U.S. DEPARTMENT OF THE INTERIOR

U. S. GEOLOGICAL SURVEY

Distribution of past debris flows and other rapid slope movements from natural hillslopes in the Honolulu District of Oahu, Hawaii

By

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Open-File Report 93-514

Prepared in cooperation with
the City and County of Honolulu,
Department of Public Works

1993

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ABSTRACT

This report documents the spatial and temporal distribution of debris flows and other rapid slope movements that occurred in the Honolulu District from about the 1930's to 1989, as detected by systematic stereoscopic examination of 19 sets of aerial photographs flown between 1940 and 1989. A total of 1,519 shallow landslides called soil slips, which initiate the great majority of debris flows in this area, are shown individually on the maps, and 260 more are included in mapped clusters. A few additional deeper landslides, called saprolite failures, have also produced debris flows and are shown on the maps. Thus, more than 1,779 landslides and resulting debris flows have been recognized in aerial photographs of the Honolulu District flown during this period of approximately 50 years. Because some proportion of debris-flow features are concealed in photographs of this steep and heavily vegetated terrain, these numbers underestimate the debris flows that have actually occurred. Significant numbers of debris flows appeared in each decade of this period, and particularly large numbers have accompanied major rainstorms, such as the New Year's Eve storm of 1987-1988.

The maps also show other features related to debris flows. Areas of pronounced aeolian effects, such as deflation pits and dunes, are shown because debris flows appear particularly abundant near these areas, and radiocarbon dating has demonstrated rapid accumulation of loose windblown materials that could explain this increased frequency. In addition, the maps show larger topographic features related to ancient debris flows and other rapid slope movements. Included is an ancient debris avalanche deposit in Manoa Valley that originated from Round Top, and several fan-shaped deposits that suggest repeated debris flows.

The maps omit abundant less specific evidences of past debris flows, including landforms that suggest abundant ancient saprolite failures similar to that which produced a major debris flow down Kupaua Valley during the New Year's Eve storm. The maps also omit slope movements from hillslopes disturbed by grading, as well as locations of falling or rolling boulders that have caused damage locally in the area over the years.

The maps provide the principal historical data for a map of debris-flow hazard by Ellen and others (1993), and complement a report by Torikai and Wilson (1992) that documents debris flows reported in newspaper articles and Civil Defense records.

INTRODUCTION

This report describes the distribution of past debris flows and other rapid slope movements from natural hillslopes in the Honolulu District of Oahu (fig. 1), as determined chiefly by systematic examination and interpretation of aerial photographs flown between 1940 and 1989. The debris flows described here, illustrated in figure 2, include slope movements that in the Honolulu area have been called soil avalanches (Wentworth, 1943; Scott and Street, 1976). Similar phenomena have also been called mud flows, debris slides, or debris avalanches (Varnes, 1978) and, in the popular literature, mudslides. Debris flows in the Honolulu area typically begin on steep hillslopes where intense rainfall triggers shallow landslides, called soil slips, that transform into fluid mixtures of soil, weathered bedrock, and vegetation that flow down hillslopes or channels (Wentworth, 1943; Scott, 1969; Scott and Street, 1976). Where debris flows enter developed areas, they may cause damage and loss of life either directly, by impact on structures and occupants, or indirectly by clogging drainage channels and diverting flood waters to damaging locations. Abundant debris flows occurred most recently in the Honolulu District during the New Year's Eve rainstorm of 1987-1988 (State of Hawaii, 1988; Interagency Flood Hazard Mitigation Team, 1988; Dracup and others, 1991; Ellen and others, 1991). As documented in this report, debris flows have been a recurring process in the area for at least the past 50 years.

The maps of this report were compiled to provide historical data for an analysis of debris-flow hazard by Ellen and others (1993), and serve as a companion to that report. A separate publication by Torikai and Wilson (1992) documents debris flows reported by agencies and individuals in suburbanized parts of the Honolulu District, as compiled from newspaper articles and Civil Defense records, and relates these debris flows to rainfall records from significant rainstorms during the period 1935 to 1991. That publication complements the present report in providing a record of historical debris flows in the Honolulu District.

ACKNOWLEDGMENTS

The study was supported in part by the Department of Public Works of the City and County of Honolulu. We appreciate the help of many individuals, companies, and governmental agencies in locating and acquiring the aerial photographs used for the study; D.K. Mukai of R.M. Towill Corporation was particularly helpful. We also appreciate the support of personnel at the U.S. Geological Survey office in Honolulu, who helped make the work both pleasant and productive. Lori Ghequiere, K.M. Schmidt, and E.S. Gil of the U.S. Geological Survey helped by producing innovative base materials, cataloguing photographs, and assisting with stereoscopic models.

USE AND LIMITATIONS OF THE MAP

The two plates of this report were prepared to document the history of debris flows and other rapid slope movements in the Honolulu District. They show quite accurately the places where debris flows have occurred in the District, and less accurately the times when they have occurred during the period from about the 1930's to 1989. Plate 1 shows debris flows mapped from aerial photographs flown in the early 1940's, as well as large topographic features suggestive of ancient debris flows and other rapid slope movements. Plate 2 shows debris flows mapped from photographs

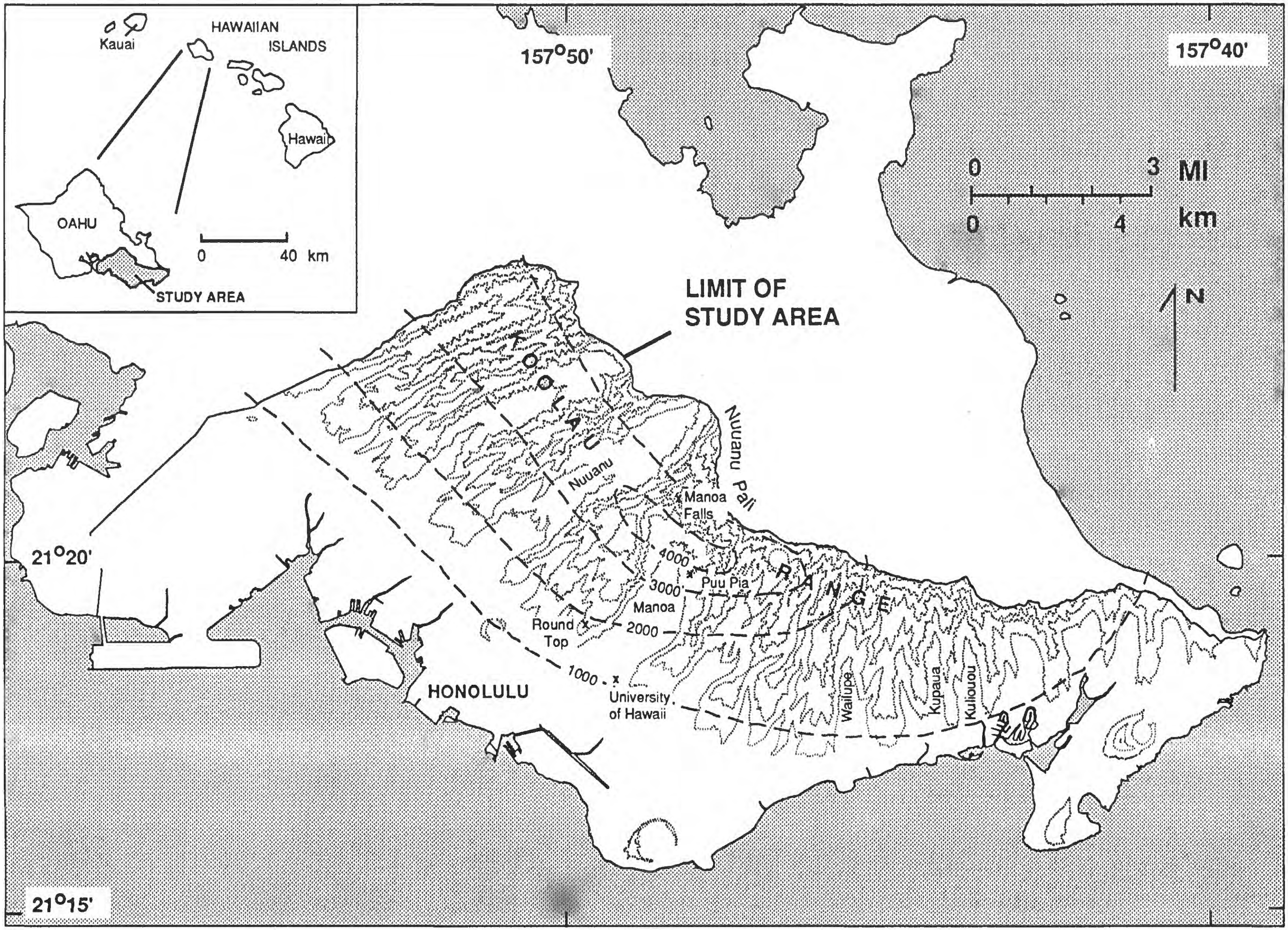

Figure 1: Study area, the Honolulu District of Oahu, showing place names used in text. Topographic contour interval 400 ft (122 m). Bold dashed contours indicate mean annual precipitation in millimeters (Giambelluca and others, 1986).

