar clustering, although at a different time period, also occurs for dated deposits in California (Figure **7**).

In the 11 deposits with multiple dated levels, only two yielded dates that were stratigraphically inconsistent, i.e., where older dates were obtained above younger dates (Deton Creek site, Figure **6**; and Snahapish #2 site). Erroneous dates may result from several causes, including the introduction of young charcoal into an older horizon by the burning of roots or by transport down animal burrows, by the mixing of soil horizons accompanying windthrow, or possibly by the erosion and re-deposition of old charcoal. The consistency of most dates obtained in this study, however, suggests that the majority are reliable and that the deposits contain an accurate stratigraphic record of continued accumulation of colluvium over time.

Colluvial Depositional Rates

The dates from multiple stratigraphic levels show that the deposits progressively thicken over time. Changes in depositional rates of colluvium are shown by inflection points on graphs of accumulated mass versus time (Figure **8**), although, because of insufficient data points and measurement uncertainties, the changes may not be as abrupt or at the precise times indicated.

At the Washington sites, no consistent pattern of increasing or decreasing depositional rates over time is apparent in the dated deposits, and instead depositional rates seem to vary irregularly in many hollows (Reneau et al. 1989). For example, the Snahapish #1 deposit shows rapid initial deposition of colluvium between 9900 and 8300 B.P. which accounts for at least 70% of the total deposition at this site (Figure **8**). In contrast, depositional rates at the Yahoo #1 deposit were relatively constant for 12 000 years, except for rapid deposition ca. 4500 B.P., while depositional rates at Yahoo #2 have progressively increased during the past 8300 years (Figure **8**).

Most dated deposits in Oregon show increasing depositional rates over time, although again variability characterizes the area, and historic land-use changes could have caused some of the apparent increase. At Railroad Creek #2, depositional rates have been relatively constant since ca. 5000 B.P., although they were slower prior to this (Figure **8**, *left*). In contrast, rapid initial deposition at Hadsall Creek ca. 4200 B.P. was followed by lower depositional rates until very recently (Figure **8**). Currently, a second-growth forest covers this site, and the recent increase in depositional rate may be attributable to erosion produced by logging operations, although this conclusion is speculative. Depositional rates at Taylor Creek were relatively constant for ~4000 years, but here again a recent increase is apparent (Figure **8**). Unfortunately, the timing of these recent changes in depositional rate is not precise and may have occurred before or after the dated stratigraphic level.

