UNITED STATES
DEPARTMENT OF THE INTERIOR
GEOLOGICAL SURVEY

PROJECT REPORT
Costa Rica Investigations
(IR) CR-9

GEOLOGY OF THE REVENTADO RIVER WATERSHED, COSTA RICA, PART A, GENERAL GEOLOGY

by

Richard D. Krushensky
U. S. Geological Survey

1968
69-147

CONTENTS

ILLUSTRATIONS

GEOLOGY OF THE REVENTADO RIVER WATERSHED, COSTA RICA, PART A, GENERAL GEOLOGY

by

Richard D. Krushensky
U. S. Geological Survey

ABSTRACT

Irazú volcano, a large composite cone, consists of interbedded lava flows, lahars, and ash beds. This rock sequence, named the Irazú Group, has been divided into four formations; from the base: Reventado Formation, Sapper Formation, Birris Formation, and Cervantes Formation. Only the Reventado and Sapper Formations crop out in the Reventado watershed. The Reventado Formation consists of at least four widespread medium-gray finely prophyritic lava flows and interbedded lahar and some ash. Where not excessively jointed, lava flows within the formation are structurally sound and generally fresh. The Sapper Formation also consists of interbedded lava, lahar, and ash; lavas are black dense and coarsely porphyritic and in the middle part of the watershed are structurally sound if not excessively jointed. In the upper part of the watershed Sapper lavas are deeply altered, pyritic and structurally unsound.

At least three major inactive and six major active landslides have been recognized in the Reventado watershed, all apparently in the Sapper Formation. Mudflows in the Reventado watershed have been supplied with debris from the caving of oversteepened stream banks and to a lesser extent from the active landslides.

INTRODUCTION

Eruptions of Irazú volcano--the southernmost of the three active volcanoes of the Cordillera Central of Costa Rica--began on March 13, 1963, and continued intermittently until early February 1965. The volcano ejected ash and some lapilli, bombs, and blocks; but no lava was erupted. Heavy ash fall on the upper slopes of the volcano killed or defoliated 95 percent or more of the vegetation. This lack of vegetation and the relative impermeability of the ash cover led to the interrelated problems of accelerated erosion, landslides, and mudflows. These problems developed to the greatest extent in the watershed of the Reventado River (fig. 1, pl. 1) and to a lesser extent in the watersheds of the Tiribi, Durazno, and Virilla Rivers.

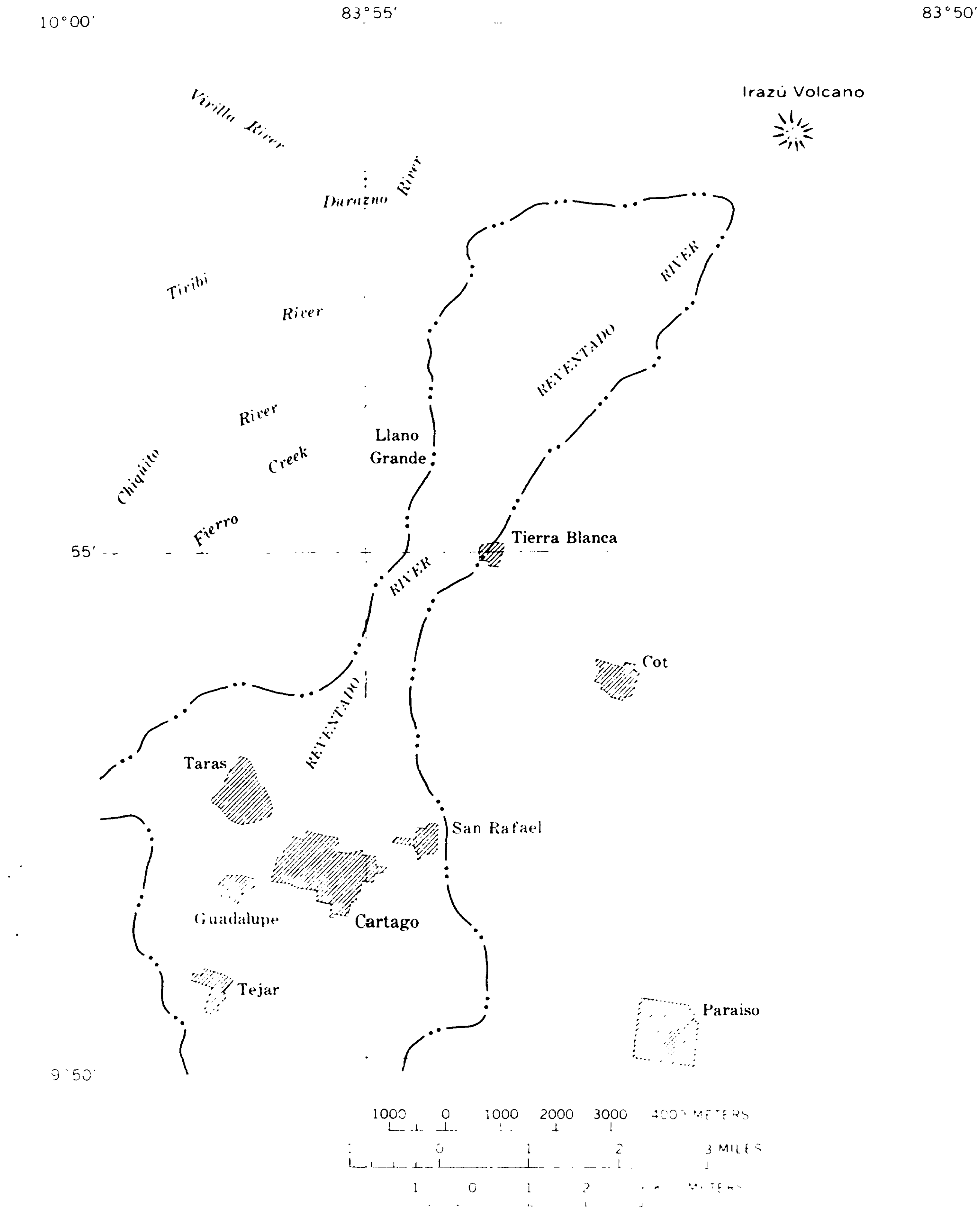

Figure 1.—Location map showing watersheds affected by mudflows in the 1963-65 periods, Cartago area, Costa Rica.

