Geological Society of America
Reviews in Engineering Geology, Volume VII
1987

Anatomy of a debris flow, Pacifica, California

Roy J. Shlemon
Roy J. Shlemon and Associates, Inc.
P.O. Box 3066
Newport Beach, California 92663

Robert H. Wright
David R. Montgomery
Harlan Miller Tait Associates
1269 Howard Street
San Francisco, California 94103

ABSTRACT

A major debris flow occurred on January 4, 1982, in the Oddstad Boulevard area of Pacifica, California. The flow emanated from a previously unrecognized colluvium-filled swale (one of many making up first-order drainages in the region), moved down a 21°, 172-m-long slope, and extended into an urban area. The failure involved the upper 4.5 m of a 6.1-m-thick colluvial section in the upper of two bedrock basins underlying the swale. Soil-stratigraphic measurements show that upper-basin colluvium accreted slowly to form a cumulic soil profile, characterized by thick surface (mollic epipedon) and subsoil (argillic) horizons. An approximately 500-yr-old mean residence time (MRT) radiocarbon date from the prefailure mollic epipedon indicates that the average sedimentation rate was about 0.6 m/1,000 yr and, accordingly, that colluviation began at least 8,000 to 10,000 yr ago. In contrast, the lower basin is characterized by at least four pre-1982 slide deposits. These deposits emanated almost wholly from within the lower basin, and are distinguished by clast lithology and angularity, and by the local presence of capping buried paleosols.

Radiocarbon MRT dates of approximately 2 to 3 ka for the upper, older debris flows, and the presence of a moderately developed argillic horizon on an underlying flow, suggest that lower basin failure recurrence is on the order of 1,000 to 4,000 yr.

A simple, three-stage evolutionary model for the Oddstad swale is postulated for engineering-geologic comparisons with swales elsewhere: (1) initial basin incision by fluvial processes in late Pleistocene time; (2) change of climatic regime and resultant colluvial filling of the upper basin in Holocene time; and (3) exhumation and renewed fluvial incision of the upper basin following the 1982 debris flow.

INTRODUCTION

On January 4, 1982, an intense rainstorm triggered thousands of shallow landslides in the central Coast Ranges of California. In the San Francisco Bay area, landslides resulted in 24 fatalities and millions of dollars in property damage (Smith and Hart, 1982; Brown and others, 1984). Almost 500 landslides occurred within the city of Pacifica, resulting in the deaths of three persons, the destruction of four homes, and an estimated $6 million in damages (Howard-Donley Associates, 1982).

One of the largest and most destructive landslides in Pacifica occurred in the 1200 block of Oddstad Boulevard (Fig. 1). Here, late in the evening of January 4, a debris flow emanated from near the crest of a hill, destroying two houses, killing three children, and damaging several other houses (Figs. 2, 3). Investigations following this tragedy provided a unique opportunity to study the debris flow and prefailure hillslope.

Initial assessments (Shlemon and Wright, 1983, 1984) re-

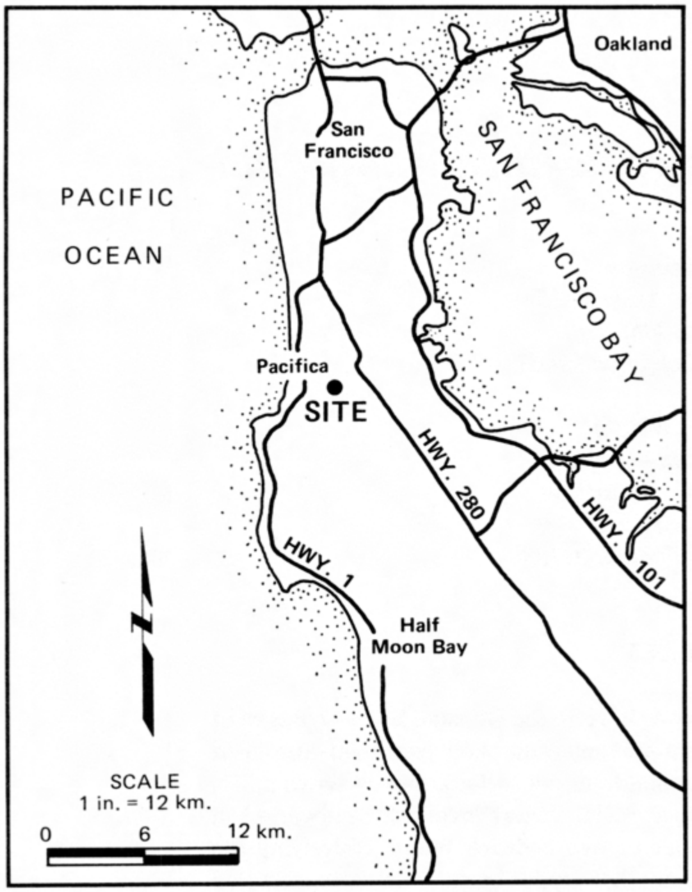


Figure 1. Location map of Oddstad debris flow, Pacifica, California.

vealed that the Oddstad failure emanated from a colluvium-filled swale, topographically expressed as a subtle "crenulation." Such features were not only previously unrecognized in Pacifica, but also, with few exceptions, elsewhere in northern and central California (see, for example, Schlocker and others, 1958; Marron, 1982; Dietrich and Dorn, 1984; Dietrich and others, 1984; Reneau and others, 1984). In the 1960s, when accelerated residential development began in the inland valleys in Pacifica, colluvium-filled swales were not being mapped as discrete geologic units nor were they recognized as potential sources of debris flows by any workers. As late as the early 1970s, these features were not recognized or mapped on geologic and landslide maps of the Pacifica area (see, for example, Brabb and Pampayen, 1972a, b).

Colluvium-filled swales have variously been called "soil wedges" (Dietrich and Dunne, 1978), "bedrock hollows" (Reneau and others, 1984; Marron, 1985), and "colluvial-filled gullies" (Shlemon and Wright, 1983). Here, we use the term "colluvium-filled swale" to designate the source of the Oddstad debris flow, a notation that best describes the prefailure topography. We also employ the term "first-order drainage" in its classical descriptive sense, that is, as the most upstream, field-discernible depression that conducts water and sediments to lower parts of a watershed (Horton, 1945; Strahler, 1964).

This chapter presents the results of our detailed investigations as a case study in engineering geology. First we describe the occurrence and geomorphic setting of the January 4, 1982, Oddstad debris flow. Second, we point out various investigation techniques employed at the site. Third, we describe the debris flow and preexisting colluvium-filled swale. Fourth, we illustrate how soil-stratigraphic techniques are used to date the colluvium and to identify pre-1982 debris flows. Finally, we offer a model to explain the evolution of the Oddstad swale, the general applicability of which may be "tested" by comparison with colluvium-filled swales elsewhere.

OCCURRENCE AND GEOMORPHIC SETTING

The Oddstad debris flow occurred about 11:00 PM on January 4, 1982, near the end of an intense 30-hr rain storm that dumped as much as 22 cm on the slope, superimposed on about 58 cm of antecedent seasonal rainfall (Fowler, 1984). The failure originated from near the head of a broad, colluvium-filled swale on a natural, coyote brush– and poison-oak–covered, east-facing hillslope in the upper portion of the North Fork San Pedro Creek drainage basin. This swale is one of numerous first-order drainages that, like others in the North Fork San Pedro Creek drainage basin (Fig. 4) is steep (15 to 40°), and, as now recognized on color-infrared photography, was filled with colluvium. Almost 50 shallow failures occurred in the upper portion of the drainage basin during the storm of January 3–5, 1982. Some failures resulted in debris flows that funneled into third- and fourth-order drainages where they eventually reached developed areas as mudflows.

Some swales, however, were free of colluvium, owing either to nonfilling or to previous debris flows. Why some colluvium-filled swales failed and others did not remains an enigma, particularly since the general geologic, geomorphic, vegetation, and climatic setting is similar. Undoubtedly, each swale is unique, although obviously local geomorphic thresholds were reached during the Jaunary 3–5, 1982, storm; failure of the Oddstad colluvium-filled swale is a case in point.

INVESTIGATIVE TECHNIQUES

The main emphasis of the initial investigation was to document existing conditions and obtain samples prior to the forthcoming winter rains (1982–1983) and/or to repair the slope (completed by others during 1983). A detailed (1 in = 10 ft; 1-ft contour interval) topographic map of the area was completed in June 1982 (Fig. 5), and field work continued through November 1982. All field locations and samples were located with respect to a surveyed and staked axial centerline so that any point on the topographic map could be identified by a centerline station number (in feet, from the base of the slope), and a left or right

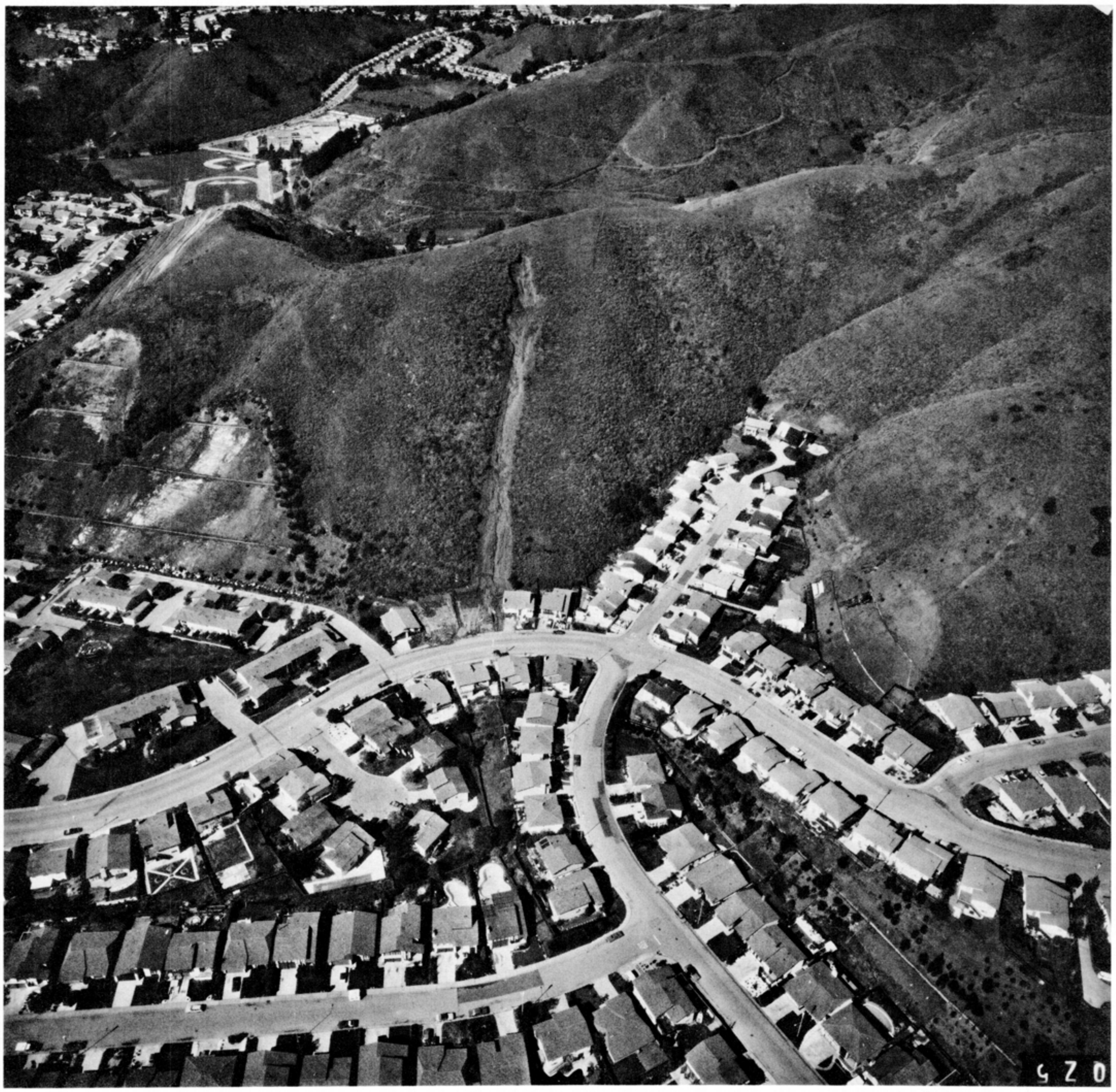


Figure 2. Oblique aerial photograph of Oddstad debris flow taken March 2, 1982 (Pacific Aerial Surveys, SMT-C15-7).