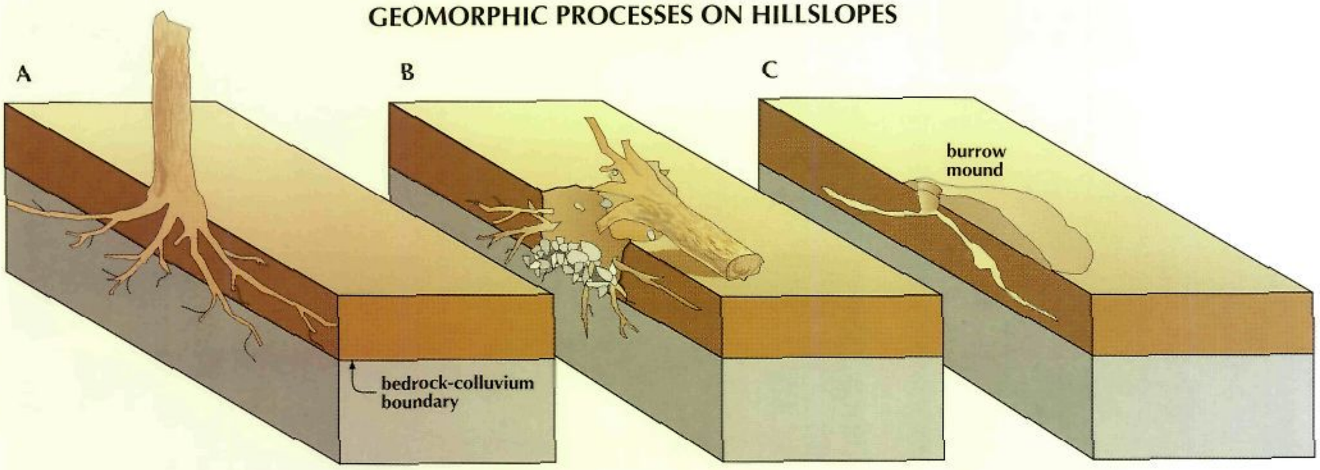

Figure 3. *Geomorphic processes on hillslopes.* ***A.*** *On slopes with shallow soils, tree roots penetrate into bedrock, prying apart the rock during growth.* ***B.*** *When trees topple during windstorms, the bedrock surface is physically lowered, with the rock broken up and mixed into the soil. Debris is transported downslope when the trees fall and during subsequent decay of the trunk and root mat.* ***C.*** *Animals' burrowing into soils causes a net downslope transport of debris.*

Calculated Erosion Rates

Average erosion rates calculated for each site in Oregon and Washington are shown in Table **1**. A summary of the calculated erosion rates for Oregon and Washington is presented in Table **2**, with erosion rates calculated from California hollows shown for comparison (Reneau 1988).

The highest regional erosion rates were calculated for the Oregon Coast Range sites, the lowest rates for the drier California hardwood forest sites, and intermediate rates for the wetter Washington sites. The erosion-rate estimates among the three areas overlap greatly, although a clear difference between the Oregon and California forests is apparent. Limited data from other sites in coastal California with different bedrock or vegetation, however, indicate higher rates that are indistinguishable from the Oregon and Washington data (Table **2**). This suggests that there is no clear climatic control on the variations in erosion rates, and that other factors may be more important.

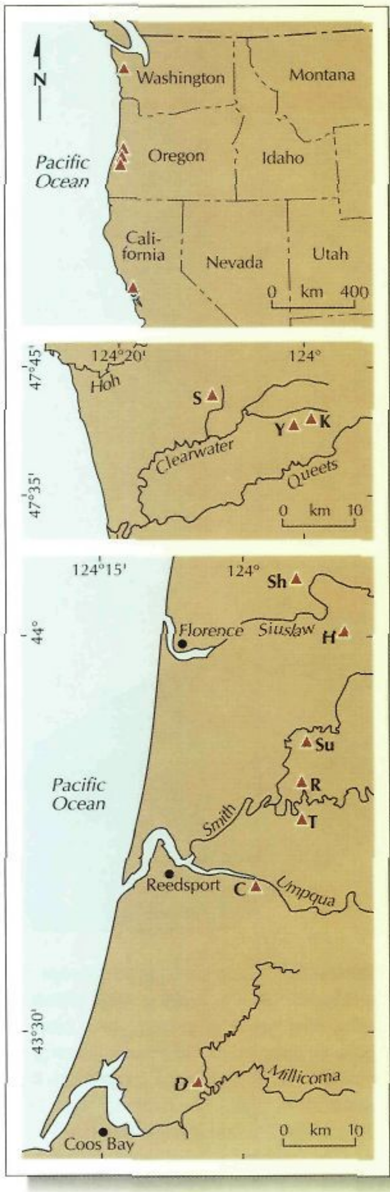

Figure 4. ***Top,*** *study areas on the Olympic Peninsula of Washington, in the Oregon Coast Range, and in the central California Coast Ranges;* **middle,** *location of dated colluvial deposits, Olympic Mountains, Washington;* **bottom,** *deposit locations in the Oregon Coast Range. Letters are keyed in Table 1.*

Figure 5, photograph. *Yahoo #1 colluvial deposit in Washington, with basal age of 12220±190 B.P. Note color change from colluvium in center of roadcut to bedrock on sides and light-colored clasts of rock within the colluvium. Deposit in roadcut across upper basin at the top of the photo—Yahoo #1a—yielded basal age of 9480±120 B.P., suggesting a later erosional event than recorded in the lower basin.*