Because of the danger of mudflows and landslides to the city of Cartago, and because of damage to the Costa Rican economy, the Government of Costa Rica requested technical assistance from the Agency for International Development (USAID/Costa Rica). This agency in turn asked that the United States Geological Survey carry out geological studies of the affected areas, evaluate potential problems, and make recommendations concerning their solution.

This report is written for the use of consulting engineers in preparing a plan of mudflow control for the Reventado River. Emphasis is placed on characteristics of rock units mapped along the Reventado River and its tributaries. Geology of the Reventado River Watershed, Costa Rica, Part B., Slope Stability will be completed by F. D. Spencer at a later date.

Acknowledgements

Costa Ricans who assisted the writer in completing this study are too numerous to list individually, but among those deserving special thanks are Ing. Rodolfo Dobles, Director, and Gregorio Escalante, Geologist, previously of the Office of Civil Defense; Ing. Manuel Corrales, Chief, Section on River Control, and Ing. Jorge Umana, Geologist, Instituto Costarricense de Electricidad; Ing. Fernando Lizano, Chief Engineer, Ministry of Agriculture; Dr. Manrique Lara, University of Costa Rica; and the late don Federico Gutirrez of the Instituto Geografico de Costa Rica.

Mr. A. E. Farwell, Director, U. S. Agency for International Development, Mission to Costa Rica; Lt. jg. H. Zassenhaus, Officer in Charge, U. S. Navy Mobile Construction Batallion; Dr. K. J. Murata, Volcanologist and Mr. H. H. Waldron, Engineering Geologist, U. S. Geological Survey; and Lt. Col. Mervin Barnes, Inter-American Geodetic Survey also contributed greatly to the success of the study.

THE 1963-65 ERUPTIVE PERIOD

Activity of Irazú during its latest eruptive period was similar to that known from the three preceding major eruptive periods of 1723, 1726, and 1917-21, in that only pyroclastic ejecta were produced. Lava flows from Irazú are historically unknown. Most of the material ejected during the 1963-65 period was volcanic ash (4 mm in diameter), but small amounts of lapilli (4 mm to 32 mm in diameter), and some bombs and blocks (32 mm in diameter) were also ejected. Most of the ash was "accessory," that is, derived from materials torn from the conduit of the volcano or from avalanches into the crater, but some of the ash and most of the lapilli were "essential," that is, formed from magma or from lava only recently cooled in the throat of the volcano. The relatively large volume of accessory ash is clearly indicated by a comparison of the ash-laden eruptions that occurred after avalanches into the crater clogged the vent, and ash-poor eruptions that occurred through an open vent (Murata, 1966). Murata (1966) has ascribed the strong production of ash by Irazú to the loss of contained gases--chiefly water vapor--by exsolution before the magma reached the surface. This gas loss plus the effect of downward percolating meteoric water tended to chill and fracture the magma rising in the conduit of the volcano. Continued loss of gases from the magma led to explosive gas eruptions within the crater, and to a grinding together of lava fragments and accessory materials until the force of the gas eruption was sufficient to blow the finely ground material free of the crater. Violent gas eruptions had sufficient force to eject larger blocks of rock, some of which were incandescent. When the magma column neared the surface, fluid lava was ejected as plastic incandescent bombs. Ash was generally blown to the west and northwest of the crater because of prevailing winds. Short-duration changes in the wind direction, however, were sufficient to allow some ash to be deposited over all the provinces of the country, and as far away as Lake Nicaragua (Murata, 1966). Lapilli, blocks, and bombs were restricted to areas immediately surrounding the crater. Lapilli was deposited mostly on the steep northwest slopes of the volcano, and the bombs and blocks were distributed mostly at random around the crater rim. Blocks of essential lava as large as 2 m in diameter were seen on the northwest slopes of the volcano, outside the crater. Cow-dung bombs as much as 1.75 m in diameter were seen most commonly on the southwest rim of the active vent. Many blocks and bombs nearly buried themselves in the ash, and many of the bombs were surrounded by a ring of secondary bombs, which broke off the main mass on impact.

Extremely strong eruptions of ash and bombs occurred on the first day of explosive activity, March 13, 1963, but activity thereafter settled down to intermittent strong eruptions of ash and ash-poor steam (Murata, 1966). Strong eruptions of ash and bombs occurred during April, May, early July, November, and December of 1963, and in January 1964. The highest magma stand and some of the most voluminous eruptions of both plastic and nonplastic material occurred during December 1963 and January 1964 (Murata, 1966). Production of ash and bombs showed a marked decline after June 1964. Incandescent blocks, however, continued to be ejected as late as January 1965. Ash eruptions ceased by February 10, 1965. By July 1965, a small lake occupied the floor of the crater, and an alluvial fan in the northwest quarter of the crater had smoothed out the formerly rough crater floor. Activity in July 1965 was restricted to the venting of steam from the eastern wall of the crater and three boiling mudpots that cut the alluvial fan.

