Debris Flow and Erosion Control Problems Caused by the Ash Eruptions of Irazú Volcano, Costa Rica

By HOWARD H. WALDRON

CONTRIBUTIONS TO GENERAL GEOLOGY

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DEBRIS FLOW AND EROSION CONTROL PROBLEMS CAUSED BY THE ASH ERUPTIONS OF IRAZÚ VOLCANO, COSTA RICA

By Howard H. Waldron

ABSTRACT

Irazú Volcano, in central Costa Rica, erupted ash almost continuously from March 1963 through February 1965. The ash created and caused widespread damage to property, crops, and livestock. Much of the damage to property was caused by accelerated erosion and repeated floods of water, mud, and rock debris from the slopes of the volcano. Debris flows and erosion were especially severe in the Río Reventado watershed and valley on the southwest slope of Irazú. In December 1963 a large debris flow in the Río Reventado valley destroyed more than 300 homes and killed more than 20 persons at Cartago. During 1964, more than 90 debris flows occurred in valleys on the south and west slopes of the volcano; about 40 of these flows were in the Río Reventado valley.

All the debris flow and erosion problems resulted from profound changes in the hydrologic regimen of the streams brought about by the accumulation of ash on the upper flanks of the volcano. The mantle of ash not only gradually buried and destroyed much of the natural vegetation, but the surface of the ash mantle rapidly and continuously formed a thin, compact, impermeable crust that very drastically reduced infiltration of rainfall into the soil. Runoff soon became so greatly accelerated that even moderate precipitation caused flash floods. Each flash flood, then, produced torrents of mud and rock debris, most of which was derived from the slumping and caving of valley walls. The scouring and undercutting of valley walls by the debris flows created many unstable slopes, reactivated several old large landslides, and started many new ones. The debris flows had high densities—as much as 1.98 grams per cubic centimeter—and reached velocities as great as 10 meters per second or more. As the flows left the mountain front, their velocity suddenly diminished, and much of the coarser sediment of the flows came to rest on a broad alluvial fan near the city of Cartago.

Emergency measures developed in 1964 for the control of erosion and debris flows included (1) downstream flood control and protection by means of channel improvements and the construction of large levees and (2) headwater flood and erosion control by means of watershed rehabilitation of the devastated areas through drainage diversions, contour ditching, small check dams, and artificial revegetation. The effects of these measures are being evaluated concurrently with the development of long-range plans for flood and erosion control.

INTRODUCTION

The prolonged eruption of ash from Irazú Volcano (fig. 1) in central Costa Rica—from March 1963 to March 1965—caused severe and widespread damage to crops, livestock, and other property in the vicinity of the volcano. Much of the damage to property was caused by accelerated erosion from the upper slopes of the volcano and by repeated floods of mud and rock debris in the valleys that drain the upper slopes; one of these floods destroyed more than 300 homes and killed more than 20 persons. The purpose of this report is to describe the problems of debris flows and erosion—their causes and effects—and to discuss some of the emergency measures applied to their control.

This report is based on work done by the author in Costa Rica from May through October 1964, under the auspices of the U.S. Agency for International Development (AID) in cooperation with the Oficina de Defensa Civil (Office of Civil Defense) and Oficina de Planificación (Planning Office) of the Government of Costa Rica. The author is indebted to R. L. Telles, U.S. Ambassador to Costa Rica, and to W. R. Stone, then mission director of AID, for their support and cooperation. Grateful acknowledgment is made for the data and reports made available to the author by the Servicio Meteorológico Nacional (SMN) (National Meteorological Service), the Instituto Geográfico de Costa Rica (Geographic Institute of Costa Rica), the

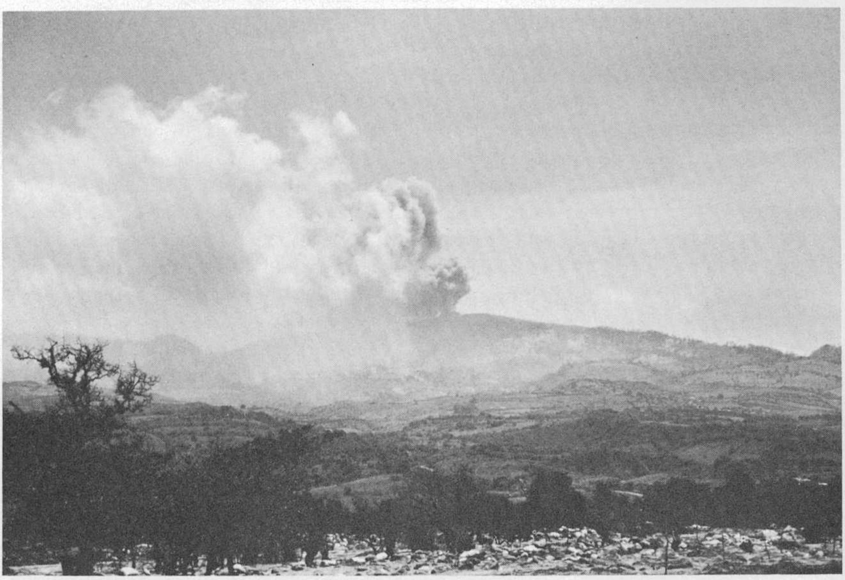

FIGURE 1.—Eruption of Irazú Volcano, showing the plume of ash being carried westward.

Ministerio de Agricultura y Ganadería (MAG) (Ministry of Agriculture and Animal Husbandry), and the Instituto Costarricense de Electricidad (ICE) (Costa Rican Institute of Electricity), and to members of their staffs, especially Ing. Manual Corrales, head of Oficina de Control de Ríos (River Control Section) of ICE. Acknowledgment is also due Ing. Jorge Dengo, then director, Oficina de Planificación, Ing. Rodolfo Dobles, director, Comité Ejecutivo de Irazú (Executive Committee of Irazú), and Gregorio Escalante, then geologist, Oficina de Defensa Civil, for their friendly cooperation and assistance.

STUDY AREA

Irazú Volcano is the highest (3,432 meters) of several composite volcanic cones which make up the Cordillera Central in central Costa Rica and which are located near the population and economic centers of this small Republic (fig 2). The summit of Irazú lies only about 24 km (kilometers) east of San José, the largest city and capital of the Republic, and only about 15 km north-northeast of Cartago, the second largest city of the Republic and the capital of the Province of Cartago.

Records indicate that although Irazú Volcano has erupted frequently, it has erupted only ash during historic time (McBirney, 1958, p. 141–144; Dondoli, 1965). The upper slopes of the volcano, therefore, are mantled by thick deposits of older, weathered ash which overlies a great pile of interbedded lava, volcanic breccia, agglomerate, ash, and lahar deposits. Several craters now occupy the summit area of the volcano (pl. 1). The geomorphic appearance of the craters suggests that the main conduit has shifted progressively westward along a major rift zone and that the youngest crater is now on the west.

ERUPTION AND ASHFALL

The most recent eruption of Irazú started with an explosion on March 13, 1963, after which the volcano erupted large quantities of ash almost continuously for about 20 months and intermittently for an additional 3 to 4 months. No new eruptions of ash have been reported since March 19, 1965. The eruption was confined to three distinct vents in the youngest, or west summit crater. Most of the erupted material is a fine to very fine, angular, lithic ash of basaltic andesite composition (Murata and others, 1966a, p. 114). At the summit about 80 percent of the ash particles was reported to be in the range of 160 to 340 microns, but at San José almost 90 percent was reported to be in the range of 100 to 150 microns (from data supplied by the Oficina Defensa Civil, San José, Costa Rica). Only a small fraction of the

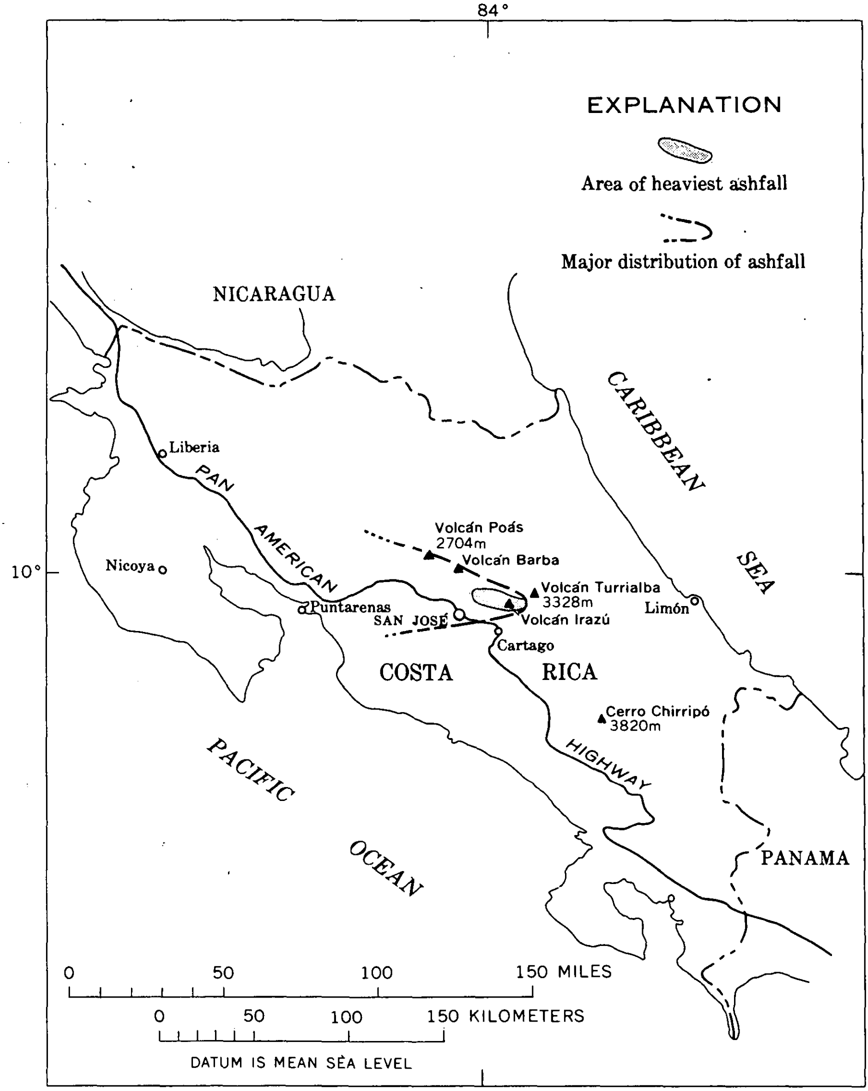

FIGURE 2.—Index map of Costa Rica, showing location of Irazú Volcano, major distribution of ashfall, and area of heaviest ashfall.

ash was fresh or juvenile material, but many slaggy incandescent bombs were blown out of one or more of the vents at various times. The newly erupted ash, with an average pH of slightly more than 4.0, was highly corrosive to both plants and metallic objects.