Discussion

In both Oregon and Washington, the calculated hillslope erosion rates for the last 4000 to 10000 years are similar to independent estimates of erosion rates based on either modern sediment yield in rivers or measurements of modern hillslope erosional processes. For example, sediment-yield data from nine Oregon Coast Range streams range from 50 to 190 t/km^2/yr (Beschta 1978, Karlin 1980, Larsen & Sidle 1980), with values from undisturbed basins generally lower than from disturbed basins. A similar sediment production rate of 122±50 t/km^2/yr was calculated from the Oregon colluvial deposits (Table **2**). On the Olympic Peninsula of Washington, Reid (1981) calculated a hillslope sediment production rate of 79±33 m^3/km^2/yr based on measurements of modern sedi-

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ment transport on undisturbed hillslopes, comparable to a value of 107±66 m^3/km^2/yr obtained from the colluvial deposits (Reneau et al. 1989). The similarity in erosion rates calculated from such different methods supports the usefulness of the colluvial deposits in estimating erosion rates and in allowing valid comparisons between different areas.

Regional variations in long-term erosion rates are influenced by many factors, including the amount and seasonal distribution of rainfall, bedrock erodibility, vegetation, and relief. Completely isolating the influence of any of these variables is difficult, if not impossible, and their relative importance is not fully understood. Although the authors' three study areas were selected to minimize variations in bedrock, vegetation, slope gradient, and seasonal distribution of rainfall, to partially isolate the effect of total annual rainfall, no clear correlation between erosion rates and climate is apparent. Local variability in bedrock and vegetation is probably important, accounting for some of the differences in erosion rates between sites and between regions.

Evidence for a relationship between bedrock characteristics and hillslope erosion rates is provided by the variability in calculated erosion rates between hollows in each study area, shown by the standard deviations in Table **2**. The smallest relative variation, 41% around the mean, is present in Oregon where the bedrock is most uniform and least deformed. In contrast, the data from Washington and California, where the bedrock is commonly folded and faulted, exhibit variations of 61% and 71% around the mean, respectively. Erosion rates in these areas of relatively hard bedrock may be limited by the rate at which the weathered and fractured bedrock is disrupted and converted to soil. In forested areas, this disruption is probably accomplished primarily by roots, both during growth and when trees topple during windstorms (Figure **3B**). Local variations in the rate of such erosion may be partially influenced by local variability in lithology and fracture density. The regional variations in this study may in turn be influenced by regional differences in bedrock and in the efficiency of the local biotic communities in converting bedrock into soil that can then be transported downslope. More research on this topic is needed.

