PROCESSES OF EROSION ON STEEP SLOPES OF OAHU, HAWAII

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ABSTRACT. The small particles of weathered rock debris derived from the lava flows and associated pyroclastic rocks of the Koolau Range, Oahu, Hawaii, are transported from the mountain slopes of the Range to the main streams below by the processes of soil flow and soil creep. The particles are moved slowly and progressively down through the ravines and across the cliffs of the leeward theater-like valleys, and over talus-veneered bedrock slopes to the valley floors. The occasional mud flows that break out through the forest vegetation contribute to the soil flow.

Variegated patches of old thick soil, maturely developed soil, youthful thin soil, or bare bedrock on the 70-80 degree slopes at the head of one leeward theater-like valley are considered evidence of avalanching and are important in the recession of these steep slopes. A cycle of recurrent sliding is suggested, similar to that postulated by Freise for steep slopes in the Brazilian tropical forests. This cycle includes the development of soil on the 70-80 degree bedrock slopes with the establishment and growth of plants, eventual soil exhaustion after maximum use, instability induced by rainfall, and avalanching with exposure of the bedrock again.

INTRODUCTION

KOOLAU Range forms the eastern mountain mass of Oahu, Hawaii (fig. 1). Basaltic lavas and associated pyroclastic rocks of the range are built up in continuous succession into an elongate volcanic dome. The western side of the island is composed of an older volcanic dome, the Waianae Range. The two mountain ranges merge in a low, saddlelike plateau. Secondary cinder cones, lava cones, and ash cones along the south shore and inland constitute the more recent features of volcanic activity on the island. Further geographic description is not necessary; adequate accounts are found in Stearns and Vaksvik (12),[1] and Wentworth and Winchell (17).

Much of Koolau Range has undergone severe erosion and very little, if any, of the original surface of the volcanic dome remains. A few highland flats near the summit divide may reflect an original surface, and possibly several gently sloping, triangular facets on the southwest side of the Range may represent in a geomorphic sense the original flow slopes (13, p. 8-9; 17, p. 55). Waianae Range is much more extensively dissected throughout.

A great cliff extends along the northeast or windward side

[1] Numbers in parentheses refer to references at the end of this paper.

of Koolau Range from the southeast tip of the island north to Kahana Valley, a distance of approximately 25 miles. This cliff or precipice probably owes its existence to a combination

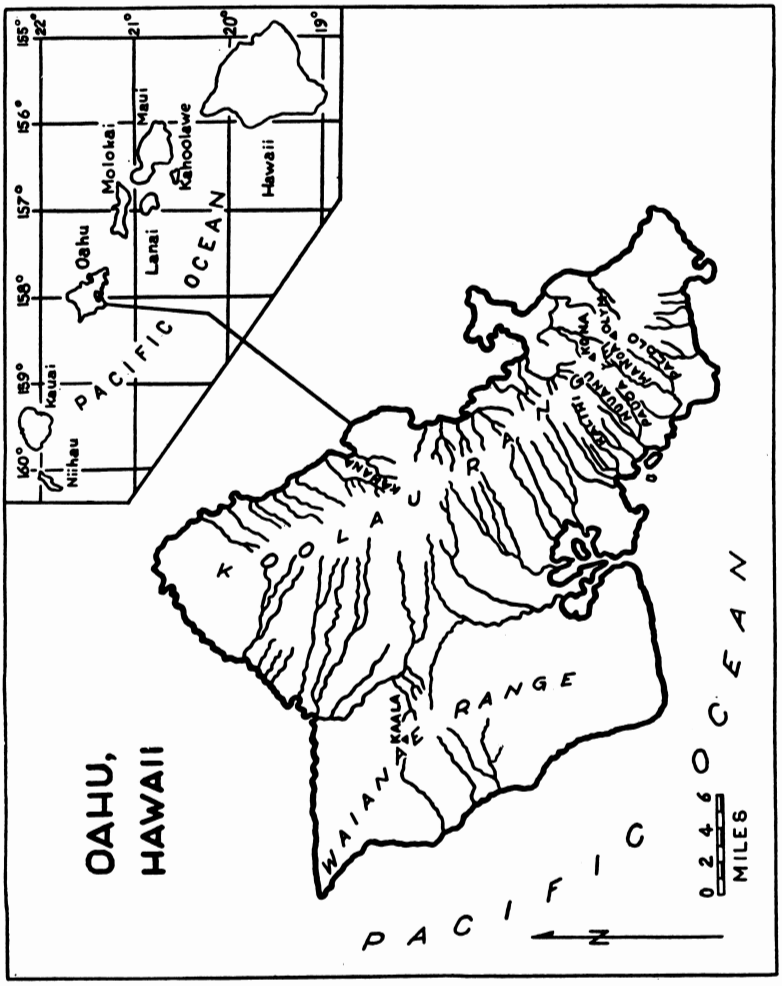

Figure 1. Index map of Hawaiian Islands, and map of Oahu, Hawaii. Kalihi Valley, Nuuanu Valley, Pauoa Valley, Manoa Valley, Palolo Valley, and Kahana Valley are indicated. Kaala—Mount Kaala, 4025 feet, is highest peak of Oahu and of Waianae Range; Kona—Puu Konahuanui; Olym—Mount Olympus.