A

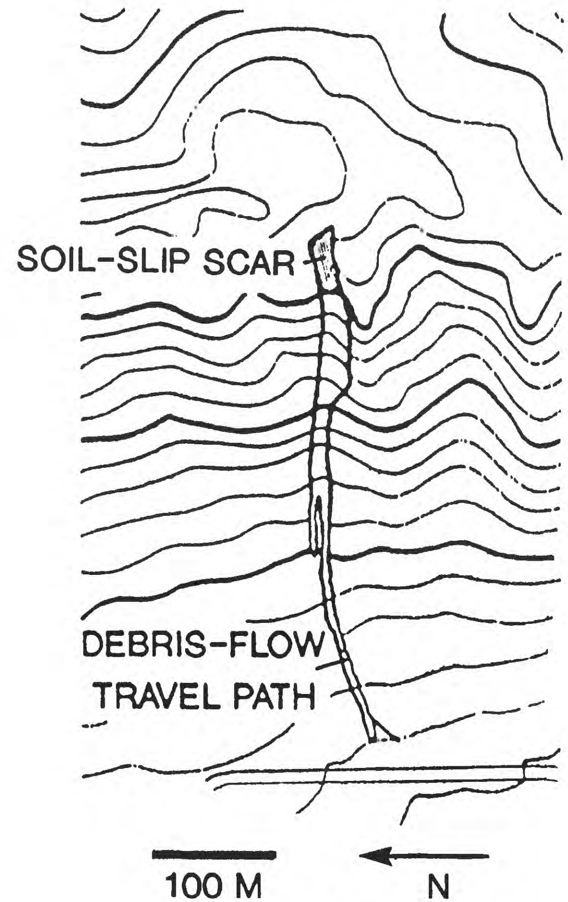

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Figure 2: Principal features of debris flows in study area. This debris flow damaged two houses in Kuliouou Valley during New Year's Eve storm of 1987-1988. A, Photograph, looking east; soil-slip scar is visible above shadowed cliff at top of debris-flow travel path. B, Map generated from aerial photographs. Base from U.S. Geological Survey, 1:24,000, Koko Head, 1983; contour interval 40 ft (12.2 m). See figures 3 and 4 for close-up views.

flown between 1952 and 1989. The plates can be used for broad-scale appraisal of the abundance and frequency of debris flows in the area, and also for detailed appraisals of past debris-flow occurrence at particular places in the study area. Together the plates provide a carefully compiled historical basis for decisions regarding hazards from debris flows and other rapid slope movements.

The maps are limited by the quality and frequency of the aerial photographs used in compilation, as well as by difficulties in identification of features left by debris flows in aerial photographs, particularly in the steep and densely vegetated parts of the study area. Two principal limitations have resulted. First, because of the time intervals between sets of photography, and because even fresh debris flows may be concealed from view in aerial photographs, the maps almost certainly do not show all historical occurrences. Second, some features mapped as resulting from debris flow may in fact have been produced by other processes, such as gully erosion, particularly where photographs are of low quality or small scale, or where features are partially concealed or subdued by passage of time. Thus, the maps may locally misinterpret features and almost certainly underestimate the abundance of past debris flows in the area.

The report is restricted to rapid slope movements from steep, natural hillslopes. It excludes discussion of slope movements from hillslopes disturbed by grading, which are described elsewhere (De Silva, 1974; Jellinger, 1977). Also excluded is information on falling or rolling boulders, which have caused damage locally, and on the slow-moving landslides on gentle hillslopes that have caused damage in the Honolulu area during the past few decades (see, for example, Baum and others, 1989; Baum and Reid, 1992). The maps even omit some features relevant to rapid slope movements from natural hillslopes, as discussed in subsequent sections.

GENERAL METHODS

This report is based primarily on interpretation of aerial photographs, although it benefitted from extensive field work that provided direct observations of features left by debris flows and related processes. The work with aerial photographs required 1) acquisition of photographs, 2) stereoscopic study of, and mapping from, the photographs, and 3) digitization of mapped features to produce the maps.

Because debris flows commonly leave only small, subtle, and short-lived features in the landscape, we attempted to obtain all available stereoscopic pairs of vertical aerial photographs relevant to the study. To this end we requested information from all companies and agencies that might produce, use, or catalogue aerial phototgraphs of the area. Responses to these inquiries provided a list of photographs flown between 1940 and 1989, consisting of several full coverages of the study area and a number of local flights that covered only parts of the area. From this list we acquired all of the full coverages and those local flights that either filled significant gaps between the years of complete coverage or offered significant areal coverage. The photographs we used are listed in an appendix. We did not examine any photographs flown before 1940, such as the vertical aerial photographs from the late 1920's on file with the U.S. Geological Survey in Honolulu, or oblique views from the collection of historical photographs at the Bishop Museum in Honolulu.

The aerial photographs listed in the appendix were examined stereoscopically using a mirror stereoscope with 1.5x and 4.5x magnification. Evidence for debris flows was plotted by hand on 1:12,000-scale topographic base maps enlarged from 1:24,000-scale U.S. Geological Survey quadrangles of the area. To facilitate transfer to the base maps, which is difficult in this steep and intricately dissected topography, some base maps combined the topographic contours with photographic images from U.S. Geological Survey orthophoto maps of the area. Except where noted, examination and mapping was accomplished by the senior author, so that interpretation of features was as uniform as possible over the area and through time.

The mapped features were digitized from stable-base materials using ARC/INFO software (ESRI, 1990) to permit digital analysis and flexible map portrayal. Each feature was tagged according to the date of the photographs in which it was detected. Digitized features were proofed for accuracy of identification and location. Locations of debris-flow sources were compared digitally with measures of hillslope steepness and curvature to characterize likely locations of future sources for a predictive map of debris-flow hazard (Ellen and others, 1993). Dates of appearance of debris flows in the photographs were used to help correlate abundance of debris flows with major rainstorms, in an attempt to define rainfall thresholds for debris flows (Wilson and others, 1992). The digital data were then used to prepare the maps presented here.

SOIL SLIPS, SAPROLITE FAILURES, AND DEBRIS FLOWS, AND THEIR DETECTION IN AERIAL PHOTOGRAPHS

The abrupt and catastrophic downslope movement of debris flows leaves behind two principal features that can be recognized by careful examination of aerial photographs: the scar left by the landslide that typically initiates the debris flow, and the path left by the flowing or avalanching debris during its destructive travel down hillslopes and channels (fig. 2). Also, where debris flows have been particularly numerous, their deposits may accumulate to produce fans near the mouths of canyons or sidehill channels.

The landslides that initiate debris flows in the study area typically occur on steep (25-60^{o}) hillslopes. The great majority of these landslides involve thin (0.1- to 1.5-m) slabs of hillside that consist largely of colluvial soil cover and vegetation, and are here called soil slips (fig. 3). Less commonly, debris flows are initiated by larger and deeper landslides, here called saprolite failures, that involve chiefly weathered bedrock called saprolite (see discussion below under "Saprolite Failures and Debris Flows"). Volumes of soil slips commonly range from several cubic meters to more than 900 m^3 (Ellen and others, 1993); volumes of saprolite failures may be as great as 35,000 m^3 or more (Ellen and others, 1991). Most soil-slip scars revegetate in about 3-5 years (significantly less than typical intervals between photographs), especially in densely vegetated parts of the area (Wentworth, 1943; Scott, 1975; Scott and Street, 1976). Once revegetated, they become practically indistinguishable from the rest of the landscape. In forested areas, even fresh soil-slip scars may be concealed by tree canopies. Saprolite failures, being larger and deeper, tend to revegetate more slowly and are less likely to be concealed by vegetation.

Travel paths of fresh debris flows appear as zones of stripped or flattened vegetation leading downslope and downchannel from landslide scars, commonly with patches of mud and transported broken vegetation left on the ground and on remaining vegetation (fig. 4). Scour of any significant thickness of soil is uncommon in the study area, and so revegetation and recovery of existing vegetation typically occurs faster than in the landslide scars. In addition to being short-lived, travel paths may be concealed by tree canopies. These qualities tend to make travel paths more ephemeral and difficult to identify than soil-slip scars.

In addition to short lifespan and vegetative concealment, several other factors tend to obscure debris-flow features in aerial photographs of the Honolulu area. First, cloud cover has been a major obstacle to aerial photography of Oahu because of its persistence over the mountains, and many photographs include some cloud cover. Second, the extremely steep and dissected topography results in strong shadows, largely on north- and northwest-facing slopes, that obscure large parts of the area in most

Figure 3: Soil-slip scar shown in figure 2, viewed from downslope end of scar. Bare soil upslope from person marks basal slip surface of landslide, which terminates at shadowed headscarp (arrows). Scar is 42 m long, 15 m wide, and averages about 1 m deep.