(looking upslope) number (in feet); e.g., Station 0+50 L 10. In this paper, all units are given in metric, except for topographic contour intervals and station numbers.

Field work consisted of the detailed mapping of (1) slide boundaries; (2) distribution of slide features and deposits; (3) remaining (unfailed) slope deposits; and (4) bedrock materials. Thirty-six seismic refraction survey lines, totaling 1,188 m, were run on a rough grid pattern on the slope (see Fig. 5) to provide subsurface data. Some 106 hand-auger holes were excavated to determine depth of slide deposits; to determine the depth of colluvial deposits/depth to bedrock; to obtain samples for laboratory analyses; and to provide calibration for seismic refraction survey lines. Detailed logs were made of three exposures in the upper part of the landslide scar. Here also, detailed soil (pedo-

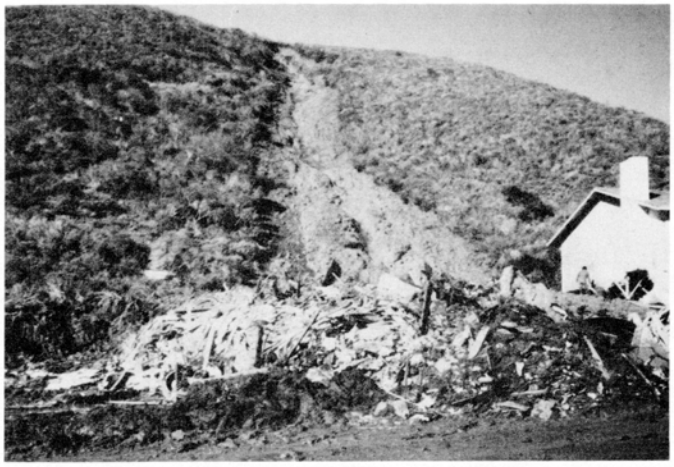


Figure 3. Photograph, January 4, 1982, Oddstad debris flow taken from Oddstad Boulevard on January 9, 1982, 5 days after failure.

genic) profiles were measured, described, and sampled. In the lower part of the landslide scar, an exploratory trench approximately 4.9 m deep (see Fig. 5) was excavated, logged, and sampled to determine the nature of sediments underlying this part of the hillslope. A detailed soil profile was also measured and described, and samples were collected for radiocarbon dating. Finally, a 12.2-m hollow-stem auger hole was drilled, logged, and sampled near the edge of Oddstad Boulvevard (see Fig. 5) to determine the depth to, and the thickness of, fill and colluvium at the base of the hillslope.

Sixty laboratory tests were performed to determine engineering properties, including moisture content, particle size (sieve and hydrometer), Atterberg limits, and triaxial shear. Soil laboratory tests, including chemical and particle-size analyses, were performed on an additional 22 samples, and radiocarbon dates (^{14}C) were obtained from three samples.

CHARACTERISTICS OF THE DEBRIS FLOW AND PREFAILURE SWALE

January 4, 1982, Oddstad Debris Flow

The failure occurred near the head of a broad first-order drainage swale on an east-facing hillslope above the 1200 block

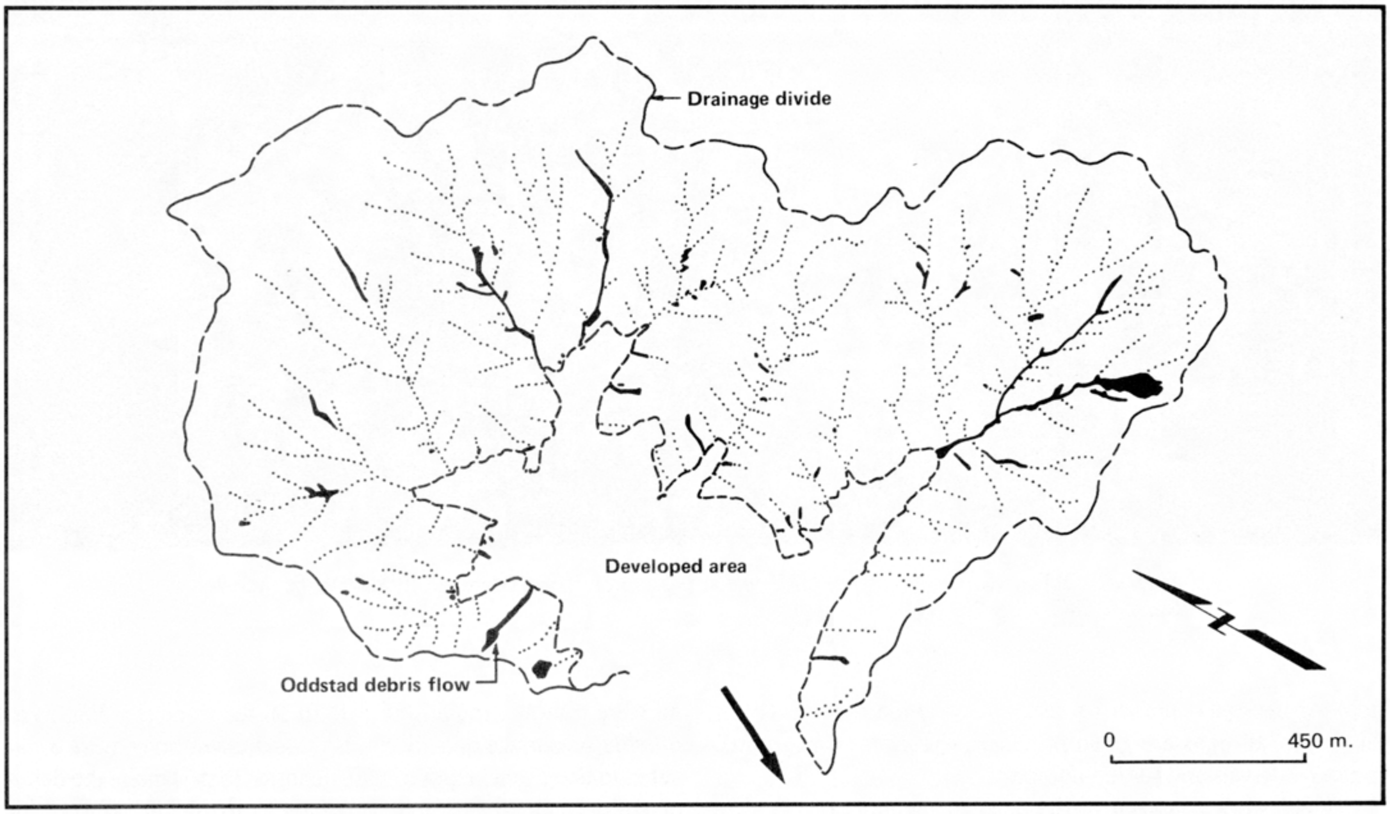


Figure 4. Map of upper portion of North Fork, San Pedro Creek drainage basin, Pacifica, showing drainage swales and channels (dotted lines), and locations of January 4, 1982, slope failure (heavy solid lines).

of Oddstad Boulevard. The scar extended some 230 m from near the top of the headscarp to the slope base. The runout area extended across the building pads at the base of the slope and into Oddstad Boulevard. The failure consisted of a source area and a main track (Fig. 6).

Source Area. The source area extended from about elevation 195 m downslope to about elevation 168 m, and was about 56.4 m long, 24 m wide at the maximum, and as deep as 4.6 m. Scarp height ranged from about 2.4 m at the crown to about 3.7 m along lateral scarps near the toe. The failure surface was irregular, but generally U-shaped in cross section and concave in longitudinal section (Fig. 7). The failure surface slope ranged, in a downslope direction, from 40 to 30° in the upper portion of the source area, and decreased downslope to 20 to 12° near the toe.

The source area contained at least an estimated 2,477 m^3 of material, the majority of which reached the base of the slope below. The failed material consisted entirely of colluvium that had underlain the prefailure, natural 25° slope; no bedrock was exposed in the source area scar. The debris, exposed in scattered deposits in the source area and as levee deposits along the margins of the main track, consisted of dark yellowish-brown (10YR 4/2; dry) to moderate brown (5YR 3/4; wet) silty sand, with 20 ± percent low to medium plastic fines, and 80 ± percent fine- to coarse-grained, poorly graded, angular to subangular sand, and less than 2 percent angular Franciscan greenstone fragments as much as 0.1 m in diameter.

Some debris remained in the source area scar and upper part of the main track. This material originated from a slump-failure on the right side (looking upslope) of the source area shortly after the initial failure. This failure locally produced multiple, superimposed flow lobes that repeated the prefailure, near-surface colluvial stratigraphy. At Station 8+00 to 8+12 (Fig. 8), five "stacked" flow lobes were recognized. These lobes were distinguished by their distinctive, dark-colored organic horizons (topsoil). This exposure was particularly instructive, for initial inspection suggested that the repeated stratigraphy might be evidence of pre–January 4, 1982, slope failures; accordingly, detailed mapping was undertaken.

Main Track. The main track extended some 172 m downslope, where the debris reached building pads at the base of the slope. The main track was roughly hourglass-shaped, flairing from about 10.7 m wide in the center to about 21.3 m wide at both the top and bottom (see Fig. 6). The majority of the slide debris flowed on the average 21° ground surface of the main track, locally stripping vegetation to the roots and removing near-surface topsoil. Elsewhere, delicate grasses were flattened, but not

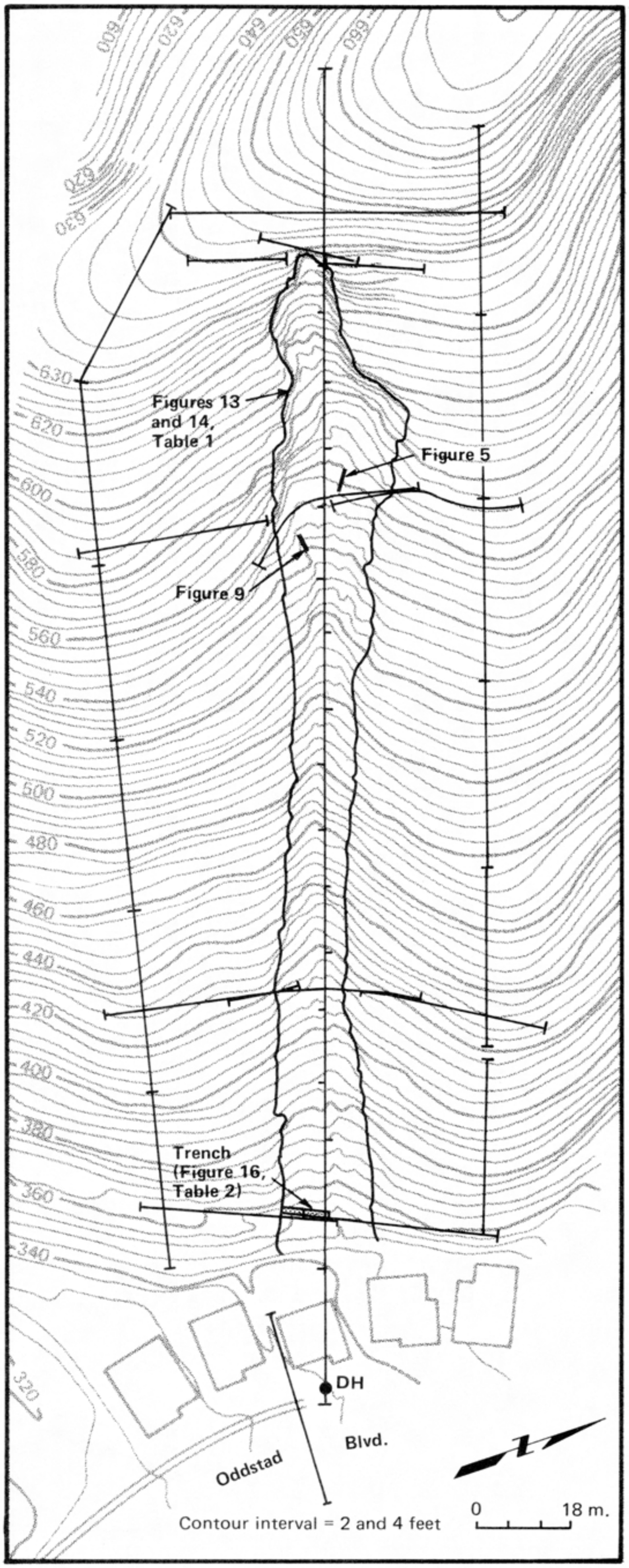


Figure 5. Map of Oddstad slope showing simplified postfailure topography (June 1982); scar of January 4, 1982, debris flow; seismic refraction survey lines; deep drill hole (DH); exploratory trenches; and locations discussed in text.