of processes of erosion which include (1) extensive headward erosion in stream valleys aided by relatively greater amounts of rainfall at higher altitudes, (2) capture of ground water from the southwest side of the divide of the Koolau Range by the deeper eroding northeast side streams, (3) steepening and possible undercutting of steep slopes and cliffs by springs,

(4) landsliding and soil avalanches, (5) coalescing of valley headwalls into one irregular, crenulated precipice, (6) removal of narrow residual spurs between valleys by marine abrasion following submergence, and (7) emergence leaving broad, flat valley floors and some valleys deeply filled with sediments (12, p. 28-29 and Pl. 8). On the southwest or leeward side of Koolau Range, however, no such great amount of erosion has occurred. There, some of the valleys were eroded so deeply, to a base level lower than the present, that their bottoms and lower sides are aggraded to form an apparent U-shaped valley. Others, cut less deeply, are correspondingly less wide and lack the aggradational features in the bottom, and appear V-shaped (16).

A study of the processes of erosion on the steep slopes at the heads of several great theater-like valleys on the leeward side of Koolau Range constituted the main purpose of the field work presented by this paper. For possible comparison by the reader with other semitropical and tropical regions, a brief discussion of the climate, vegetation, and soil of Oahu is first reviewed. Description and discussion of the origin of the theater-like valleys is included.

ACKNOWLEDGEMENTS

The writer wishes to express his indebtedness to Dr. Kirk Bryan of Harvard University who first called his attention to the general lack of precise knowledge concerning slopes in tropical regions during a series of lectures in 1940. Dr. Chester K. Wentworth of the Honolulu Board of Water Supply has kindly reviewed this paper, and Mr. Charles E. Stearns of Tufts College has read the manuscript and made various suggestions for its improvement. The original field work was conducted while the writer was stationed on Oahu in 1944; discovery at a later date (and subsequent study) of the publication *Soil Avalanches on Oahu, Hawaii*, by Wentworth, a paper which largely anticipated the writer's field work, has stimulated this publication.

CLIMATE

The Hawaiian climate, generally speaking, is dominated by two elements: trade winds and orographic rainfall. Winds blow more than 80 per cent of the time from the northeast and

east. Uniformity of temperature is especially noticeable. Altitude continually controls both temperature and precipitation.

The North Pacific subtropical anticyclone is the immediate source of the trade winds. These oceanic winds, however, are relatively stable when they reach the Hawaiian Islands, are of shallow depth and give little rain; the effects of orographic lifting are the cause of precipitation. The majority of rain showers are heavy, most intense over mountains, some quickly dying away to leeward, others general over both islands and ocean. Cyclonic fronts, however, produce the most changeable weather, known by the Hawaiian word *kona* for leeward or southwest, and the islands' winter rainfall maximum. Kona weather is characterized by rain-producing fronts of short duration associated with high humidity and southerly winds, often followed by heavy precipitation; coastal regions on the southwest sides of the islands are most affected (9, pp. 29-51).

Figure 2 shows the distribution of rainfall on Oahu, taken from Carson (2). Average annual rainfall on Koolau Range varies from less than 30 inches to more than 300 inches. Part of Waianae Range lies in a rainfall shadow caused by Koolau Range. The amount of rainfall on Koolau Range increases with altitude, and with distance west or southwest of the Range crest. As a consequence, maximum torrential precipitation falls not upon summit crests but to leeward, as shown by figure 2. Annual precipitation for certain leeward valleys along the southwest side of Koolau Range, such as Kalihi, Nuuanu, Pauoa, Manoa, and Palolo Valleys, varies from 40 to 180 inches. Rainfall along the length of any one valley also varies. For Manoa Valley, approximate annual average at the valley portal is 41 inches, in mid valley 90 inches, on the upper valley floor 176 inches, and near summit ridges of the Range 106 inches (10, p. 566). With such precipitation, main streams never run dry. Water enters the main valleys from steep tributaries by means of waterfalls and cascades, and flows from series of springs along the foot of headwalls and cliffs. The waterfalls and cascades, however, are usually ephemeral, flowing only a few hours or a few days after a rain.

VEGETATION

Rainfall is the controlling factor in the phytogeography of the leeward valleys and of the Hawaiian Islands in general.