The prevailing southeast to east winds deposited the ash along a narrow zone that surrounded the summit crater and extended downwind for several tens of kilometers to the northwest and west (fig. 2).

The Oficina de Planificación estimated that an area of about 100 km^2 (square kilometers) was devastated, another 300 km^2 was seriously affected, and another 2,000 to 3,000 km^2 was moderately affected by the ashfall. The thickness of the ash on the south and southwest sides of the volcano ranges from a trace on the lower slopes to as much as 2m(meters) at the summit (Murata and others, 1966b, p. 787) and averages about 15 cm (centimeters) in the upper basin of the Río Reventado. Greater thicknesses of ash were reported from the northwest flanks of the volcano but these were not confirmed. Ashfall measured by the Servicio Meteorológico Nacional in San José amounted to an accumulated total of more than 26 kg per m^2 (kilograms per square meter) during the period March 1963 through March 1965. Maximum accumulations of 4825 g per m^2 (grams per square meter) occurred during December 1963 and 3825 g per m^2 during January 1964; minimum accumulations of 39 g per m^2 occurred during September 1963. The average bulk density of the ash was about 1.276 g per cm^3 (grams per cubic centimeter); hence a total thickness of about 2.1 cm of ash accumulated in the city during the period of eruption.

METEOROLOGY AND HYDROLOGY

Very little was known about the meteorology of the upper slopes of the volcano until several months after eruption began. Similarly, virtually nothing was known about the hydrology of the streams draining the slopes of the volcano. Of the four rain-gaging stations in the area, the oldest and highest is at Sanatorio Duran (pl. 1), about 6.5 km southwest of the summit at an elevation of 2,337 m; it has been in operation since 1943. The other three stations are much lower on the flanks of the volcano; they have been in operation about 6 to 14 years. During a brief period in August 1963, Coen (1964) investigated the influence of meteorological factors on the eruption of the volcano. In April 1964, several flash-flood warning stations (observation posts) were established by the Costa Rican Government at various locations on the volcano (pl. 1). These stations were manned continuously in order to report on rainfall, river stage, and flood potential of the major watersheds draining the southwest flank of the volcano. Consequently, almost no basic data about the hydrologic or meteorological conditions that existed on the volcano were available for either planning or forecasting purposes until more than a year after the eruption began. During the 1964 rainy season 8 stream gages and 16 rain gages were installed in the area (pl. 1), chiefly under the direction of R. D. Tarble, hydrologist, U.S. Weather Bureau and United Nations. A radar unit also was put into operation in San José and proved to be extremely valuable for tracking the path and development of storms over the volcano and for forecasting the probable extent and intensities of rainstorms in the various watersheds.

Precipitation in the area is extremely variable in both time and place. It ranges from less than 950 mm (millimeters) to more than 2,000 mm annually, as indicated by the more than 22 years of record at Sanatorio Duran. About 90 percent of this precipitation falls during the months of May through November. Although Irazú Volcano is situated on the Atlantic slope, it is also very near the Continental Divide and is subject to the movement of storms from both the Pacific and Atlantic Oceans. From May through September the flow of humid air from the Pacific Ocean predominates, whereas from October into December the principal storms originate from the Atlantic side. Occasionally storms may originate nearly simultaneously from both oceanic areas, and when these storms merge in the vicinity of the volcano, violent and prolonged local storms may result. Daylight morning hours during the rainy season commonly are clear or accompanied by a high overcast. By noon, however, storm clouds usually have built up, and thundershowers and heavy rainstorms may occur at any time throughout the afternoon, evening, or the following morning. Fortunately most of the high-intensity storms are brief and confined to relatively small localized areas; the most disastrous floods occur when a high-density storm is either more widespread or prolonged.

RÍO REVENTADO BASIN

Because the problems related to debris flows and erosion were especially severe in the Río Reventado drainage basin on the southwest slope of the volcano, most of this report is concerned with the problems of this stream and its watershed (pl. 1). For convenience of description the watershed is divided into three subbasins (pl. 1): The upper basin includes all the watershed area upstream from the confluence of the Río Reventado with the Quebrada Pavas; the middle basin extends from the mouth of the Quebrada Pavas down to the mountain front; and the lower basin extends from the mountain front down to the confluence of the Río Reventado and the Río Agua Caliente. Actually, the lower basin is very extensive, but for the purpose of this report it is arbitrarily restricted to a width of about 500 m. The Río Reventado, which originates high on the southwest flank of the volcano, is joined in its upper basin by two tributaries on the west, the Río Retes and Quebrada Pavas. Normally the Río Reventado is a small stream that rarely exceeds 1 to 2 m in width or about 15 cm in depth. On the slopes of the volcano the stream generally is confined within a deep, narrow, V-shaped canyon. More than 45 percent of the upper basin has slopes steeper than 25 percent, so that steep gradients prevail (table 1 and fig. 3) in the upper basin, and falls and rapids are numerous throughout both the upper and middle basins. At the foot of the volcano, at an elevation of about 1,450 m, the stream emerges from the mountain front and flows out over the nearly flat floor of an intermontane basin that borders the volcano on the south. Here the stream has built a large alluvial fan whose gradient is only about 4 to 5 percent. Cartago and several smaller suburban communities are situated on this fan. Physiographic data on the Río Reventado and its watershed are shown in figure 3, plate 1, and table 1.

TABLE 1.—*Physical characteristics of the Río Reventado watershed*

[Data from Istaru topographic map, scale 1:50,000, sheet 3445 IV, Instituto Geográfico de Costa Rica, San José, 1961]

Subbasin	Drainage	Area of basin (km²)	Length of stream (km)	Average stream gradient (percent)
Upper	Quebrada Pavas	3.6	4.4	18.0
	Río Retes	4.8	3.8	17.1
	Río Reventado	6.0	6.6	17.4
Middle	do	7.1	7.0	8.5
Lower	do	3.2	6.4	4.5
Total		24.7	20.0	
Average				9.8

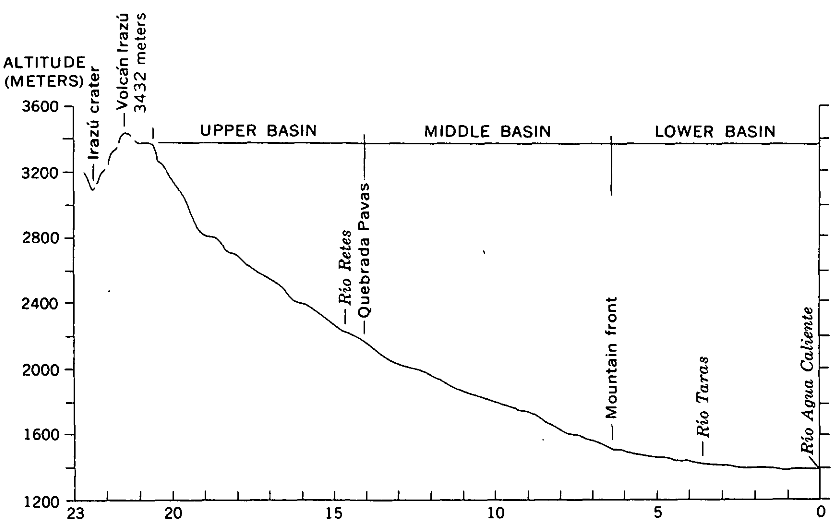

FIGURE 3.—Profile of the Río Reventado, showing limits of the upper, middle, and lower watershed subbasins. From Istaru topographic map, scale 1:50,000, sheet 3445 IV, Instituto Geográfico de Costa Rica, San José, 1961.

PROBLEMS CAUSED BY ERUPTION

ASH ACCUMULATION

All the debris flow and erosion problems that have plagued the country since the eruption can be attributed to the accumulation of ash on the upper slopes of the volcano and to its effect on the hydrologic regimen of the streams draining these slopes. Prior to the eruption these slopes were covered with a luxuriant growth of vegetation, chiefly shrubs, but interspersed with open pasture areas that were mantled with thick grasses and a scattering of oak trees. Two very significant changes in the ground surface resulted from the ashfall. First, the mantle of ash rapidly destroyed much of the vegetation and buried the normal protective surficial mat of vegetal litter, so that a large area surrounding the summit was almost completely denuded of vegetation (pl. 1, fig. 4). Second, the ash continuously formed a thin, hard, and comparatively smooth crust that was virtually impervious.

The origin of this crust, which was only 10 to 15 mm thick yet strong enough to support a man's weight, is not fully understood. Segerstrom (1950, p. 56) described a similar crust that formed on the surface of the ash at Parícutin Volcano in Mexico. He considered it to be largely the result of compaction and sorting of the ash by raindrop impact and erosion. At Irazú, however, the continued formation of this crust only at the surface, despite the almost continuous deposition of new ash, suggests that the crust is primarily a chemical phenomenon rather than the result of raindrop impact and erosion. Because of the large quantities of halogens, especially fluorine, that are discharged in the gases of erupting volcanoes, D. E. White (oral commun., 1965) suggested that one of the soluble salts in the ash is possibly a halide. The halide is brought by capillary action to the surface, where it is precipitated by evaporation in the upper few millimeters of the ash to form the crust. When this crust is buried by newly deposited ash, the precipitated salts are redissolved and again carried upward by capillary moisture to the surface to be redeposited and to form a new crust. By this method, then, the formation of the crust is an almost continuous process that accompanies the deposition of the ash. The formation of the crust by such a process, however, cannot be a long-lived phenomenon because it will be dependent on the replenishment of soluble salts through additions of halogens from successive ashfalls. Without a renewed source of halogens, the volatility and solubility of these salts are such that the crust probably could not be maintained for any great length of time.

