SIGNIFICANCE OF THICK DEPOSITS OF COLLUVIUM ON HILLSLOPES: A CASE STUDY INVOLVING THE USE OF POLLEN ANALYSIS IN THE COASTAL MOUNTAINS OF NORTHERN CALIFORNIA[1]

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ABSTRACT

Distinct bedrock hollows with a colluvial fill are common in soil-mantled hillslopes. It has been proposed that these hollows are sites of recurrent emptying by landsliding and subsequent slower refilling with colluvium. On a hillslope in Northern California we have quantified the time since emptying and the three-dimensional configurations of the underlying bedrock surface. Correlation of the pollen record in the colluvium with a nearby pollen core from a lake with an accurate age control indicates that the oldest colluvium was deposited 11,000 to 13,500 years in the bedrock hollow. Since then deposition of colluvium in the hollow has been equivalent to 1.5 m of landscape lowering in the surrounding source area and to a local lowering rate of about 0.1 mm/yr. The longitudinal profile of the hollow is concave upward, a form that causes the groundwater flow to rise toward the surface downslope, leading to saturation and possibly to landsliding.

INTRODUCTION

Thick deposits of colluvium in discrete bedrock hollows on hillslopes are common in the coastal mountains of Northern California, Oregon, and Washington and play an important role in controlling discharge of sediment into stream channels (Dietrich and Dunne 1978; Dietrich et al. 1982; Marron 1982; Lehre 1982*a*, 1982*b*; Swanson and Fredriksen 1982). The bedrock hollows often occur in the headwaters of first-order basins and are interpreted as sites of recurrent but infrequent rapid emptying, usually started by a landslide, followed by slower refilling with colluvium from surrounding upslope areas. Colluvium in the bedrock hollows may exceed 7 m in depth; when a portion of it fails as a landslide, the resulting torrent of rapidly moving debris can destroy property and cause loss of life. In steep-forested areas, debris torrents from colluvium in hollows may scour first- and second-order channels to bedrock. In some areas, scouring is the primary process that transports debris accumulated in these channels downstream (Dietrich and Dunne 1978).

An essential step in constructing sediment budgets for drainage basins or in studying and modeling hillslope form and transport processes is the quantification of the dominant transport processes moving debris toward channels. Where colluvium-mantled hollows are ubiquitous, landslides not involving the bedrock appear most frequent in sites underlain by these hollows. Elsewhere, soil creep and biogenic transport probably dominate the downslope transport of the soil mantle (Dietrich and Dunne 1978). Hillslopes where colluvium-mantled hollows are common can be divided into regions of downslope transport dominated by periodic flushing of accumulated debris and regions where transport is by more continuous processes (on a geologic time-scale) of soil creep and biogenic transport. The latter regions, are in part, the source areas for the colluvium in the hollows. New hollows may be initiated by a landslide involving the bedrock where, for example, lithologic differences or jointing and fracturing of the rock have led to local concentration of groundwater flow. Subsequent erosion into the bedrock and growth of the depressions probably occur through the combined effects of landsliding involving some bedrock and weathering and erosion by water during periods when the bedrock surface is exposed. The colluvial fill may become stabilized, perhaps because of a change in hollow geometry, and the hollow and colluvium it contains may be eroded slowly from

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the hillslope by soil creep and biogenic transport. As yet this model has not been demonstrated quantitatively in the field, although its importance to construction of sediment budgets has been recognized (Dietrich and Dunne 1978; Lehre 1982*b*; Marron 1982; Swanson and Fredriksen 1982).

Marron (1982) reported the first map of the areal distribution of hollows mantled with colluvium in an area underlain by graywacke and shale in Redwood National Park near Orick, California. By inspection of a dense network of logging road-cuts, she found about 76 in 3.8 km^2, which is close to the density of 22/km^2 reported as a minimum by Dietrich and Dunne (1978) for an area in central coastal Oregon. Lehre (1982*b*) estimates there are about 129/km^2 in a grassland area underlain by graywacke near Mt. Tamalpais, 14 km northwest of San Francisco. Although this estimate may be high, the frequency of colluvium-filled hollows is considerably higher in the coastal mountains surrounding the San Francisco Bay Area than in any other location observed to date. It would be useful to define the percentage of a basin occupied by these hollows, but without extensive data on the subsurface bedrock topography this is difficult to obtain. Based on data on average hillslope swale length and width in the Lehre study site, we estimate that the partially-filled bedrock hollows cover about 20 to 40% of the basin.

A distinct gravel layer is found at the base of the colluvium in many of the bedrock hollows. Dietrich and Dunne (1978) have proposed that this gravel is a lag deposit that forms when the bedrock surface is exposed and overland flow retards the accumulation of fine debris. Typically, colluvial fills are gravelly; many are crudely stratified and some have several gravel-enriched layers alternating with finer textured debris. Marron (1982) has made detailed sketches of the stratigraphy of five colluvial fills exposed in road cuts and suggested that coarse gravel interlayers record either landslides within the colluvium in the hollow or landslides into the depositional area of the hollow.