Manoa Valley, for example, becomes progressively hygrophytic headwards (10, p. 566). MacCaughey (10, p. 569) has divided Manoa Valley into ecologic zones: (1) Valley Floor

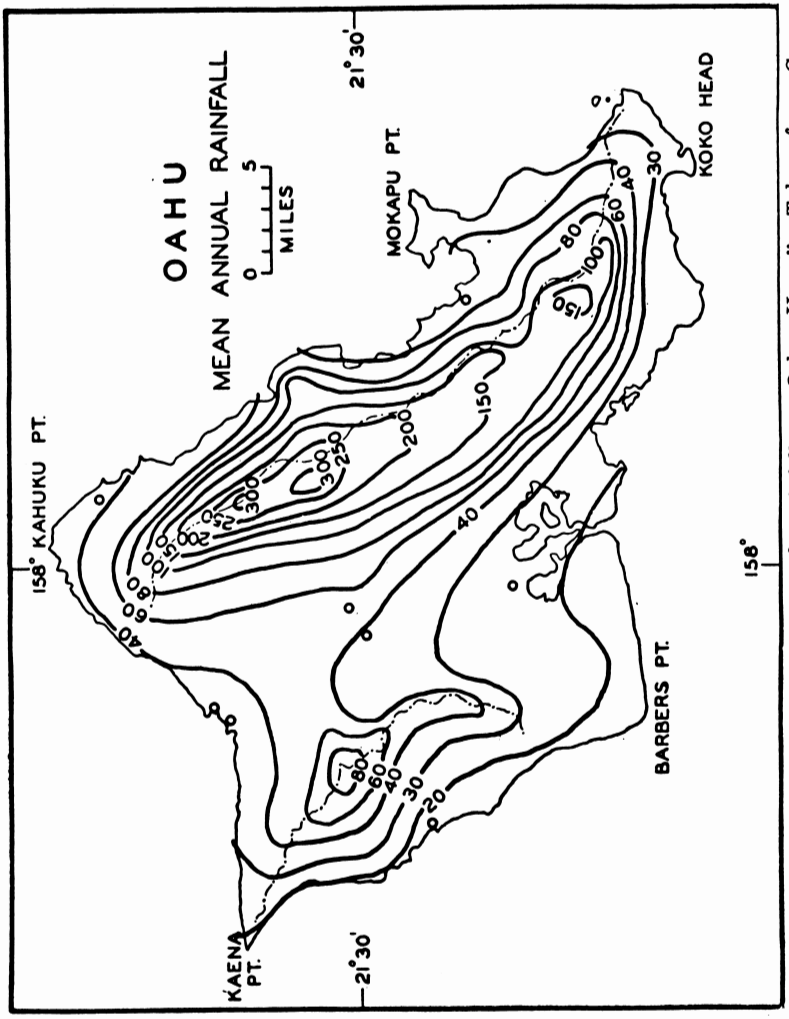

Figure 2. Distribution of mean annual ra infall on Oahu, Hawaii. Taken from Carson. Dot-dash lines represent the crests of Walanae Range and Koolau Range.

(lower floor near portal, upper floor near head), 50-300 feet in altitude; (2) Manoa Stream and its tributaries; (3) Talus zone, 100-300 feet; (4) Valley Walls or Lateral Ridges, 50-1000 feet and 1000-2000 feet; (5) Kukui zone (ravines and precipices), 300-1000 feet; (6) Koa and Lehua zone, 1000-1400 feet; (7) Hanging Valleys (rain forest), 1000-3000

feet; and (8) Summit Ridges and Peaks (including Mount Olympus, 2330 feet, and Puu Konahuanui, 3150 feet), above 2000 feet. Other leeward valleys may be divided into similar ecologic zones.

Valley floors near the heads of the valleys are heavily forested with a jungle of hau trees (*Hibiscus tiliaceus*) especially adjacent to the stream channels. Groves of the guava tree (*Psidium guajava*) are found on higher slopes, along with *Lantana camara, Eugenia malaccensis, Cordyline terminalis, Verbena litoralis,* and *Pandanus odoratissimus.* The steeper, upper valley walls and the walls of ravines are covered with luxuriant kukui groves (Kukui or Candle-Nut tree, *Aleurites moluccana* Willd.) which often form light green bands across the heads of the valleys. Steep slopes and precipices at the heads of the theater-like valleys support heavy shrubby growth, but may also be covered with hilo grass (*Paspalum conjugatum*). Above the kukui groves is the zone dominated by koa trees (*Acacia koa*), lehua trees (*Metrosideros collina*) and other rain forest types. Undergrowth is scanty at this altitude, consisting mainly of bryophytes and lesser species of pteridophytes (10, pp. 593-596). A few grass forms exist.