Figure 4: Debris-flow travel path, viewed downslope from top of cliff shown in figure 2A (near viewpoint for figure 3). Path (arrows), marked by bare soil and disrupted vegetation, extends across view from bottom left to right center, where it enters residential development near valley bottom. In foreground, path is approximately 25 m wide. Extent of travel, shown in figure 2, is approximately 350 m.

flights. The steepness and dissection also result in strongly oblique views that enhance the likelihood of vegetative concealment. Third, the photographs vary in scale, in quality of prints, and in time of year and time of day taken, making some sets of photographs much more useful than others and making comparison between sets difficult. Fourth, the different photocenters and altitudes of photographs in this steep terrain have resulted in concealment of different parts of the terrain. Finally, some sets of photographs locally fail to overlap, leaving unphotographed areas between flight lines.

In summary, the persistent clouds and steep dissected topography of Oahu have resulted in difficult conditions for aerial photography, and these conditions, combined with dense vegetation, have resulted in significant difficulties in interpretation and mapping of the delicate and short-lived features left by debris flows. As a consequence, the maps may locally misinterpret features, and almost certainly omit some significant proportion of the debris flows that have occurred in the study area.

HISTORICAL DEBRIS FLOWS

The principal task of this study was to document where and when historical debris flows have occurred in the study area. This information is shown on two plates. Plate 1 shows debris flows mapped from photographs flown in the early 1940's; plate 2 shows those mapped from photographs flown between 1952 and 1989. Both plates also show mapped areas of aeolian features, such as deflation pits and dunes, that appear related to debris flows, as discussed below under "Relation of Debris Flows to Aeolian Processes."

Early 1940's map (plate 1)

Soil slips, saprolite failures, and debris-flow travel paths were mapped by stereoscopic interpretation of aerial photographs flown largely in 1940, obtained from the National Archives in Washington, D.C. Photographs flown in 1943, obtained from the same source, were used to fill gaps in areal coverage (see appendix). Most of these early photographs are plagued by high contrast, which made interpretation difficult.

These features are shown individually on plate 1, where they are designated either fresh or subdued. Fresh features are distinct in the photographs and have light photo tone suggestive of bare soil. Subdued features appear less distinct; they range from fairly distinct with light photo tone to very indistinct with intermediate photo tone, and probably overlap to some degree with the fresh group. Based on reported revegetation rates (Wentworth, 1943; Scott, 1975; Scott and Street, 1976) and our field observations, the features shown as fresh probably occurred in the late 1930's or early 1940's; subdued features probably occurred earlier in the 1930's.

1952-1989 map (plate 2)

Plate 2 shows landslides and debris flows mapped from aerial photographs flown between 1952 and 1989. The plate consists of three components. The principal map portrays the debris flows that appeared in the entire study area during this time period. On this map, some groups of contemporaneous debris flows are shown as "clusters" rather than individual scars and travel paths. One inset on the plate shows individual scars and travel paths in the Nuuanu Valley part of the study area, which was mapped in special detail. A second inset shows individual scars and travel paths resulting from the New Year's Eve storm of 1987-1988 in the eastern part of the area, as mapped by Ellen and others (1991).

Entire study area

The principal map on plate 2 shows the landslides and resulting debris flows that appeared on aerial photographs flown during this time interval throughout the Honolulu District. Debris-flow features are identified by the year of the earliest photographs in which they were detected. Debris-flow occurrence during this time period is shown less thoroughly than on plate 1. Where debris flows similar in apparent freshness occur in notable concentrations on a given set of photographs, scars and travel paths generally are not shown individually but rather are depicted as clusters. The mapped clusters are loosely defined, and range in spatial density from about 7 soil-slip scars/km^2 to as many as 85 scars/km^2 (table 1). Outside of mapped clusters, debris flows of significant size and those near habitable valley bottoms are depicted individually, but small debris flows in remote areas may not be shown. Within clusters, only particularly notable scars and travel paths from the cluster are shown. Also shown are features related to saprolite failures that developed during the New Year's Eve storm of 1987-1988 (see discussion below under "Saprolite Failures and Debris Flows").

Nuuanu Valley area

The Nuuanu Valley area, shown as an inset on plate 2, was examined in detail to determine as closely as possible the dates of occurrence of debris flows. This detailed examination also served to explore the limitations and reliability of available aerial photography for identification of debris flows in the extreme conditions of the study area, and it revealed the extent of the limitations discussed above under "Use and Limitations of the Maps."

Detailed mapping and dating of individual landslides, some quite subtle, required careful and systematic comparison of the many sets of photography. Significant variations in image parameters among the sets were quickly recognized as an obstacle to accurate comparisons. The greatest difficulties were presented by variations in flying altitude and camera focal length (which together determine scale of the photograph), pitch and yaw of the aircraft (particularly in early sets of photography), and, perhaps most importantly, location of photo centers. These qualities, combined with the extremely steep and dissected terrain, resulted locally in small areas that lacked photo coverage within broad areas of otherwise complete coverage. These same qualities in places also produced extreme distortional differences between sets of photography. Other varying parameters, such as image contrast, color as opposed to black-and-white image, overall negative and print quality, sun angle, cloud cover, and annual and long-term vegetation changes, contributed uncertainties as well.

To minimize uncertainties caused by these variations in the Nuuanu Valley area, two identical stereoscopes were used side-by-side to facilitate comparison of time-sequential stereo models. This procedure was particularly helpful in dating subtle landslide scars because distortional differences altered shapes as well as apparent locations sufficiently to require constant comparison of stereo models. Potential uncertainties in dating landslides, resulting from slight errors in transferring locations from photographs to base map, were thus eliminated. In addition, landslide dates could be further refined by rechecking previous sets of photography once a scar or track was discovered. As an example, when a faint scar was recognized for the first time, perhaps on a photograph with a superior image, older corresponding photographs were reexamined to check whether the feature had been overlooked. In some cases, faint scars could be detected several sets of photography back from the set on which they were discovered.

The Nuuanu Valley study area is portrayed twice on plate 2. On the map of the entire Honolulu District, debris flows in the Nuuanu Valley area, as on the rest of the

Table 1: Spatial density of debris flows in clusters shown on plate 2

[Date, date of photographs in which debris flows were recognized; area, map area (km^2) occupied by cluster; scars, number of soil-slip scars in cluster; scars/km^2, areal density of soil-slip scars in cluster]

Date	Location	Area (km2)	Scars	Scars/km2
1952	Kaau Crater - Wailupe Gulch	2.8	30	10.9
	Kupaua and Kuliouou Valleys	1.1	36	33.0
1963-1965	NW wall Nuuanu Valley	0.5	16	30.2
	Kaau Crater	2.2	23	10.4
1967	East of Kaau Crater	1.0	27	26.9
1978	Moanalua and Manaiki Valleys	0.7	9	12.5
	Upstream from Manoa Falls	0.1	11	84.6
1980	N wall Kalihi Valley	0.4	18	49.7
	NW wall Nuuanu Valley, W cluster	0.3	6	22.1
	NW wall Nuuanu Valley, E cluster	0.3	10	32.8
	Near Manoa Falls	0.2	5	31.6
	Kaau Crater	2.7	20	7.4
	Kupaua and Kuliouou Valleys	0.4	15	41.5
1988	Wailupe Gulch - Kamiloiki Valley	6.7	280	41.7
1989	Nuuanu Valley, SE wall	0.5	15	30.1
	West of Kaau Crater	0.2	9	38.1
	Near Kaau Crater	2.7	25	9.1

map, are identified by the year of the earliest photographs in which they were detected. On the inset map that shows the Nuuanu Valley area alone, features are identified by the span of time during which they appeared in the photography, as determined by the careful cross-checking described above.

1987-1988 debris flows in eastern part of area

Individual landslide scars and debris-flow travel paths produced by the New Year's Eve storm of 1987-1988 in eastern Oahu are shown in the second inset on plate 2. These scars and travel paths, compiled from mapping by Ellen and others (1991), are included here for sake of completeness. This mapping used 1988 photographs flown especially for this purpose shortly after the storm, and these photographs permitted uncommonly complete depiction of debris flows. Features of uncertain identification in that mapping were omitted from plate 2, as were features related to cut slopes and fill slopes. As shown on the map of the entire Honolulu District, some debris flows detected in later 1989 photography appear to have been triggered by this storm in areas beyond coverage of the special-purpose 1988 photography.

Summary

Plates 1 and 2 document where and when debris flows have occurred in the Honolulu District during the period of approximately 50 years between the 1930's and 1989. Plate 2 portrays debris flows in less rigorous fashion than plate 1 in that many features are not shown individually but rather are included within boundaries of mapped clusters. Also, beyond clusters some small features in remote areas may be omitted. This more cursory treatment contrasts to the rigorous portrayal of each individual debris-flow feature employed for plate 1 and for the inset maps on plate 2. The inset map of the Nuuanu Valley area gives the most accurate depiction of dates of historical debris flows because of careful cross-checking between sets of photography. The inset map of debris flows triggered by the New Year's Eve storm of 1987-1988 probably gives the most complete depiction of debris flows from a major storm because the photographs were flown at optimal scale promptly after the storm, while features remained fresh and discernible.