MUDFLOW ACTIVITY 1963-1965

Unconsolidated clayey materials exposed at the surface, steep slopes, abundant but intermittent rain, and a lack of vegetation are conditions which characteristically favor the formation of mudflows (Blackwelder, 1928 p. 465-480). Most of these conditions are typical of the slopes of Irazú even though volcanic activity has not acted as a trigger for accelerated erosion. Stream channels, especially in the upper reaches of the Reventado River watershed, are cut in unconsolidated clayey lahar; the area seasonally receives large amounts of rain, chiefly from intense showers of short duration; the slopes of stream banks and canyon walls are at high angles; and vegetation tends to be sparser or more shallow rooted than that on lower slopes. The term "mudflow" is used in this report for water-saturated debris of various rock types that moves downslope as a fluid in response to gravity. The term "lahar" is restricted to mudflows consisting solely of volcanic debris.

A thick and relatively impermeable ash cover, which killed or defoliated 95 percent of the vegetation in the upper part of the Reventado River watershed, accentuated the already existing ideal conditions for mudflow formation. In most of the previous major floods 1724, 1861, 1928, and 1951 prolonged heavy rains were necessary to produce floods in the lower reaches of the Reventado River. Increased runoff because of lack of vegetation, in addition to the ash cover, changed conditions so greatly that during 1964, rainstorms of even light intensity (20 mm/hour) and of short duration were sufficient to cause serious floods and mudflows on the Reventado River.

As many as 46 mudflows occurred in the Reventado River between May 1963 and July 1965 (ICE, 1965, p. 135-139). Five of the 1963 mudflows proved disastrous for the western suburbs of Cartago. The mudflow of December 9, 1963, the most devastating, flooded the western part of Cartago, caused the death of 20 or more people and the destruction of more than 200 homes. Supplies of potable water electricity, and communication via telephone, road, and rail were temporarily interrupted. This mudflow followed a strong rain of 7 hours duration.

Mudflows of June and July 1964 were so closely spaced and dumped so much debris into the western part of the city that emergency measures to protect the city were severely strained. A protective dike system was within a meter of being overtopped, and it was necessary to abandon a section of the Inter-American highway and construct a new one. Mudflows again became common occurrences on the Reventado River with the coming of the 1965 rainy season. The highest mudflows on May 25 (9m) and May 26 (10 m) destroyed six gabion check dams in the main channel of the Reventado River.

GEOLOGY OF THE REVENTADO WATERSHED

Irazú volcano is a large composite cone that consists of a thick sequence of interbedded lava, lahar, and ash of presumed Quaternary age. The sequence has been named the Irazú Group and has been divided into four formations, from the base: Reventado Formation, Sapper Formation, Birris Formation, and Cervantes Formation. Only the Reventado and Sapper Formations lie within the mapped area (pl. 1 and sections). Both of these formations consist of interbedded lava, lahar, and ash. The formations are differentiated on the basis of characteristic lava flows; medium gray and finely porphyritic in the Reventado Formation, and black and coarsely porphyritic in the Sapper Formation. Lahars in the two formations are much alike. The Birris Formation consists of coarsely porphyritic dark brown to black lava. The Irazú Group lies on apparently undeformed bedded tuff in the valley of the Cajón River on the northern border of the map and on welded tuff in the canyon of the Agua Caliente River on the southern border of the map (pl. 1). Similar undeformed bedded and welded tuffs overlie folded sedimentary rocks of Tertiary age 15 km southwest of the southwest corner of the map (pl. 1).

Pre-Irazú rocks

Undifferentiated rocks of Tertiary Age

Folded marine and continental sandstone, siltstone, limestone, shale, lava, and volcanic breccia of Tertiary age crop out near Tejar and Hervidero along the southern margin of the mapped area, and in the Carpintera Hills on the western margin of the area. Outcrops are generally scattered and, where found, are limited to more resistant limestone, quartzitic sandstone, and lava. Major parts of the area mapped as "Tertiary rocks undifferentiated" are covered by scrub forest or grasslands. Siltstone in the section has been dated as Middle Miocene on the basis of included foraminifera (E. Malavassi, Department of Geology, Ministry of Industries oral commun.).

Outcrops of rock of Tertiary age near Hervidero and Tejar are limited to two small areas of limestone. The limestone south of Hervidero forms a low cliff that is bordered on the east and west by vertical normal faults. Bedding planes are poorly defined and generally undulatory. The limestone strikes N.70°W. and dips 25°S. A limestone outcrop near Tejar shows the same faulted boundaries and about the same altitude. Some ill-defined zones within this outcrop consist of a mass of broken fossil fragments cemented by finely crystalline limestone. The exposure indicates a thickness of about 10 meters. It appears to be a bioclastic limestone deposited under near-shore conditions. In both areas the limestone is fine to medium crystalline, massive, and ranges from pale bluish gray to light buff.

Poorly sorted clayey sandstone overlies the limestone near Hervidero. Originally this sandstone consisted of a mixture of fine angular quartz grains with at least 40 percent sand- to silt-size lithic grains. Although the lithic grains are now entirely weathered to red and orange clay, texture retained in some of the grains suggests that they were derived from lavas. Facies changes in the sandstone are rapid both along and across the strike, and locally the rock crops out as a well sorted, friable, medium-grained, quartz sandstone. No outcrop occurs above the limestone in the Tejar area.

Outcrops of rock of Tertiary age west of Taras are limited to some poorly preserved sandstone, siltstone, volcanic breccia, and one thin lava flow. All are deeply weathered and now mostly clay. The presumed lava flow shows some white ghosts of feldspar phenocrysts and some irregular areas of iron oxide, presumably once mafic phenocrysts, in a matrix of white to medium-gray plastic clay. Attitudes could not be determined as bedding is not preserved. The stratigraphic relationship of this outcrop area to those near Tejar and Hervidero is unknown.