SOIL

In general, on lower Koolau Range slopes, a sublateritic soil exists in contrast with that on the upper slopes. Oxidation and relative accumulation of iron, with little soil movement, is indicated on lower slopes, whereas, with lower temperatures and greater rainfall, reducing conditions and the loss of iron are possible on upper slopes. In Hawaii, the soil absorbs rainfall and is relatively resistant to soil erosion. With a heavy forest cover, a thick soil mantle is maintained, which can stand even on very steep slopes. In the high, upland areas of Koolau Range, however, soil materials are moved so rapidly that normal soil development is rare (17, pp. 63-64).

In the lower valley bottoms, thick deposits of old alluvium are thoroughly weathered, stable, somewhat indurated, and rammed tight by weathering expansion. On high mountain slopes the alluvium is less weathered, much more permeable, and is much younger than that in the valley bottoms. Soil and mantle rock are more susceptible to slow creep and soil ava-

lanching in the mountain areas (17, p 65; 16). The chief soil masses on the mountain slopes in the heavy rainfall belt are only 10 to 30 feet thick (16); on the steep slopes of 70-80 degrees the soil is considerably thinner.

THEATER-LIKE VALLEYS

Mature looking, U-shaped theater-like valleys, eroded by consequent streams into leeward slopes of Koolau Range, are rimmed by steeply pitching ravines and precipitous walls (fig. 3). These valleys lack important tributaries. The floors of many of the valleys near the portals are flat surfaced and filled with hundreds of feet of alluvium. This partly accounts for their mature appearance. Stearns (11, p. 15) states that "Manoa Valley is a typical amphitheater-headed valley carved by stream erosion when the island stood at least 1200 feet higher than at present . . . . The flat valley floor has been produced by slow filling with silt, sand, gravel, secondary volcanic deposits, and probably coral, as the island submerged."

At the foot of ravines and precipices in the upper parts of the valleys, there are slopes covered with talus derived from the surrounding high walls. These slopes vary in width from 100 to 1000 feet, and are inclined 15 to 30 degrees from the horizontal; some approach 40 degrees. The writer believes that these are bedrock slopes veneered with talus, and not cones or fans entirely composed of talus material. Wentworth and Winchell (17, p. 55) make the following statement about similar slopes at the foot of the great cliff (or pali, meaning precipice) on the windward side of the Range: "The base of the pali is flanked by fans of debris, but in many places these apparent fans are only a veneer over buttresses of bedrock which have been left after retreat of the cliff." The talus veneered bedrock slopes in the leeward valleys may be increasing in width at the expense of the cliffs. If this is true, the erosional processes which produced the steep cliffs are no longer as operative as in the past. Blocks and boulders fill the upper courses of the streams, and appear to impede stream flow and hinder downcutting. Coarse gravel chokes the streams, but this may move during excessive rainfall.

Steep walls near the heads of the valleys are serrated by narrow, steep ravines or chutes. The walls of many of these ravines are precipitous; several are true cliffs. Cliffs rim the

heads of the valleys, a few being 200 to 300 feet high with 70 to 80 degree slopes. Above these cliffs, hanging valleys open upwards and extend back to the main summit ridges of the Range. The sides of these hanging valleys often have slopes of 45 to 65 degrees. Being in the region of heavy precipitation, the hanging valleys periodically fill with rainwater which cascades as waterfalls down the face of the cliffs below. The courses of these ephemeral waterfalls are outlined perpendicularly on the cliffs by wide zones of black, glistening water-stained volcanic rocks.

J. D. Dana, W. T. Brigham, C. E. Dutton, and C. H. Hitchcock, all early visitors to the island, described many of the topographic features and called attention to the physiographic problems involved in the origin and dissection of Koolau Range. Origin of the leeward theater-like valleys has been a source of controversy for many years. Davis (4, p. 173) observed these valleys in 1914, and stated that the great cliff on the windward side owed its origin to the retreat of weak underlying beds, and that a cliff at the head of "a southward discharging valley" probably owed its origin to the retreat of "the same series of weaker and less resistant underlying beds." Davis accompanied this discussion with a sketch of Manoa Valley (4, p. 174), reproduced here as figure 3.

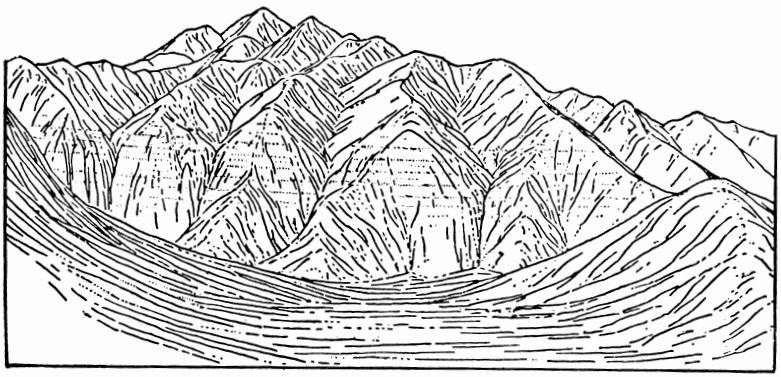

Figure 3. Generalized view of upper valley floor and theater-like head of Manoa Valley, Oahu, Hawaii. Taken from Davis. Highest peak in background is Puu Konahuanui.