ANCIENT FEATURES (PLATE 1)

During examination of aerial photographs for historical debris flows, we noted large topographic features produced chiefly by ancient debris flows and other rapid slope movements, and some of these are shown on plate 1. In particular, we show 1) prominent fan-shaped deposits that appear to constitute long-term accumulations of debris flows, and 2) a large debris avalanche near Round Top. Other features indicative of ancient debris flows are not shown. These include colluvial aprons, discussed below under "Fans," and landforms suggestive of ancient saprolite failures, discussed under "Saprolite Failures and Debris Flows."

Fans

Fan-shaped deposits, particularly those with steep or uneven topographic surface, suggest concentrations of past debris flows. Past debris flows were also indicated by field exposures in the colluvial aprons that are almost ubiquitous along valley margins of the study area; in all exposures that we examined, these aprons consisted of crudely interbedded, poorly-sorted, matrix-supported bouldery deposits that we interpret as debris-flow deposits interleaved with pedogenic soils (fig. 5).

Figure 5: Ancient debris-flow deposit exposed in channel on colluvial apron in Kuliouou Valley, looking upslope. Deposit is the light-colored, blocky material that extends from foreground up channel past hammer.

These aprons are difficult to map in consistent fashion, and so we show on plate 1 only prominent fan-shaped deposits that are steep or that have irregular topographic surfaces particularly suggestive of debris-flow origin. Examples are shown at A and B in figure 6. The several fans shown on the map thus are only the most clearly defined geomorphic evidence of ancient debris flows in a landscape where debris-flow deposits are widespread and abundant. Most of the volume of these fans appears to have accumulated in the distant past, probably centuries ago.

Debris fan near Puu Pia

A particularly distinct and steep fan lies at the mouth of a steep chute-like drainage basin south of Puu Pia, near the north end of the Manoa Valley (fig. 1; plate 1; B in fig. 6). We describe this fan because it is a clear example of past debris-flow processes in the area. The axial slope of the fan is 10°. A roadcut in this deposit exposes poorly-sorted, matrix-supported, bouldery rubble; boulders as large as 3 m in diameter are exposed on the fan surface and in walls of the drainage incised into the fan. The fan appears to consist of deposits either from a large number of debris flows or from a smaller number of exceptionally large debris flows, originating in the chute-like drainage basin. This fan has displaced, and may have dammed, the drainage that runs along its distal margin near the base of Puu Pia.

Debris avalanche from Round Top

Features on Round Top and in nearby parts of the Manoa Valley suggest the occurrence of a large fast-moving landslide or series of landslides that moved from the flank of Round Top to as far as the present University of Hawaii campus (fig. 1; plate 1). Judging from its jumbled remnants, this landslide would be classified a debris avalanche (Varnes, 1978). The perspective view in figure 6 shows the steep scarp and irregular hummocky deposits that together suggest a debris-avalanche origin. Geologic mapping by Stearns (1939) did not recognize a landslide origin for these features.

The landslide source lies in firefountain deposits of the Honolulu Volcanics (Stearns, 1939; Langenheim and Clague, 1987). This source material suggests that the landslide resulted from instability of fresh volcanic accumulations, rather than from the weathering of preexisting rocks that is responsible for all other landslides described in this report. The landslide deposits, delineated by lumpy, irregular topography at C in figure 6, appear to overlie the Sugarloaf (or Moiliili) basalt flow (D in fig. 6), which has been dated at 66,000-68,000 years before present (Gramlich and others, 1971). Thus the landslide appears to have occurred within the past 66,000 years, probably during prehistoric time near the culmination of volcanism at Round Top.

DISCUSSION

Number of landslides and debris flows

A total of 1,519 soil-slip scars are shown individually on the maps, and 260 more were mapped on photographs but included in clusters on plate 2. In addition, the maps include 11 landslides large enough to be shown to scale, which include most of the probable saprolite failures. Thus, a total of 1,790 landslide scars were mapped from aerial photographs of the Honolulu District flown during the approximately 50-year period between 1940 and 1989. Of this number, 894 were mapped from the 1940's photographs (plate 1) and 896 were mapped from photographs flown between 1952 and 1989 (plate 2), of which 311 were fresh soil slips mapped by Ellen and others (1991)

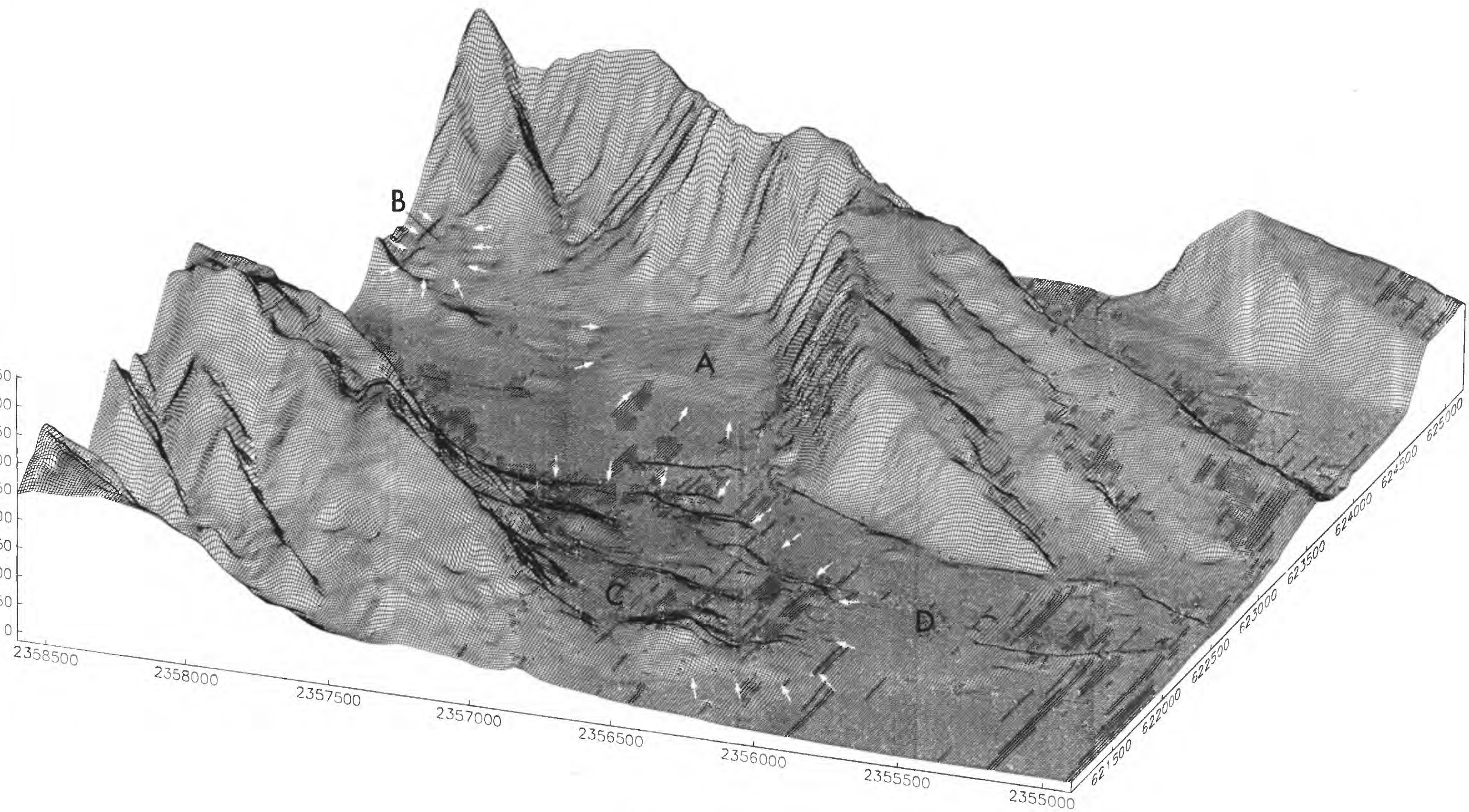


Figure 6: Perspective view of lower part of Manoa Valley, looking northeast. Arrows indicate features mapped in plate 1 and discussed in text. A, Irregular fan of Woodlawn area. B, Steep fan from chute-like drainage south of Puu Pia. C, Deposits of debris avalanche from Round Top. D, Sugarloaf (or Moiliili) basalt flow. Axes of diagram are north-south and east-west; coordinates in meters; vertical exaggeration 2x. View generated using ISM software (Dynamic Graphics, Inc., 1975)

from photographs taken shortly after the New Year's Eve storm of 1987-1988. Because some significant proportion of soil-slip scars are concealed in the photographs, these numbers underestimate the soil slips that actually occurred in the area during this period.

A total of 1,878 line segments that represent debris-flow travel paths and segments of travel paths are shown on the maps. The 1940's photographs documented in plate 1 showed 1,124 of these line segments, and the 1952-1989 photos showed 754, of which 364 appear to result from the New Year's Eve storm.