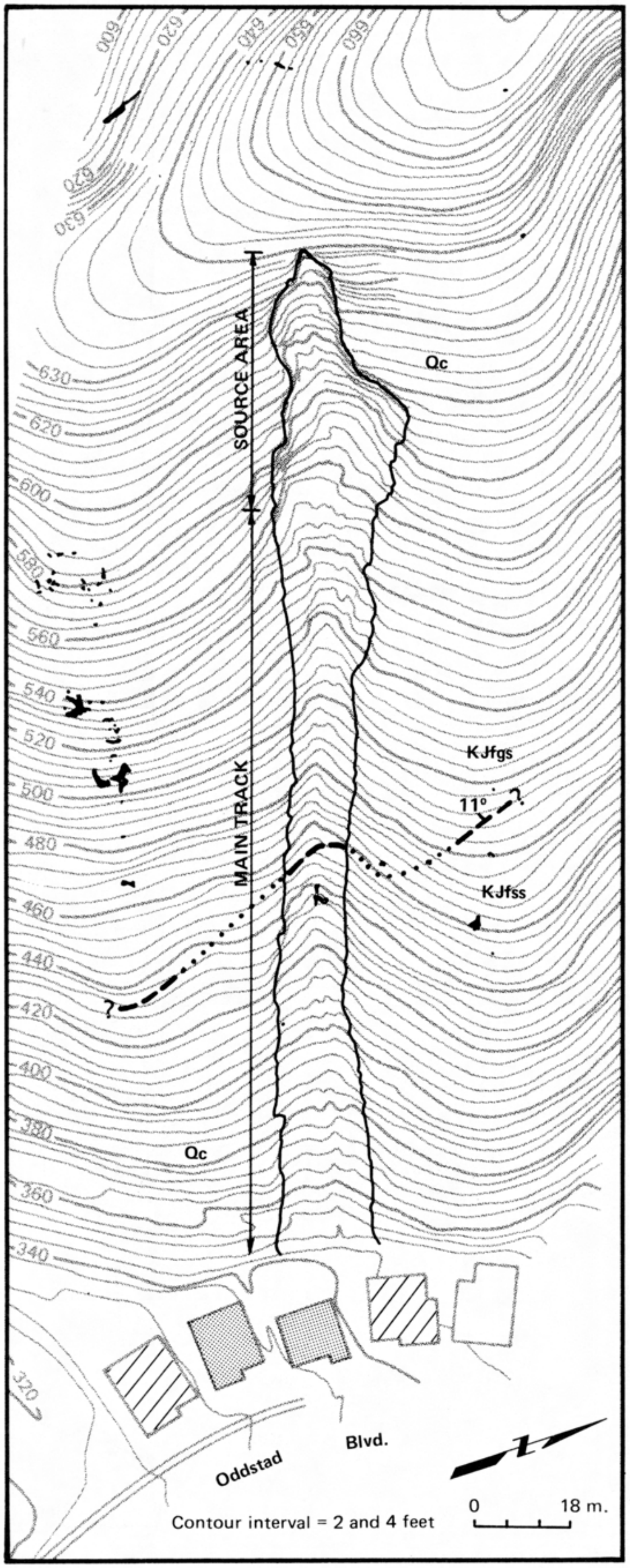


Figure 6. Map of Oddstad slope showing postfailure topography (June 1982) and scar of January 4, 1982, debris flow. Underlying bedrock consists of Franciscan greenstone (KJfgs) and Franciscan sandstone (KJfss), separated by a north-striking, gently west-dipping (11°) shear zone. Solid black areas indicate bedrock outcrops; dot pattern, location of destroyed houses; line pattern, damaged houses.

stripped or buried, suggesting that the debris flow was fluidized and rapid, perhaps "cushioned" by air. Along the margins of the main track, debris was deposited as linear levees, locally exceeding 0.61 m thick, on the prefailure ground surface (Fig 9). Later runoff eroded an axial channel, locally about 1.0 m deep, in the main track, removing debris flow deposits and underlying colluvium, and exposing sheared shale in the vicinity of the bedrock high (see Fig. 7).

The Oddstad failure probably initiated as slump-translational sliding of the saturated colluvium in the lower third of the source area. This apparently resulted in loss of support and near-simultaneous, progressive upslope failure of the remaining two-thirds of the source area. As noted previously, an area on the right side (looking upslope) of the source area failed as a slump sometime after the initial failure, and much of its debris was deposited within the source area scar and upper part of the main track.

Pre-Failure Swale

The natural configuration of the Oddstad slope is shown by the prefailure topography (Fig. 10). The east-southeast–facing slope consisted of a broad, linear, first-order drainage between two parallel spur ridges. The distance between the crests of the ridges was about 76.2 m, and the local topographic relief in the upper swale was about 18 m. The overall axial slope was about 25°.

Stereographic aerial photography extending back to 1941 confirms that the slope was in a natural state, and that no failure had occurred since at least 1941. Pre-late 1960s aerial photography shows that, prior to development in the late 1960s, the swale merged downslope into a fluvial terrace bordering the North Fork of San Pedro Creek. Development essentially buried the terrace and the lower part of the slope beneath fill (see Fig. 7).

Comparison of pre- and postfailure topography (see Fig. 5, 10) and photographic interpretation indicate that bedrock was not exposed in the swale prior to failure. Scattered outcrops on spur ridges and in the eroded axial channel of the main track scar (see Fig. 6) show that the upper half of the slope is underlain by Franciscan greenstone; the lower half is underlain by Franciscan sandstone and shale. The two units are separated by a north-south–trending, gently west-dipping (11°) bedrock fault (see Figs. 7, 10).

The greenstone is intensely to closely fractured, hard, moderately strong to strong, and deeply weathered. The sandstone is generally intensely to closely fractured, hard, strong, and moder-

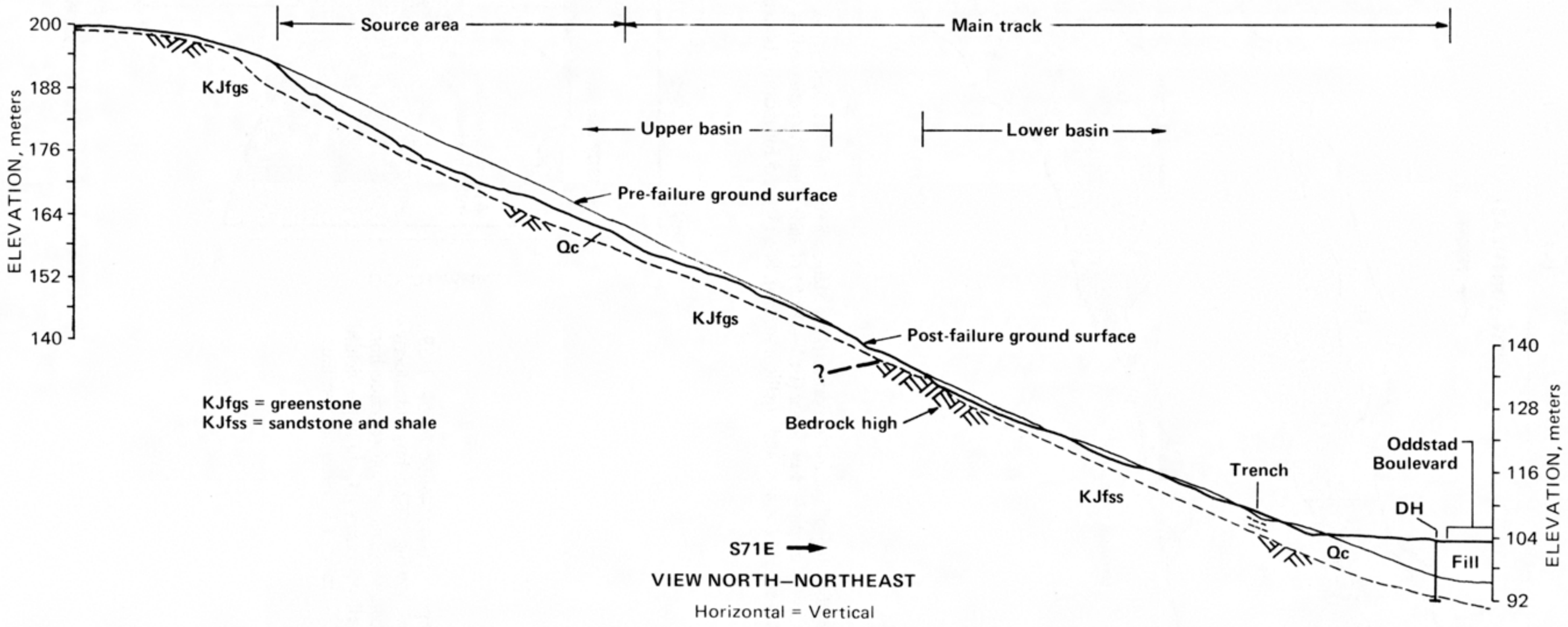


Figure 7. Simplified axial cross section, January 4, 1982, Oddstad debris flow showing prefailure topography; postfailure topography; and approximate colluvium-bedrock contact.

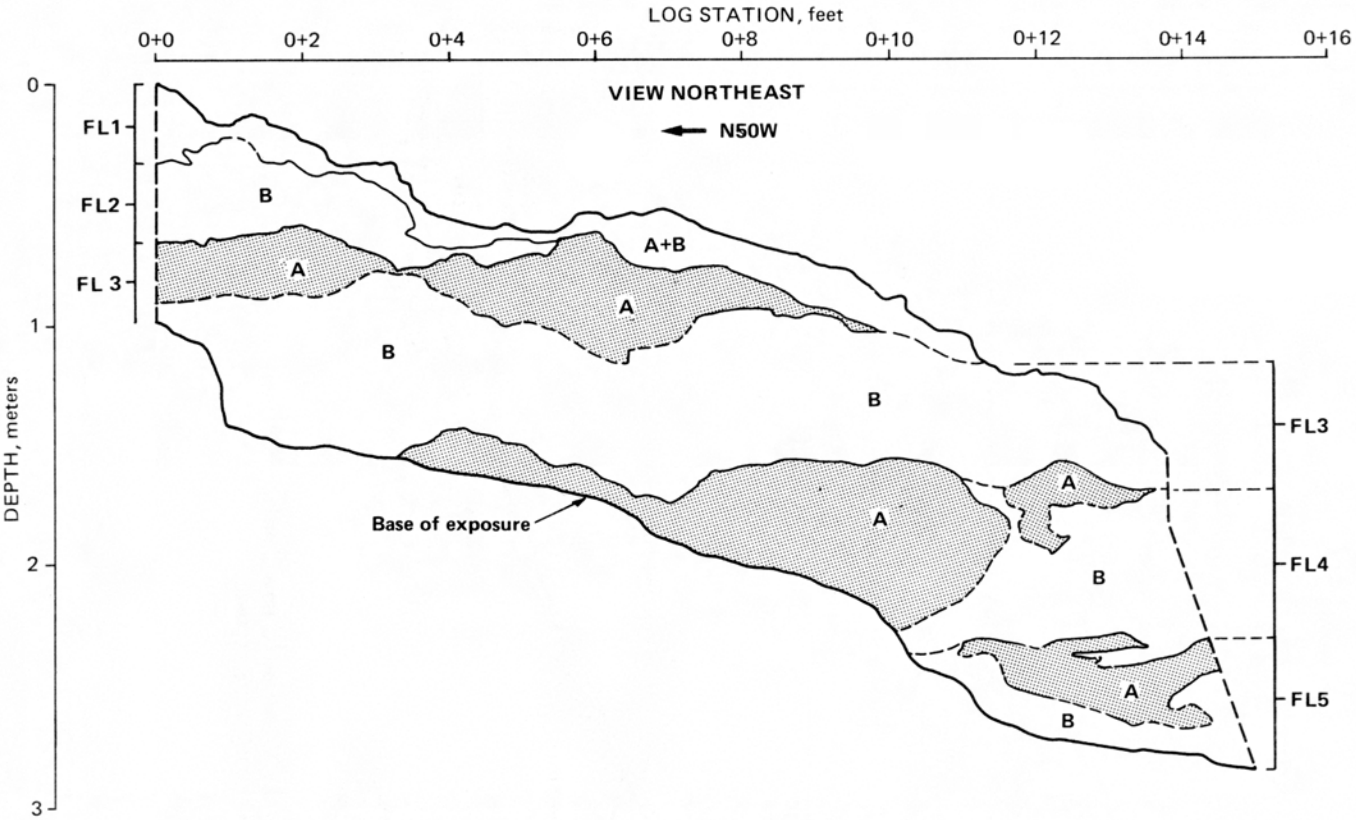
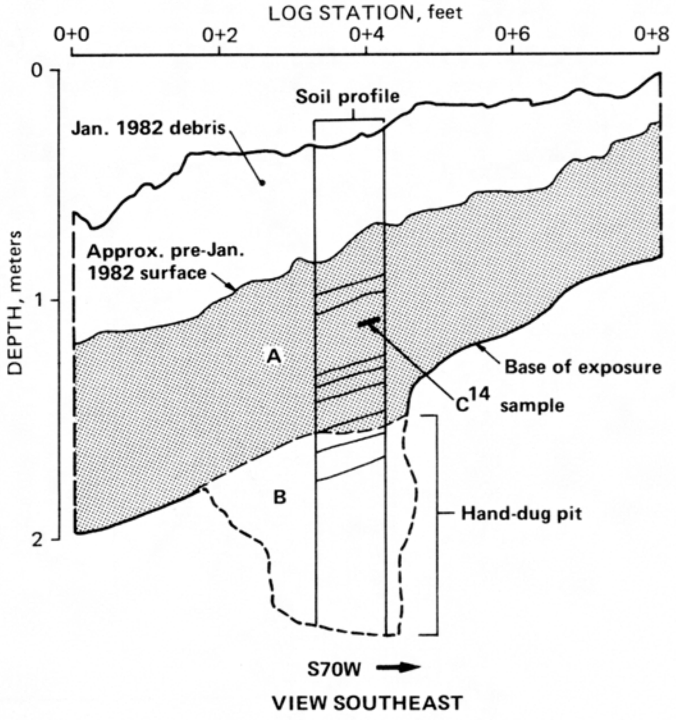