The basal age of a colluvial deposit in a hollow records the inception

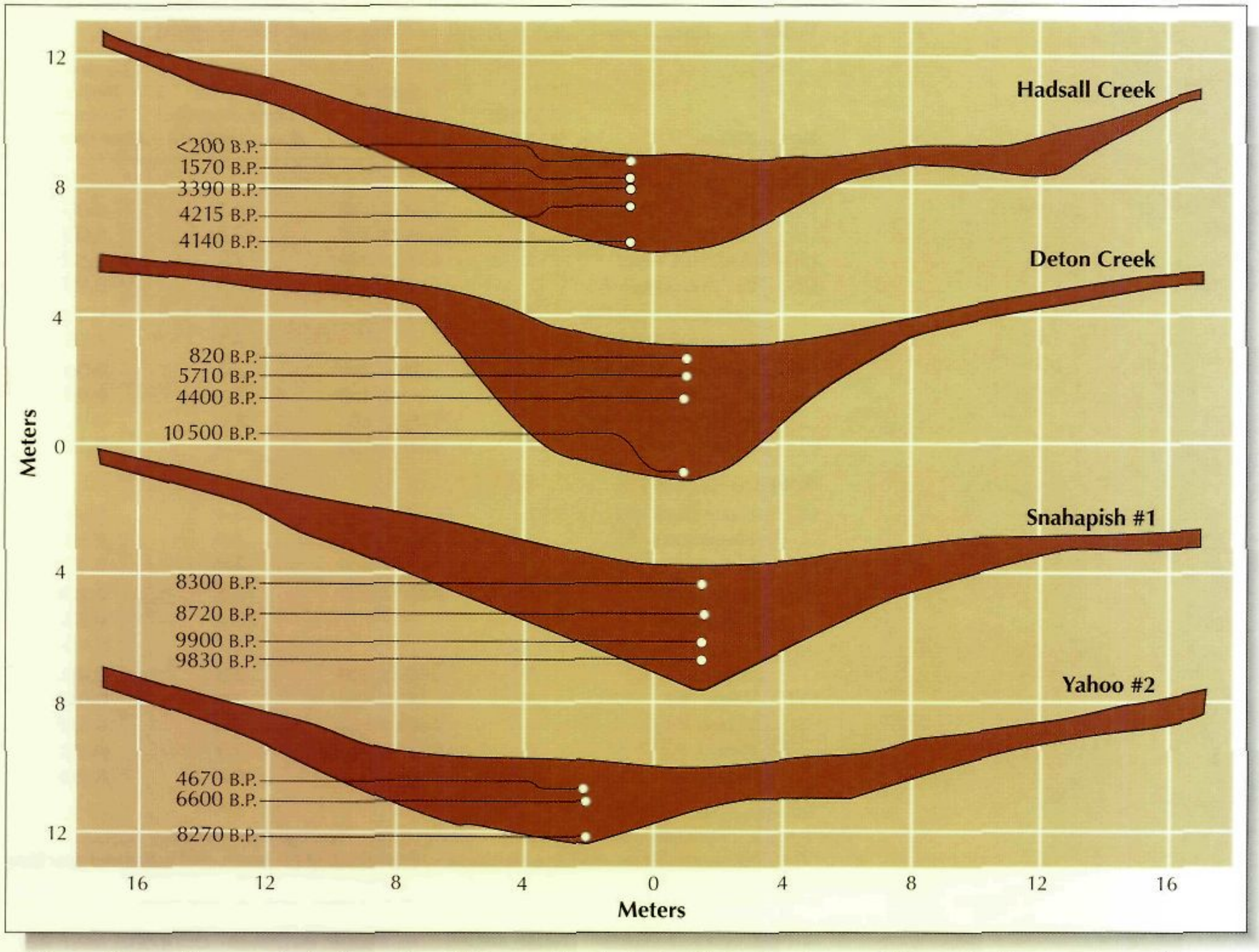


Figure 6. *Cross sections of four dated deposits in Oregon and Washington, showing location of radiocarbon-dated samples.*

of deposition after a period of erosion. This erosion is typically by landsliding or by the extension of a stream channel up into a landslide scar (Figure **1**), and the basal age thus approximates the time of a previous landslide. The clustering of basal dates in each of the three study areas in the coastal mountains of the western United States (Figure **7**) suggests that landsliding has not been uniformly distributed through time, but instead that landslide frequency has been affected by climatic changes that differ in each region. An alternative hypothesis—that the clustering in each area reflects an inherent time scale for failure in the deposits—is not supported by available data. An inherent time scale for landsliding would be largely controlled by depositional rates of colluvium and the deposit size required for failure, and can be calculated as the time required to accumulate the volume of colluvium eroded in an average landslide event (Reneau 1988). The calculated time between landslides in part of a hollow is significantly less than the age of most dated deposits, providing evidence that the history of the dated deposits cannot be explained entirely by an inherent time-scale concept.