Recognizing that conditions differed greatly from those in most temperate humid climates, Wentworth (14, pp. 385-410) believed that "steep-walled, blunt-headed box canyons" were

the product of normal processes of erosion for the area and enumerated as principal factors in their formation the porosity of the rocks and their tendency to weather chemically, as well as the climatic factors of high annual temperatures and rainfall. He also suggested that rapid chemical weathering near water table level allowed streams to continue undercutting headwalls and thus determine the configuration of the valleys.

Stearns (12, pp. 24-25) bases his theory for the origin of these valleys upon four conditions: (1) Streams flowing on slopes steeper than three degrees have developed amphitheater-headed valleys; those flowing on gentler slopes have not. (2) Streams undercut nonresistant beds beneath more resistant beds and form waterfalls. The alternating resistant and nonresistant beds usually dip downstream; the waterfalls "increase in height as they follow the dip upstream and tend to coalesce into one high fall." It is intimated (12, p. 25) that the waterfalls are actively incising their canyons in bedrock today. This may be true along the windward slopes of Koolau Range, and for the waterfalls in leeward valleys in the past, but the presence of hydrophytic mosses growing on the face of the cliffs along the course of the falls in the leeward valleys studied suggests the inability of the falls to incise on the face of these cliffs today. (3) Major streams as well as tributary streams erode headward into regions of high altitude and greater rainfall. The tributary streams, increased in number and in vigor, capture headwaters of streams on adjacent sides and enlarge the catchment basins of the major streams near their source, and theater-like valley heads result. The confined water in the dike complex in the interior of the Koolau dome is tapped by the more powerful streams, and this "accelerates stream capture . . . " (4) Captured hanging tributaries plunging over the cliffs produced by the waterfalls remove the narrow ridges between tributary streams by plunge pool action. These narrow ridges also are reduced by landsliding.

Stearns further suggests (12, pp. 25-26) that the valleys are oversized for the volume of water now flowing in them, but it must be rememered that under such conditions no "normal" size has ever been determined for either stream or valley. A considerable amount of talus veneers the bedrock slopes at the foot of the cliffs and occupies the floors of the upper valleys. This suggests that erosion is no longer as active as it was

in the past, and that changes have occurred which prevent streams from keeping the upper valley floors clear. If, as Stearns has specified (12, p. 26), the drainage areas above the heads of the leeward valleys have been greatly reduced by piracy from the windward side, and, if general reduction of the height of the Range of approximately 1000 feet by erosion and more than that by submergence has reduced rainfall by one half, then streams flowing in the leeward valleys are much smaller than those that once must have existed. If it can be proven that the talus veneered bedrock slopes are increasing in width, as previously suggested, then the statement that rainfall has been reduced by one half will be substantiated.

Hinds (7) and Jones (8, pp. 55-56) have called attention to these valleys, but did not advance any new explanation for their origin. Cotton (3) has presented a composite review concerning problems involved in the origin of all U-shaped Oahu valleys. He stresses need for objective study of valley sculpture in all tropical rain forest regions.

So little is known of the relative importance of processes of erosion and climatic factors that enter into the formation of these theater-like valleys that the critical reader today is still uncertain of their origin. The correct solution may be determined by conducting further field studies in the Hawaiian Islands and in tropical regions, by study of the literature concerned with similar problems of erosion in tropical climates, and by careful comparison between processes of erosion in the Hawaiian Islands and in other tropical regions.

MOVEMENT OF SMALL PARTICLES ON STEEP SLOPES

The following discussions are based upon many observations in leeward valleys on the movement of small particles of weathered rock debris down through the steep ravines and over the talus veneered bedrock slopes to the main streams on the valley floors below.

The bedrock of the leeward slopes of Koolau Range is highly permeable. It is permeable because of the great number of thin, vesicular lava flows and beds of cinders that form the Koolau dome, and also because of joints, cooling cracks, irregular contacts between flows, and lava tubes and tunnels. The interstices in these volcanic rocks are continually being