Figure 8. Simplified log of natural exposure (Log Station 8+00 – 8+12), January 4, 1982, Oddstad debris flow showing multiple flow lobes (FL1 – FL5) of slide. Unit A (patterned) is topsoil (organic horizons); unit B subsoil (cambic and argillic horizons). See Figure 5 for location of exposure.

Figure 9. Simplified log of natural exposure (Log Station 7+55 – 7+59), January 4, 1982, Oddstad debris flow showing 1982 debris and underlying (unfailed) colluvium. Unit A (patterned) is topsoil (organic horizons); unit B, subsoil (cambic and argillic horizons). C^{14} sample yielded date of 490 ±60 yr (MRT) BP. See Figure 5 for location of exposure.



ately to little-weathered. The shale below the bedrock fault (topographically and structurally) is intensely fractured (sheared and foliated), moderately strong, and moderately to little-weathered.

The configuration of the bedrock topography underlying the slope is reconstructed from outcrops, hand-auger holes, seismic refraction survey lines, and comparison of pre- and postfailure topography. Such reconstruction (Figs. 7, and 10) shows that the bedrock topography defines two distinct subsurface basins. The upper basin is a closed, elongate trough, concave in longitudinal section, that extends from almost the ridge crest to midslope, just above the bedrock fault. This basin is asymmetric: the right (looking upslope) flank is somewhat steeper than the left, and the "deepest" part of the basin is located in the upper part. The axis of the upper basin is coincident with the axis of the prefailure swale. The concavity of the upper basin bedrock subsurface is similar to the January 4, 1982, failure surface; namely, ranging from about 43° in the upper part, and decreasing to 24 to 21° in the lower part.

The lower basin is downward-opening trough, extending from midslope—below the bedrock fault—downslope and beneath the fill of the developed area (see Fig. 10). The bedrock fault and underlying shale essentially form a relatively resistant bedrock high, separating the two basins.

Following the January 4, 1982, failure, colluvium was exposed everywhere in the source area scar, or upper Oddstad basin. Lateral scarps locally exposed up to 3.7 m of colluvium, generally characterized by grayish-brown (5YR 3/2) to dusky-brown (5YR 2/2) sandy clay topsoil (organic horizons) and moderately yellowish-brown (5YR 5/4) to moderate-brown (5YR 4/4) sandy clay and gravelly clay subsoil (cambic and argillic horizons). Colluvial exposures, together with hand-auger holes, seismic reflection survey lines, and comparison of pre- and postfailure topography permit construction of an isopach map showing the original thickness of upper basin colluvium (Fig. 10). These data indicate that the prefailure thickness of colluvium in the upper basin ranged from more than 6.1 m in the upper part to about 0.61 m over the bedrock high (see Figs. 7, 10).

In addition to distribution and thickness of colluvium, measurements of in-situ dry density and shear test results provide some information about engineering properties (summarized on Figs. 11, 12).

Density of the upper basin colluvium does not progressively increase with depth (see, for example, Reneau and others, 1984), but rather is "scattered." Samples taken from just below the 1982 failure surface show a wide range of densities (Fig. 11). Consoli-

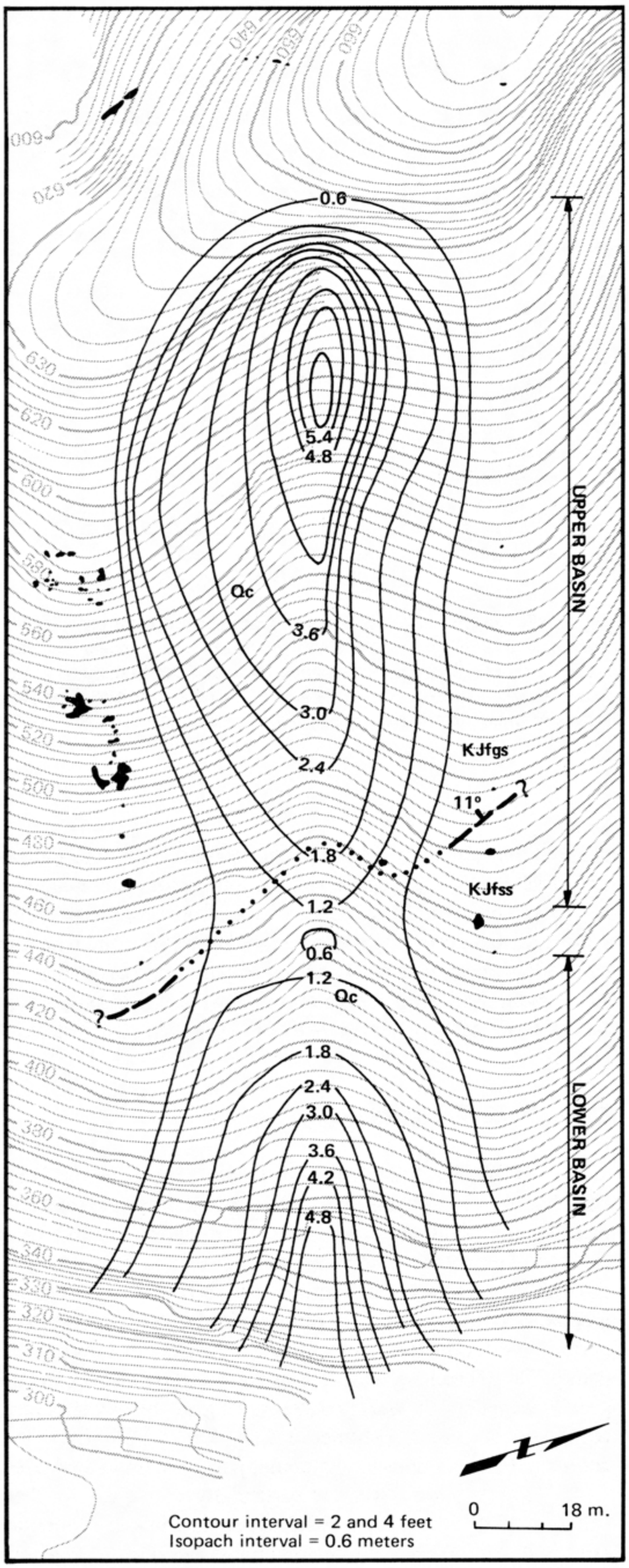


Figure 10. Map of Oddstad slope showing prefailure topography (pre-1970) and isopachs of original colluvium thickness that define two distinct basins. Bedrock units are same as in Figure 6; solid black areas indicate bedrock outcrops. Isopachs based on exposures, auger holes, and seismic refraction survey lines (see Fig. 5).

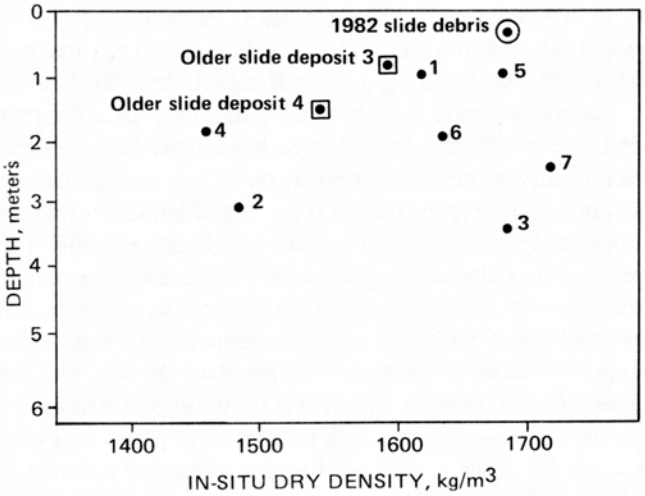


Figure 11. In-situ dry density data from Oddstad colluvium (upper basin: seven samples), derived from Franciscan greenstone; 1982 debris, derived from Franciscan greenstone; and (3) older slide deposits (3 and 4, lower basin), derived from Franciscan sandstone and shale. Upper basin colluvium samples plotted with respect to prefailure ground surface: samples 1 through 3 from just below basal failure surface; sample 4 from lateral scarp; samples 5 through 7 from headscarp.

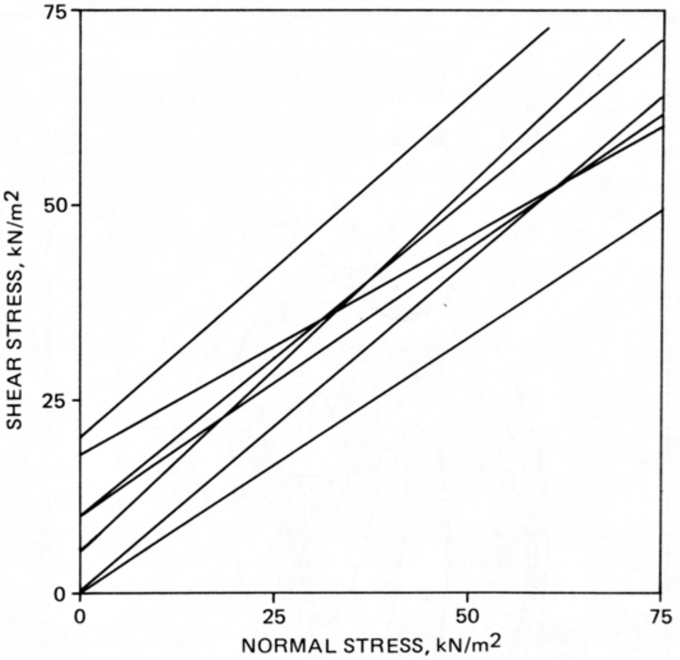


Figure 12. Effective stress failure envelopes derived from consolidated undrained, multistage triaxial shear test data from unfailed Oddstad colluvium (upper basin: seven samples), derived from Franciscan greenstone on undisturbed samples saturated by back pressure. Cohesion ranges from cohesionless to 19.6 kN/m^2; friction angles range from 29 to 43°.

dated, undrained, multistage triaxial shear tests on undisturbed samples of unfailed colluvium saturated by back pressure yield cohesion values from 0 to 1,953 kg/m^2, and angles of internal friction range from 29 to 43° (Fig. 12).

Mechanical analysis and soil stratigraphic data also show that the upper basin colluvium was essentially homogeneous; that is, there were no distinct zones of roots, pedogenic clay, or gravels that might have given rise to distinct permeability contrasts, as has been reported elsewhere (Reneau and others, 1984). Thus, why failure in the Oddstad upper basin swale occurred above the base of the colluvium, rather than at the colluvium-bedrock contact (Fig. 7), remains enigmatic.