Very little quantitative information exists on bedrock hollows and their infilled colluvium. Initial observations in road cuts revealed that the deposits thin upslope. Because the colluvial origin of the fill was not certain, the deposit was termed a "soil wedge" (Dietrich and Dunne 1978). To avoid confusion in usage of the term "soil" we will use here "colluvial wedge," or simply "wedge." Although it is clear that colluvial wedges thin upslope, little else is known about the geometry of the bedrock hollows they occupy, yet this is a very important control on groundwater flow. On soil-mantled hillslopes, rainwater infiltrates rapidly through the soil mantle to underlying and less permeable weathered bedrock. Here water accumulates and travels laterally as shallow groundwater flow, generally following the slope of the bedrock surface (e.g., Campbell, 1975, for further discussion). If the bedrock surface is indented, as it is in hollows, groundwater from upslope will flow toward the center of the depression causing higher pore pressures in the axis of the hollow than in the surrounding planar hillslope (Hack and Goodlett 1960; Swanston 1967, 1970; Pierson 1977, 1980; Anderson and Burt 1978). Field observations suggest that colluvial wedges mantle spoon-shaped bedrock hollows, and thus have a concave upward longitudinal profile. For example, the hollows studied by Pierson (1977) in the Oregon Coast Range appear to have concave upward profiles and to saturate in their downstream portions during major storms. Humphrey (1982) has developed a finite-element subsurface flow model which predicts that the spoon-shaped geometry will cause the thickness of the perched groundwater to increase rapidly downslope, leading in large rainstorms to saturation of the colluvium at the downslope end of the wedge and, perhaps, to landsliding. Quantification of the geometry of bedrock depressions is thus very important: the stability of the colluvium is largely controlled by concentration of groundwater flow.

Also of importance to understanding hillslope geomorphology is the determination of the time since the bedrock hollows were last free of colluvium. This may provide information about the recurrence interval of landsliding at a particular location on a hillslope, which is essential to constructing sediment budgets (see Dietrich et al. 1982, for further discussion). Combined with quantification of the volume of colluvial fill, age-determination of the colluvium should yield data on rates of geomorphic processes.

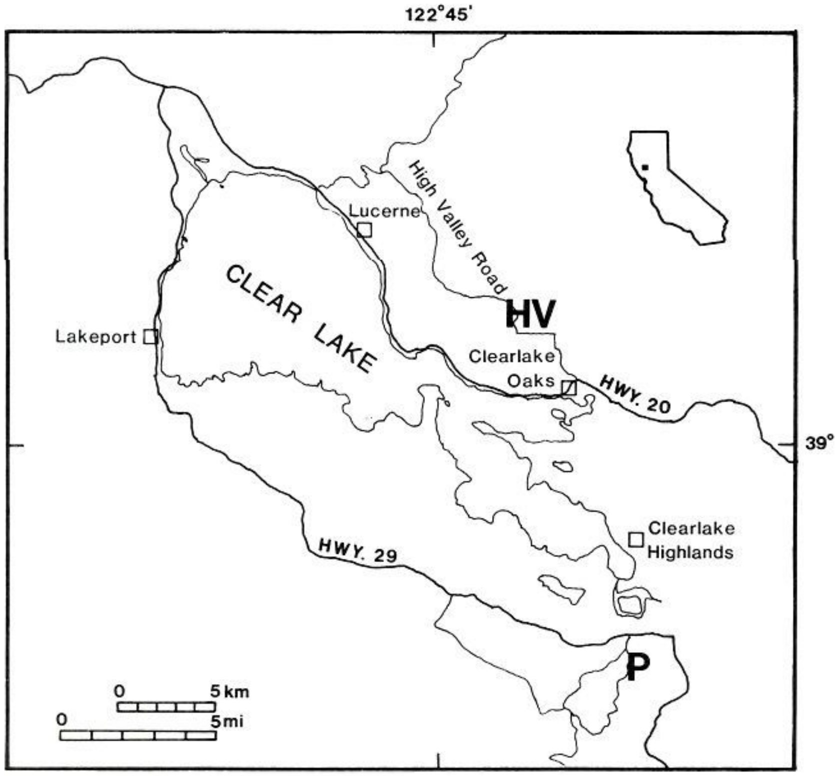

FIG. 1.—Map of the Clear Lake region in the Coast Range of Northern California. HV and P indicate the locations of the High Valley and Perini colluvial wedges.

Here we quantify the three-dimensional geometry of a bedrock hollow that is mantled with a thick colluvial fill on a hillslope near Clear Lake, California. The site was selected because of a recent and thorough study of radiocarbon-dated pollen cores in Clear Lake by Adam et al. (1981). We found well-defined pollen changes in the wedge that, when correlated with Adam et al.'s pollen stratigraphy, provide an approximate age of the oldest colluvium in the hollow. In conjunction with documentation of the volume of colluvium in the hollow, we have obtained unique data on local rates of landscape lowering.

STUDY SITE

A small swale on a hillslope on the north side of High Valley, near Clear Lake, California (figs. 1 and 2) is the focus of this study. The present source and depositional areas in the swale are about 1.72×10^4 m^2 and 1.29×10^4 m^2, respectively. Figure 3 illustrates the topography of the 3 hectare High Valley swale. Contours were taken from the Clearlake Oaks 7½ minute quadrangle and were modified by surveying with a plane table at the site.