As a result of the ash deposition and the destruction and burial of vegetation in the upper watersheds of the Río Reventado streams,

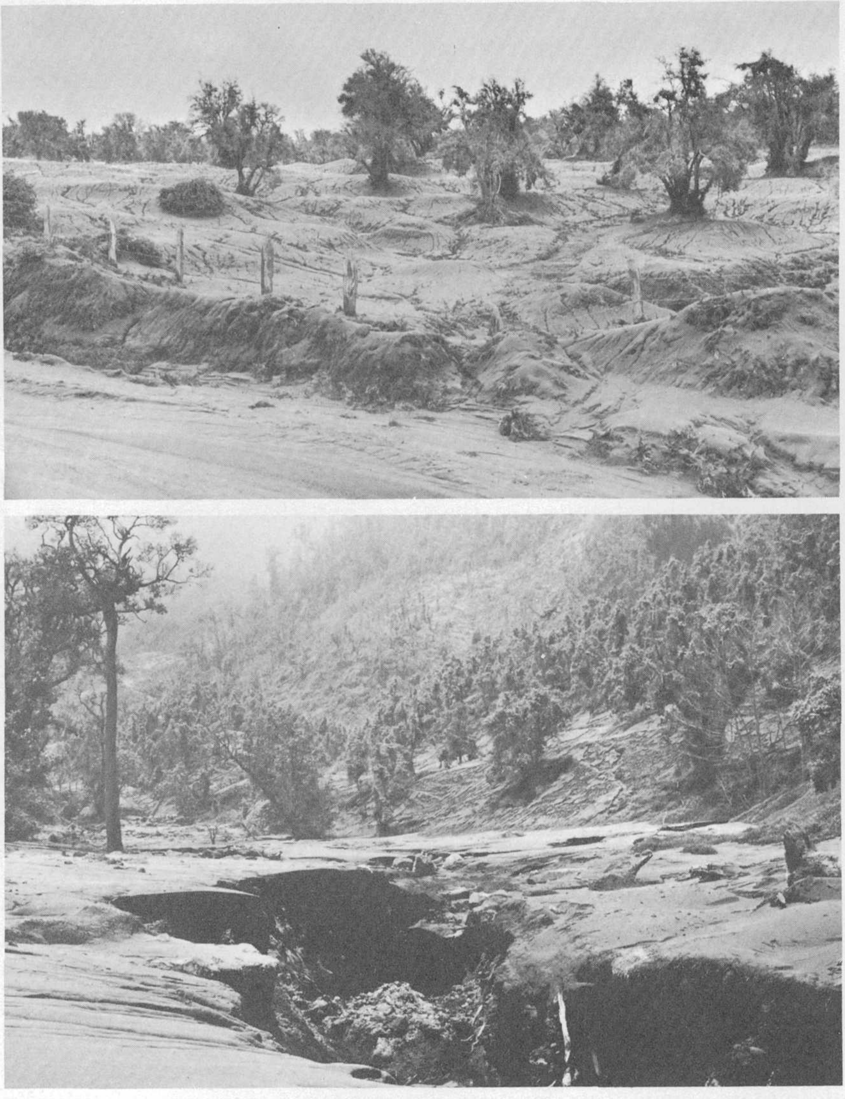

FIGURE 4.—Destruction of vegetation by ashfall. Upper: Along summit road near eastern summit crater. Lower: In Laguna area; in center foreground, beginnings of deep gully erosion by the Río Reventado.

some drastic changes also occurred in the relative rates of infiltration and runoff of precipitation. The capacity of the soil to absorb water was greatly reduced and runoff of rainwater was correspondingly increased. R. D. Tarble (oral commun., 1964) and the author estimated that runoff in the upper basins of the Río Reventado exceeded 80 percent of precipitation during any sustained low-intensity rain-

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fall and that it may have been as much as 95 to 100 percent during periods of high-intensity rainfall. As a consequence, flash floods became frequent during the rainy seasons, and erosion was so accelerated that each flash flood became a debris flow.

ACCELERATED EROSION

Accelerated erosion on the slopes of the volcano was directly related to the increase in rate of both overland and stream runoff accompanying precipitation. Overland runoff caused sheet, rill, and gully erosion, and stream runoff caused channel erosion. Gully erosion, as used here, refers to erosion of new channels; channel erosion refers to erosion of preexisting channels. The accelerated channel erosion created many unstable slopes and resulted in an increase in landsliding.

The eroding capacity of overland flow is a function of several variables, namely: The rate of precipitation, infiltration capacity of the soil, length and steepness of the slope, and the natural resistance of the soil to erosion. The resistance of a soil to erosion is primarily a function of the degree of vegetal cover, but it is also related, in part, to the physical structure of the soil in the surface layers. According to Horton (1945, p. 318), the resistance of soils to erosion generally will tend to increase with the fineness of the soil particles or soil texture and with the degree of cementation or compaction of the soil.

In many ways the effects of the ashfall can be compared to the effects on erosion that result from the destruction of vegetation by fire in areas in the Western United States. Soil erosion studies in these areas by the U.S. Forest Service (Anderson, 1962; Copeland, 1965; Krammes, 1960, 1965; Sartz, 1953) indicate that overland flow and soil erosion can increase very rapidly when the vegetative cover is reduced below 60 to 70 percent. Studies in Utah indicate that runoff may increase as much as 36 times and soil erosion as much as 110 times when the vegetative cover is reduced to 10 percent from 60 to 70 percent (Copeland, 1965, p. 76–79; Noble, 1965, p. 116–118).

The erodibility of the newly deposited ash tended to be variable despite its apparent uniformity. The resistance of the ash was initially very high because of the hard crust that formed on its surface. However, beneath the crust the ash remained soft and loose. Consequently, once the crust was broken or destroyed, sheet and rill erosion soon began to remove the underlying loose ash. Because erosion of this loose ash in turn also undermined the crust it collapsed. Destruction of the crust thereby was accelerated and the erodibility of the ash-covered slopes was correspondingly increased.

Erosion on a slope will not occur until the available energy produced by the overland flow exceeds the resistance of the soil to erosion

(Horton, 1945, p. 320). Hence, the eroding force will be increased progressively downslope from a divide or watershed, and a zone of little or no erosion will be preserved near the crest of the divide. (See fig. 5.) Observations by Renner (1936, p. 12–13) and computations by Horton (1945, p. 321) indicate that the amount of erosion tends to increase to a maximum on a slope of about 70 to 84 percent (35° to 40°) and thereafter to decrease to zero on a slope that approaches vertical.

During the 1964 rainy season most of the erosion of the fresh ash from the upper slopes of the volcano resulted from the headward and lateral growth of rills and gullies. Neither mass movement nor minor landslide failure of the new ash was observed. The stability of the new ash probably can be attributed to the high degree of internal friction and shearing resistance that is inherent in a mass composed almost entirely of fresh, angular, rock particles. From measurements made of ash removal and from a study of photographs taken periodically of the erosion features, it was estimated that one-third to one-half of the newly fallen ash had been removed from the upper slopes of the volcano by the end of the 1964 rainy season. Some of this material was redeposited on valley floors and other areas of low gradient, such as roadways and ditches; the remainder was carried on downstream.

Channel erosion by streamflow (fig. 6) was many times more severe

FIGURE 5.—Sheet and rill erosion of ash from upper slopes of Irazú Volcano.

than the sheet, rill, and gully erosion that occurred on the ash-covered slopes. The eroding capacity of streamflow depends largely on velocity and discharge of the stream. These factors are determined chiefly by the depth, width, and gradient of the channel, character and quantity of sediment load, and the material forming the channel. Much of the Río Reventado channel consists of poorly consolidated, altered and weathered, clayey lahar and ash deposits. Shear strength of these deposits is probably very low, particularly when saturated, owing to their high clay content; much of the original volcanic glass in the ash and lahar has been altered to a clay mineral. Thus, a combination of easily eroded channel material of low shear strength, high discharge, and high-velocity flow resulted in a very high eroding capacity for the Río Reventado and other streams draining the volcano.

LANDSLIDES

The growth of old landslides and the formation of new landslides along the valley walls of streams that drain the upper slopes of the volcano were both extensive and very rapid. Prior to the eruption, the walls of most of these valleys commonly were oversteepened and barely stable even with a cover of vegetation. The importance of vegetation on slope stability was pointed out several years ago by Bailey (1941, p. 241), who found that densely vegetated slopes in

FIGURE 6.—Accelerated channel erosion in the upper Río Reventado valley. Much of the upper basin of the Río Reventado is underlain by soft, clayey lahar and ash deposits.

Idaho and Utah were stable at gradients up to 173 percent (60°), but the barren talus-covered slopes were stable only at gradients of 68 to 80 percent (34° to 38°). The numerous flash floods that swept down the valleys during the 1963 rainy season, however, soon stripped the vegetation from the lower parts of valley walls, repeatedly scoured and progressively deepened stream channels, and severely undercut the oversteepened valley walls. Thus, the stage was set for the reactivation of numerous old landslides and the formation of many new ones.

The development and rapid growth of both old and new landslides was especially prevalent in the upper basin of the Río Reventado. The upper basin is underlain chiefly by poorly consolidated, clayey lahar and ash deposits of low resistance to shearing stresses. Fewer landslides formed in the middle basin, where the slopes are not quite as steep as in the upper basin and where more of the valley walls are underlain by lava flows and well-cemented agglomerates and volcanic breccias. Although several small landslides had formed in the Río Reventado valley by the end of the 1963 rainy season, only one large slide, the Prusia landslide, was evident at the beginning of the 1964 rainy season (pl. 1, fig. 7). By the end of the season, however, undercutting of slopes by channel erosion was so severe that the Prusia slide had nearly doubled in area and volume, several other large slides had formed, and smaller slides not directly underlain by more resistant rock virtually lined all the valley walls in the upper basin. All the larger slides and many of the smaller ones appear to be old landslides that have been reactivated. Figure 8 shows a part of the large, reactivated Llano Grande landslide. The numerous old landslides along the Río Reventado channel indicate that accelerated stream erosion and mass movements also must have accompanied some of the previous ash eruptions of the volcano.

Downslope movement along these unstable valley walls was almost continous during the rainy season, so that a nearly constant supply of earth and rock debris was contributed to the valley floors. The three largest slides—Llano Grande, Prusia, and Retes (pl. 1)—moved downslope at rates of 2 to 4 meters per week during the peak of the 1964 rainy season. They continued to move during the dry season but at a greatly reduced rate; movement on the smaller slides, however, virtually stopped during the dry season (Gregorio Escalante, written commun., 1965). R. D. Krushensky (written commun., 1965) estimated that by March 1965 these three large slides involved the mass movement of a total of more than 60 million cubic meters of earth and rock.

The numerous landslides not only contributed large quantities of material to the debris flows but destroyed roads and bridges (fig. 9)

FIGURE 7.—Parts of the Prusia landslide. The average rate of movement of this landslide, which in October 1964 covered about 22 hectares, ranged from 12 meters per month during the rainy season to less than 1 meter per month during the dry season (Gregorio Escalante, oral commun., April 1965). The Río Reventado channel is in the foreground just out of both views. Upper: Southern part. Lower: Northern part.