SOIL-STRATIGRAPHIC AGE ASSESSMENTS

Soil-stratigraphic techniques are being increasingly applied to engineering-geologic investigations, particularly to reconstruct local geomorphic history, to date last displacements of faults, and, in some cases, to determine the recurrence intervals of mass movements (Shlemon, 1985). Soil stratigraphy includes the field of paleopedology, and generally employs the terms and concepts of the soil scientist. Soil (pedologic) units particularly applicable to the Oddstad debris flow are the organic (A) horizons of the modern solumn and of buried paleosols, frequently containing sufficient organic matter (mollic epipedon) for radiocarbon dating; and the cambic or argillic (B) horizons, subsoil units indicative of relative soil (pedogenic) age. A total of four representative soil profiles were measured and described from headscarp, lateral scarp, and main track exposures in the upper basin, and from the east wall of an approximately 4.9-m-deep trench excavated in the lower basin. Soil-stratigraphic terminology and field procedures follow those of Soil Survey Staff (1951, 1975) and Birkeland (1984).

Upper Basin Soil Stratigraphy

A soil profile from the south lateral scarp (Station 8+64; Figs. 13, 14) is representative and illustrates the unusual thickness of colluvium filling the upper basin. Here, some 7 organic (A_{11} through A_{17}; mollic epipedon) and 11 argillic horizons (B_{11} through B_{110}) composed a more than 3.7-m-thick soil-stratigraphic section (Table 1). The mollic epipedon contained about 5 percent organic matter, and was thus amenable to radiocarbon dating. The subsoil argillic horizons were slightly developed and generally typified by weak, coarse, subangular-blocky structure, reddish-brown colors (Munsell 7.5YR 4/4 = 5YR 4/2), and common, thin clay films filling tubular pores and lining ped faces.

The argillic horizons were particularly instructive, for their "abnormal" thickness in this Mediterranean climatic regime did not result from residual weathering, but rather from pedogenesis

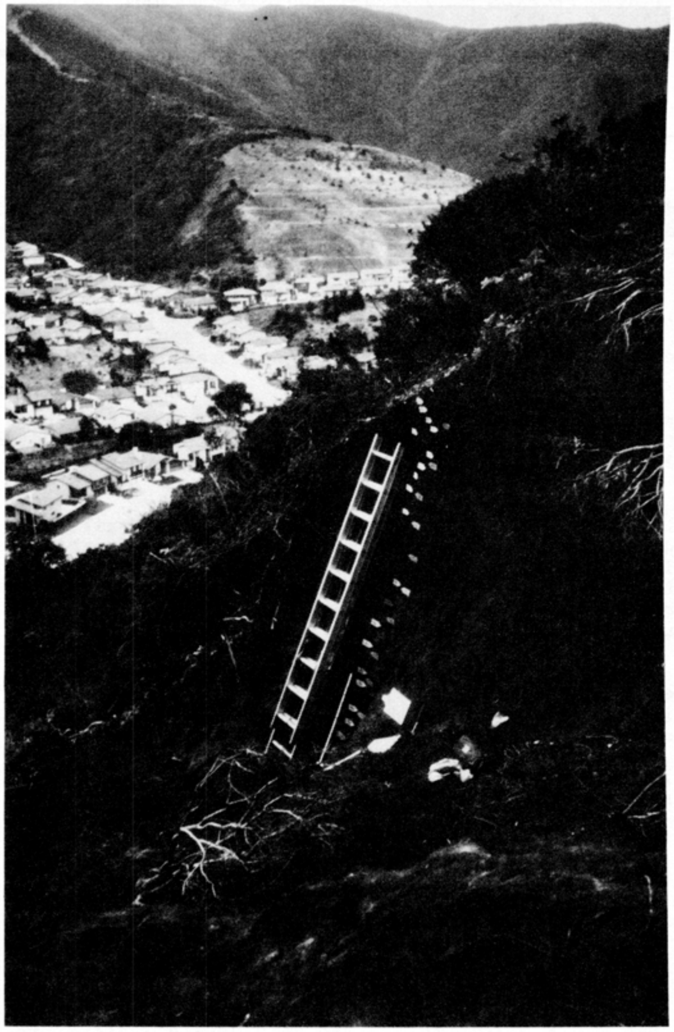


Figure 13. Photograph of lateral scarp of January 4, 1982, Oddstad debris flow taken from source area looking southeast downslope. Ladder and flagging are at soil profile location (Log Station 8+64; see Fig. 5 for location of profile; see Fig. 14 for detail).

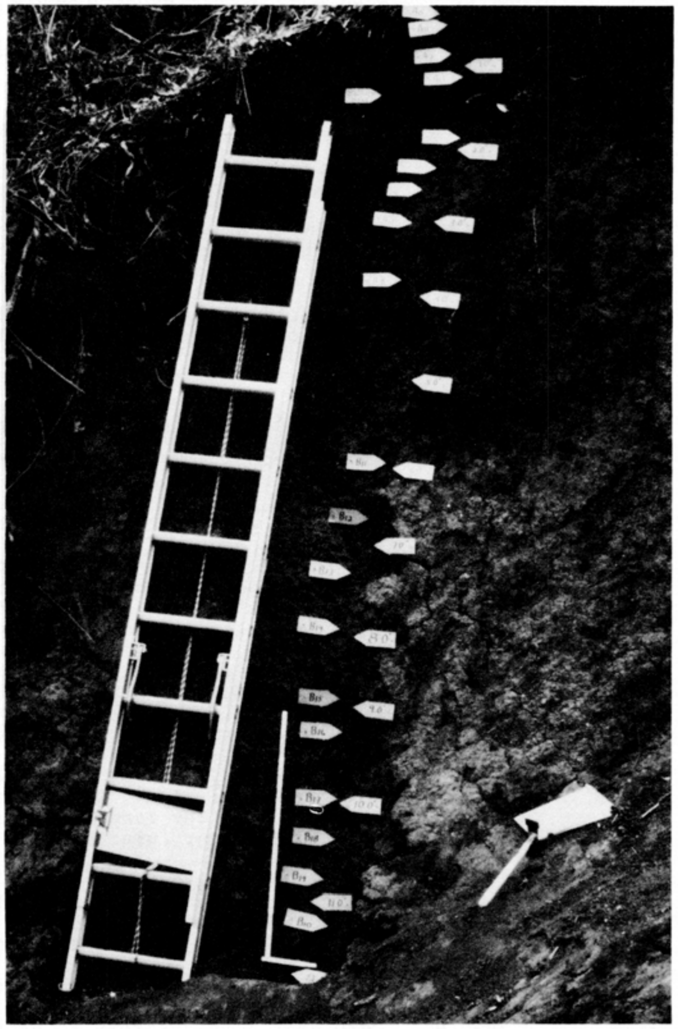


Figure 14. Photograph of Log Station 8+64, south lateral scarp of January 4, 1982, Oddstad debris flow. See Figure 5 for location; see Table 1 for soil profile, measurement, and description; see Figure 15 for soil profile data.

keeping pace with slow sideslope and headwall accretion. The thick soil in the upper basin is thus a cumulic profile ("cumulative" of Birkeland, 1984).

Slow colluvial filling of the upper basin is also substantiated by laboratory mechanical and chemical analyses (Fig. 15). In particular, organic matter decreases uniformly from about 5 percent at the surface to less than 1 percent at depth. These data support field observations that no buried organic horizons, indicative of significant unconformities, occurred in this section.

In addition, particle-size distribution remains relatively constant with depth. This is seen well by the almost uniform distribution of clay in the soil column (see Fig. 15). There were, however, some minor changes in colluvial sedimentation rates as indicated by the presence of weak stonelines in the A_{14} and B_{13} horizons, and by local abrupt and smooth lower boundaries of some soil horizons (see Table 1).

The lack of significant unconformities in the upper basin colluvial section is also shown by the general vertical distribution of sodium and pH at the measured profile. The influx of sodium, presumably eolian-derived from nearby ocean source areas, may cause dispersal of illuvial clays, accelerate soil profile development, and thus give rise to a buried paleosol inherently indicative of an unconformity (Shlemon and Hamilton, 1978). Accordingly, minor breaks in the colluvial section may be recorded by the slight sodium increase in the A_{14} and B_{13} horizons (see Fig. 15).

Soil pH usually reflects contemporary weathering environments, although abrupt changes with depth may well indicate unconformities in a soil-stratigraphic section. However, the cu-

TABLE 1. SOUTH LATERAL SCARP, SURFACE SLOPE 31°, SOIL PROFILE MEASUREMENT AND DESCRIPTION, NATURAL EXPOSURE, STATION 8+64, JANUARY 4, 1982, ODDSTAD DEBRIS FLOW*

Horizon	Depth (m)	Description
0	0.00-0.09	Very dark gray (10YR 3/1) to very dark grayish-brown (10YR 3/2) when moist, silty clay loam; strong, fine granular to moderate fine subangular blocky structure; slightly hard firm, very slightly sticky, nonplastic; many medium to coarse random roots, locally forming organic mat; common, medium vertical roots; common fine pores; gradual wavy to gradual smooth boundary
A_{11}	0.09-0.18	Very dark grayish-brown (10YR 3/2) to very dark brown (10YR 2/2) when moist, silty clay loam; moderate, medium subangular blocky structure; hard to very hard, very firm, nonsticky and non plastic; common, medium vertical roots; common fine pores; gradual wavy to gradual smooth boundary
A_{12}	0.18-0.27	Very dark brown (10YR 2/2); dry and moist, pebbly silty clay loam; hard to very hard, firm, slightly sticky and nonplastic; common fine to medium vertical roots; common fine pores; approx. 10-15 percent angular clasts to 5 mm in diameter, gradual smooth to abrupt smooth boundary
A_{13}	0.27-0.37	Very dark grayish-brown (10YR 3/2) to very dark brown (10YR 2/2) when moist, silty loam; moderate, medium angular blocky to columnar structure; slightly hard, friable to slightly firm, nonsticky and nonplastic; few medium vertical roots; common fine pores; approx. 5 percent angular clasts to 5 mm in diameter, locally, lower boundary typified by few angular clasts to 1-in diameter, forms weak stoneline and unconformity parallel to modern slope; abrupt smooth boundary
A_{14}	0.37-0.55	Very dark gray (10YR 3/1) to very dark brown (10YR 3/2) silty clay; moderate medium to coarse subangular blocky structure; slightly hard, firm, slightly sticky and slightly plastic; few fine and coarse vertical roots; common fine pores; few angular fragments scattered throughout horizon; gradual wavy boundary
A_{15}	0.55-0.67	Very dark grayish brown (10YR 3/2) dry and moist, pebbly silty clay; weak, medium to coarse angular blocky structure; slightly hard, firm slightly sticky and slightly plastic; few fine random roots; few fine pores; approx. 5 percent angular clasts to 5 mm in diameter, gradual wavy to gradual diffuse boundary
A_{16}	0.67-0.79	Very dark grayish-brown to brown (10YR 3/2-7.5-7.5YR 4/2) to very dark grayish-brown (10YR 3/2) when moist, silty clay to silty clay loam; moderate fine to medium angular and weak coarse angular blocky structure; slightly hard, friable, nonsticky and nonplastic; few fine random roots; common, thin, black (10YR 2/1) organic stains on ped faces; approx. 5-8 percent angular clasts to 8 mm in diameter, increasing to approx. 10 percent near base; abrupt smooth boundary
A_{17}	0.79-0.91	Very dark grayish-brown to dark brown (10YR 3/2-7.5YR 3/2) to very dark grayish-brown (10YR 3/2) when moist, silty loam; weak medium angular blocky structure; slightly hard, firm nonsticky and nonplastic; few fine to coarse random roots; common fine pores; few to common, thin, black (10YR 2/1) organic stains on ped faces; common manganese staining within root tubules; approx. 5-8 percent angular clasts to 5 mm in diameter, gradual wavy to gradual diffuse boundary
A-B	0.91-1.16	Brown (7.5YR 4/2) to dark brown (7.5YR 3/2) when moist, silty clay; weak medium angular blocky structure; hard, firm, slightly sticky and slightly plastic; common fine pores; few thin organic stains forming "tongues" on ped faces grading downward into dark brown (7.5YR 3/2), few, moderately thick clay films on ped faces and filling old vertical root tubules; few angular clasts to 5 mm in diameter, gradual smooth boundary
B_{11}	1.16-1.83	Brown (7.5YR 4/2) dry and moist, light silty clay; moderate medium angular blocky structure; slightly hard to hard, firm, sticky and plastic; few to common fine roots; few fine pores; 5-6 stratified illuvial clay lenses to 5-mm thickness superimposed on weakly stratified colluvial parent material; few, moderately thick dark reddish-brown (5YR 3/2) clay films on ped faces; stratified colluvial units with apparent dip of 18-20° downslope; horizon is cumulic, weakly stratified silty clay-silty clay loam; clay films concentrated in old root tubules and channels; approx. 5 percent angular clasts, random, to 5 mm in diameter, gradual wavy boundary
B_{12}	1.83-2.04	Brown (7.5YR 4/4) to brown (7.5YR 4/2) when moist, sandy clay loam; moderate medium angular blocky structure; hard, firm, sticky, slightly plastic to plastic; common fine to coarse vertical roots; common, thin clay films bridging mineral grains, and common, thin dark brown (7.5YR 3/2) clay films lining root tubules; approx. 5 percent very angular clasts to 10 mm in diameter, gradual smooth boundary
B_{13}	2.04-2.25	Brown (7.5YR 4/2) dry and moist, pebbly sandy loam; moderate medium to coarse subangular blocky to weak medium to coarse columnar structure; hard, firm, slightly sticky and slightly plastic; few medium random roots; common, moderately thick dark reddish brown (5YR 3/2) clay films on ped faces, and common, thin, illuvial clay lining root tubules; approx. 15 percent angular clasts to 8 mm in diameter, horizon delimiting weakly stratified colluvial parent material; gradual smooth to gradual wavy boundary