Two possible causes for a climatic influence on landslide frequency are changes in storm characteristics and changes in fire frequency accompanying regional climatic changes. Shallow landslides in colluvial soils are generally triggered during periods of high-intensity storms, and increases in storm magnitude or frequency may be responsible for widespread landsliding in hollows in some areas. Increases in storm intensity would produce higher groundwater levels, and thus higher pore pressures, which would cause failure in some colluvial deposits that had been stable during storms of lower intensity. Increases in the frequency of major storms may result in repeated failures at landslide scarps and channel heads, similarly causing more widespread erosion of colluvium from hollows. The central California dates cluster at ca. 14000 to 9000 B.P. (Figure **7**), a time of generally cooler and moister climate, and may record an increase in storm intensity or in the frequency of high-intensity storms during this period (Reneau et al. 1986, in press).

Table *1*. Data from Dated Hollows in Oregon and Washington

Key	Hollow	Number of Dates	Length of Record (^{14}C Years)	Average Colluvial Depositional Rate (t/m/ka*)	Equivalent Bedrock Lowering Rate (mm/yr)
OREGON SITES					
(C)	Charlotte Ridge	1	4660 ± 110	0.7	0.067
(D)	Deton Creek	4	10500 ± 500	3.5	0.089
(H)	Hadsall Creek	5	4215 ± 250	7.7	0.129
(R)	Railroad Creek #1	2	7400 ± 140	1.5	0.035
	Railroad Creek #2	4	>40000	2.3†	0.034†
	post-15000 B.P.			4.1	0.069
(Sh)	Shoemaker Creek	2	5600 ± 210	2.5	0.040
(Su)	Sulphur Creek #1	1	6940 ± 200	3.1	0.056
	Sulphur Creek #2	1	7260 ± 80	1.4	0.083
(T)	Taylor Creek	4	4570 ± 190	5.0	0.049
WASHINGTON SITES					
(K)	Kloochman #1	1	10630 ± 280	6.4	0.076
	Kloochman #2	2	8500 ± 200	2.0	0.026
	Kloochman #3	1	8420 ± 200	2.0	0.194‡
(S)	Snahapish #1	4	9900 ± 200	5.1	0.129
	pre-8300 B.P.			23.4	0.525
	post-8300 B.P.			1.7	0.054
	Snahapish #2	5	8600 ± 200	2.8	0.068
(Y)	Yahoo #1	3	12220 ± 190	2.7	0.018
	Yahoo #1a	1	9480 ± 120	0.6	0.010
	Yahoo #2	3	8270 ± 200	3.3	0.072
	Yahoo #3	1	7180 ± 200	0.8	0.013

**ka = thousands of years.*
†Rates are maximum values due to an infinite radiocarbon age from the lower horizon.
‡Probably unreliable because deposit occupies virtually all of the basin, and calculated rate here is very sensitive to deposit width.

Changes in fire frequency can also cause changes in landslide frequency due to the effect of vegetation on slope stability. Much of the strength of shallow cohesionless soils is provided by roots (e.g., Burroughs & Thomas 1977, Gray & Megahan 1981, Ziemer 1981), and reductions in root strength may occur after fires that destroy a significant portion of the forest vegetation, temporarily decreasing slope stability (Swanson 1981). Under such conditions, failure can be triggered during storms of lower intensity than required under a full forest cover.

The basal dates from steep-hillslope hollows in Washington—clustered ca. 10000 to 7000 B.P. (Figure **7**)—correspond to a period of greater warmth and dryness in western Washington and British Columbia, a period that is well documented by pollen analysis. A greater importance of fires during this period, associated with periods of extended summer drought, has been proposed by many palynologists in the Pacific Northwest (e.g., Barnosky 1981, Cwynar 1987, Hansen & Easterbrook 1974, Leopold et al. 1982, Mathewes 1985). These fires may have contributed to increased landsliding, thereby accelerating the discharge of colluvium from the Washington hillslopes.