Dimensions and volumes of landslides

Lengths and widths of landslide scars are shown in figure 7. Surface area of scars ranges from less than 10 m^2 to 5860 m^2; median area is 111 m^2 and mean area is 291 m^2. Average depths of 33 soil-slip scars, measured normal to the hillslope during this study and by Scott (1969), range from 0.3 m to 1.5 m; mean depth is 0.79 m, with standard deviation of 0.34 m. Soil-slip scars measured recently northwest of the study area in North Halawa Valley averaged only 0.15 m deep (B.R. Hill, oral commun., 1992). Scott (1975) found soil-slip scars under forest significantly deeper than under ferns.

Volumes of soil-slip scars were compiled by Ellen and others (1993) for the purpose of characterizing the likely volume of future soil slips and debris flows. Measured and estimated volumes of soil slips range from several cubic meters to more than 900 m^3, with a mean of 120 m^3. Failures of saprolite may be much larger, in part because they may involve a thicker mass of material. The scar left by the saprolite failure in Kupaua Valley, discussed below under "Saprolite Failures and Debris Flows," measured as much as 17.5 m deep and had a volume of about 35,000 m^3.

Temporal distribution of debris flows

Time of occurrence of debris flows is shown by symbol in plates 1 and 2, and their abundance over time is summarized in figure 8. Occurrences are grouped by decade in figure 8 because the aerial photographs did not provide specific dates of occurrence, and even the decades are only approximate. Figure 8A shows the number of mapped soil slips by decade of occurrence for the entire study area. Debris flows were particularly abundant in the decade shown as the 1930's (the subdued scars on the 1940 photographs), and again in the 1980's, which includes the New Year's Eve storm of 1987-1988. Figure 8B shows similar relations for the Nuuanu Valley area, where temporal distribution was constrained as closely as possible by systematic cross-checking between photographs from different periods. In this smaller area, debris flows were most abundant during the 1960's.

Spatial distribution of debris flows

Plates 1 and 2 show debris flows most common near the crest of the Koolau Range in areas characterized by high annual rainfall (fig.1), and less common in the dryer areas that lie downstream from the crest and toward the eastern end of the Honolulu District. Debris flows have been so much less abundant in these dryer areas, that a previous study near Honolulu considered debris flows limited to the wet areas where they are most abundant (Scott, 1969, p. 79). The present report, however, demonstrates that significant numbers of debris flows have also occurred in the dryer areas. Plate 1 shows fans suggestive of abundant past debris flows in these areas; valley-margin aprons in these areas are documented to consist of old debris-flow deposits (fig. 5); and the plates show that debris flows have occured repeatedly in these

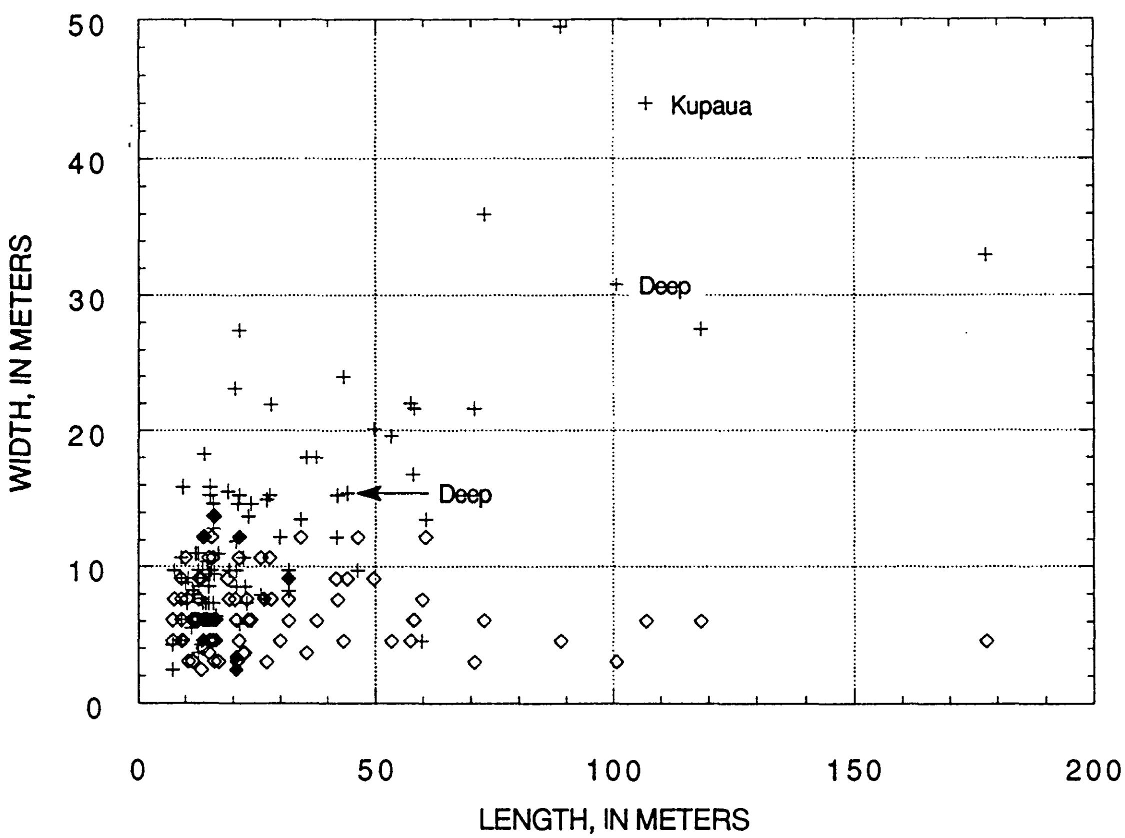


Figure 7: Length and width of landslides. Length is measured downslope, width across slope. Solid diamonds, 10 scars measured with tape by Scott (1969); open diamonds, 115 scars estimated in the field by Scott (1969); plus sign, 88 scars measured during this study with tape, remotely in the field, or on aerial photographs. "Kupaua", saprolite failure in Kupaua Valley ; "deep", deep landslides that are probably saprolite failures; see "Saprolite failures and debris flows."

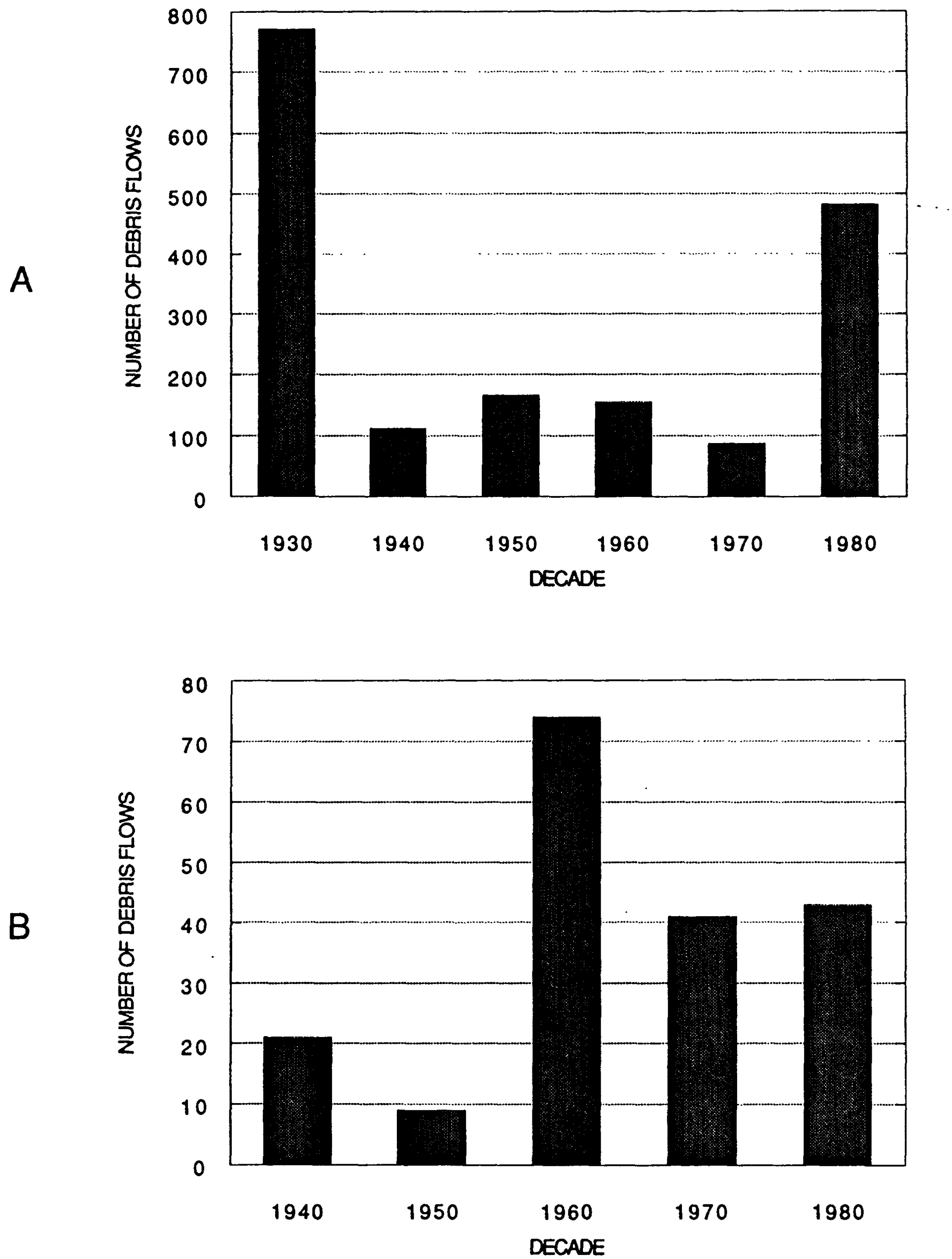


Figure 8: Temporal distribution of historical debris flows in study area. A, Plot for entire study area. Decade indicated is decade of photography in which debris flows were detected, except debris flows shown for 1930's are the subdued features mapped on 1940's photographs. Number of debris flows is number of soil-slip scars mapped, including numbers represented by clusters in plate 2. B, Plot for Nuuanu Valley study area (inset, plate 2). Decade indicated is decade in which debris flow probably occurred, as inferred from dates bracketing appearance of each soil-slip scar.

dryer areas during recent decades, commonly from sources that may be influenced by aeolian processes near ridgecrests, as discussed below.