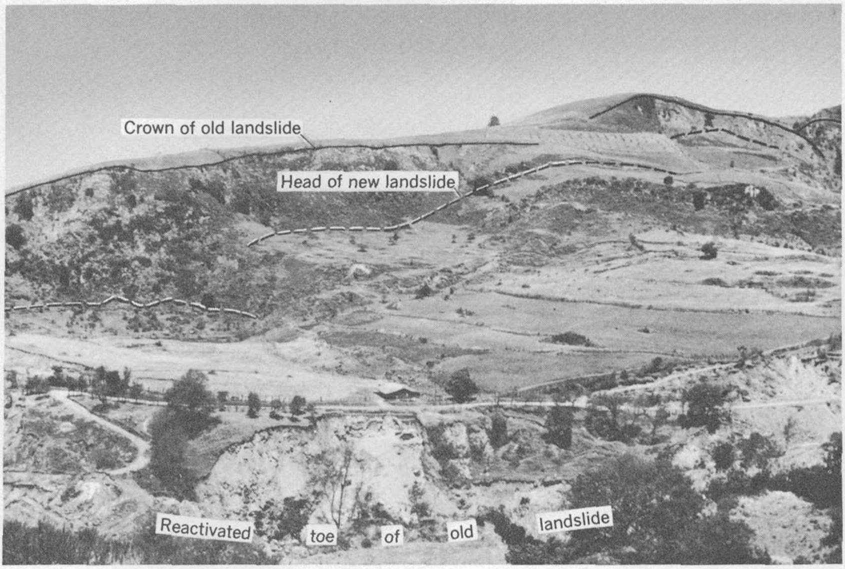

FIGURE 8.—Part of the Llano Grande landslide. Limits of the old landslide are evident in the steep scarp along the skyline (solid line). The head of the newly reactivated landslide is along this same scarp (dashed line). The average rate of movement of this large landslide, which in October 1964 covered about 41 hectares, ranged from 6 meters per month during the rainy season to less than 1 meter per month during the dry season (Gregorio Escalante, oral commun., April 1965).

and much valuable agricultural land. Many individuals also considered the larger landslides to be potentially very hazardous to Cartago and environs. If a more rapid or sudden movement of one or more of these slides occurred, it was feared that the slide debris would fill the valley and dam the stream. If such a dam is overtopped or breached in any way, the rapid release of ponded waters through the breach can produce a catastrophic flood of mud and debris downstream. Such an event occurred in the Gros Ventre River valley in Wyoming in 1925 (Alden, 1928). Considerable damage certainly could be expected from any sudden release of floodwaters that might be temporarily dammed behind one of these large landslides; however, the possibility of a catastrophic flood occurring in the Río Reventado valley appears remote. The steep gradients of the Río Reventado combined with the narrowness of its valley preclude the formation of any large body of water behind such a dam.

DEBRIS FLOWS

GENERAL FEATURES

Debris flows proved to be one of the most damaging of the many problems created by the eruption, and their control proved the most costly and difficult. Although some small floods and debris flows occurred in the Río Reventado and other streams soon after the eruption began in March 1963, the most disastrous debris flow occurred in the Río Reventado in December at the end of the 1963 rainy season. A violent rainstorm, which raged over much of the country for several hours, culminated in a torrent of water, mud, and debris that swept down the Río Reventado valley with destructive force in the late evening hours of December 9. From detailed studies of the storm and the debris flow, it was estimated (Instituto Costarricense de Electricidad, 1965, p. 56) that the discharge of this large flow was about 407 cubic meters per second, or approximately 29 cubic meters per second per square kilometer, and that it was composed of about 65 percent water and 35 percent sediment by volume. This large flow removed most of the accumulated debris from the valley floor, stripped the vegetation from lower parts of valley walls, and severely eroded valley walls and floors. In places the flood reached a height of more than 12 m. Near Cartago the debris flow spread out over the surface

FIGURE 9.—Highway bridge destroyed by the Llano Grande landslide. View is looking upstream at observation post 2. Toe of the slide (on left) destroyed the abutment of the bridge.

of the alluvial fan in a tongue of destruction about 1 km wide, devastated an area of nearly 3 km², and inundated another several square kilometers with muddy waters. More than 20 persons were killed by this disastrous debris flow and more than 300 homes were destroyed. Damage sustained by this debris flow has been estimated by the Oficina de Planificación to be as much as 25 million colones (or more than $3½ million).

The floods of mud and debris started again with the first storm of the 1964 rainy season and they continued to be a hazard and menace to lives and property throughout the 1965 rainy season (Ulate and Corrales, 1966, p. 124). Although damage to property was considerable, no additional lives were lost, chiefly due to the efficiency of a warning system that was established early in 1964 by the Oficina de Defensa Civil. More than 90 debris flows occurred during the 1964 rainy season in valleys draining the south and west slopes of the volcano; about 40 of these flows were in the Río Reventado valley. Although none were as large as the flow in December 1963, nearly half of them were large enough (higher than 3 m at post 2) to constitute a hazard to Cartago and environs. Figure 10 shows some of the effects of these debris flows in the Cartago area. Hydrographs of some of the larger Río Reventado flows of 1964 are shown in figure 11.

A survey of the literature reveals only meager data concerning mud and debris flows and their properties. Many individuals have studied the results but few have been privileged to observe and study the phenomena personally. For a review of the literature on mud and debris flows the reader is referred especially to Sharpe (1938) and to Sharp and Nobles (1953).

A mud or debris flow represents a form of mass movement of sediment that is intermediate between a normal streamflow and an essentially dry landslide. However, it is very difficult to assign any precise limits of definition to a mud or debris flow because they are members of a broad gradational series in which the relative proportions of sediment to water may vary widely. Sharp and Nobles (1953, p. 550) suggested that "debris flow should be used as a general designation for all types of rapid flowage involving debris of various kinds and conditions" and that "mudflow is simply a variety of debris flow in which the mud, although not necessarily quantitatively predominant, endows the mass with specific properties and modes of behavior which distinguish it from flows of debris devoid of mud." Varnes (1958, p. 37) distinguished between mudflows and debris flows solely on the basis of particle sizes. He applied the term "debris flow" to mixtures of water and sediment that contain a relative high percentage of coarse fragments, and he restricted the term "mudflow"

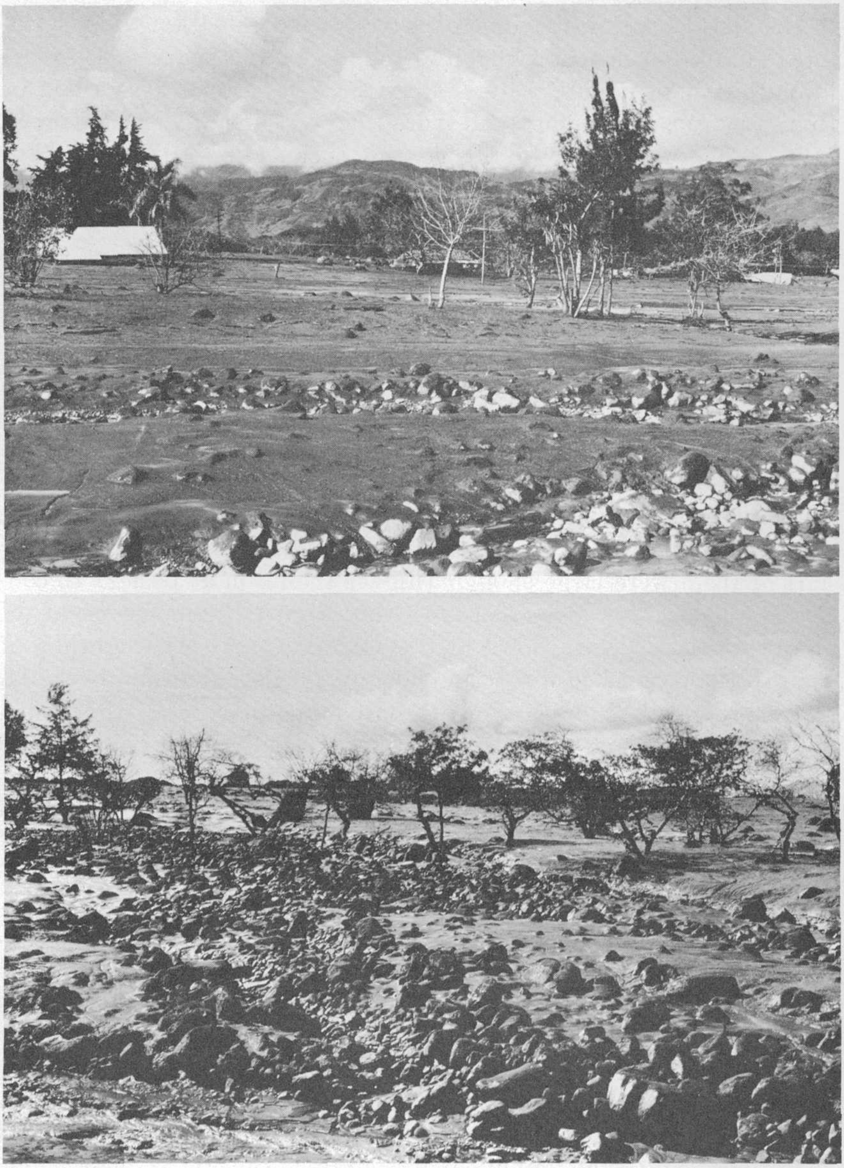

FIGURE 10.—Effects of the debris flows near Cartago. Upper: Some of the few homes that were damaged but not completely destroyed by the flows in the vicinity of the Pan-American Highway. Lower: Upstream from area shown above; bouldery content of the debris flows deposited on the upper part of the alluvial fan.