Welded and bedded tuffs

Undeformed bedded tuff and welded tuff of presumed post-Tertiary age crop out beneath the Reventado Formation in the valley of the Cajón River on the northern border of the map area and in the canyon of the Agua Caliente River south of the map area outside the Reventado watershed. (Plate 1). The welded tuff that crops out in the canyon of the Agua Caliente River unconformably overlies folded and faulted conglomerate, sandstone, and siltstone of lower Miocene age (Malavassi, Dept. of Geol., Ministry of Industry, oral comm.) and is overlain conformably by the Reventado Formation. Outcrops of welded tuff identical to that seen in the Agua Caliente canyon and vents that apparently produced all of these welded tuffs are seen 15 km southwest of the mapped area.

Irazú Group

The Irazú Group includes, from oldest to the youngest, the Reventado, Sapper, Birris, and Cervantes Formations, all of presumed Quaternary age. The breakdown into formational units is based strictly on characteristic lava flows because lahars and ash beds within the Reventado and Sapper Formations are similar in appearance and cannot be differentiated without considerable study or reference to the enclosing lava flows. Contacts that cross areas where lava outcrops are lacking are, therefore, indefinite. Widespread geologically recent, but superficial, ash beds and lahars, which cover much of the volcano, have been disregarded in mapping the Irazú Group.

Reventado Formation

The name Reventado Formation is here used to describe a series of interbedded andesitic lava flows, lahars, and ash beds. The formation constitutes the oldest unit of rocks in the Irazú Group and crops out extensively in the canyon of the Reventado River. The Reventado Formation overlies with apparent conformity unnamed non-folded welded tuff in the canyon of the Agua Caliente River, and overlies unfolded bedded tuff in the canyon of the Cajon River north of the Reventado watershed. The Reventado is overlain disconformably by the Sapper Formation in the headwaters area of the Reventado watershed. The Reventado Formation is presumed to be Quaternary in age chiefly because of the prevalence of constructional slopes. For convenience in mapping and in order to show the greatest detail possible, two rock-outcrop units have been used in mapping the Reventado Formation: lava and lahar, and lahar. Locally the Reventado Formation is undifferentiated from the Irazú Group.

Lava and lahar.--Outcrops of the lava and lahar unit are restricted to steep-walled canyons in the Reventado watershed (Plate 1, sections B-B', C-C'). Areas of lava and lahar east of Banderilla on the Reventado River consist of interbedded lava 10 to 20 m thick and lahar 2 to 5 m thick. The more resistant lava commonly forms the floors of stream beds and is the cap rock of waterfalls as much as 20 m high. Nearly vertical jointing in the lavas commonly results in vertical or nearly vertical canyon walls. Regional dip of the lava flows ranges from 15° to 21° S. Locally (as in the outcrop area near Misión), flow surfaces, which are also parting surfaces within the flows, range from horizontal to vertical within 100 m laterally. The lower surfaces, and to some extent, the upper surfaces of flows locally change elevation by as much as 10 m in a distance of 40 m. These changes in the top and bottom surfaces of the flows clearly indicate flowage of the lavas over and around topographic irregularities. Apparently lava flowed into depressions and smoothed the topography. Deposition of lahars and subsequent erosion produced a new uneven surface on which new lava flows were later emplaced. As a result, the lava and lahar unit shows lava flows having uneven bases and smooth tops, and lahars having smooth bases and uneven tops.

There appear to be at least four major areally extensive andesitic lava flows in the lava and lahar unit. All are dark to medium gray, show abundant phenocrysts of plagioclase (2-6 mm long) and scarce clinopyroxene phenocrysts (as much as 3 mm long). One areally widespread flow also contains abundant biotite. The matrix is very fine grained, and both matrix and phenocrysts are commonly fresh. The degree of jointing varies greatly; rocks in which internal flow-parting surfaces change attitude are closely jointed (5 to 15 cm), such as the outcrop area immediately southwest of the Misión landslide near Tierra Blanca. More commonly, joint blocks are 30 cm to 2 m on a side. Because most of the joints are closed, the lava flows are resistant to erosion.

Lower surfaces of individual lava flows lack vesicles, but imbricate, nearly horizontal flow-parting surfaces locally may cut the base of the flow into slabs of rock 5 cm or less thick. Upper surfaces of lava flows vary greatly. Two of the most widespread flows show slightly vesicular tops, but the vesicles are not mineralized. Upper surfaces of lava flows exposed on the floors of stream channels are structurally sound and commonly free of finely jointed rock and rubble. The upper surfaces of lava flows that crop out in the stream channel walls, however, commonly show a rubble zone, which may grade up into lahar or be covered by another lava flow. These rubble zones are composed of rock fragments ranging from sand to boulder size, angular to slightly rounded, and commonly vesicular. Fragments in these zones generally show the same texture and mineralogical composition as the enclosing lava flows. If present, the matrix is a clayey, finer grained counterpart of the large rock fragments; if matrix is absent, the rubble zone is held together by close packing of the fragments. Thicker zones (as much as 4 m) of angular rubble appear to be tops of lava flows that were surficially chilled and then broken as the underlying molten lava continued to flow. Continued movement of the mass mixed the crustal fragments together and to some extent broke them into smaller sizes. Rubble zones are structurally stronger than the lahars but neither as strong nor as resistant to erosion as the lava flows.

Beds of ash uncontaminated with lahar deposits are rare in the lava and lahar unit. The best-preserved crop out in the area of the Misión landslide, where ash beds as much as 2 m thick are preserved beneath lava flows. All these ash beds are soft, clayey, and easily eroded. The orientation of sharp bends in the lava and lahar outcrop area south of Banderilla was determined chiefly by the occurrence of easily eroded ash beds near stream level. Where ash beds have been eroded by the laterally moving stream, stream walls are overhanging. Collapse of the unsupported lava flows is common in such areas.