Relation of debris flows to aeolian processes

Several ridgetops in the Honolulu District, particularly in its eastern part, include barren, denuded areas and nearby dunes that result chiefly from erosion, transport, and deposition by wind (fig. 9). We mapped aeolian features in preliminary fashion using 1940's photographs, then more carefully using the superior 1952 photographs, and this mapping is shown on both plates 1 and 2. Most of these areas showed only minor changes during the approximately 50 years for which aerial photography was examined in this study. During our field visits, some of these areas displayed aeolian processes in action, including sand blowing toward fresh dunes. Aeolian processes thus have been active during at least the past half century, and they remain active in substantial parts of the area.

Plates 1 and 2 show that many debris flows have originated in or near these mapped areas of aeolian activity. A part of Kuliouou Valley that shows particularly strong association between aeolian features and historical debris flows is illustrated in figure 10. Such associations suggest that aeolian processes locally promote the occurrence of debris flows by moving loose surficial materials from gently-sloping, stable sites on ridgecrests to steep unstable sites immediately leeward from deflated crests.

We explored the rate at which aeolian processes can deliver loose materials to potentially unstable sites by radiocarbon dating a sample of charcoal buried by about 1.4 m of windblown sand on a ridge near Kuliouou Valley. The date of 380$\pm$80 years before present (by convention, before 1950) establishes an average accumulation rate at this site of 3.24 mm/yr, which is more than 50 times the calculated rate of in-situ weathering at this site (Ellen and others, 1993). If nearby steep hillslopes were characterized by similar rates of accumulation and soil slips of typical size, debris flows from these hillslopes would be approximately 50 times more frequent than elsewhere.

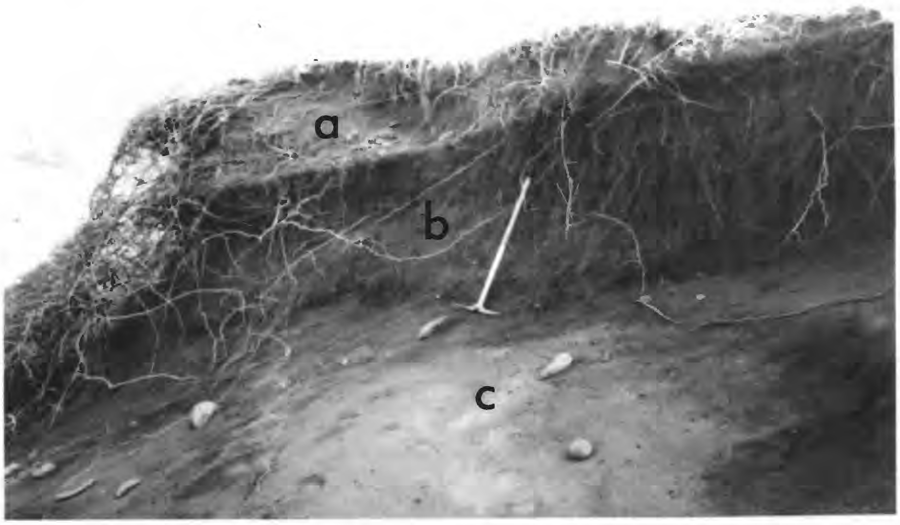
Saprolite failures and debris flows

Deep landslides of weathered bedrock (saprolite) have occurred infrequently in the study area during the past 50 years. The most recent example, shown in figure 11 and plate 2, resulted in a major debris flow down Kupaua Valley during the New Year's Eve storm of 1987-1988 (Ellen and others, 1991). An arcuate crack suggestive of an incipient landslide of this type, also shown in plate 2, appeared in the headwaters of Wailupe Gulch, probably during this same storm (fig. 12).

Depths and materials of landslides are difficult to determine confidently from the aerial photographs used in this study, and so the number of large failures that have consisted chiefly of saprolite can only be estimated. Slow revegetation of 2 large landslides mapped from the 1940's photographs suggests that they are deep failures involving significant thicknesses of saprolite (fig. 7); other large landslide scars may represent saprolite failures, but alternatively may result from broad, shallow failures or multiple smaller landslides. Only one of the mapped large landslides (along Lulumahu Stream, north of Manoa Falls on plate 1) appears to have produced a debris flow even roughly comparable to that in Kupaua Valley. The occurrence of 3 to perhaps 8 such landslides during the past 50 years suggests that they recur on the order of about once a decade in the study area.

Numerous landforms suggestive of older saprolite failures were recognized in the photographs but are not shown on the maps, chiefly because they are difficult to map

A



B

Figure 9: Aeolian features on ridge east of Kuliouou Valley. A, Deflated area near crest of ridge. Abundant dark blocks on denuded surface constitute lag deposit of rock fragments left behind by erosion of sand- and silt-size fragments of weathered bedrock. Person in lower left for scale. B, Exposure at margin of deflated area. Loose, recent windblown sand (a) overlies poorly consolidated older windblown sand (b) that shows slope-parallel layering, which overlies weathered bedrock (c). Pick is 66 cm long.