TABLE 1. SOUTH LATERAL SCARP, SURFACE SLOPE 31°, SOIL PROFILE MEASUREMENT AND DESCRIPTION, NATURAL EXPOSURE, STATION 8+64, JANUARY 4, 1982, ODDSTAD DEBRIS FLOW* (continued)

Horizon	Depth (m)	Description
B_{14}	2.25-2.50	Brown (7.5YR 4/4) to brown (7.5YR 4/2) when moist, silty clay loam; weak to moderate angular blocky structure; slightly hard, firm, slightly sticky and slightly plastic; few medium random roots; common, moderately-thick dark reddish gray (5YR 4/2) clay films bridging mineral grains and lining ped faces; few angular clasts near horizon base with few moderately thick illuvial clay coating on pebble faces; gradual wavy boundary
B_{15}	2.50-2.74	Brown (7.5YR 4/4) dry and moist, silty clay; weak, moderate subangular blocky structure; slightly hard to hard, firm, slightly sticky and slightly plastic; very fine to fine random roots; common, moderately thick, dark reddish-gray (5YR 4/2) clay films bridging mineral grains and lining ped faces; approx. 5 percent angular clasts near top of horizon to 10 percent angular clasts near base to 5 mm in diameter, gradual smooth to abrupt smooth boundary
B_{16}	2.74-2.86	Brown (7.5YR 4/4) to brown (7.5YR 4/2) when moist, heavy pebbly silty clay; weak, fine subangular blocky structure; hard, firm, slightly sticky and slightly plastic; few fine vertical roots and few to common old root channels; common, moderately thick clay films lining ped faces and coating clasts; approx. 30 percent, highly weathered angular clasts; gradual wavy to gradual smooth boundary
B_{17}	2.86-3.14	Brown (7.5YR 4/4) dry and moist, pebbly silty clay; weak, medium angular blocky structure; hard, firm, slightly sticky and slightly plastic; many fine old root channels, reticulate form; common, moderately thick, dark reddish-brown (5YR 3/2) clay films lining root tubules; local manganese staining bordering few, medium modern roots; illuvial clay films increasing toward base of horizon; horizon weakly stratified colluvial unit; gradual smooth boundary
B_{18}	3.14-3.26	Brown (7.5YR 4/2) to dark reddish-gray (5YR 4/2) when moist, silty loam; weak, fine subangular blocky structure; slightly hard, friable, slightly sticky and slightly plastic; common, old root channels, reticulate form; common, moderately thick, dark reddish-brown to weak red (5YR 3/2-2.5YR 4/2) clay films lining ped faces and filling old root tubules; local manganese staining; approx. 5 percent fine, weathered angular clasts; gradual wavy boundary
B_{19}	3.26-3.41	Similar to B_{18} in color, texture, structure, plasticity, and consistency; many very fine old root channels with reticulate form; common, moderately thick to thick, weak red (2.5YR 4/2) illuvial clay films filling root channels; gradual wavy boundary
B_{110}	3.41-3.65+	Similar to B_{18} in color, texture, structure, plasticity, and consistency; many fine pores; common fine old root channels; random with reticulate form; approx. 15 percent angular clasts to 5 mm in diameter, base of exposure

*See Figure 5 for location of profile; see Figure 15 for soil profile data.

mulic, upper basin soil displays no major breaks in pH gradient, but rather decreases gradually with depth, most likely reflecting the distribution of subsoil organic acids (see Fig. 15).

An upper basin soil-stratigraphic section was also described from an exposure along the eroded axial channel just below the source area (Station 7+57; see Fig. 9). Here measurements were made and samples collected from the natural exposure and from a 0.9-m-deep hand-dug pit. At this locality, between 0.3 and 0.9 m of 1982 slide debris (levee deposits) overlay organic horizons developed on older colluvium. About 1.7 m of buried organic and underlying argillic horizons were exposed here; an additional 2.6 m of colluvium underlay this section, and more than 6.1 m was present in the deepest part of the upper basin (see Fig. 10). The colluvium here was comparable to that in the headscarp and lateral scarp areas; namely, silty and clayey sand bearing several black (10YR 2/2) to dark gray (10YR 3/1) organic horizons overlying dark reddish-brown (5YR 3/2), slightly developed, argillic horizons.

Field measurements and laboratory data indicate that no buried paleosols or unconformities were present in this section. This, together with the relatively homogeneous grain-size distribution, suggests that here sediments slowly filled the upper basin. An approximate sedimentation rate is provided by a radiocarbon date of 490 ± 60 yr (Beta-5054), obtained at about 0.45 m below the prefailure ground surface, from the organic horizon buried by the January 4, 1982, debris flow (A_{14b}; see Fig. 9). The radiocarbon age is minimal, for it is a mean residence time date, derived from a bulk sample with 4.9 percent organic matter. Such near-surface samples are inherently contaminated by modern organic acids, but nevertheless, with appropriate corrections, have proven useful to estimate colluvial sedimentation rates (Yaalon, 1971). The almost 500-yr-old MRT age, dating the upper 0.45 m of an

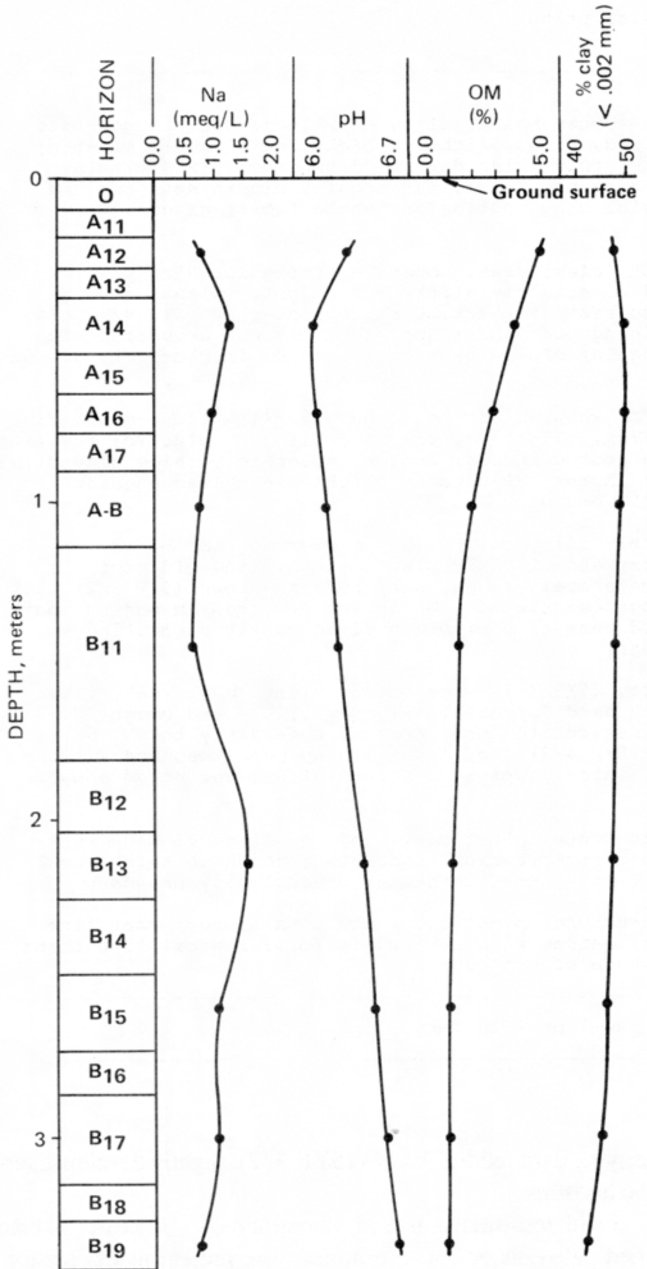


Figure 15. Soil profile data, natural exposure (Log Station 8+64), unfailed colluvium in lateral scarp of January 4, 1982, Oddstad debris flow, showing sodium (Na) content in milliequivalents per liter; pH; percentage of organic matter (OM); and percentage of clay content. See Figure 5 for location of profile.

approximately 6.1-m-thick total cumulic section, yields an average sedimentation rate of about 0.61 m/1,000 yr, thus suggesting that fluvial incision on the Oddstad swale ceased, and that colluviation began some 8,000 to 10,000 yr ago (Shlemon and Wright, 1983).

Lower Basin Soil Stratigraphy

A representative soil stratigraphy for the lower basin was measured on the east wall of an approximately (maximum) 4.9-m-deep trench exposure (Station 3+26; see Fig. 5). Here, including the January 4, 1982, deposits, five debris flow deposits were identified (Fig. 16). The deposits were distinguished by lithology, angularity of clasts, and capping buried paleosols. In contrast to the homogeneous colluvium of the upper basin, these deposits and soils indicate that at least four debris flows had occurred in the lower basin prior to the January 4, 1982, event. Moreover, based on clast lithology (sandstone and shale) and size, the flows emanated almost wholly from within the lower basin, apparently originating at or downslope from the bedrock high (see Fig. 7).

Debris Deposit 1. Levee deposits of the January 4, 1982, debris flow up to 0.24 m were present at the trench site. The deposits (1) consisted of moderate brown (5YR 3/4) silty sand containing approximately 20 percent low plastic fines, 75 to 80 percent fine- to coarse-grained sand, a trace to 5 percent fine gravel. Up to 50 percent plant debris was layered at the base of the deposit.

Older Debris Deposit 2. Of the four older debris flow deposits beneath the January 4, 1982, debris, three were present at the measured profile. An older debris flow deposit (2) was encountered within 0.3 m of the surface (Table 2). This deposit bears a slightly developed paleosol. The now-buried organic horizons (A_{11} through A_{13}) were very dark brown (10YR 2/2 – 3/2) in color, and silty clay to pebbly loam in texture. Field observations showed that an apparent abrupt increase in clay content between the A_{11} and A_{12} horizons, indicated by laboratory mechanical analyses data (Fig. 17), was not pedogenic in origin, but rather the result of parent-material stratification.

The subsoil was a cambic horizon (B), distinguished mainly by its reddish-brown (5YR 5/6) color. A few thin clay films lined ped faces and bridged mineral grains, but were insufficient to classify the horizon as argillic. An abrupt wavey lower boundary marked the unconformity with the underlying buried paleosol (see Table 2).

Laboratory data showed that soil organic matter decreased with depth. However, the A_{11} horizon contained about 4 percent organic matter (see Fig. 17), adequate to yield an MRT date of 1950 ± 170 yr (Beta-6023). This date indicates that slide debris in the lower basin had not failed nor had been capped by upslope sediments for at least the last 2,000 yr.