filled and flushed out with rainwater. This water, after it falls on the surface of the ground, trickles down towards the water table in the rocks beneath. As it passes through the soil, it carries some of the smaller particles of weathered rock with it. Many particles are washed into the cracks and interstices of the rocks below. Some emerge, however, after moving relatively short distances. Those particles that do emerge are deposited on the walls of the steep cliffs and ravines in the leeward valleys. Many are moved farther downhill during subsequent periods of rainfall. Those that emerge out of the rocks on the walls of ravines during a shower either are carried away immediately by the water flowing in the ravine, or, if deposited on the walls above the flowing water, accumulate as thin, reddish brown layers of mud. This mud is deposited as stalactites or incrustations of mud, and veneers the ravine walls. Depending upon shower intensity and volume of rainfall, the interstices of the rocks continue to drain for several minutes or for hours, leaving the ravine walls sheathed with mud. After the water that was flowing through the ravine has drained away, the ravine floor also becomes incrusted with mud. This accumulation of muddy particles makes ascent or traverse of ravines and steep walls not only difficult but dangerous. If the intervals between showers are long, the mud may dry and harden; then travel is easier. Another rainfall, however, cleans away the mud previously deposited; more is dropped again after the next shower. The small particles of weathered rock debris, derived from the high mountain slopes above, are thus removed and transported downward by rainwater—an effective process of erosion.

Movement of rainwater from the cliffs, ravines, and hanging valleys about the heads of the valleys results in the transfer of small particles in the form of a muddy sludge down to the talus veneered slopes below. Quantities of soil and larger rocks from the higher summits above, of course, are also washed down through the ravines to the gentler slopes below. Plant growth is relatively dense on these talus slopes; in some places large blocks and boulders rest on the slopes, but the trees, ferns, and small plants grow up between them. Beneath the plants and decaying masses of humus and forest litter and below the zone of root mats and network of rhizomes, the muddy sludge of tiny rock particles is in continual motion

during and for a short time after heavy rainfall. The mud moves downhill through the network of roots, around tree trunks and between the huge boulders that protrude above the decaying forest litter and rotting slimy humus. Travel across such slopes during or immediately after a shower is a slippery process. Occasionally the muddy particles, in the form of mud flows, break out through the forest litter and move down across the forest floor. In this manner, mud flows are spread out on top of the soil and decaying vegetation; new plant growth eventually develops on the surfaces of the mud flows and hinders any further movement. During long intervals between showers, the mud beneath the vegetation becomes dry and hard. Heavy rains soften the hardened mud and movement of the mud continues. If sufficient soil, muddy particles, and decomposed rock debris are carried out from beneath large enough areas of thick matted masses of plants, the forest is thereby lowered onto less decomposed bedrock. Further chemical decomposition will occur, and the surface of solid bedrock beneath the talus thus becomes weathered down to a lower level. Continued removal of overlying soil and weathered rock debris by flow and extrusion of the muddy particles is a valid method of slope erosion. The rate of erosion on these gentler slopes in this fashion cannot compare with that on the steeper slopes above, and proceeds at a slower rate. This flow and creep of small particles of weathered rock debris, however, is a process of erosion that trims off and lowers the talus veneered slopes. Large protruding boulders and rocks also disintegrate by chemical weathering, and are removed particle by particle. Some decayed material is removed in solution.

Perennial streams, flowing on the floors of the upper parts of the valleys between talus veneered bedrock slopes, are hindered somewhat by larger blocks and boulders that have dropped and rolled down from the steep slopes above. Most of the water in these streams is derived from the waterfalls, and from the springs that emerge along the foot of the headwalls and cliffs. A considerable amount of water, however, enters through the sides of the stream channels. This water carries with it the muddy particles that have moved across the adjacent slopes. Most of the particles are transported during heavy showers. Their appearance on the channel sides is not conspicuous during high water periods, as they are quickly swept

away. The channel walls continue to drain for several hours after a shower. They become coated with mud as the stream water diminishes in volume and no longer washes off the channel walls. During the next rainy period, the remaining mud is swept away. Accordingly, comminuted debris that has moved across the slopes above is shifted downstream.

Movement of small particles of weathered rock debris, from the higher summits and mountain slopes, down through the ravines and across the cliffs, over the talus veneered rock slopes below to the main streams on the valley floors, is accomplished by these slow processes of soil flow and soil creep. These are important, continual processes of erosion, which operate in tropical and semi-tropical regions, and cannot be disregarded in an inquiry concerning denudation.

AVALANCHING ON STEEP SLOPES

One method of erosion, not overlooked, but which has been neglected by some and considered unimportant by others, is that of landsliding or avalanching. Stearns (12, p. 25) emphasizes landsliding as an active means of erosion which should not be omitted. Wentworth (15) devoted considerable study to the process of soil avalanching with excellent results. He has pointed out its importance as a controlling factor in determination of land forms in semi-tropical mountainous regions. The writer is in full agreement with his observations and conclusions.

Wentworth ably describes abundant evidence of soil avalanching on 40-50 degree slopes; his compilation (15, p. 57) shows "80 per cent of the total between 42 and 48 degrees, with an occasional slope as high as 55 degrees." In addition to this and to the sliding on very steep knife-edge ridges mentioned by Wentworth (15, pp. 61-62), evidence of avalanching was observed by the writer on the 70-80 degree steep slopes at the head of Manoa Valley.