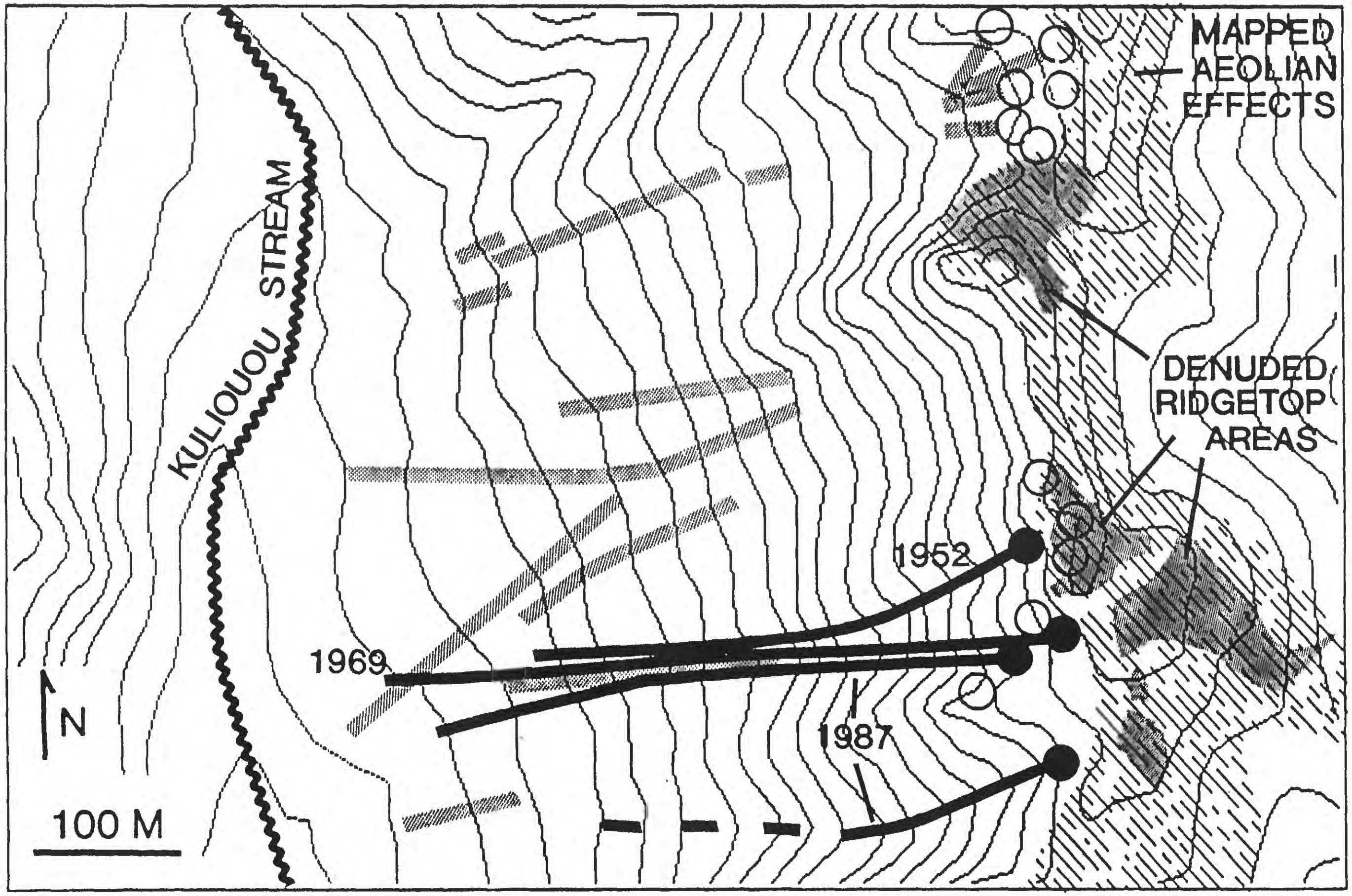


Figure 10: Sketch map showing relation of historical debris flows to wind-denuded ridgetop areas east of Kuliouou Valley. Wind transports soil and weathered bedrock from denuded areas to nearby steep slopes, which accumulate these loose materials susceptible to soil slip at rapid rates, leading to frequent debris flows. Shading, denuded areas; striped pattern, mapped aeolian effects; circles and bold gray lines, soil-slip scars and debris-flow travel paths identified on 1940 aerial photographs; dots and bold black lines, scars and paths identified on 1952 and 1969 aerial photographs and in the field after the 1987-1988 New Year's Eve storm. Northernmost 1987 debris flow is shown in figures 2, 3 and 4. Contour interval 40 ft (12.2 m).

A

Figure 11: Saprolite failure and resulting debris flow in Kupaua Valley, triggered by New Year's Eve storm of 1987-1988. A, Failure scar and upper end of debris-flow travel path, looking south. Failure removed ridgecrest to right of arrow; travel path extends from arrow downslope to left and then downcanyon toward top of view. Width of failure at base of steep scarp to right of arrow is 44 m; maximum depth of failure is 17.5 m. B, View downcanyon from point marked by arrow in (A). Debris flow scoured soil and vegetation from opposing wall of canyon. C, Debris-flow travel path, looking down Kupaua Valley to south. Debris flow traveled about 3.5 km into residential area near coast in background. Relief of valley sides approximately 180 m.

B

C

Figure 11: Continued

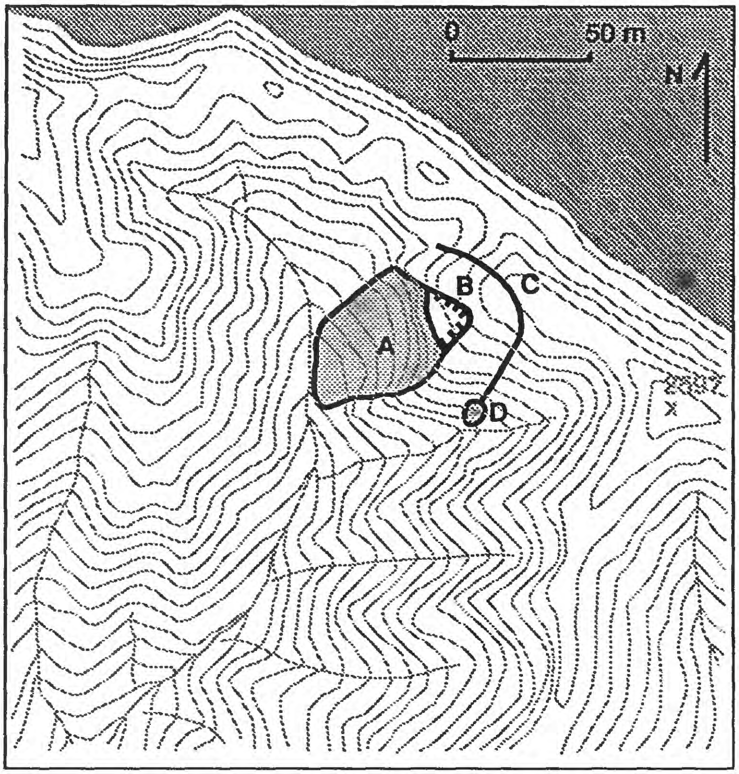


Figure 12: Sketch map showing geomorphic evidence for large saprolite failures in headwaters of Wailupe Gulch. A, Abrupt concave termination of sidehill ridgecrest that trends west from point C, suggesting past failure of ridge on steep, deep, arcuate slip surface. Shaded area at A indicates approximate extent of missing ridgecrest. B and C, Cracks apparent in aerial photographs flown shortly after New Year's Eve storm of 1987-1988. Hachured line at B indicates significant vertical offset, and crack here may be older than crack at C, which is a delicate, fresh-appearing feature that shows little vertical offset. These cracks appear to bound incipient large landslide masses, like that at A, that could produce large debris flows like that in Kupaua Valley during the New Year's Eve storm of 1987-1988. D, Scar of soil slip. Solid gray lines, topographic contours with interval of approximately 20 ft (6.1 m); broken gray lines, drainages; dark shading at top of map, extremely steep slopes of Nuuanu Pali.

systematically. These landforms are abundant in steep headwaters of the area, and are particularly pronounced as abrupt, concave terminations of steep sidehill crests, as shown in figure 12.

SUMMARY

Plates 1 and 2 show the distribution of about 1800 debris flows and other rapid slope movements that occurred in the Honolulu District from about the 1930's to 1989, as detected by systematic stereoscopic examination of aerial photographs flown between 1940 and 1989. Use of the available aerial photographs has permitted locations to be determined more accurately than years of occurrence. The maps attempt to be comprehensive in depiction of the debris flows that are revealed in aerial photographs, but limitations inherent in photographs of this terrain surely have resulted in misinterpretations and prevented detection of some of the debris flows that have occurred during the period of photography. The maps omit widespread and abundant, but less specific, evidences of debris flows in the more distant past. These include colluvial aprons, which consist of deposits from debris flows that line valley margins throughout the study area, and old landforms that suggest deep, fast-moving failures of saprolite similar to that which produced a major debris flow down Kupaua Valley during the New Year's Eve storm of 1987-1988. The maps also omit rapid slope movements from hillslopes disturbed by grading, which are described elsewhere (De Silva, 1974; Jellinger, 1977), and information on falling or rolling boulders that have caused damage locally over the years.

The maps complement a report by Torikai and Wilson (1992) that documents debris flows reported in newspaper articles and Civil Defense records. The maps were compiled to provide the historical basis for a map of debris-flow hazard by Ellen and others (1993), and serve as a companion to that report.

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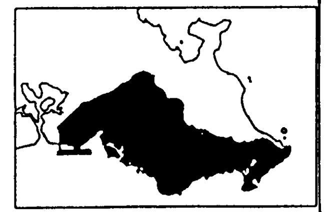
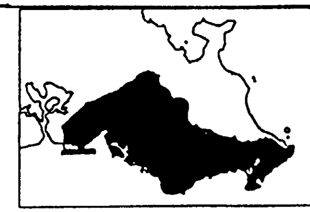
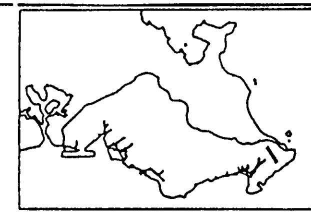
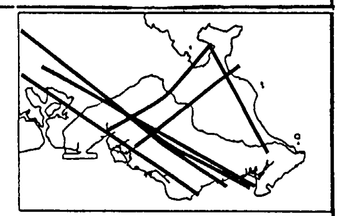
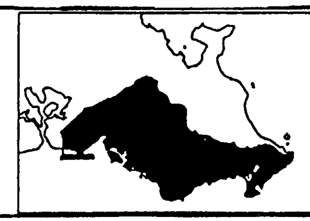
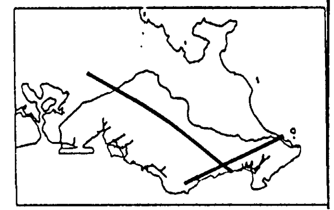
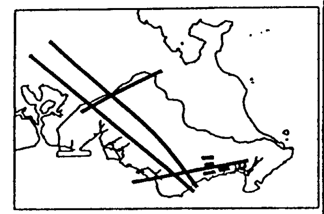
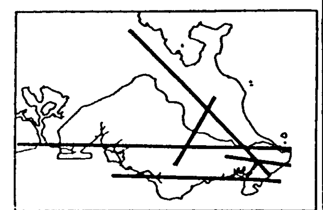
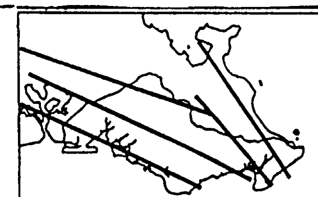
APPENDIX