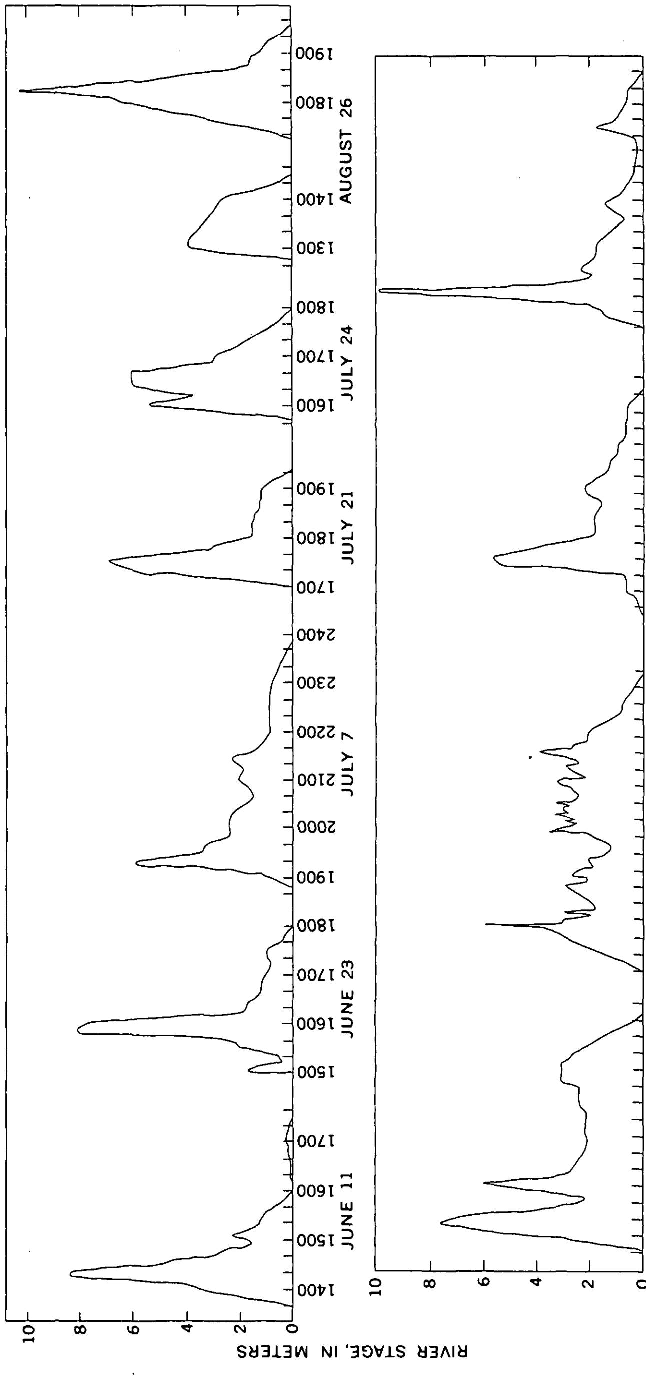

FIGURE 11.—Hydrographs of some of the larger Río Reventado debris flows in 1964, based on measurements made at observation post 2 by Oficina de Defensa Civil.

to mixtures that contain at least 50 percent sand, silt, and clay-sized particles. Thus, according to Varnes' classification, all the flows from Irazú are debris flows, as they contain a relatively high percentage of coarse fragments.

Recently Beverage and Culbertson (1964, p. 125–126) proposed an arbitrary limit of 80 percent concentration of sediment by weight to "differentiate between the commonly accepted concepts of 'streamflow' and 'mudflow.' " Such a limit of concentration may be applicable to mudflow, as defined by Varnes, but it cannot be applied to the Río Reventado debris flows. Mackin (1948, p. 469) pointed out that the use of any such arbitrary limit of concentration has little value or significance unless it is also accompanied by some statement as to the grain sizes involved, or to the range in grain sizes.

Studies of alluvial fan deposits in California by Bull (1962; 1963; 1964) indicate that certain sediment parameters, based on measurements obtained from grain-size analyses of sediments, might be utilized to distinguish three types of alluvial fan deposits: Mudflow deposits, water-laid sediments, and deposits intermediate between the two. The Río Reventado debris flows appear to be more correlative with Bull's intermediate deposits than with his mudflow deposits. (See table 3.)

PHYSICAL CHARACTERISTICS

A summary of some of the physical characteristics of the Río Reventado debris flows is given in table 2, and the particle-size distribution of some of the flows is shown in figure 12. These data are based on velocity measurements and sediment samples obtained and analyzed by the Instituto Costarricense de Electricidad (1965, p. 252–258) during the period September 8 through November 11, 1964. All the sediment samples were collected by means of an open-mouthed container, 15 cm in diameter, dipped from the debris-flow surface.

The physical characteristics of Río Reventado debris flows varied greatly from one flow to another and during the final phase of their fluid stage. Most flows became very thick and pasty during the final phase, much like a thick, flowing concrete, but some became thin and watery. These thin flows were potentially more dangerous, as they were capable of severly eroding levees and other manmade protective structures. The range in grain size and sediment concentration, of course, is much higher than indicated in either figure 12 or table 2, simply because it was impossible to obtain a sample of the total range in particle size. Boulders as much as 2 to 3 m in diameter were very common in all the flows, and several as large as 4 to 5 m in diameter were observed. The largest boulder known to have been transported

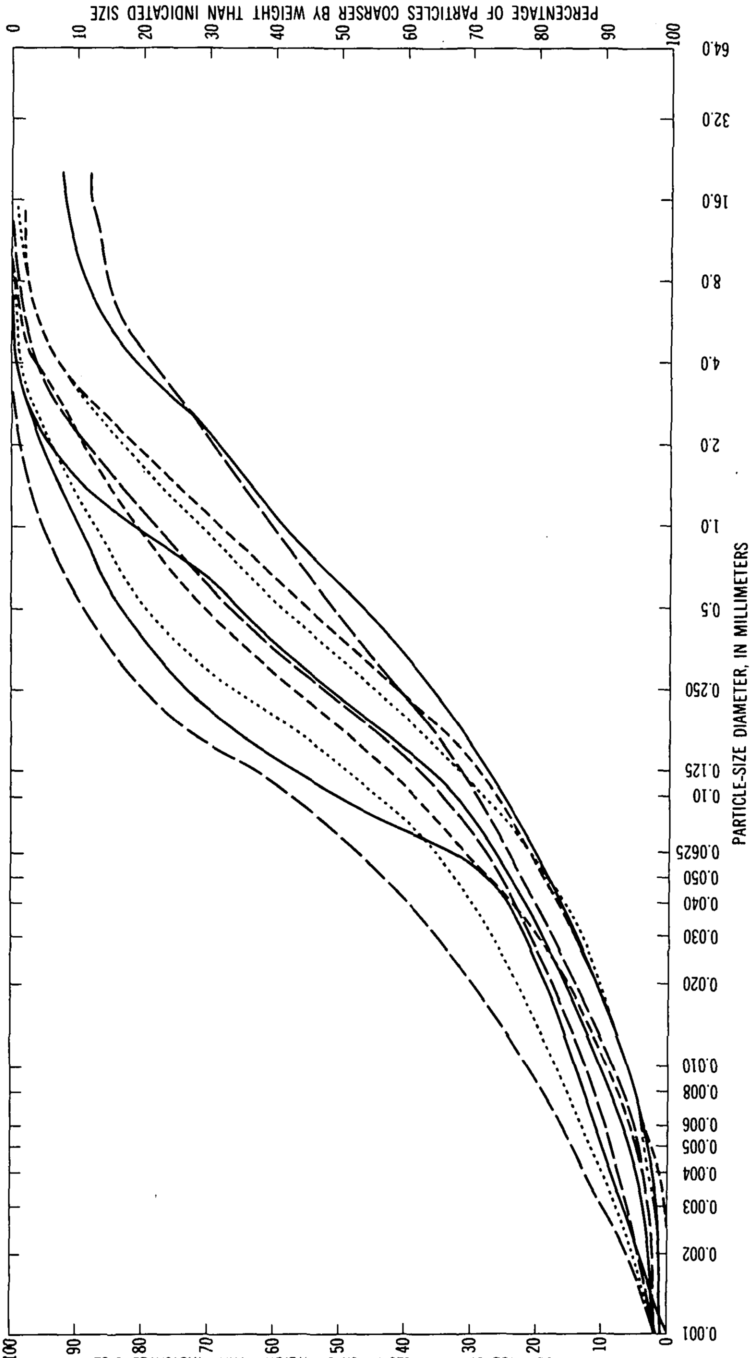

FIGURE 12.—Size distribution of particles from samples of some of the 1964 Río Reventado debris flows. (From data furnished by Instituto Costarricense de Electricidad, 1965.

TABLE 2.—*Summary of some of the physical data on the Río Reventado debris flows*

Physical data	Number of samples	Range	Average
Velocity ...m per sec..	31	2.86–10.00	5.27
Density ...g per cm³..	80	1.13–1.98	1.61
Specific gravity (solids) ...	15	2.50–2.70	2.61
Concentration ...ppm..	89	200,000–788,000	574,000
Discharge ...m³ per sec..	17	57–407	170
Grain-size distribution:			
Median (*Md*) ...	10	.07–.60	.28
Phi median (Md_ϕ) ...	10	3.87–3.35	1.88
1st quartile (Q_{25}) ...	10	.013–.10	.054
3d quartile (Q_{75}) ...	10	.19–3.00	1.15
16th percentile ...	10	.006–.040	.022
84th percentile ...	10	.32–6.20	2.06
Sorting indices:			
$S_o=\sqrt{\frac{Q_{75}}{Q_{25}}}$ ...	10	2.58–7.01	4.61
$Sk=\frac{Q_{25}Q_{75}}{Md_2}$ ...	10	.50–1.28	.84
$\sigma_\phi=\frac{1}{2}(\phi_{16}-\phi_{84})$ ...	10	2.62–4.04	3.12
$QD_\phi=\frac{1}{2}(\phi_{25}-\phi_{75})$ ...	10	1.37–2.94	2.09

by one of the flows measured approximately 7.5 by 5.5 by more than 3 m and must have weighed at least 200 tons (fig. 13).

Sediment concentrations and surface velocities of the debris flows varied considerably both in time and in place. Although no direct relation is apparent, a crude general trend of an increase in sediment concentration with an increase in velocity can be seen in figure 14. A total of 90 samples was taken from the Río Reventado on 19 different days, and a total of eight samples was taken from the Río Agua Caliente on 2 different days. All samples with a sediment concentration below 200,000 ppm (parts per million) were arbitrarily eliminated, so that a total of 89 samples remained (fig. 16). Of these, 82 were taken in the upper basin—65 at observation post 2, from 17 of the flows, and 17 at post 3, from 7 of the flows. Another seven samples were taken in the lower basin from the Río Agua Caliente at a gaging station about 2 km downstream from the confluence of the Ríos Reventado and Purires (pl. 1). Sediment concentrations of the 89 samples ranged from 200,000 ppm (20.0 percent by weight) to 788,000 ppm (78.8 percent by weight). The samples average about 574,000 ppm (57.4 percent by weight), with a median of about 609,400 ppm (60.94 percent by weight). All the 82 sediment concentrations from the upper basin should be increased by an unknown, but certainly considerable, factor in order to account for the large number of unsampled sediment particles in the flows that are greater than 15 cm in diameter. Similar ranges in the sediment concentration of small ash-laden streams from