Older Debris Deposit 3. A third, older debris flow deposit (3), approximately 1.4 m thick, was also exposed in the trench (Fig. 16). This deposit was likewise capped by a buried paleosol, here typified by approximately 0.61- and 0.91-m-thick organic

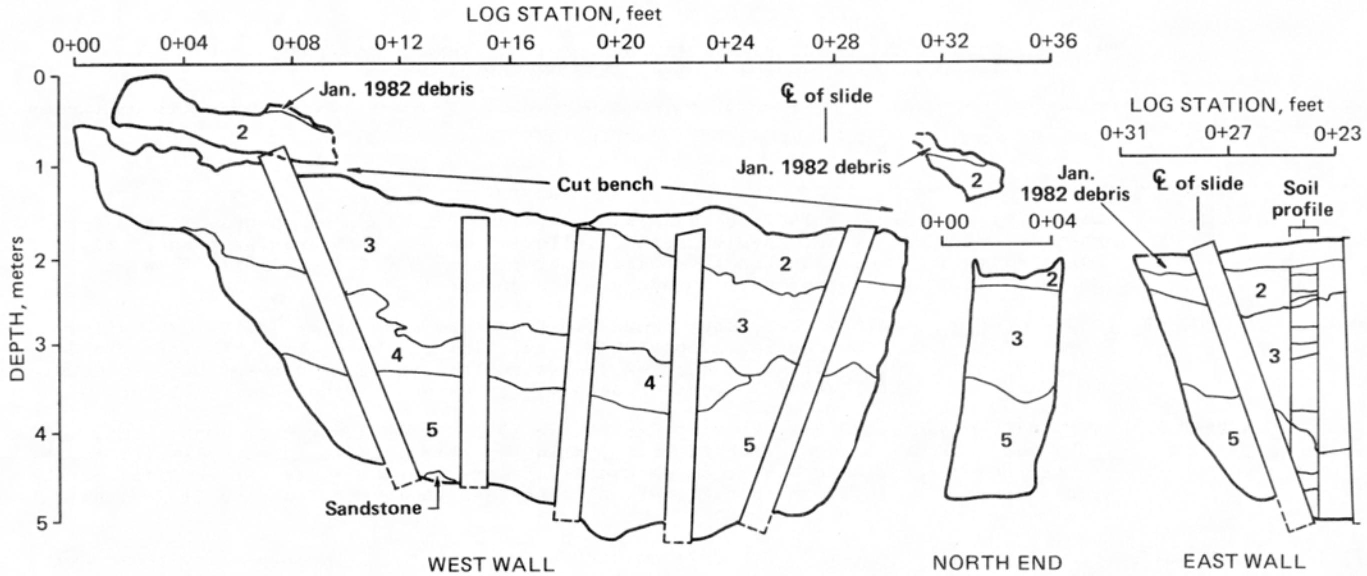


Figure 16. Simplified log of trench exposure, January 4, 1982, Oddstad debris flow showing 1982 slide debris overlying superimposed older debris deposits (2 through 5) of lower basin. C^{14} samples from deposits 2 and 3 yielded dates of 1,950 ± 170 yr (MRT) BP, and 2,910 ± 80 (MRT) BP, respectively. See Figure 5 for location of trench; see Table 2 for soil profile measurement and description; see Figure 17 for soil profile data.

($11A_{11b}$ through $11A_{13b}$) and cambic ($11B_{11b}$ through $11B_{12b}$) horizons, respectively (see Table 2).

The buried organic horizons contained up to 3 percent organic matter (horizon $11A_{11b}$; see Fig. 17), and yielded an MRT radiocarbon date of 2,910 ± 80 yr (Beta-6024). Soil textures ranged from clay loam to pebbly clayey loam; but angular clasts of sandstone and shale, derived wholly from the lower basin, were common throughout the unit. An approximately 5 to 8 percent increase in subsoil clay (see Fig. 17) was essentially pedogenic in origin, indicated by thin clay films lining ped faces and filling tubular pores (see Table 2).

Older Debris Deposit 4. A fourth, older debris flow deposit (4), approximately 0.6 m thick, was exposed in the left end (looking upslope) of the trench (Fig. 16). It was not present at the measured profile, and was either not originally deposited at this location or was eroded prior to deposition of older debris deposit 3. This deposit consisted of moderate yellowish-brown (10YR 4/4) sandy clay with approximately 60 percent medium plastic fines, 40 percent fine- to coarse-grained, poorly graded, subangular sand, and 2 percent subangular gravel up to 13 mm in maximum dimension.

Older Debris Deposit 5. A still older debris deposit (5) and capping buried paleosol was encountered in the trench at a depth of 1.9 m (see Table 2). Only the buried argillic horizon was preserved: the organic horizons typically were either mechanically eroded or chemically oxidized. The argillic horizon was a dark reddish-brown (5YR 3/4 – 4/4) gravelly sandy clay, with moderate medium- to coarse-angular blocky structure, and common, moderately thick clay films lining ped faces ($IIIB_{2b}$; see Table 2). This soil was moderately developed, and, by comparison with the overlying radiometrically dated, slightly developed buried paleosols, probably represented some 2,000 to 4,000 yr of weathering. It therefore appears that the four pre-1982 buried debris deposits and their capping soils in the lower basin trench probably formed over a several-thousand-year period. Accordingly, episodic debris flows apparently occurred in the lower basin about every 1,000 to 4,000 yr. The deposits exposed in the trench thus record an almost complete history of lower basin slide occurrence from early Holocene and perhaps even from late Pleistocene time.

EVOLUTION OF THE COLLUVIUM-FILLED SWALE

The Oddstad swale is one of hundreds in the Pacifica area in which at least some colluvium failed during the January 3–5, 1982, storm. However, many more did not fail. Based on our site-specific information, and on reconnaissance in the San Francisco Bay area, we propose a general three-stage evolutionary model for the Oddstad colluvium-filled swale. This swale may be unusual, for it contains two distinct basins, an upper and a lower, each of which had a different history of colluvial filling and failure. Nevertheless, because similar swales may occur in a wide variety of geomorphic and geologic environments, and the processes are applicable to all swales, we present the Oddstad case as

TABLE 2. SOIL PROFILE MEASUREMENT AND DESCRIPTION, TRENCH EXPOSURE, STATION 3+26, JANUARY 4, 1982, ODDSTAD DEBRIS FLOW*

Horizon	Depth (m)	Description
		Debris Flow of January 1982: very dark brown (10YR 2/2) to pinkish-gray (7.5YR 6/2) when moist; mixed organic sediments and colluvium with common angular clasts; many large horizontal roots at base; deposits contorted; 0.5-0.6 m of debris flow at measured locality; abrupt wavy boundary (unconformity)
A_{11}	0.00-0.09	**Older Debris Deposit 2:** Very dark brown (10YR 2/2) to dark brown (7.5YR 2/2) silty clay loam; weak, fine angular blocky structure; slightly hard, friable, sticky and plastic; many fine vertical roots; few coarse roots; approx. 5 percent angular pebbles to 3 mm in diameter, gradual smooth boundary; C^{14} date of 1950±170 yr (MRT) BP
A_{12}	0.09-0.30	Very dark brown (10YR 2/2) to very dark brown (7.5YR 3/2) sandy clay loam; weak, medium subangular blocky structure; hard, firm, slightly sticky and slightly plastic; few fine roots; few coarse roots with thin manganese stains; approx. 5 percent reddish, angular sandstone clasts to 51 mm in diameter, slickensided shale fragments to 51-mm-long diameter, gradual smooth boundary
A_{13}-B	0.30-0.40	Very dark grayish-brown (10YR 3/2) to dark brown (7.5YR 3/2) pebbly silty loam; weak, medium subangular blocky structure; hard to very hard, firm, slightly sticky and slightly plastic; few medium and few coarse random roots; few thin clay films in root tubules; approx. 5 percent angular clasts to 3 mm in diameter, gradual wavy boundary
B	0.40-0.52	Dark brown (7.5YR 3/2) to reddish-brown (5YR 4/4) pebbly silty clay loam; common fine to medium subangular blocky structure; hard, firm, sticky and plastic; few fine vertical roots with manganese stains; few thin clay films on ped faces and bridging mineral grains; approx. 10 percent very angular shale and red sandstone clasts concentrated near base; horizon lenticular increasing to 0.6 m+ laterally; lower boundary relief to 76 mm, abrupt wavy boundary (unconformity)
$11A_{11b}$	0.52-0.73	**Older Debris Deposit 3: Buried Paleosol:** Very dark brown (10YR 2/2) silty clay loam; weak fine to dark medium subangular block structure; slightly hard, firm, sticky and plastic; few fine vertical roots; common fine pores; approx. 5 percent very angular reddish sandstone and volcanic clasts; gradual smooth boundary; C^{14} date of 2,910±80 yr (MRT) BP
$11A_{12b}$	0.73-0.88	Dark yellowish-brown (10YR 3/4) silty clay; weak to moderate fine angular blocky structure; hard, firm, sticky and plastic; few fine roots; common, fine pores; few coarse roots with manganese stains; approx. 5 percent angular reddish volcanic clasts to 3 mm in diameter, gradual smooth boundary
$11A_{13}$-B_b	0.88-1.06	Dark yellowish-brown (10YR 3/4) to dark brown (10YR 3/4) to dark brown (7.5YR 3/2) silty clay; moderate, medium subangular blocky structure; very hard, firm, sticky and very plastic; few fine roots; few very fine pores; few thin clay films bridging mineral grains and filling tubular pores; gradual smooth boundary
$11B_{11b}$	1.06-1.62	Dark yellowish-brown (10YR 3/4) pebbly silty clay loam; moderate medium to coarse subangular blocky structure; hard to very hard, firm, sticky and plastic; few coarse old root casts with manganese stains; few thin clay films filling tubular pores and lining ped faces; approx. 5-10 percent angular clasts; continuous wavy boundary
$11B_{12b}$	1.62-1.89	Dark brown (10YR 3/3) silty clay; moderate to strong, medium to coarse angular blocky structure; hard to very hard, very firm, sticky and very plastic; common, fine old root casts; few thin clay films on ped faces; common pressure faces; abrupt wavy to abrupt irregular boundary (unconformity)
$111B_{1b}$	1.89-2.38	**Older Debris Deposit 5: Buried Paleosol:** Dark reddish-brown (5YR 3/4) pebbly silty clay; moderate medium to coarse angular blocky structure; hard to very hard, very firm, sticky and very plastic; few common clay films (thin) bridging mineral grains and filling tubular pores; approx. 10 percent highly weathered clasts to 3 mm in diameter at top of horizon increasing to approx. 25-30 percent shale clasts to 51-mm diameter near base; gradual wavy boundary
$111B_{2b}$	2.38-2.74	Reddish-brown (5YR 4/4) gravelly sandy clay loam; moderate medium angular blocky structure; hard, firm, sticky and plastic; few fine old root casts; few to common thin to moderately thick clay films on ped faces; approx. 50-60 percent very angular shale clasts from upslope fault zone (bedrock) to 76-mm diameter, resistant unit to base of trench

*See Figure 5 for location of profile; see Figure 17 for soil profile data.

a comparative model to understand better the engineering geology of such features.

Stage 1: Fluvial Incision

The initial highland topography of the San Pedro basin had greater relief than the present. First-order drainages, as now, probably extended to ridge lines, but were essentially devoid of colluvium. Fluvial incision, rather than channel filling, was the dominant slope-forming process. Here, both the upper and lower Oddstad basins were formed, with bedrock relief reflecting differential erosion across a bedrock fault and various lithologic units comprising the underlying Franciscan Formation. Based on radiocarbon, soil-stratigraphic and palynologic dating of swales in California, such fluvial incision most likely took place during the late Pleistocene, a time of different climatic, vegetative, and hydrologic regimes (Shlemon and Wright, 1983; Dietrich and Dorn, 1984; Reneau and others, 1984; Marron, 1985).

Stage 2: Swale Filling

With the onset of the Holocene, changing environments apparently led to accumulation of colluvium in formerly incised low-order drainages. As shown by the Oddstad swale, the filling history was likely very complex. For example, in the upper basin, colluvium slowly accumulated. No buried paleosols, stonelines, or other evidence of significant unconformities were present to indicate possible episodic colluvial filling and flushing. Colluvial accretion here occurred for at least the last 8,000 to 10,000 yr. In contrast, the lower basin was filled and partially emptied several times. Here, the presence of multiple debris flow deposits, some capped by slightly to moderately developed buried paleosols, attest to episodic filling and failure. Radiocarbon dates and relative soil profile development suggest that lower basin debris flows occurred in intervals of about 1,000 to 4,000 yr. This frequency may be the geologic "norm," for comparable filling and failure frequency has been reported for swales in northwestern California (Marron, 1985) and elsewhere in the San Francisco Bay area (Reneau and others, 1984).