Lahars in the lava and lahar unit in the Reventado Formation are unconsolidated, clayey, and structurally unstable. Rock fragments in the lava and lahar outcrops south of Banderilla and just downstream from the Ortiga landslide range in size from sand to blocks 5 m on a side; fragments range from fresh to deeply weathered and from angular to rounded. The matrix is invariably clayey and locally shows characteristics of bentonite: swelling and high plasticity when wet, disintegration on drying. Rock fragments, when fresh enough to be identified, are of Reventado-type lava and, rarely, like some dikes known to intrude the Reventado Formation.

Lahar unit. -- The lahar unit in the Reventado Formation is mapped only along the Reventado River and it consists of lahar deposits like those described above; it is composed of fresh to deeply weathered rock fragments, which show an extrem size range enclosed in a clayey matrix. Stream side slopes of as much as 70° are common in this unit.

Sapper Formation

The name Sapper Formation is here used to describe a sequence of 15 or more lava flows, interbedded lahars, and some ash beds. The formation is well expose in the upper part of the Reventado watershed, especially in Cerro Sapper in the no east corner of the mapped area. The Sapper Formation is differentiated from the Reventado Formation on the basis of characteristic lava flows; lahars in the two formations are much alike. The Sapper Formation overlies the Reventado Format disconformably, but it is doubtful that much time separated the deposition of the two units. Erosion of the Reventado Formation prior to the deposition of Sapper lavas and lahars is clearly demonstrated from the Sapper filled channels in the Reventado Formation (Plate 1, section A-A'). Apparently the Sapper lavas and lahars flowed into and filled the headwaters area of a proto-Reventado drainage system. The Sapper Formation was divided for mapping purposes into the units lava and lahar, lava, and lahar, in a manner similar to that used for the Reventad Formation.

Lava. -- Sapper lava and minor associated rubble crop out at the junction of Pavas Creek and the Reventado River, and can be seen south along the Reventado and for some tens of meters up Pavas Creek. Below the Pavas-Reventado junctior Sapper lava forms the stream bed and extends up the west wall and locally the east wall for a few meters. This lava consists of a dense black matrix enclosing very abundant fresh, glassy, feldspar phenocrysts as much as 8 mm long, and scarce clinopyroxene phenocrysts as much as 4 mm long. Jointing in this outcrop area is generally close, and blocks 15-20 cm on a side are common. Vesicles are absent, but the lava flows and rubble zones have been strongly mineralized with an unidentified zeolite. Rubble zones consist both of well-compacted alluvium and autobrecciated lava. The autobrecciated lava rubble commonly shows a clayey sof matrix. Rare alluvial rubble zones, such as those near the Pavas-Reventado junction, are without a matrix but are cemented by secondary zeolites. Above the Pavas-Reventado junction, Sapper lava forms the stream bed, extends up both canyon walls as high as 10 m, dips 15° to 20°S. and includes thicker beds that are less closely jointed. Vertical joint faces in individual lava flows create waterfalls where a stream crosses the lava. The lithology of these thicker flows is essential the same as that below the Pavas-Reventado junction: dense black matrix with clear glassy plagioclase phenocrysts.

Sapper lava in the headwaters of the Reventado watershed differs considerably from that downstream. Most of the Sapper lava that crops out in the north-central and northeastern parts of the mapped area has been deeply altered to hard to soft, white to light buff remnants of the original rock. Most of the iron appears to have been removed by the leaching action of sulfuric acid-bearing water. Joint surfaces are limonite stained. At first glance the rock resembles a white clay, but closer examination reveals a silica-impregnated rock. Locally the altered rock is so highly impregnated with silica as to appear chalcedonic. The degree of jointing in the silicified rock varies considerably, but blocks 15 to 20 cm on a side are the most common. Lava in stream beds draining the high slopes has been largely altered to a very plastic gray-green clay, which retains ghosts of feldspar and pyroxene phenocrysts. These clays and the underlying weathered rock are heavily impregnated with pyrite.

Lava and lahar.--Areas mapped as lava and lahar show outcrops much like the same unit in the Reventado Formation. Channel walls are commonly cliffed, and lahars cropping out in the canyon wall are protected from erosion by lava flows. Channels mapped as lava and lahar along the Reventado River below the Prusia landslide in the middle and upper reaches of Pavas Creek and above Retes landslide (Plate 1, section A-A'), are impassable on foot because of the numerous high waterfalls and vertical canyon walls. The areal and stratigraphic distribution of lava flows and lahars seems erratic. The lava and lahar area immediately below the junctions of the Retes and Reventado Rivers shows only a few relatively thin lava flows separated by thick lahars, whereas the lava-lahar outcrop areas near Prusia landslide, that above the Retes landslide, and the outcrop area high in Pavas Creek show at least 15 thick lava flows, as well as some rubble zones cemented with an unidentified zeolite, and interbedded thinner lahars. Lava flows in this unit are essentially like those described above: dense black matrix containing common, glassy, transparent to opaque plagioclase phenocrysts as much as 8 mm long, and some clinopyroxene phenocrysts as much as 3 mm long. Locally entire flows and rubble zones in the outcrop area just above the Retes landslide are vesicular and mineralized with unidentified zeolites. Jointing is generally widely spaced (40 cm to 1 m) and the joints are closed.

Lahars within the lava and lahar unit range from very soft and clayey deposits that are easily eroded, to beds that are hard and relatively resistant to erosion. Rock fragments range from sand size to blocks 4 m on a side, and from angular hard fresh rock to rounded clayey ghosts, which can be distinguished from the matrix only on the basis of color. Lahars exposed in the drainage divide on the northern margin of the map have been pyritized and altered to plastic swelling clays.