The mean annual precipitation for the High Valley area is about 940 mm, almost all between October and May. The mean annual temperature is about 15°C. Although the mean temperature was probably closer to 7°C in the Pleistocene (Adam and West 1983), no part of the Clear Lake area was glaciated. The swale is underlain by the Franciscan formation with a graywacke member under the lower portion of the swale and metavolcanics under the upper part. In order of areal dominance, the current woody plant species in the swale are blue oak (*Quercus douglasi*), manzanita (*Arctostaphylos manzanita*), chamise (*Chamise adenostoma*), Christmasberry (*Heteromeles arbutifolia*), and digger pine (*Pinus sabiniana*). Most of the woody plants are blue oak and manzanita, with chamise occurring in the more exposed aspects. There was only one digger pine in the swale, with a

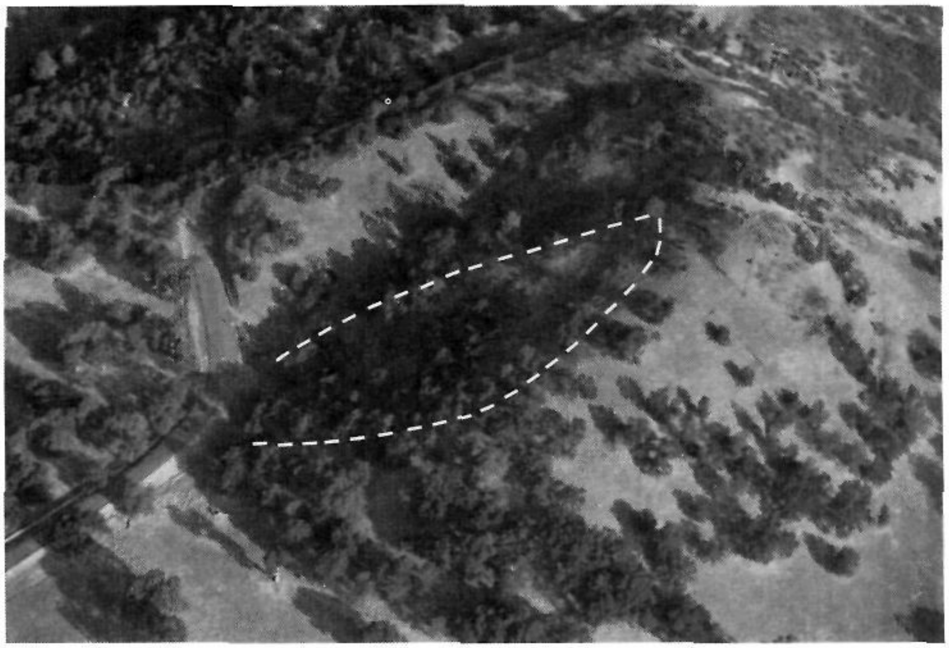

FIG. 2.—Oblique aerial photograph of the High Valley swale and colluvial wedge. The dashed line delineates the margins of the swale. Location is in the southwest corner of Section 13, Township 14 North, Range 8 West on the Clear Lake Oaks 7½ minute U.S. Geological Survey quadrangle.

relatively small population in the surrounding High Valley area. The hillslope is not cut by a road. The bedrock hollow appears to be still filling in with colluvium transported downslope by small earthflows similar to the active one shown in figure 3, by animal burrowing, by tree throw, and probably by soil creep. Frost may occasionally occur in the winter months. Evidence of rainsplash and overland flow was found only on surfaces exposed by biogenic processes.

GEOMETRY OF THE BEDROCK DEPRESSION AND THE COLLUVIAL FILL

A 15-cm-diameter soil-auger was used to determine the depth of the colluvium/weathered bedrock interface. These measurements (fig. 3) provide a generalized view of the geometry. The wedge has a maximum length of about 200 m, a typical width of 70 m, and a maximum depth of 5.1 m. Figure 4 shows isopachs of the wedge at High Valley. The wedge consists of two converging bedrock depressions; figure 5 presents a longitudinal profile of the fill along the main axis of the colluvial wedge. These measurements also suggest that, at the lowest portion of the wedge, the bedrock hollow narrows significantly.

The wedge volume is approximately 2×10^4 m^3. This estimate was obtained by superimposing a 20×20 m grid over the wedge, as portrayed in figure 3. The average depth of each grid square (or portion of grid square) was estimated by the auger depths and by a subjective interpolation of the auger-depths in combination with field observations. The final volume was approximated by multiplying each grid area by its estimated average depth and then summing the individual grid volumes.