Table 2. Calculated Average Erosion Rates for all Study Areas[a]

Study Area	Number of Sites	Bedrock Lowering Rate (mm/yr)	Equivalent Sediment Production Rate (t/km²/yr)
Oregon Coast Range	9	0.061 ± 0.025	122 ± 50
Olympic Mountains	8	0.041 ± 0.025	91 ± 55
CALIFORNIA COAST RANGES			
San Pedro Ridge[b]	11	0.018 ± 0.013	41 ± 29
Third Valley[c]	2	0.070 ± 0.042	161 ± 97
Lone Tree Creek[d]	2	0.039 ± 0.009	90 ± 21

[a]*Values are approximately corrected for differences between radiocarbon ages and calendar ages (from Reneau 1988, Reneau et al. 1989).*
[b]*Hardwood forest sites with sandstone bedrock.*
[c]*Mixed Bishop pine and hardwood forest sites with granitic bedrock.*
[d]*Grassland sites with sandstone bedrock.*

The mid-Holocene clustering of dates in Oregon, at ca. 7500 to 4000 B.P. (Figure **7**), suggests a later period of more widespread landsliding. Unfortunately, climatic changes in Oregon are less certain than in Washington due to an absence of long pollen records. However, Barnosky's pollen study (1985) shows an apparent persistence of a warmer and drier climate until ca. 4500 B.P. in southernmost Washington, which suggests that similar climatic conditions may have existed in western Oregon. In addition, maximum warmth and dryness in the Great Basin of Nevada occurred from ca. 8900 to 4000 B.P. (Van Devender et al. 1987), and similarly suggests widespread, drier conditions during the mid Holocene. Landsliding associated with fires during a period of more frequent summer droughts is thus again a possibility, although climatic changes in Oregon are poorly constrained. In both Oregon and Washington, changes in storm characteristics may also have contributed to changes in the abundance of landsliding.

Field observations on the relative abundance of charcoal in the colluvial deposits supports the hypothesis that fires have been more important at the Oregon and Washington sites than at the California sites. Whereas charcoal is rare in upper horizons of studied California deposits, charcoal was commonly found throughout the entire thickness of Oregon and Washington deposits. Even in the horizons that were sampled in California, charcoal fragments were scarce and required much search. Clearly, though, the correlation between fires and landsliding is not one-to-one, and increased groundwater levels that accompany high-intensity rainfall is the ultimate triggering mechanism.

Conclusion

The dating and analyses of colluvial deposits in Oregon and Washington have further demonstrated that these sites contain a unique record of long-term hillslope erosion. Dates from multiple stratigraphic levels in 11 deposits show that they are cumulative and continue to thicken over time. Calculated erosion rates are greater at the Oregon sites than at the wetter Washington sites, and erosion rates at both are greater than at sites in a drier California hardwood forest. The reasons for these differences are uncertain; no clear correlation with regional climate is apparent, and variations in vegetation and bedrock lithology and structure between areas may be important.

The clustering of basal radiocarbon dates suggests climatic influences on the timing of landslides in each area. Widespread landsliding may have occurred during the warmer, drier early Holocene in western Washington, associated with an increased frequency of major fires. Increased landsliding in the mid Holocene of western Oregon is suggested by the dates there; a warmer, drier climate may have existed in Oregon at this time, although paleoclimatic data are sparse. In contrast to the Oregon and Washington sites, basal dates from California suggest widespread landsliding at the close of the Pleistocene in a cooler, wetter cli-