Lahar.--Lahars mapped separately in the Sapper Formation, particularly those north of the Retes and Prusia landslides, are generally soft, deeply weathered, and unstable in stream cuts. The lack of stability stems both from the lack of supporting lava flows and from the deeply weathered condition of the material.

Irazú Group undifferentiated.--Areas mapped as undifferentiated Irazú Group are generally without outcrop. Geologically recent ash covers the ridges and channel sides are covered by wash from upper slopes. Ash from the 1963-65 eruptions ranges from about 5 cm in the area of the Llano Grande landslide to as much as 2 m on the crest of the northern drainage divide. In most areas, however, the thickest 1963-65 ash deposits do not exceed 20 cm.

Alluvium

Alluvial fan deposits

The Reventado River, because of the sudden gradient change where it debouches from the highlands, has deposited two alluvial fans; the oldest is the Quircot Fan north of Cartago, and the youngest is the Cartago Fan, the site of the city of Cartago.

Sometime before the deposition of the Quircot Fan, lateral cutting by the Reventado River cut a structural bench on the lavas and lahars of the Reventado Formation. The bench extended from Banderilla south to about the 1680 contour. The bench was enclosed to the east and west by steep sided canyon walls, parts of which are preserved. The Quircot Fan, which headed about half way up this structural bench, extends from Quircot on the west to San Rafael on the east, and from about the 1800-m contour on the north to some unknown distance beneath the Cartago Fan. The Quircot fan has been extensively channeled, but its surface still shows excellent topographic form. Typically, the coarsest debris occurs at the head of the fan, mostly in the area of the structural bench. Bedding and sorting in the fan are generally absent; blocks of rock as large as 4 m on a side are surrounded by smaller pebbles, sand, and clay. Downstream, deposits just above the old turbine site (Turbina on the map) still show some large blocks but they are chiefly sand and clay. Banks cut by the Reventado River in the Quircot Fan are nearly vertical and they appear to be stable if they are not undercut. Quircot Fan deposits show a minimum thickness of 45 m measured in the canyon wall of the Reventado River. At the abrupt westward bend in the Reventado River, just west of the old turbine site, the river has been undercutting the west bank for some time. If erosion is allowed to continue for about another 30 m, the Reventado River will be diverted into a new course through the suburb of Taras.

Deposition of the Cartago Fan took place at the southern margin of the Quircot Fan. Boulders as large as 5 m on a side are seen from the head of the Cartago Fan as far south as Campo Ayala. The composition of the fan is essentially the same as the Sapper and Reventado Formations, except that clay is much less abundant. Bedding in the fan is only very crudely and locally developed. Sorting is minimal, except for a southward lessening of coarser debris. A comparison with the most recent mudflow deposits on the Cartago Fan suggests that both the Quircot and Cartago fans owe their origin chiefly to mudflow deposition. The channel of the Reventado River is now entrenched as much as 60 m in the Quircot Fan and about 18 m in the Cartago Fan.

Terrace deposits

Shortly after the deposition of the Quircot Fan, renewed downcutting and reworking of the Quircot Fan deposits by the Reventado River and later deposition of mudflow deposits formed the terrace between Banderilla and the 1600 m contour. It is difficult to separate the terrace deposits and Quircot Fan deposits as both consist chiefly of mudflow debris, but it appears that the northern two thirds of the terrace is underlain directly by the lava and lahar unit of the Reventado Formation (Plate 1, section C-C') and the southern third of the terrace is underlain by deposits of the Quircot Fan. Renewed downcutting of the Reventado River has left the terrace flat about 60 m above river level.

Lacustrine deposits

Beds of fine to medium sand, silt, and clay form a relatively flat plain west of the Reventado River and south of Hacienda Escarre. These recent sediments were laid down in temporary ponds west of the low natural levee, which borders the Reventado River.

Stream deposits

Stream deposits outlined on the map were derived chiefly from the Reventado River and, therefore, follow the course of that river in an arc around the Quircot and Cartago Fans and the low hills of the Reventado Formation south of Cartago. Sorting is poor but the sediments are mostly fine grained, that is, fine sand, silt, and clay sizes. Near Dulce Nombre, stream deposits from the Toyogres and Barquero rivers consist of gravel.

<u>Mudflow deposits of 1963-65</u>

Areal distribution of mudflows deposited in the Cartago area by the Reventado River between September 1963 and January 1965 is shown on the geologic map; deposits confined to within 5 m of the normal stream course are not shown below the Lima Cemetery. Material in these mudflows typically duplicates that seen in the Quircot and Cartago fans; it is generally only very rudely sorted, varies from clay to boulder in size, and is soft when wet but capable of maintaining a near vertical cliff when dry. All the boulders and blocks are relatively fresh and hard; any deeply weathered materials presumably were ground into sand and clay and now comprise part of the matrix of the mudflow.

Landslides

Landlsides of various ages have developed over most of the Reventado River watershed, particularly along the Reventado River channel. At least three major inactive and apparently stable landslides have been recognized in addition to several major active landslides. Both active and inactive landslides chiefly involve lahar deposits containing some ash beds and a few thin, structurally weak lava flows. Outcrops of lacustrine sands and gravel are seen in one inactive landslide.

Inactive landslides

Misión landslide.--The southernmost inactive landslide, here called the Misión landslide, consists chiefly of lahar deposits. Topographically, the slide is a typical slump, displaying a very steep head scarp and some backward rotation of the mass as seen just below the road that crosses near the center of the landslide. The toe of the slide is interpreted as a debris fall, which resulted from movement of the mass over a steep canyon wall (see section B-B'). The toe of the landslide is now protected from removal by low bedrock scarps, and the slide appears to have been inactive during the 1963-65 period. The topography of ridges north and south of the Mision landslide suggest that large quantities of debris must have been removed from the slide by the Reventado River.