POLLEN STRATIGRAPHY

Dating of the colluvial fill was done by correlation of the pollen record from the fill with a nearby pollen core from a lake that has accurate age-control. Adam et al. (1981) analyzed a 130,000-year continuous pollen record from two cores taken from Clear Lake, a lake large enough to integrate the surrounding region's pollen rain. The pollen cores clearly delineate a Pleistocene-Holocene transition in which oak pollen replaces pine and other coniferous grains as the dominant

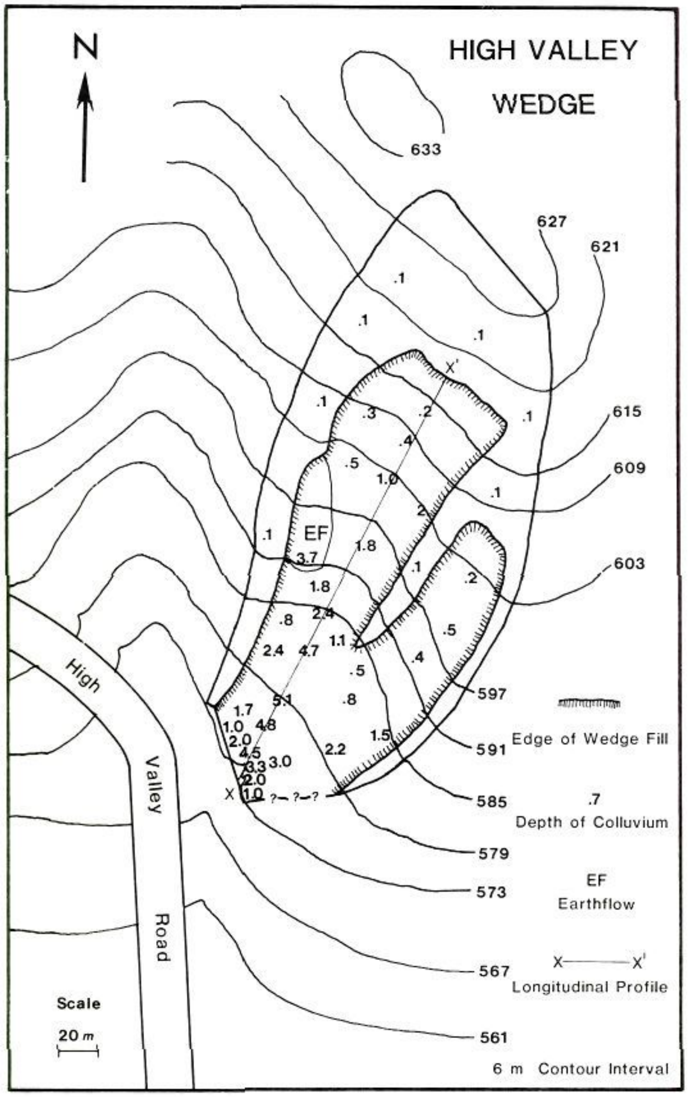

FIG. 3.—Topographic map and location of depth determinations on High Valley colluvial wedge. Present source area was estimated to be the region with soil depth less than 0.1 m on the periphery of the wedge fill, shown on the map between the hatched line and the drainage basin boundary.

pollen type in the Holocene. Adam and West (1983) have subsequently proposed that the Pleistocene vegetation was associated with an 8°C cooling and possibly as much as 2 m more annual precipitation relative to present conditions. To take advantage of this well-defined pollen and climatic history we selected a wedge from a nearby area currently dominated by oak, so that we could correlate the wedge pollen record with the contemporary and Holocene dominance of oak in the Clear Lake pollen cores.

Subsurface colluvium samples were taken from the face of a small slump at the base of the High Valley swale, which exposes 330 cm of colluvium and soil above a graywacke substrate. Twelve samples were taken at 40 cm intervals throughout most of the exposed surface and at 20 and 10 cm intervals near the bedrock boundary. The face of the slump was cleared off with a hand shovel, and samples were taken 5 cm in from the exposed face with a spatula cleaned with distilled water. All samples were processed to concentrate

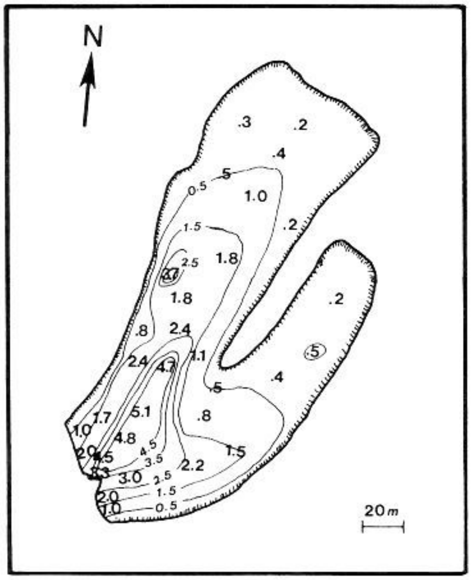

FIG. 4.—Contours of the colluvial wedge thickness.

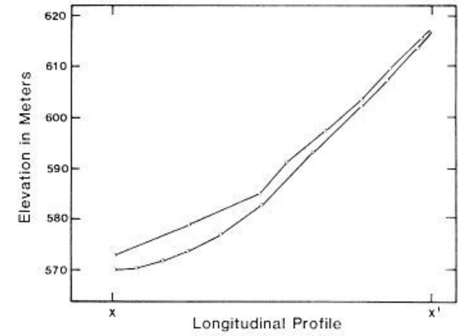

FIG. 5.—Longitudinal profile of the High Valley wedge. Profile is from X to X′, as shown in figure 3. Horizontal scale same as in figure 3, but vertical scale is exaggerated 3½ times to show the soil thickness. Upper part of the profile slopes about 15°, whereas the lower portion slopes to less than 4°.

pollen by disintegration, dissolution, and removal of the nonpollen matrix. The samples were subdivided into two subsamples, and grains of the exotic spore *Lycopodium* were added as a control (Stockmarr 1971). Pollen was extracted by the general procedures described by Faegri and Iverson (1975): in short, treatment was with KOH (10%), HCl (10%), HF (30%), and acetolysis. The pollen was then stained with safranin and mounted in silicone oil.