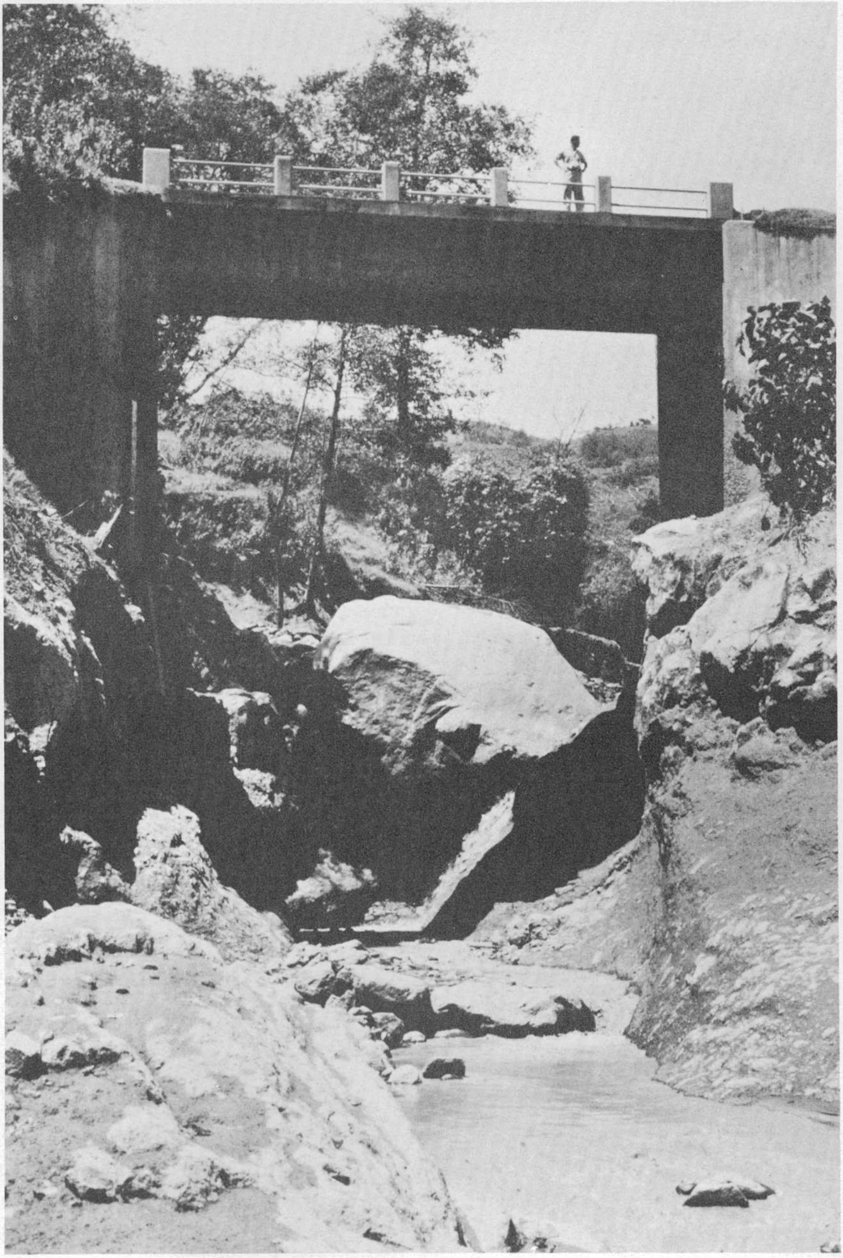

FIGURE 13.—Massive andesite boulder transported by a Río Reventado debris flow. Photographed at site of bridge that was later destroyed (fig. 9). Boulder measures about 7.5 by 5.5 by more than 3 m and is estimated to weigh at least 200 tons.

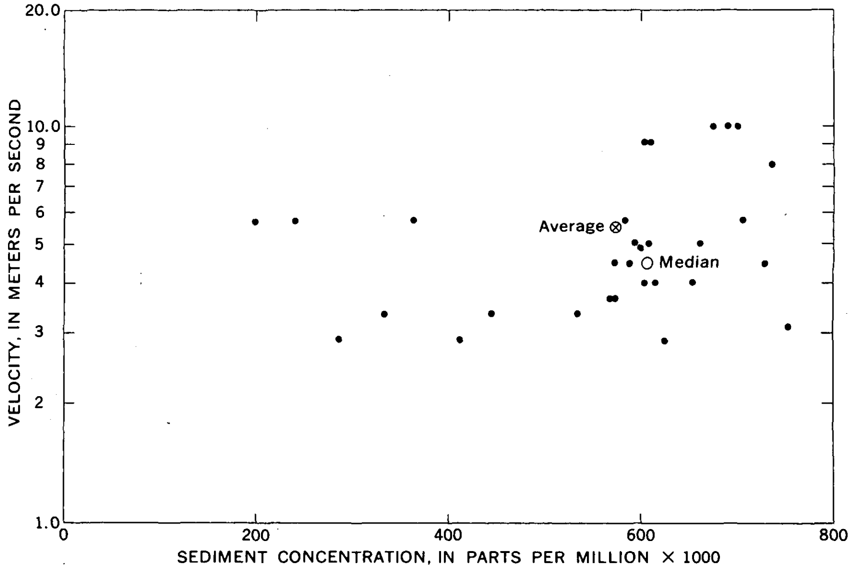

FIGURE 14.—Relation of velocity and sediment concentration for some of the Río Reventado debris flows. From data provided by Servicio Meteorológico Nacional (unpub. data, 1964) and Instituto Costarricense de Electricidad (1965, p. 255–258).

Parícutin Volcano in Mexico—from less than 20 percent to nearly 80 percent by weight—were reported by Segerstrom (1950, p. 96–107).

Thirty-one velocity measurements were made at post 2 on 12 of the flows (figs. 14, 15). Four others were made but were deleted—three, because they were measured on flows whose concentration of sediment was less than 200,000 ppm, and one, because its velocity of 1.02 m per sec (meters per second) was so much lower than any of the others that it might be in error. The 31 measurements ranged from 2.86 to 10 m per sec, with an average of about 5.27 m per sec and a median of about 4.46 m per sec. Peak velocities of 8 to 10 m per sec were measured on only two flows. The river stages of these two flows, as measured at post 2, ranged from 1.8 to 5.5 m (fig. 15) at the time of sampling, or from a low to a moderate flood stage. The sediment concentrations of these two high-velocity flows ranged from 606,000 to 737,000 ppm (fig. 14). Unfortunately, the velocities of some of the larger flows were not measured; therefore the maximum velocities attained are not known, but it seems very likely that speeds in excess of 15 to 20 m per sec were attained by some of these larger flows. Flood stages of 10 to more than 12 m at post 2 were reached by these larger flows. Sharp and Nobles (1953, p. 552) reported surge-front velocities for the Wrightwood debris flows in southern California that ranged

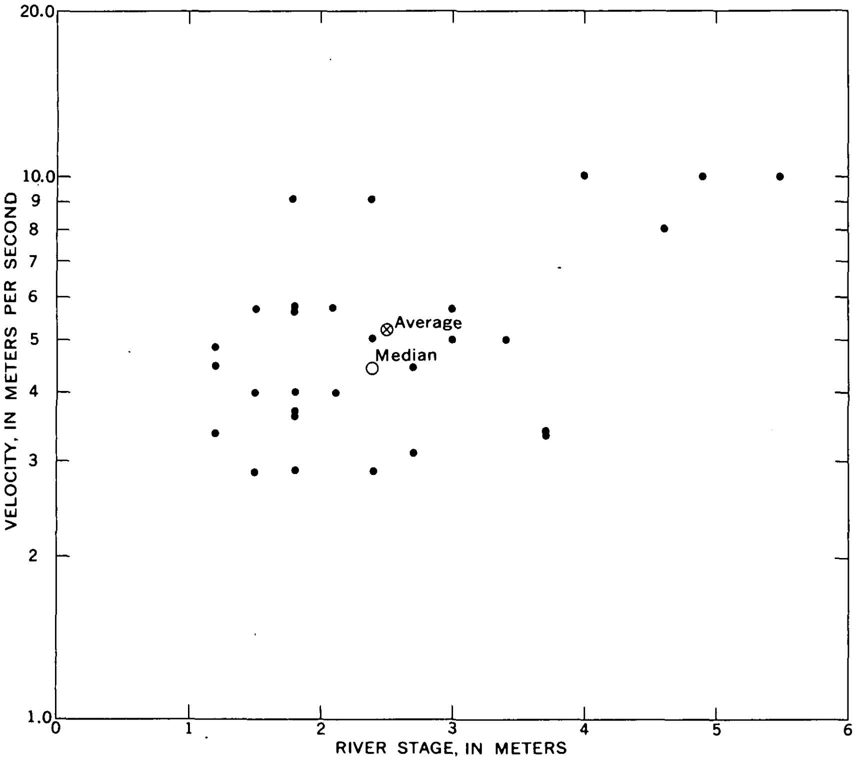

FIGURE 15.—Relation of velocity of some of the Río Revantado debris flows to river stage of the Río Reventado at post 2 at the time of measurement. From data supplied by Servicio Meteorológico Nacional (unpub. data, 1964) and Instituto Costarricense de Electricidad (1965, p. 255–258).

from less than 0.5 to 4.41 m per sec and averaged about 2.87 m per sec. The Wrightwood debris flows, however, were flowing on much lower gradients than the Río Reventado. Lynch (1941, p. 216) reported probable velocities as high as 9 m per sec for debris flows that occurred in 1934 in Los Angeles County, Calif. Curry (1966, p. 772) reported surface velocities as high as 16.3 m per sec for alpine mudflows in Colorado. Iida (1938, p. 681) estimated a velocity of 25 m per sec for a mudflow from Mount Bandai in Japan. Recently, however, Lang and Norris (1966, p. 589) pointed out that visual estimates of speed commonly tend to be too high, especially when violent motion is involved.

Although an increase in discharge of the Río Reventado normally was accompanied by an increase in the velocities and sediment concentrations of the flows (figs. 15, 16), the amount of sediment in the flows varied widely (fig. 16). Despite numerous difficulties that were encountered both in sampling the flows and in measuring the river stages, data on a few of the debris flows suggested that the sediment concentration increased during a rising stage of the stream and decreased during a falling stage. The flash-flood and variable nature of these flows, however, made it difficult to ensure that a sample of the sediment load was obtained precisely at the time of maximum discharge. Both sediment concentration and discharge are very sensitive to the areal distribution and intensity of rainfall. Consequently, only minor differences in rainfall intensity, or slight shifts in the path of a storm, or both, can easily result in major differences in the relative proportions of sediment and water that are contributed to and carried by different segments of the stream.