Ortiga landslide.--Another inactive landslide, here named the Ortiga landslide, lies east of the junction of Pavas Creek and the Reventado River. This slide also consists chiefly of lahar deposits and some lacustrine deposits of well-bedded ash, sand, and gravel. The toe of the landslide is protected from removal along the northern third of its length; but that part of the toe not protected by bedrock was removed early in 1964 and the landslide was reactivated locally. The head scarp is neither as steep nor as well defined as that of the Misión landslide, and evidence for the backward rotation of the slide is lacking. Hummocky topography and closed depressions, however, easily serve to distinguish the area of the landslide from the surrounding, more stable, smoothly rounded ridges.

Old Retes landslide.--The third inactive landslide area extends from the junction of the Retes and Reventado Rivers to about the 2480-m contour. This landslide consists chiefly of lahar deposits and some thin and structurally weak lava flows. Lahar deposits in this inactive slide are highly plastic and unstable. The head scarp of the Old Retes landslide is the steep westward-sloping face of the ridge which borders the slide to the east. Northward the head scarp swings to the west where it separates the Old Retes landslide from smaller and topographically distinct landslides. Toward the south the head scarp intersects the canyon of the Reventado River. Movement on this head scarp, as measured from the top of the steep slope to the top of the landslide block, is at least 65 m. The bench formed by this eastern part of the Old Retes landslide is well preserved, and its broad eastward sloping surface clearly suggests backward rotation of the slide mass. Only a small part of this eastern part of the Old Retes landslide appears to have been reactivated during the 1963-65 period. Most of the debris which once constituted the Old Retes landslide west of the Retes River has been carried downstream by the Retes River.

A small apparently stable landslide is also present on the western bank of Pavas Creek at the northern end of the Llano Grande slide. It involves only lahar deposits, and it is protected from removal of the top by a bedrock scarp 5-10 m high.

Active landslides

Four major, two minor, and numerous small landslides not shown on the map are now actively moving in the Reventado River watershed.

Llano Grande landslide.--Movement of the slide called the Llano Grande landslide from the nearby village of the same name was first noted in mid-1964, long after movement in the other major slides was first observed. Movement in this slide began initially in and near a small rock quarry just southwest of the Tierra Blanca-Llano Grande bridge. Within a few months the road within the area of the slide as mapped was impassable, the bridge had been destroyed, and the head of the landslide had reached about the westward limit indicated on the map. The Llano Grande landslide extends over 48 hectares and has been estimated to include about 38,000,000 cubic meters of material. Aerial photographs taken in 1956 indicate that this was the area of an old slide. New movement along the western border of the southern part of the slide has been minimal, as fresh scarps are only a few meters high. New movement at the head of the northern part of the slide, however, has been much greater; three new scarps now show a progressive drop toward the east of 8 to 12 m each, and an aggregate movement of at least 35 m. Scarps with a height of as much as 3 m and an opening of as much as 2 m are developed over much of the landslide surface. Movement at any one point within the slide is along a vector that lies somewhere between the direction of the Reventado River and the regional southward dip of the underlying lavas. Dip in these lavas ranges from about 21° in the northern part of the outcrop area to almost horizontal in the center and to 15° in the southern part.

The Llano Grande landslide consists chiefly of lahars and minor thin lava flows. Rock fragments range in size from blocks 6 m on a side to clay. Many larger blocks were plucked from the slide mass and moved downstream by the high floods of May 1965. Some were left on top of the gabion check dams constructed in the main channel of the Reventado River. Fragments range in shape from angular to subrounded, and are fresh to deeply weathered. Not uncommonly, large boulders are only clay ghosts, which show the same softness and high plasticity as the surrounding matrix. The ghost boulders are easily distinguished from the matrix on the basis of color and texture. Major constituents of the slide are sand and clay, the sand derived from ash and possibly some attrition of lava, and the clays chiefly from alteration of the ubiquitous finer ash. Locally lenses of relatively pure, highly plastic swelling clay similar to bentonite are seen in the slide face. When dry, these lenses of plastic clay show abundant slickensides, indicative of considerable internal shearing. Springs along the slide face are common during the wet season and only slightly less so during the dry season. These springs commonly break out of the slide face as a debris avalanch; flow freely for some minutes, and then are buried by the collapse of the overlying undermined material. During a rainstorm, the entire face of the slide sheds immense quantities of mud and rock into the stream.

The latest movement of the Llano Grande landslide is clearly related to the removal of the toe, which has occurred only since the beginning of higher than normal streamflow in 1963-65. The surface of the slide shows the same vegetative cover as that before the 1963-65 eruptions of Irazú, and rainfall has not changed appreciably in the last 10 years. Deforestation and overgrazing clearly have contributed somewhat to the development of this slide, and probably to all of the slides in the Reventado watershed, but the dominant factor, which triggered the latest movement, has been the removal of lateral support. In 1965, floods on the Reventado River had cleared the river course of debris and exposed a rock channel perhaps 3 m deep on the west side of the river. Continued slow movement of the slide, however, has refilled this rock channel during the last dry season (November 1965 to April 1966). Removal of this debris and the lubrication afforded by the normally high rainfall, will again result in a faster movement of the slide mass and a greater increment of debris is the stream during the next rainy season.

Pavas I and II landslides.--Pavis I, the larger, and Pavas II, the smaller, are two active landslides that lie at about the middle course of Pavas Creek. Both were first noted in 1964 and both are of small areal extent. Aerial photographs of Pavas I indicate that this is an old slide that has been reactivated. Margins of the slide are cliffed to about 5 m and open surface cracks are common over the entire surface. Pavas I and II appear to consist entirely of lahar deposits. Pavas I may move on a bedrock base, as bedrock crops out just south of the slide in the channel of Pavas Creek.