Figure 6 presents the relative abundances of oak (*Quercus*) and pine (*Pinus*) pollen in the High Valley wedge. At least 300 grains were counted in all samples. The graph suggests that the High Valley vegetation changed from pine to oak when the bedrock hollow was nearly empty. Auger samples were also processed from the 5.1 m core about 35 m upslope from the site used to construct figure 6, and a pollen count revealed the presence of the same pine to oak transition 20 to 25 cm above the base of that core. Although the shift in pollen types is more abrupt in the High Valley wedge, it mirrors the regional shift in *Quercus* abundance in the Clear Lake cores of Adam et al. (1981) who estimate from radiocarbon dates that this shift and, thus, the Pleistocene-Holocene transition occurred between 11,000 and 13,500-yr-ago. Because the pollen change in the High Valley wedge is in the basal deposits, we conclude that the bedrock depressions started to fill during this pollen-dated transition period.

A second colluvial wedge located about 20 km southeast of the High Valley wedge (fig. 1) was also sampled for pollen analysis. The site, referred to as the Perini wedge, is in an area also dominated by blue oak (*Quercus douglasi*). However, unlike the High Valley swale, the Perini depression is almost completely filled and shows virtually no topographic expression. The colluvial deposit in the depression extends 350 cm above the base of road cut. The underlying parent material was not exposed at its base in the center of the wedge. The same pine to oak transition occurs in the Perini wedge (fig. 7), but well above the base of the wedge and on the other side of Clear Lake from High Valley, suggesting that the pine-oak transition is from the regional pollen shift recorded by Adam et al. (1981) and not from localized changes due to succession on a recently exposed landslide scar.

A critical assumption is required to interpret accurately figures 6 and 7 as synsedimentary deposits: that pollen grains do not experience significant percolation after airborne fallout and homogenization into the soil surface. This assumption is probably correct. Havinga (1974) noted that downwash is probably of minimal importance in soils, because pollen grains are quickly enclosed in aggregates of organic matter or tiny mineral particles upon deposition. Also, Riezebos and

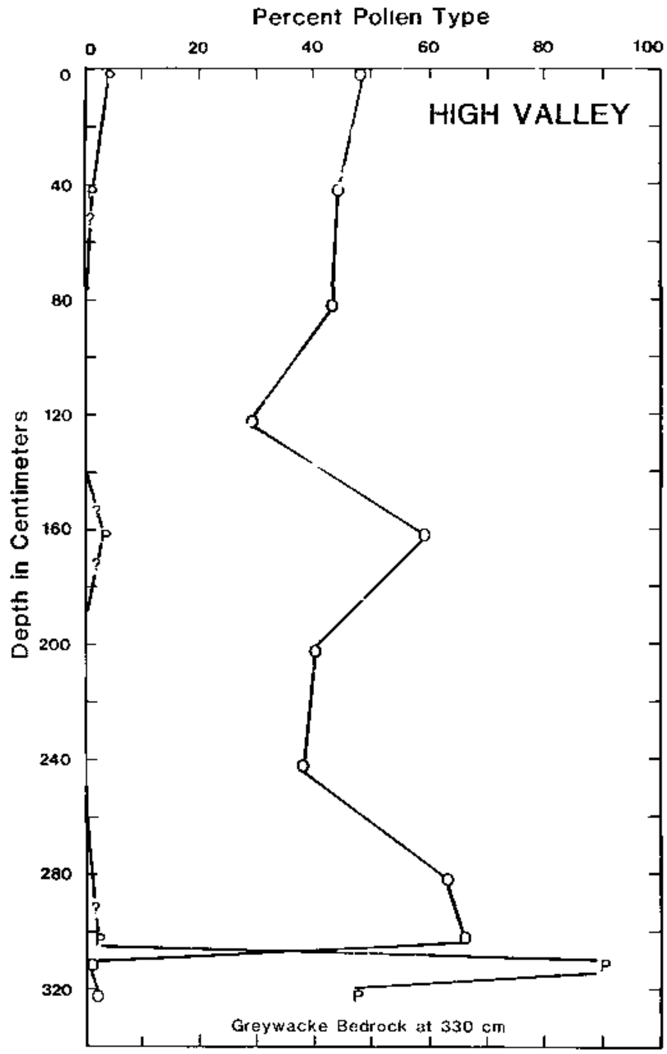

FIG. 6.—Abundances of pine (*Pinus*) and oak (*Quercus*) pollen with depth in the High Valley wedge. Percent is relative to all pollen counted. "O" and "P" indicate oak and pine pollen types, respectively.

Slotboom (1974) and Shaetzle and Johnson (1983) concluded that there was little downwash after the initial near-surface homogenization of pollen in their studies. At High Valley absolute concentrations of counted pollen (based on the addition of 33,800 *Lycopodium* spores to each cm^3 of processed sample) were relatively low, generally around 5000 grains/cm^3 below the first 5 cm of colluvium. These low concentrations probably result from the biological destruction of pollen in soils, as described by Havinga (1974). Oak pollen may corrode more extensively than pine in soils (D. P. Adam, personal comm., 1983). The oak pollen sampled near the base of the High Valley wedge, however, appears to be slightly less corroded than the pine pollen (fig. 8).