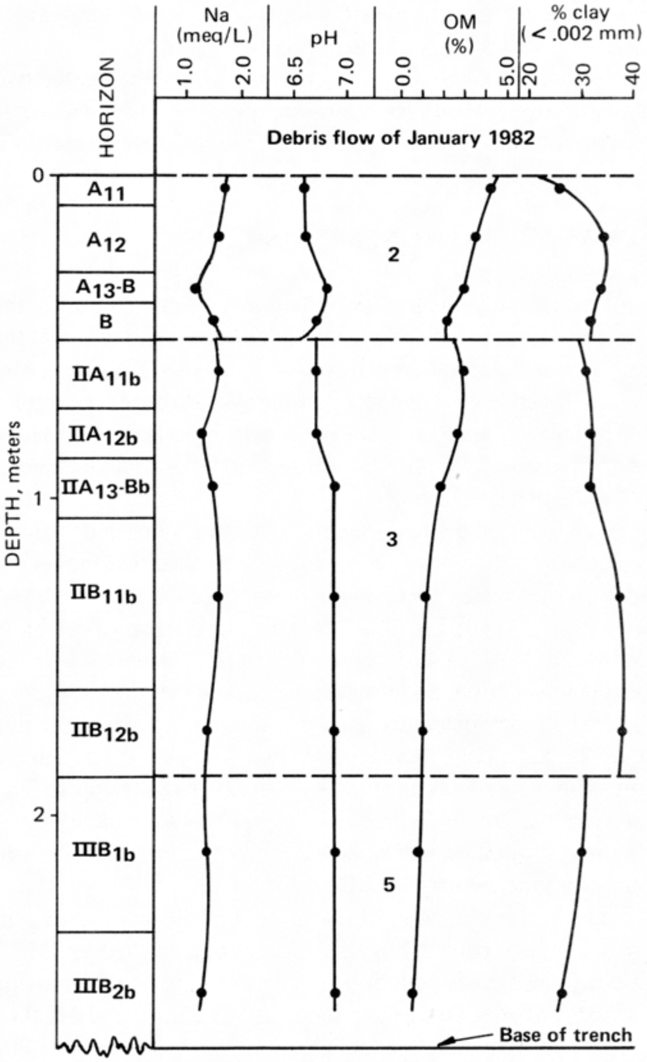


Figure 17. Soil profile data, trench exposure (Log Station 3+26), January 4, 1982, Oddstad debris flow, showing: sodium (Na) in milliequivalents per liter; pH; percentage of organic matter; and percentage of clay content. Unconformities (dashed lines) separate older debris deposits 2, 3, and 5 of lower basin. See Figure 5 for location of trench; see Figure 16 for trench log; see Table 2 for soil profile measurement and description.

Stage 3: Failure and Swale Exhumation

With slope failure occasioned by long and intense precipitation, the upper Oddstad basin became partially exhumed, and, but for subsequent slope repairs, would have left a complex stratigraphic legacy. For example, although much of the upper basin colluvium was removed during the January 4, 1982, failure, some remained in the source area, either in place or locally slumped or overriding other slump blocks. This added to stratigraphic complexity by apparent "stacking" of soil organic horizons (see Fig. 8). Superficially, these organic horizons resembled multiple buried paleosols. Only detailed mapping showed that these were but remnants of prefailure near-surface materials. If left unrepaired, the remaining slide debris and unfailed colluvium in the upper basin would have failed over time, essentially exhuming the upper basin. In time, the upper basin would again slowly fill with colluvium.

The final, exhumed stage of swale evolution in the lower Oddstad basin was precluded by urban development along the base of the slope in the 1960s. During the 1982 event, near-surface sediments were locally scoured by the passing debris flow and by later runoff that eroded gullies down the center of the main track. Elsewhere, as in the vicinity of the trench, debris was deposited as levees. If the slope had been left unrepaired and the debris not removed by subsequent erosion, the deposits would have added to the late Pleistocene and Holocene stratigraphic record of debris flows in the lower basin.

In sum, although only a single topographic feature, the two colluvium-filled subsurface basins underlying the Oddstad swale evolved differently, providing contrasting models of fluvial incision, episodic filling, and exhumation.

SUMMARY AND CONCLUSIONS

Of the many shallow slope failures in Pacifica during the storm of January 3–5, 1982, the Oddstad debris flow was the most destructive, producing loss of life and substantial property damage. Later detailed investigations provided special opportunities to analyze the anatomy of the debris flow, to determine the age and recurrence of prior failures, and to reconstruct the evolution of the prefailure slope.

The Oddstad debris flow emanated from a first-order drainage, a complex two-basin, colluvium-filled swale that previously had been manifested only by a small topographic "crenulation." The January 4, 1982, debris flow originated in an upper basin filled with at least 6.1 m of colluvium. The flow essentially passed over the lower basin, and into the developed area downslope.

Soil-stratigraphic measurements and descriptions show that the upper basin colluvium accumulated very slowly such that a more than 3.7-m-thick cumulic soil profile had developed. This colluvium was internally free of buried paleosols, stonelines, and other unconformities, indicating that colluviation essentially continued until the January 4, 1982, failure.

The mollic epipedon of the upper basin cumulic soil contained about 5 percent organic matter, and yielded an MRT radiocarbon date of about 500 yr. This date, although inherently minimal, provides an average sedimentation rate of about 0.61 m/1,000 yr, suggesting that colluviation here began about 8,000 to 10,000 yr ago.

In contrast, the lower basin contained evidence of several older debris flows. Here, a 4.9-m-deep trench exposed five distinct debris flow deposits, including those of January 4, 1982. The older debris flow deposits were distinguished mainly by clast lithology and angularity, and by the presence of capping buried paleosols. MRT radiocarbon dates of approximately 2 and 3 ka provided minimum ages for the upper two deposits underlying the January 4, 1982, debris. A stratigraphically lower and older deposit was capped by a moderately developed argillic horizon that, when compared in morphology to the overlying, dated paleosols, probably formed in about 2,000 to 4,000 yr. Accordingly, debris flows originating in the lower basin recurred episodically about every 1,000 to 4,000 yr.

A generalized three-stage model is proposed to explain the contrasting evolution of the upper and lower basins. Initially, first-order drainages were incised by fluvial processes, presumably under climatic, vegetative, and hydrologic conditions of the late Pleistocene. With onset of the Holocene, a second stage of evolution began when colluvium began to fill the upper basin. Such colluviation continued essentially uninterrupted until a local geomorphic threshold was reached, and failure ensued on January 4, 1982. In contrast, the lower basin was, in part, episodically filled and flushed. Each debris flow on the lower slope remained sufficiently stable such that a soil profile formed, eventually to be buried by younger deposits. The third stage of slope evolution was attained by the upper basin on January 4, 1982, when failure occurred and exhumation began. Here, fluvial incision would likely again have taken place had not slope repairs been made. In contrast, slope evolution in the lower basin was essentially aborted in the 1960s. Locally it received sediments from upslope on January 4, 1982, and was, in essence, still in a stage of filling, albeit episodic, prior to being repaired.

The Oddstad debris flow is but one of many that occurred in the central Coast Ranges of California. Its anatomy and evolution are complex; nevertheless, the case study data obtained may prove beneficial to engineering geologists who encounter colluvium-filled swales elsewhere.

ACKNOWLEDGMENTS

We gratefully acknowledge the support of R. Burford, F. Latimore, and J. McKibben for authorizing this investigation. Additionally, we thank P. Frame and P. Shires for field assistance, specifically for carrying out mapping and geophysical surveys, respectively. Our appreciation also extends to T. Camara for preparation of illustrations, to J. Costa and G. Wieczorek for review, to M. Vail for word processing services, and to Harlan Miller Tait Associates for use of laboratory facilities.

REFERENCES CITED

Birkeland, P. W., 1984, Soils and geomorphology: New York, Oxford University Press, 372 p.

Brabb, E. E., and Pampeyan, E. H., 1972a, Preliminary geologic map of San Mateo County, California: U.S. Geological Survey Miscellaneous Field Studies Map MF-328.

——, 1972b, Preliminary map of landslide deposits in San Mateo County, California: U.S. Geological Survey Miscellaneous Field Studies Map MF-344.

Brown, W. M., III, Sitar, N., Saarinen, T. F., and Blair, M. L., 1984, Debris flows, landslides, and floods in the San Francisco Bay region, January 1982; Overview and summary of a conference held at Stanford University, August 23–26, 1982: Washington, D.C., National Research Council and U.S. Geological Survey, 83 p.

Dietrich, W. E., and Dunne, T., 1978, Sediment budget for a small catchment in mountainous terrain: Zeitschrift für Geomorphologie, Supplement Bd. 29, p. 191–206.

Dietrich, W. E., and Dorn, R., 1984, Significance of thick deposits of colluvium on hillslopes; A case study in the coastal mountains of northern California: Journal of Geology, v. 92, p. 133–146.

Dietrich, W. E., Reneau, S. L., and Wilson, C. J., 1984, Importance of colluvium-filled bedrock hollows to debris flow studies: Geological Society America Abstracts with Programs, v. 16, p. 488.

Fowler, W. L., 1984, Potential debris flow hazards of the Big Bend Drive drainage basin, Pacifica, California [master's thesis]: Stanford, California, Stanford University, 101 p.

Horton, R. E., 1945, Erosional development of streams and their drainage basins: Hydrophysical approach to quantitative morphology: Bulletin of the Geological Society of America, v. 56, p. 275–370.

Howard-Donley Associates, 1982, Geological investigation, landslide type and distribution, and mechanics details of nine representative failures, January 1982 rainstorms, city of Pacifica, California: Consultant's Technical Report, Job No. 834-01A, 108 p.

Marron, D. C., 1982, Hillslope evolution and the genesis of colluvium in Redwood National Park, northwestern California; The use of soil development in their analysis [Ph.D. thesis]: University of California at Berkeley, 187 p.

—— , 1985, Colluvium in bedrock hollows on steep slopes, Redwood Creek drainage basin, northwestern California, *in* Jungerius, P. D., ed., Soils and geomorphology: Catena, suppl. 6, p. 59–68.

Reneau, S. L., Dietrich, W. E., Wilson, C. J., and Rogers, J. D., 1984, Colluvial deposits and associated landslides in northern San Francisco Bay area, California, USA: Proceeding of the Fourth International Symposium on Landslides, Toronto, Canada, p. 425–430.

Schlocker, J., Bonilla, M. G., and Radbruch, D. H., 1958, Geology of the San Francisco north quadrangle, California: U.S. Geological Survey Miscellaneous Geologic Investigations Map I–272.

Shlemon, R. J., 1985, Application of soil-stratigraphic techniques to engineering geology: Association of Engineering Geologists Bulletin, v. 22, no. 2, p. 129–142.

Shlemon, R. J., and Hamilton, P., 1978, Late Quaternary rates of sedimentation and soil formation, Camp Pendleton–San Onofre State Beach coastal area, southern California, USA: Tenth International Congress on Sedimentology, Jerusalem, Israel, p. 603–604.

Shlemon, R. J., and Wright, R. H., 1983, Soil-stratigraphic dating of colluvial-filled gullies, Pacifica, California: Geological Society of America Abstracts with Programs, v. 15, no. 5, p. 328.

—— , 1984, Soil-stratigraphic dating of debris flows: Geological Society of America Abstracts with Programs, v. 16, no. 6, p. 654.

Smith, T. C., and Hart, E. W., 1982, Landslides and related storm damage, January 1982, San Francisco Bay region: California Geology, v. 35, p. 139–152.

Soil Survey Staff, 1951, Soil survey manual: Washington, D.C., U.S. Government Printing Office, U.S. Department of Agriculture Agricultural Handbook 18, 754 p.

—— , 1975, Soil taxonomy: Washington, D.C., U.S. Government Printing Office, U.S. Department of Agriculture, Soil Conservation Service Agricultural Handbook 436, 754 p.

Strahler, A. N., 1964, Quantatitive geomorphology of drainage basins and channel networks, *in* Chow, V. T., ed., Handbook of applied hydrology: New York, McGraw-Hill, section 4-11.

Yaalon, D. H., ed., 1974, Paleopedology: Jerusalem, Israel Universities Press, 350 p.

MANUSCRIPT ACCEPTED BY THE SOCIETY DECEMBER 29, 1986