At a distance the steep slopes at the head of the valley present a mottled or spotted appearance. Close inspection reveals that although diversified, the steep slopes have plants in some form growing on them. Some parts of the slopes are mantled with a thick soil and well developed plant society, other parts with thick soil and stunted, scrubby grass growth. Certain other sections maintain no soil at all, but instead are sheathed

with yellow-brown mud so thin that layered volcanic cinders can be seen beneath. The soil and vegetation on the slopes are in various stages of development from youthful thin soil to maturely developed thick soil, and old thick soil. No ecologic zoning can be distinguished; distribution of variegated patches of vegetation has no obvious relation to topography or climate.

The writer believes that avalanching occurs on these steep slopes, that maintenance of the slopes has depended upon avalanching as a method of erosion in the past, and that avalanching and mass movement of particles of weathered rock debris control the recession of the steep slopes today.

Wentworth (16) believes that the surface of the bedrock and the base of the detached debris layer, with the presence of rainwater plus the indigenous weathered residuum, should be a surface of movement. He states that this is apparent because of the discontinuity of mechanical properties between the two layers. There can be no doubt that an element of discontinuity exists between the two layers, and that it is of major importance in the movement of debris. In fact, this element of discontinuity should increase when considering the steeper slopes. Avalanching also depends, however, upon the ability or inability of vegetation to aid the soil in adhering to slopes. This factor also increases when considering steeper slopes. The added weight of many plants can easily upset the equilibrium necessary for continual adherence to a steep slope. Certain types of deeply rooted trees can be most tenacious, whereas a mat of shallow rooted grasses and plants responds more readily to the pull of gravity. In addition, the weight of rainwater, suddenly multiplied, can supply the necessary impetus that sets an avalanche in motion. A thick, heavy old soil, which supports only a decadent growth of grasses, is the least tenacious. Mature soil supporting a thick mass of many plants and trees, weakened due to exhaustion of underlying soil, is very susceptible to avalanching. A youthful soil supporting young, luxuriant plant growth is the most adhesive and usually able to withstand every cloudburst.

The variegated patches of plant growth on the cliffs and steep slopes at the head of Manoa Valley and the presence here or absence there of thick soil strongly suggests that intermittent, catastrophic avalanching has occurred. The parts of the steep slopes covered by a thick, old soil which support only

grass are locations for immediate avalanching. The areas of mature soil supporting thick masses of plants and trees will avalanche in the distant future. The parts of slopes supporting a thin soil with young, luxuriant plants are locations of past avalanching and of recent soil development. The sections of bedrock sheathed with yellow-brown mud are the recently exposed volcanic rocks. Such alternate, intermittent removal of soil and vegetation and weathered rock is a method of slope recession that appears to be active today.

Recession of steep slopes in the past would certainly have been greatly facilitated by the larger drainage areas above the heads of the valleys, which are now considerably reduced, and by the higher rainfall possible during the periods of emergence and greater height of Koolau Range, as previously discussed. Any further argumentation would be pure speculation at this writing; proof of such erosion for the past will be revealed only by further field work.

CYCLES OF RECURRENT AVALANCHING IN TROPICAL REGIONS

Avalanches occur repeatedly on the face of the steep slopes and cliffs, although recurrent sliding at any one place is dependent upon many factors. These factors should include the rapidity of soil development and the establishment and growth of plant societies, the speed of soil exhaustion and decay of plant remains, and the instability of the weakened mass of soil and plant debris. A cycle of recurrent avalanching is tentatively suggested, briefly, as follows (1) fresh bedrock exposed; (2) the establishment and succession of mosses, plants, ferns, and trees to the culmination of maximum plant relationships possible, with accompanying soil development to great depths; (3) long and continued use of all available soluble minerals and organic matter; (4) final exhaustion of the soil mantle with deterioration of the plant societies, and alteration to a degenerate growth of grasses; (5) desiccation and hardening of the mass of soil, decaying litter, and rotting humus; (6) instability of the mass of debris produced during prolonged rainfall; and (7) catastrophic avalanching exposing fresh bedrock slopes again.

If the thickness of soil at the time of avalanching and the time required for one cycle of recurrent avalanching could be determined, a rough estimate for the rate of recession of such

steep slopes could be given. Wentworth (15, pp. 62-63) estimated that in a period of eight years in an area of about 15 square miles, in that part of the Honolulu watershed best known to him, an equivalent of 200 slides involving an acre each had occurred. He also estimates (15, p. 63) that an average thickness of one foot of material is removed by each slide, and that if the material is carried out of the area, that would be "equivalent to a rate of about 1 foot in 400 years for the whole area." Freise (6) in his study of Brazilian tropical rain forests postulated similar cycles of recurrent avalanching. The avalanching he describes occurs on steep slopes and cliffs of granite and gneiss. He has realized that he, too, is limited by the lack of precise knowledge as the writer, for he states (6, p. 155): "When numerical values for the progress of weathering, for erosion by disintegration, and for the rise and decline of ever-moist tropical primeval forests . . . are determined, then a figure for rate of erosion can . . . be postulated." (S.E.W., free translation) Freise's estimates for the rate of recurrent avalanching, however, of about 300-400 thousand years, do not seem to be based upon any statistical data, and cannot be considered useful at this time.