DISCUSSION

Data on the volume of the colluvial fill, the depositional and source areas, and the time since last emptying provide unique geomorphic information. Division of the colluvial fill volume by the approximate source area yields the total lowering represented by the accumulated colluvium. In the High Valley wedge this equals 1.5 m. Here we have made

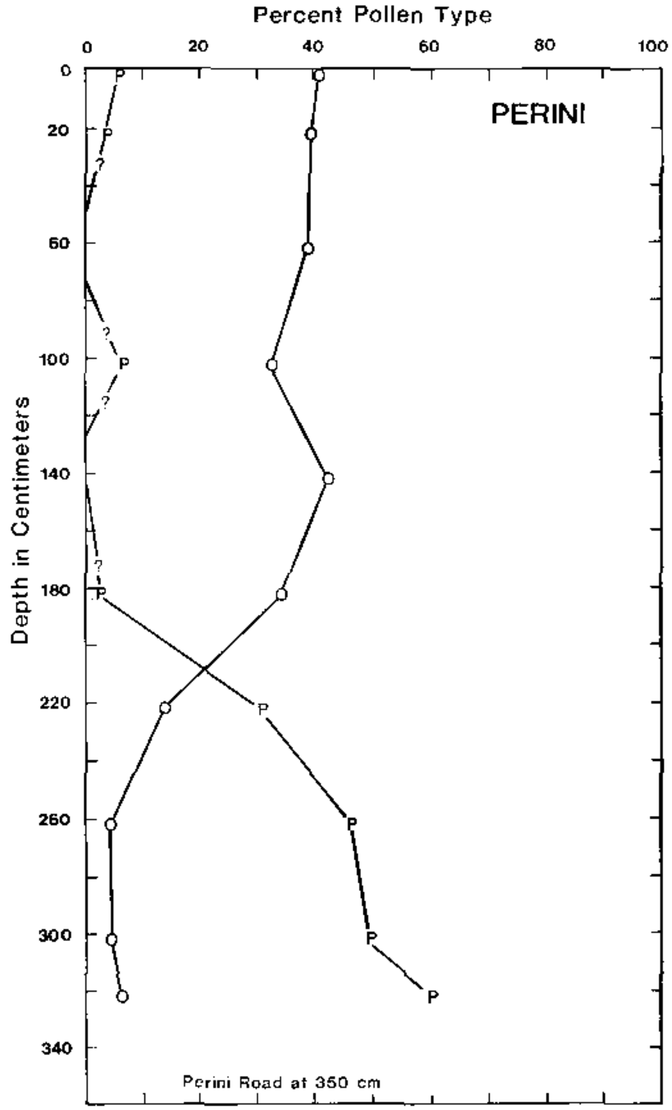

FIG. 7.—Abundances of pine (*Pinus*) and oak (*Quercus*) pollen with depth in the Perini wedge. Percent is relative to all pollen counted. "O" and "P" indicate oak and pine pollen types, respectively. Location of wedge identified by P in figure 1 is next to Perini Road in the southeast corner, Section 9, Township 12 North, Range 7 West on the Lower Lake 15 minute U.S. Geological Survey Quadrangle.

the counterbalancing assumptions that the contributing area has remained constant during colluvial deposition in the hollow and that all material derived from upslope was deposited in the bedrock depression rather than discharged directly into the channel at its base. Estimates of the annual lowering rate can be obtained by dividing the volume of wedge colluvium by the area lowered and the time since emptying. The major assumption required is that the hollow emptied completely in a relatively short time period and then refilled without additional debris loss to the channel at the base of the hillslope. Inspection of recent landslides in wedges in the Pacific Northwest indicates that most of wedge discharges in a single event. In the Coast Range of California, however, the wedges generally do not empty completely in a single event. Instead the lower, least stable portion of the wedge usually fails first. Landslide failures in the hill surrounding the San

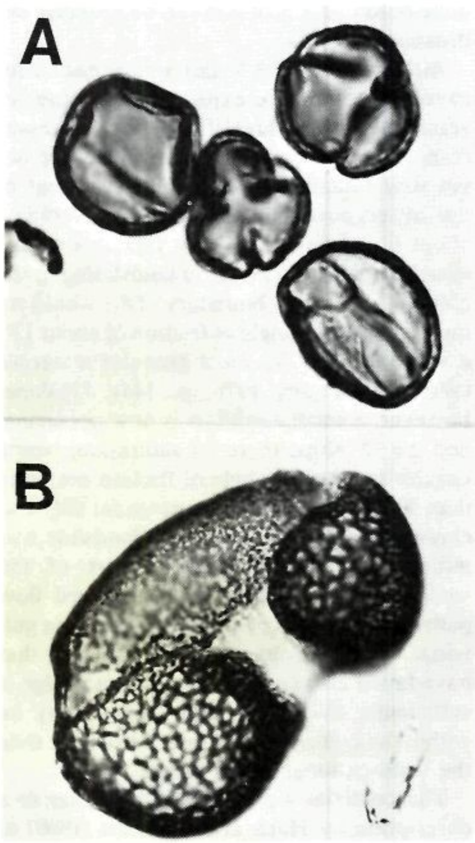

FIG. 8.—Photomicrographs of *Pinus* and *Quercus* pollen from the High Valley wedge, showing the relatively good condition of pollen in the deepest levels. Pollen shows greater corrosion in the 60 to 180 cm levels; they are the sandiest depths. A. *Quercus* pollen from the 300 to 305 cm depth, indicating grains in relatively good condition. Grain sizes about 25 micrometers in diameter. B. *Pinus* grain from the 310 to 315 cm level, illustrating a slightly disturbed bladder. Grain size about 50 × 30 micrometers.