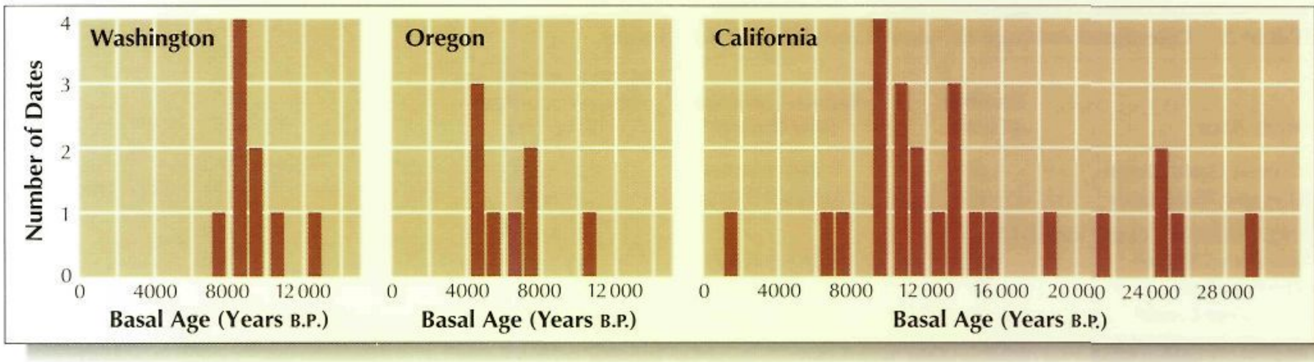
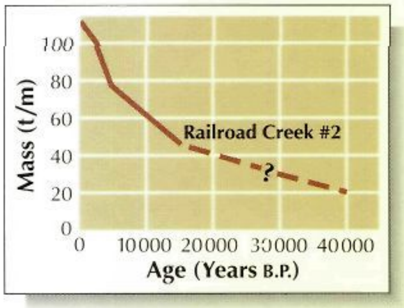


Figure 7. Basal radiocarbon dates from hollows in Washington, Oregon, and California. Some California dates are below recognized unconformities, and unconformities may also be present at other sites. These dates thus do not necessarily record the last evacuation event at each site.



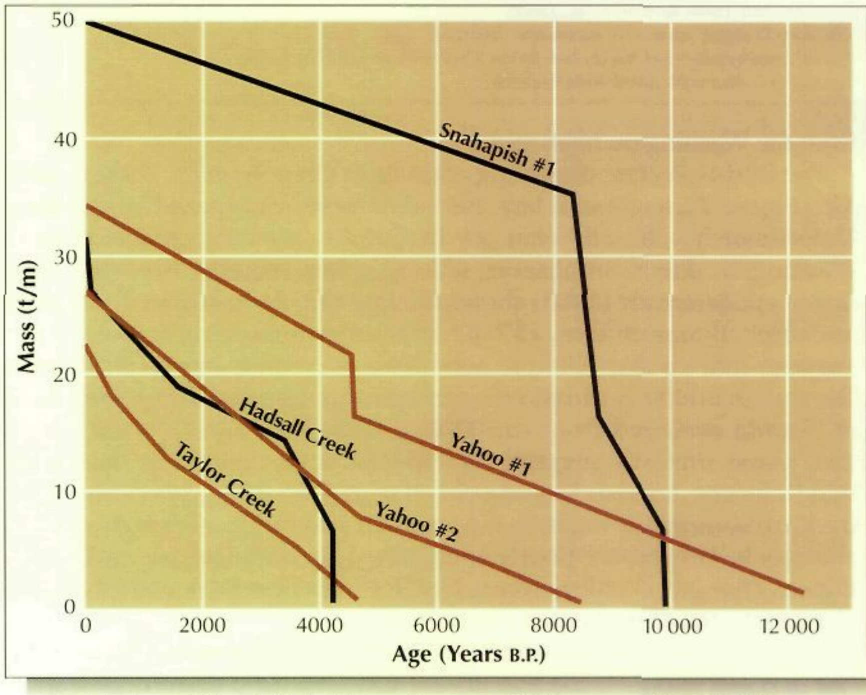


Figure 8. Accumulated mass for six dated deposits in Oregon and Washington. Units of mass are metric tonnes per meter length of hollow axis.

mate, possibly caused by more frequent high-intensity storms.

Chronologic studies of colluvial deposits in hollows provide a unique means to evaluate the geomorphic history of hillslopes in humid temperate environments. Because hillslopes change very slowly and because long periods elapse between landslides at a site, the approach presented here provides one of the few ways to obtain information on the rates and timing of hillslope erosion. Landscapes dominated by hollows occur in many parts of the world, and similar dating and analyses would offer a means of comparing hillslope processes in diverse areas.

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