The Río Reventado debris flows were poorly sorted, containing material that ranged in size from clay to large boulders. The flows also commonly carried abundant fragments of tree trunks and limbs and other vegetative matter that was derived from the caving of the channel walls. The clay-sized content of the debris flows was low, ranging from about 1 to 10 percent and averaging about 5 percent. The combined silt- and clay-sized content also was low, ranging from 16 to 49 percent and averaging about 27 percent. Sorting of the Río Reventado debris flows is summarized in table 2 and compared with other mud and debris flow deposits in table 3. In order that comparisons could be made, the author used the same indices that were used by Bull (1964, p. A24): The Trask sorting coefficient, S_o the phi standard deviation, σ_ϕ; and the quartile deviation, QD_o. In table 3, the Río Reventado flows appear to be more comparable with the intermediate deposits (between mudflow deposits and water-laid sediments) than with the mudflow deposits of Bull (1964, p. A18). This may be because the Río Reventado sorting ratios do not include any particles larger than 15 cm in diameter and, hence, tend to be lower than would be expected. The very low range in the sorting indices of the Osceola Mudflow suggests that it may have some unique properties that distinguish it from the other deposits. The matrix of the Osceola, although poorly sorted, appears to have changed very little in composition from near its source on Mount Rainier to its distal end, some 20 miles down the White River valley (Crandell and Waldron, 1956, p. 349).

MOVEMENT

Most observers report that mudflows move in successive waves or pulsations. Many of the Río Reventado flows, however, did not show this pulsating characteristic, but rather they appeared to flow down the channel in a single surge, one for each rainstorm or torrential downpour that occurred in the watershed or within parts of the water-

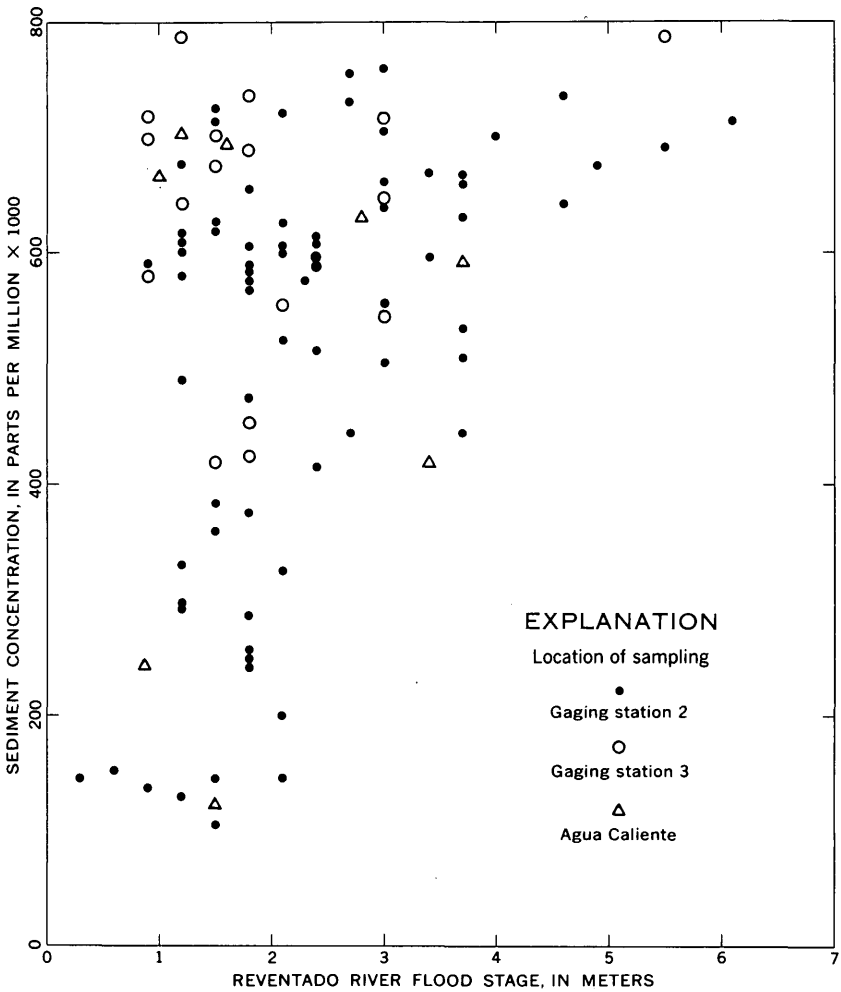

FIGURE 16.—Relation of sediment concentration of some of the Río Reventado debris flows to the river stage of the Río Reventado at post 2 at the time of sampling. From data supplied by Servicio Meteorológico Nacional (unpub. data, 1964) and Instituto Costarricense de Electricidad (1965, p. 255–258).

shed. Each flow was preceded by a slow to rapid rise in the level of the stream, depending on the rate or intensity of rainfall, and most flows were accompanied by an increase in the amount of sediment carried in the stream. Subsequently, the main flow of mud and rock debris would appear in the channel as a rapidly advancing wave or surge with a definite frontal lobe. It is estimated that the fronts of those lobes observed ranged in height from less than 30 cm to at least 2 m; the maximum surge height is not known, however, because none of the larger debris flows were seen by the author. After the initial surge,

TABLE 3.—*Comparison of sorting indices of the Río Reventado debris flows in Costa Rica with those of similar deposits in the United States*

Deposits and locality	Age	Number of samples	Sorting coefficient (S_o) Range	Sorting coefficient (S_o) Avg	Phi standard deviation (σ_ϕ) Range	Phi standard deviation (σ_ϕ) Avg	Quartile deviation (QD_ϕ) Range	Quartile deviation (QD_ϕ) Avg
Río Reventado debris flows, Costa Rica.[1]	1964	10	2.6–7.0	4.6	2.6–4.0	3.1	1.4–2.9	2.1
Wrightwood debris flows, California.[2]	1941	10	2.7–5.0	3.9				
Mount St. Helens lahars, Washington.[3]	Recent—about 2,000 yr B. P.	6	4.9–10.2	7.8	3.3–4.1	3.8	2.4–3.2	2.9
Osceola Mudflow, Washington.[4]	Recent—about 4,800 yr B. P.	8	9.0–16.0	11.7	4.5–5.8	5.0	3.2–4.0	3.5
Mudflow at Trout Lake, Klickitat County, Wash.[5]	Recent	3	5.8–11.0	7.7	3.8–4.3	3.1	2.1–4.1	2.9
Mudflow deposits on alluvial fans, Fresno County, Calif.[6]	do	50	5.0–25.0	9.7	4.1–6.2	4.7	2.3–4.7	3.1
Intermediate deposits on alluvial fans, Fresno County, Calif.[6]	do	16	2.6–5.0	4.0	3.1–4.7	3.9	1.4–2.3	2.0

[1] Instituto Costarricense de Electricidad (1965).
[2] Sharp and Nobles (1953).
[3] Mullineaux and Crandell (1962).
[4] D. R. Crandell (written commun., 1965).
[5] F. O. Jones (written commun., 1959).
[6] Bull (1964).

either the stream level dropped off rapidly or, more commonly, the flow decreased to a lower level that approximated the level of the flow immediately behind the surge front. The duration of flood flow ranged from less than 1 hour to as much as several hours (fig. 11), during which time both river stage and sediment concentration varied. Most of the fluctuations shown in figure 11 reflect either successive rainstorms or the effects of differences in the peak flows from tributary watersheds during the passage of a single storm over the area. Only the flow of September 8 (fig. 11) suggests a pulsating character of flow.

The coming of the main flows always was heralded by a loud roaring and rumbling noise, and the passing of the flows always was accompanied by considerable noise and a noticeable shaking of the ground. This ground motion undoubtedly was due to the violent turbulence of the flow and especially to the bumping, rolling, and grinding of the numerous boulders in the fluid mass. Some of the many slope failures that occurred along the channel may be attributed, in part, to the effects of this ground motion on the unstable walls.

Superelevation or banking of the debris flow surfaces was common, especially in the upper basin where channel gradients are steep. Banking at sharp bends in the channel occurred whenever velocities of the flows were sufficiently high. Depending on the size and velocity of the flow, the surface of the flow at these localities could be as much as several meters higher on the outside than on the inside of bends. A maximum difference in elevation of approximately 7 m was noted between the high flow marks left on opposite sides of a 90° bend in the channel of the upper Río Reventado, which was about 15 m wide at the bend.

The actual mechanics of flowage of debris flows is not fully understood at present. The increased transport capacity of a stream having a high concentration of suspended sediment is apparently largely due to the increased density and viscosity of the mass and to the greatly reduced fall velocities of the sediment particles. Other factors, however, also are involved, such as the buoyant and hydrodynamical lift forces acting on the particles of sediment (Am. Soc. Civil Engineers, 1966, p. 292), the chemical and physical properties of the fine sediment (Simons and others, 1963, p. G45), and the dispersive forces acting between the moving grains (Bagnold, 1956, p. 270). That loads of fine and coarse sediment in a stream tend to be largely independent of each other (Passega, 1957, p. 1953) is another factor that may affect the suspension capabilities and flowage characteristics of debris flows. According to Bagnold (1962, p. 316), the transport rate or capacity of the coarser grades is a function of streamflow, whereas that of the finer grades appears to be unlimited.

CONTROL MEASURES

The engineering problems involved in the control of erosion and of floods of mud and rock debris include several mutually related but diverse activities. Most flood-control measures are designed to reduce the hazards associated with flooding, and, consequently, the measures will provide flood protection rather than complete control; seldom, if ever, can absolute control of a river and its flood plain be attained. The principal methods of flood control are (1) downstream control, which is aimed primarily at flood protection and which is accomplished by means of improvement of channels and construction of dikes or levees and the construction of diversion channels and (2) headwater control, which is aimed primarily at decreasing the rate of runoff and retarding peak discharges and which is accomplished through the rehabilitation of watersheds and the construction of temporary reservoirs or detention basins. The principal methods of erosion control are (1) reduction of slope erosion by watershed rehabilitation, (2) reduction of channel erosion by channel stabilization, and (3) reduction of the quantity of debris by retention and temporary storage of sediment in debris basins. Each method of flood or erosion control has its advantages and also its limitations. Consequently each stream basin, and even each segment of the stream, must be analyzed individually in order to determine which method, or combination of methods, may prove to be the most effective and the most economical for that stream.

The control of mud or debris flows involves some special engineering problems in that some of the measures commonly used for the control of flood waters cannot be used effectively for the control of flows of mud and rock debris. One problem is due to the destructive forces that are generated by the flows as a result of their high velocities and densities and their bouldery contents. Another problem is due to a rapid reduction in velocity that occurs in areas where the stream channel is unconfined or where the stream gradient is suddenly diminished. As a consequence, when a layer of mud and rock debris spreads over a gently sloping area, such as the surface of an alluvial fan or a broad flood plain, it will gradually come to rest and congeal into a permanent deposit of earth and rock, whereas a layer of water spread over the same surface will eventually drain away. According to Bull (1964, p. A17), deposition on an alluvial fan occurs not only as the result of a decrease in slope, which brings about a decrease in the velocity of the flow, but also because of the decrease in depth and velocity of the flow that results from the widening and thinning of the flow as its spreads over the fan. The thickness and extent of the resulting deposit will be dependent upon the viscosity of the flowing mass and on the relative proportions of sediment to water in the flow. Thus, although the bulk volume of two debris flows may be equal, a thicker mixture of sediment and water not only will come to rest more quickly than a thinner mixture, but it will produce a layer of greater depth of earth and rocks over a smaller area (Woolley, 1946, p. 81).