Francisco Bay Area are often entirely within colluvium and typically occur at apparent textural or root density changes (S. Reneau, personal comm., 1983). An exposure in a road cut across a wedge in the Berkeley hills near the UC Berkeley campus has also revealed a buried soil, suggesting that in some cases only partial excavation occurs before refilling.

Although other instances of abrupt changes in weathering in colluvial wedges will most likely be found, commonly there is no obvious evidence of multiple phases of emptying and refilling in colluvium. Also, gully networks may develop in landslide scars in wedges and excavate a considerable amount of the remaining colluvium (Lehre 1982*a*). On the time scale of emptying and filling of the wedges, the period of continued excavation is probably brief. Considerable work must yet be done on this problem, but techniques including pollen analysis, radiocarbon dating, and relative weathering criteria may help to distinguish materials of distinctly different ages within wedges.

Despite these complications, the distinct pollen change found in two locations at the base of the High Valley wedge suggests a complete emptying of the hollow to the bedrock-colluvium boundary 11,000–13,500 years ago. The approximate lowering rates of the source area and the swale as a whole are 0.08 to 0.10 mm/yr and 0.05 to 0.06 mm/yr respectively. When bedrock is converted to soil, there may be volume expansion caused by the physical disturbance associated with soil formation which would reduce the actual lowering rate. For example, Dietrich (1975) calculated that 1 m of basalt bedrock will produce 1.2 m of soil in the coastal mountains of Oregon. At present the uncertainty in our estimate doesn't warrant accounting for this effect.

If the colluvium stored in the wedge since it last emptied had been released into the adjacent stream channel instead, the average sediment discharge from the entire hillslope (source and depositional areas) would have been 48 to 59 m^3/km^2-yr. Samples collected for pollen analysis were also used to determine a bulk density and gave a value of 1.3t/m^3. The equivalent sediment discharge from the wedge, then, is 62 to 76 t/km^2-yr. We can check the estimated lowering rates in two independent ways: by comparisons with sediment discharge records and by examining soil creep rates.

The areas immediately north and east of High Valley drain into the North Fork of Cache Creek. Lustig and Busch (1967) found that during the 4 year period 1960–1963 suspended sediment discharge at a gage 12 km east of High Valley wedge on the North Fork of Cache Creek averaged 211 t/km^2-yr from a 513 km^2 catchment. Mean annual runoff in the creek is about 300 mm/yr. Bedload transport estimated by the modified Einstein method in a section of Cache Creek downstream was approximately 7% of the total sediment discharge. During the period of observation, high flows were lower than average, and thus the total sediment discharge of 227 t/km^2-yr is an underestimate. Lustig and Busch noted (p. A4–A5 of their report) that in the lower reach of the North Fork of Cache Creek there were areas of intense erosion with badland-type gullies in steep bluffs. These observations suggest the sediment discharge should be much higher at the measurement site on the North Fork Cache Creek than from the High Valley wedge, but because the sediment contribution from the badlands was not evaluated separately this difference cannot be quantified.

A less direct test of the estimated sediment discharge is to compute the equivalent soil creep rate of the entire soil column across the perimeter from the source into the depositional area. For simplicity we assume that creep is perpendicular to the perimeter, which is reasonable when a hollow first empties, but becomes progressively less accurate as a hollow fills. The perimeter is approximately 778 m long, and 0.1 m thick. Dividing these numbers and the pollen age estimate into the volume of the wedge yields the approximate transport rate of 2 cm/yr of soil movement toward the wedge. This rate is high compared to reported soil creep values (e.g., Saunders and Young 1983), but these values may be more representative of coarse granular soils less susceptible to creep. Also, a small portion of the wedge perimeter is currently undergoing movement as an earthflow (see fig. 3). The computed soil creep rate encompasses such local processes.

The timing of emptying of the High Valley hollow and its association with a vegetation and climatic change raises the issue of whether climate fluctuations influence the emptying and filling process. Dietrich et al. (in prep.) have found that charcoal from basal colluvium in four wedges in the San Francisco Bay Area have late Pleistocene radiocarbon ages. Simple mass balance for an idealized hollow suggests, however, that because of their size and their slow rate of refilling by soil creep and biogenic transport, the time scale for the bedrock depression to refill should be of the order of 10,000 years (Dietrich et al. 1982). Much more work on dating the colluvial fills of wedges and modeling conditions leading to emptying must be done before this problem can be properly addressed.