In 1940, Bryan (1) called attention to the work of Thorbecke (1927), Jaeger (1927), and Sapper (1935),[2] as well as to that of Freise (5; 6), on the retreat of slopes in tropical regions. The writer has been unable to study the works of Thorbecke or Jaeger. Sapper describes in detail processes of soil flow and soil creep similar to those that occur on the steep slopes of Oahu. Freise (5) presents his observations in the coastal mountains of Brazil with a complete description of the tropical forest cover and its effect upon the supporting soil. The processes of soil flow and soil creep that he sets forth are similar to those described by Sapper and to those presented above for Oahu. Freise also recognizes (5, p. 91) that soil flow and creep due to the delayed effects of rainwater in reaching

[2] Taken from Bryan, p. 268:

Thorbecke, F.: Der Formenschatz im periodish trockenen Tropenklima mit überwiegender Regenzeit. *Morphologie der Klimazonen* (ed. by Thorbecke). *Düsseldorfer geogr. Vort. u Erört.* Breslau, 1927.

Jaeger, F.: Die Oberflächenformen im periodish trockenen Tropenklima mit überwiegender Trockenzeit. *Morphologie der Klimazonen* (ed. by Thorbecke). *Düsseldorfer geogr. Vort. u. Erört.* Breslau, 1927.

Sapper, K.: Geomorphologie der feuchten Tropen. *Geogr. Schriften*, 7, 154 p., 1935.

the soil by way of tree trunks and their roots is a different process of soil flow than that recorded above. In 1938, he first describes the form, size, construction, and environment of "inselberge," then analyzes their origin meticulously as they developed both in the dry regions of northeast Brazil and in the constantly moist tropical coastal forests. It was in this paper (6, p. 154) that he advanced the doctrine of "erosion induces deforestation" (Erdfliessen Entwaldung schafft), and introduced a cycle of recurrent avalanching for such moist tropical regions. His cycle (6, p. 155) is summarized briefly, as follows:

"exposed granite (or gneiss) ridges — humus formation (upon a covering of lichen and small plant growth) — immigration of trees (probably leguminous at first) — development of a great primeval forest on a large scale with a combination of carbonic acid and humous acid type of decomposition — decay phenomena with soil flow and soil incrustations — atrophy of the forests to a deterioriation forest — domination and conquest by the grassy growths, destruction of the impoverished soil residue — emergence of the vegetation-freed ridges again (S.E.W., free translation)."[3]

When examined in detail, this cycle of recurrent avalanching is quite similar to that suggested for the steep slopes on Oahu. Differences in the rate of decomposition of the two types of underlying rocks, volcanic rocks in Hawaii and granite and gneiss in Brazil, make it difficult to compare what appear to be similar processes of erosion in nearly similar climatic regions. Freise's cycle, however, is much more complicated and involves a greater number of special conditions than does the one postulated for the Hawaiian Islands. Correlation between the two areas should not be attempted at present.

CONCLUSIONS

The movement of small particles of weathered volcanic rocks from high mountain summits to the valley floors by soil flow and soil creep has been recorded as observed in certain leeward valleys of Koolau Range, Oahu, Hawaii. Emphasis has been placed upon this form of erosion as a valid and important corollary to the more obvious methods of stream abrasion,

[3] Freise did not mention avalanching in this summary, probably because he discussed it at such great length in his text, but his intent is obvious.

sliding of debris and avalanching of soil. The processes of soil flow and creep are not manifest, and need to be examined and studied during their spasmodic occurrence. The avalanching on 70-80 degree slopes in one leeward valley is advanced as supplemental to Wentworth's excellent presentation of analogous features on 40-50 degree slopes. A cycle of recurrent sliding, similar to that claimed by Freise for steep slopes in the wet tropical coastal regions of Brazil, is suggested for Oahu, and includes the development of soil on 70-80 degree bedrock slopes with establishment and growth of plants, later soil exhaustion after maximum consumption, instability of soil and decaying plant debris induced by rainfall, and avalanching to expose bedrock again. Figures for rates of recurrence, especially those of Freise, cannot be considered at this writing.

With the exception of that of Freise, precise, exacting work on the erosion of slopes in tropical regions is rare. No one has come forward in the literature to attract attention to the mechanics of movement of debris on slopes in tropical regions, as, for example, has Walther Penck for humid regions. The need, however, for such an endeavor is evident; additional, accurate, discriminating field work is essential.

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