Initially, due to the almost complete lack of basic data available, it was necessary to start some of the emergency control measures with little or no prior planning or preparation. As soon as possible, therefore, programs were developed for the collection and collation of basic data on the meteorology, hydrology, engineering geology, topography, volcanology, soils, and vegetation of the Irazú area, and especially of the Río Reventado watershed. A network of rain and river gaging stations was installed for collecting the meteorologic and hydrologic data. Detailed topographic maps and profiles were compiled of the Río Reventado basin and of the larger landslides. Periodic measurements also were made of the larger slides in order to determine the magnitude and direction of their movements; some subsurface investigations of the large slides also were undertaken. Geologic mapping and investigations of the volcano, its products, and its history were started; and engineering geologic maps and studies were made of parts of the Reventado, Retes, and Pavas channels in order to determine the foundation conditions that existed in the channels and to determine the geologic settings of the landslides. The soils and vegetation of the area were studied; before the revegetation program began, test plots were established on the ash-covered slopes to determine which plants would grow the fastest and thrive the best in the new ash. Concurrent with these investigations, consulting engineers began preparing plans, designs, and cost estimates based on the available data, both for implementing the emergency control measures and for developing long-range plans for the control of erosion and protection from flooding (Instituto Costarricense de Electricidad, 1964, 1965).

Downstream control measures applied to the Río Reventado in 1964 were concerned chiefly with the urgent and vital need to protect life and property in the city of Cartago and its environs. All three methods of flood protection were considered—stream diversion, channel improvements, and construction of levees.

Although diversion of some of a flood flow can frequently be the most direct and effective way to cope with the situation, the economic, political, and social aspects of the problem, particularly in a heavily populated area, often can offset obvious technical and engineering benefits. Implementation of proposals made for diversion of part of the Río Reventado was not attempted during 1964 primarily for these very reasons. Any long-range plans for flood control of the area, however, should certainly investigate thoroughly the possibilities of diverting at least a part of any large discharge by means of an emergency spillway and auxiliary channel. Such an auxiliary channel is most effective when the diverted water can be taken away completely from the main channel. If the diverted water must be returned to the stream channel downstream, it should be returned as far downstream as economically feasible in order to reduce or eliminate any backwater effect on the main channel. If sufficient land can be made available, the auxiliary channel can be designed to provide storage capacity as well as discharge capacity. Temporary storage of debris in a debris basin, although costly to construct and maintain, is perhaps the best protection yet devised for the positive control of debris (Eaton, 1936, p. 1324; Dodge, 1950, p. 343–345).

Channel improvements undertaken during the 1964 dry season included the widening, deepening, and straightening of parts of the Río Reventado channel in its lower basin. Unfortunately these measures proved to be only of very limited value for controlling debris flows. Instead of increasing the discharge capacity of the stream channel, as would be expected with an ordinary flood of water, the channel improvements actually functioned as miniature debris basins. The first storm of the rainy season promptly filled the enlarged channel with a deposit of mud and rock debris. The main flow was then forced to leave its old channel and seek a new one on a lower part of the alluvial fan. Thus, during a flood the stream might be diverted by as much as 50 m from its previous channel. The gradient of the stream channel on the alluvial fan was much too low and the volume of debris brought down by the flows was much too large for these minor channel improvements to be effective, particularly in the upper part of the lower basin where most of the coarser material was being deposited. Farther downstream, where only sediment of sand size and smaller was carried by the stream, some increase in the carrying capacity of the channel might be realized by means of channel improvements. Future work should include a compilation of data on discharge capacities of the channel throughout various stretches of the lower basin and an investigation of the probable effects on the channel of any improvements that might be made in the lower basin.

The construction of dikes or levees is one of the oldest and most extensively used methods of flood protection in the world. Often they also are the most rapid and economical means of obtaining this protection. These features, however, also can be potentially very hazardous in that, although they can provide complete protection up to a certain flood stage, a major disaster can result if the levees are breached or if a higher flood stage occurs and the levees are overtopped. The design and construction of levees, therefore, should conform to standard engineering practice, in which the height, width, side slopes, and construction should be such that the levees will not fail owing to seepage or piping, or to undercutting by the stream, or through failure of the side slopes.

Two large levees were constructed in 1964 along the Río Reventado channel extending downstream for several kilometers from where the stream debouches from the mountain front. These levees involved the emplacement of more than 1½ million cubic meters of material. Most of this construction was done by U.S. Navy Seabees in cooperation with the Oficina de Defensa Civil and other Costa Rican government agencies. Some minor levees farther downstream on the Río Reventado and in other river basins also were constructed by the local government agencies. Work on the levees was hampered by numerous debris flows that occurred during the 1964 rainy season, but fortunately the size and spacing of the flows was such that no overtopping or breaching of the levees occurred during construction. Although considerable minor damage to property did occur from the debris flows, major damage was confined to secondary roads and bridges and to the frequent disruption of rail traffic between San José and the vital port of Limón on the east coast, which can be reached only by rail or air. These downstream control measures, which were extremely valuable and necessary for the safety of the Cartago area, however, did not solve the basic problems of excessive runoff and accelerated erosion.

The most effective means of alleviating the basic problems of runoff and erosion can be accomplished only through headwater-control measures. If runoff can be decreased, then erosion is lessened, peak discharges of the streams are reduced, and the undercutting of channel slopes is greatly diminished. Effective stabilization of the channel slopes and streambeds can be accomplished by a system of check dams only after the runoff has been decreased. Consequently, in 1964 a program of watershed rehabilitation was initiated which was aimed at reducing runoff and retarding erosion of those watershed slopes that were the most seriously affected by the ashfall. These rehabilitation measures included surface diversions of drainage, contour ditching of slopes, construction of brush-check dams in the smaller gullies, and the artificial revegetation of the ash-covered, devastated areas. The revegetation in 1964 consisted of planting a mixture of fertilizer, oats, and pasture grasses in hand-hoed rows. All this watershed rehabilitation work was done under the direction of the Ministerio de Agricultura y Ganadería, utilizing funds provided by the U.S. Agency for International Development. The revegetation program was revised and expanded in 1965 (Ulate and Corrales, 1966, p. 127).

The emergency control measures developed for Irazú in 1964, although developed independently, were almost identical to those used by the U.S. Forest Service after a fire in 1960 in the San Dimas Experimental Forest in southern California (Rice and others, 1965). The emergency measures used at San Dimas included the broadcast sowing of annual grasses, contour trenching, side-slope stabilization by contour furrow planting, and channel stabilization by check dams.

The effects of the Río Reventado watershed control measures, in conjunction with some natural revegetation that took place as the ash was eroded from the slopes, began to show up in the rainfall-runoff pattern by the end of the 1964 rainy season. Early in the rainy season the duration of runoff was almost the same as the duration of rainfall, but by late October, R. D. Tarble (oral commun., 1964) noted that the duration of runoff was beginning to exceed the duration of rainfall by a considerable margin.

A flood-control reservoir also can be a very effective means of storing water during times of extreme flow because the water can then be released later when the critical flood conditions have passed. Such a measure, however, is not an emergency flood control measure and only can be considered in a long-range plan. Unfortunately no suitable reservoir sites exist on the Río Reventado. Throughout most of its length the channel is too narrow and the gradient is too steep to provide any appreciable volume of storage behind a low dam. The high cost and lack of storage also precluded any consideration of a large dam for this purpose. Only at one locality is the gradient low enough and the valley broad enough to be considered a potential site for a storage reservoir. This site is in an area in the upper basin known locally as the Laguna (pl. 1). However, at this site it was determined that the foundation conditions for a dam were poor, and the storage available behind a low dam was not sufficient enough to make the site economically feasible or practical.

Check dams have been used successfully for channel stabilization in many countries, notably in the alpine regions of Europe, and in Japan, China, South America, and the United States (Baumann, 1936; Ferrell, 1959; Ferrell and Barr, 1965; and Morum, 1936). Such a stabilization system, however, rarely proves to be an effective emergency measure, but it should be a major part of any long-range plans that are developed for the area. A series of low check dams installed in a mountain stream such as the Río Reventado can be one of the most practical and effective means of controlling channel erosion and thus reducing debris production. Unlike high dams, low check dams cannot provide any immediate or direct protection against large floods, but if properly designed and installed they can rapidly reduce the production of debris from channel downcutting and from undercutting and slumping of channel slopes during minor floods. To attempt to utilize check dams for channel stabilization in a valley such as the Río Reventado before headwater-control measures have become effective, however, can be disastrous and very costly. Six gabion check dams, which were built at the toe of the Llano Grande landslide in 1965 by the Government of Costa Rica, were nearly completed when all were destroyed by two large successive debris flows in May 1965 (Instituto Costarricense de Electricidad, 1965, p. 286–312; Ulate and Corrales, 1966, p. 127).

SUMMARY

Large volumes of fine lithic ash were erupted from Irazú Volcano during the period March 1963 to March 1965. The continued deposition and accumulation of this ash on the slopes of the volcano created many problems in the area. Some of the most serious were due to changes that occurred in the hydrologic regimens of the streams that drained the upper slopes of the volcano, especially in the watershed of the Río Reventado on the southwest slope of the volcano. The mantle of ash not only destroyed much of the original vegetative cover that existed on the slopes, but it also formed a hard crust that was virtually impervious. As a result, infiltration of rainfall was very greatly reduced and runoff was very greatly increased. The accelerated runoff increased slope erosion and produced frequent flash floods. The flash floods severely eroded channels and created many unstable slopes.

As a result of the accelerated erosion of slopes and especially of stream channels, each flash flood became a debris flow, more than 90 of which were produced during the 1964 rainy season. Most of the sediment in these flows was derived from channel erosion in the upper parts of the watersheds where steep slopes and stream gradients produce high-velocity flows and where the channel floors and walls largely consist of easily eroded material of low shear strength, mainly deposits of poorly consolidated, clayey ash and lahar. Debris flows in the Río Reventado overflowed streambanks and inundated lowland areas, destroyed much agricultural land and other private and public property, and seriously threatened the city of Cartago and environs.

Emergency measures that were applied to the problems included channel improvement and the construction of levees in the lower Río Reventado basin to promote flood protection for Cartago and environs, and watershed rehabilitation by terracing, contour trenching, drainage diversion, and artificial revegetation in the upper basin. The effects of all these measures are still being assessed, and data on these measures, along with other basic data, will be utilized in the final preparation of long-range plans for the control of erosion and debris flows from Irazú Volcano.

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