Although the High Valley wedge has a concave upward profile expected from stability arguments (Humphrey 1982), the processes responsible for emptying the wedges are not yet well established. The gentle gradient of the lower portion of the wedge, averaging about 6°, makes it unlikely that this wedge initially begins to empty by landsliding at the colluvium-bedrock boundary. This would require an internal angle of friction of about 12°, a value too low for most granular materials (Wu and Sangrey 1978, p. 144). Upslope, however, a small earthflow is now occurring, and the 15° slope there (at saturation) would require an internal angle of friction not more than 30°, a value within the range for silty and clay-rich colluvium. Perhaps a landslide was initiated in the intermediate part of the wedge, and the scar and the scoured flow paths became sites of subsequent intense gullying. Observations of other wedges that have failed also suggest that once a wedge is sufficiently thick, the failure plane may be within the colluvium and may be steeper than the bedrock longitudinal profile.

The colluvial wedge model is similar to a description by Hack and Goodlett (1960) of processes associated with debris avalanching in the northwestern Virginian mountains. They observed that debris avalanches generated during a large rainstorm formed troughed-shaped scars or chutes, typically 15 m wide, extending from near the ridge crest down to the channel. Most chutes occupied former shallow depressions or groove-like areas which they interpreted as incipient hollows. They proposed that these hollows tend to fill with mass movement debris and are only infrequently flushed out and deepened by runoff and debris avalanches. Woodruff (1971, p. 406) examined chutes formed by Hurricane Camille in southern Virginia and argued for similar processes of scour and fill, although he also suggested that in situ soil formation contributes to the accumulation of thick colluvium in hollows. Neither Hack and Goodlet (1960) nor Woodruff (1971) proposed a time scale of emptying and filling in their respective studies.

Aspects of the colluvial wedge model are expressed by Thomas (1939, p. 45–46) in his study of landslides in the San Francisco Bay Area. He observed numerous thick deposits of colluvium in road cuts and proposed that landslides were more likely to occur in these areas of "deep regolith." He also suggested that local bedrock depressions or "pockets" would concentrate groundwater flow and contribute to landsliding (p. 47–49). Kesseli (1943) disputed this latter proposal, claiming that bedrock pockets were not present in deep highway cuts on the Marin Peninsula of the Bay Area. Lehre (1982*c*) has shown that bedrock hollows mantled with colluvium are common in this area, and we have found that particularly good exposures of colluvial wedges are found in road cuts near the northern abutment of the Golden Gate Bridge in Marin County.

The colluvial wedge model differs from models proposed by Bryan (1940), Parizek and Woodruff (1957), and Mills (1981) to explain similar deposits in U- and V-shaped bedrock depressions in the Appalachians and the southern Piedmont province of the United States. Parizek and Woodruff, who also observed that some of the deposits were lenticular or canoe-shaped, suggested that gullying during the late Tertiary or Pleistocene led to the formation of bedrock troughs lined with coarse stones. After an unspecified climatic change, the troughs were filled with fine debris. Bryan argued that gullying forms the bedrock depressions, but he proposed that once filled with more permeable coarse debris the trough was *more stable* than the adjacent interfluves. Eventually the interfluve would gully, leading to a new bedrock trough. The process of alternating stability and gullying would cause general slope retreat, and Bryan called the process "gully gravure." After examining deposits similar to those described by Bryan, Mills (1981) argued that after the gullies formed, they were filled with immobile coarse debris that forced the channel flow against adjacent slopes, leading to lateral migration of the bedrock troughs. Like Bryan, Mills feels that the deposits in bedrock depressions are more stable than surrounding hillslopes.

None of these authors, however, has provided conclusive field evidence for the processes which they invoke. Corroborative data are needed to support Parizek's and Woodruff's interpretations. Bryan's explanation seems unlikely to be valid under the current climatic conditions in the Southeastern U.S., as gullying is rare in most soil-mantled forested environments. Further, Bryan did not directly observe gullying of interfluves. Although Mills offers field observations to support his explanations, no data are provided on the lateral movement of gullies, and he does not consider the possibility that the fills may flush out downstream by infrequent landsliding as Woodruff (1971) proposed. The origin and significance of colluvial deposits in the Appalachian and southern Piedmont physiographic province, as compared to the Pacific Coast Ranges, remain unclear.

CONCLUSION

We have attempted to quantify the geometry, volume, and time-scale of emptying and filling of a hillslope bedrock hollow nearly filled with colluvium. These fills, referred to here as colluvial wedges, are very common in many areas of the coastal mountains of the Pacific Northwest. We and our colleagues have seen colluvial wedges (or at least deposits much like them) in Hawaii, New Zealand, and the Solu region of Nepal. It appears that they are typically found in humid and semiarid regions on soil-mantled hillslopes with bedrock resistant to deep-seated slumps or flows. At present very little quantitative information is available on colluvial wedges, and considerable work is still required to understand their role in landscape evolution.

We can conclude, however, that the recurrence interval of emptying is at least on the order of 10,000 years; that more than a meter of debris eroded from upslope areas may be stored in a wedge; that the estimated lowering rate may be a good approximation for the undisturbed erosion rate in areas with colluvial wedges; that wedges may have a distinct concave upward profile; and that useful information on vegetation changes may be obtained by pollen analysis of the colluvium in wedges.

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