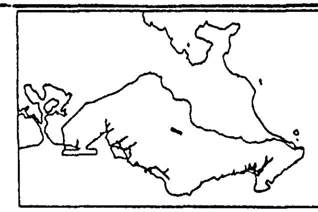
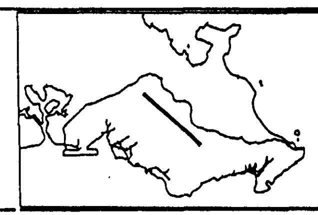
Aerial photographs used in this study

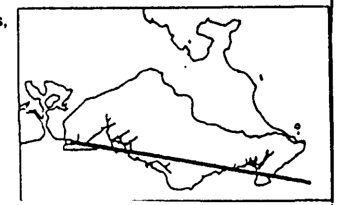
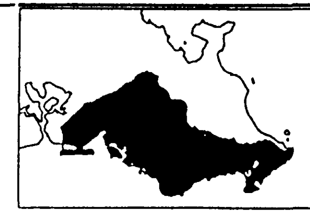
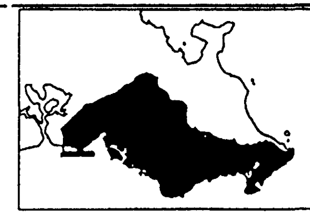
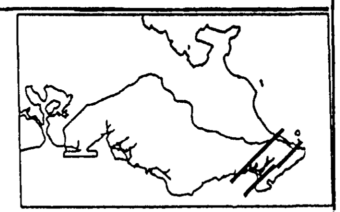
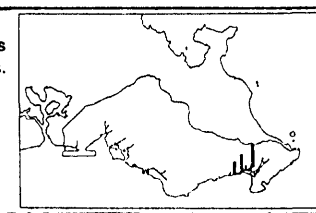
The aerial photographs used in this study are described in the following table. Some of the photographs that are listed extend beyond the study area, but our examination was restricted to the study area.

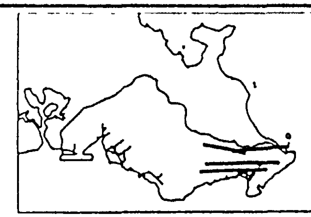
The table describes each set of photographs under the following headings. *Date*, date of the flight. *Source*, company or governmental agency from which the photographs were obtained. *Identification*, code used by the source to identify the photographs. *Roll* and *frames*, film roll and frame numbers. *Color*, indicated by the following abbreviations: B+W, black and white; color IR, color infra-red; color, natural color. *Scale*, the approximate scale of the photographs. *Comments*, notable qualities of the photographs. *Coverage*, extent of the area covered by the photography. Maps of coverage show the eastern end of Oahu with the study area delineated. Maps of incomplete coverage show flightlines only; actual coverage extends beyond flightlines and can be estimated from scale and size of photographs. All photographs listed are 9-by-9-inch contact prints except conversion stereo photographs, which are 7 by 7 inches.

Date	Source	Identification	Roll	Frames	Color	Scale	Comments	Coverage
1940	National Archives	118008NR	M-8	52-75	B+W	1:10,000 - 1:11,000	Nearly complete coverage.	
	Washington, D.C.	118032NR	M-46	1-12, 35-58, 78-95			Severe problems with high-contrast or	
		118033NR	M-47	96-190			washed-out images and gaps in coverage	
		118037NR	M-51	59-91				
		118038NR	M-52	70-106				
		118039NR	M-53	43-73				
		118040NR	M-54	41-71				
		118042NR	M-56	39-62				
5/28/43	National Archives	063670NR	1C	17-43, 86-98	B+W	1:22,000	Covers gaps in 1940 coverage	
	Washington, D.C.							
1952	R.M. Towill Corp.,	Oahu, T.H.	892	1-16	B+W	1:14,500 - 1:17,500	Complete coverage; excellent quality	
	Honolulu, Hawaii		893	1-16				
			924	1-10				
			925	7-10				
			934	1-21				
			935	1-17				
			936	3-8				
			939	1-20				
11/58	R.M. Towill Corp.,	1760		1, 2; each A, B, C	B+W	1:16,000	Conversion stereo	
	Honolulu, Hawaii	1762		1, 2; each A, B, C				
1/6/59	R.M. Towill Corp.,	1808		1-15; each A, B, C	B+W	1:15,000	Conversion stereo	
	Honolulu, Hawaii							
1/59	U.S. Geological Survey	GS-VX59	2	16-33	B+W	1:22,000		
	Menlo Park, California		3	1-8, 22-74				
1962-1965	U.S. Department of Agriculture	EKM	1CC	166-171	B+W	1:24,000 - 1:27,000	Complete coverage; somewhat fuzzy	
	Salt Lake City, Utah		2CC	201-206, 209-217				
				240-247, 251-256				
				259-260				
			3CC	35-40, 48-56, 59-66				

Date	Source	Identification	Roll	Frames	Color	Scale	Comments	Coverage
11/20/63	R.M. Towill Corp., Honolulu, Hawaii	2962 2968		1-14 1-22	B+W	1:15,000	Sharp and clear	
1/6/66	R.M. Towill Corp., Honolulu, Hawaii	3530 3531		1-24 1-23	B+W	1:14,400		
1/14/66	R.M. Towill Corp., Honolulu, Hawaii	3559		1-12, 14, 15	B+W	1:12,000		
10/8/66	R.M. Towill Corp., Honolulu, Hawaii	3805		1-13	B+W	1:13,400		
11/29/66	R.M. Towill Corp., Honolulu, Hawaii	3879 3880 3881 3882 3883 3884		1, 2 1, 2 1, 2 1, 2 1, 2 1, 2	B+W	1:6,000		
2/6/67	R.M. Towill Corp., Honolulu, Hawaii	3992 3993		1-7 1-7	B+W	1:18,000		
5/14/67	R.M. Towill Corp., Honolulu, Hawaii	4171 4172		1-8 1-7	B+W	1:17,600		
8/29/67	R.M. Towill Corp., Honolulu, Hawaii	4335 4336		1-11 1-25	B+W	1:30,000		
10/6/67	R.M. Towill Corp., Honolulu, Hawaii	4370		1-15	B+W	1:36,000		
2/68	U.S. Geological Survey Menlo Park, California	GS-VXJ-S	1 2 3 4 5	1-17 1-20 1-19 1-13 1-12	B+W	1:22,000	Some problems with high-contrast or washed-out images and much shadow	

Date	Source	Identification	Roll	Frames	Color	Scale	Comments	Coverage
10/69 - 1/70	R.M. Towill Corp., Honolulu, Hawaii	5110		13-17	B+W	1:13,400	Complete coverage; excellent quality	
		5112		1-5				
		5134		6-15				
		5135		6-16				
		5194		1-15				
		5195		1-15				
		5196		1-12				
		5221		1-7				
		5222		1-7				
		5237		1-6				
		5251		1-7				
		5253		1-4				
		5254		1-13				
		5255		1-6				
		5256		1-12				
		5257		1-15				
		5258		1-20				
		5259		1-16				
		5260		1-13				
		5261		1-14				
		5262		6-23				
		5263		6-22				
		5265		1-5				
		5266		3-6				
		5267		3-9				
1/17/72	R.M. Towill Corp., Honolulu, Hawaii	5641		1-4	B+W	1:4,800	Nearly useless local views	
6/17/74	R.M. Towill Corp., Honolulu, Hawaii	6280		1-9	B+W	1:15,000		

Date	Source	Identification	Roll	Frames	Color	Scale	Comments	Coverage
1974-1975	U.S. Geological Survey Menlo Park, California	NASA-AB575	2147	2909-2914	Color IR	1:65,000	Not useful because of small scale, clouds, and area of coverage	
1-2/78	U.S. Geological Survey Menlo Park, California	GS-VEEE	9 13	72-76, 90-92 9-20	B+W	1:48,000	Complete coverage; small scale	
1980	Fairchild National, Inc. Birmingham, Alabama	none	5 6 7 8 9 10 11 12 13	13-20 14-19 3-9 3-17 2-17 3-18 1-11 23-41 3-17	B+W	1:28,000	Complete coverage; somewhat muddy	
12/5/84	R.M. Towill Corp., Honolulu, Hawaii	8350		7, 9, 11-16, 19-26	Color	1:26,000	Wonderful photographs	
1/7/88 2/1/88	R.M. Towill Corp., Honolulu, Hawaii	8519 8522		8-14, 22-34 1-5	B+W	1:3,600 1:4,000	Flown immediately after New Year's Eve storm of 1987-1988 to document effects in Hahalone, Kuliouou, and Kupaua Valleys. Large scale, mostly in residential areas	

Date	Source	Identification	Roll	Frames	Color	Scale	Comments	Coverage
3-7/88	R.M. Towill Corp., Honolulu, Hawaii	8534 8540 8553		1-32 1-4 1-4	B+W	1:12,400 - 1:15,000	Flown to document debris flows from New Year's Eve storm of 1987-1988. Mapped by Ellen and others, 1991	
1989	Air Survey Hawaii Honolulu, Hawaii	1131	6A 6B 7A 8A 9 9A	1-11 1-8 1-6 1-11 1-7 1-3	Color	1:36,000	Complete coverage; good photographs