Retes landslide.--Retes landslide consists of a slice of the western part of the Old Retes landslide, reactivated during 1964, and the southernmost point of the eastern part of the Old Retes landslide. The western part of the Retes landslide includes three or four thin lava flows separated by thick beds of lahar. The lavas are well exposed in the western face of the Reventado River canyon south of the Retes landslide. The flows crop out as far as the slip face, from which point they break up and slump downward until all coherence as flows is lost and they are included in the jumbled debris of the slide. As opposed to other major slides in the Reventado watershed, the Retes landslide appears to be a debris slide rather than a slump, that is, a landslide in which a relatively rapid movement of earth and rock occurred without backward rotation.

Prusia landslide.--Prusia landslide, located on the upper course of the Reventado River west and slightly south of Hotel Robert, is a classic example of a slump, in which movement toward the river and down the regional slope has taken place in a series of independent units, all of which show backward rotation. The slide appears to consist of lahar deposits only; discrete lava flows are not seen. As with the Llano Grande landslide, springs flowing from the face of the slide create debris avalanches, which undermine and cause the collapse of the overlying material. The face of the toe of Prusia landslide is generally a sodden mass resembling wet gumbo. During rainstorms, movement of the mass into the Reventado River is greatly accelerated, not by movement of the whole slide, but rather by debris avalanche and debris fall along the slide face.

Sabanilla landslide.--The Sabanilla landslide named from the area of that name was first noticed as slump along stream courses in the valley above Sabanilla on the upper Reventado River; slump away from streams has increased greatly since 1964. The three branches of the Reventado River cut deeply into unconsolidated lahar deposits. Erosion by these streams has resulted in oversteepening and slumping of the stream banks, particularly between the 2600 and 2800 contours. Open crescentic cracks with low scarps and small "terracettes" with backward rotation are present both above and below this steep slope. Although extensive movement has not occurred above the 2800 contour, the presence of healed crescentic cracks, slopes with reverse rotation, and recently opened cracks with an indicated movement of 1 m indicates that some movement has taken place in the near past. Clay which constitutes the bulk of the lahar debris, is very plastic, and is in large part the product of alteration associated with the pyritization that is concentrated along the east-west drainage divide at the head of the Reventado watershed. Streams between the 2600 and 2800 contours have deepened and widened their channels by more than 200 percent since the end of 1964.

STRUCTURE

Interbedded lava flows, lahars, and ash beds in the Reventado watershed dip southward unaffected by folding and only locally affected by faulting. The constancy of eruptions from a summit vent throughout the known history of Irazú was the chief determinant of the position of lava flows and lahars. Ash beds owe their position chiefly to prevailing winds blowing from the east and northeast, and, as a result thicker ash sections are restricted to the upper part of the watershed and to the western and northwestern slopes of the volcano. Thin ash beds are, however, seen as far south as the lava and lahar unit south of Banderilla. These show the expected southward dip but no indication of subsequent folding. Lacustrine ash deposits in the canyon walls of the Tiribi River 7 km to the northwest are also unfolded. Tracing of individual lava flows for long distances along the Reventado River canyon and laterally in adjoining canyons clearly suggests that the lava flows flooded the countryside with little regard for the previous drainage. Lahars, not so easily traced because of their relative uniformity of composition, also appear to have flooded the countryside. Initially both lava flows and lahars were channeled by pre-existing stream courses, but as these stream courses were poorly incised, they were soon filled. Some evidence of this is seen in the lava and lahar area southwest of the Misión landslide where thin lavas (3 to 4 m thick) flowed around and then over low hills of previous lahar and lava. Erosion during Reventado time appears to have been minimal in the area of the present Reventado watershed, as relief within the Reventado Formation only locally reaches as much as 10 m. That appreciable erosion did occur after Reventado time and before Sapper time, is indicated by the near vertical erosional contact between the lava and lahar unit of the Reventado Formation and the Sapper materials that constitute the Llano Grande landslide.

Discernable faulting in the Reventado watershed is restricted to two areas on Pavas Creek 300 m and 800 m above the junction with the Reventado River. The northernmost fault near the first major northeast trending tributary on Pavas Creek is seen only in lava flows cropping out in Pavas canyon; possible extensions to the northeast and southwest are covered by lahar and ash.

This fault shows no discernable vertical displacement and yet the plane of the fault consists of a fault gouge easily traced across the canyon. Presumably, movement on the fault was chiefly strike slip. The southernmost fault on Pavas Creek borders a small patch of alluvium. This fault has been intruded by a dike of porphyritic andesite, apparently a feeder dike for Sapper lava flows. The northwestern margin of this dike shows a fault gouge like that seen in the fault upstream. Again, vertical displacement is not seen, and extension of the fault away from the stream is prohibited by the lahar and ash cover. The two northwest-trending faults that cut rock of Tertiary age on the southern border of the map area parallel the major right-lateral fault system to the west. These small faults in the map area may also be right-lateral faults, but evidence is lacking. Faults mapped by Escalante and Waldron on the southwest border of the Llano Grande slide, on the first north-trending tributary on Pavas Creek, at the junction of the Retes and Reventado Rivers, just above the major tributary-join on the Retes River, and at the southwestern edge of the Prusia slide (in Escalante, 1965, plate 5) with the exception of the two faults noted above, are unsupported by field evidence.

REFERENCES

Blackwelder, E., 1928, Mudflows as a geologic agent in semiarid mountains: Geol. Soc. America Bull., v. 33, p. 465-480.

Escalante, G., 1965. Geology of the upper watershed of the Reventado River (Geologia de la cuenca superior del Rio Reventado); in Report on the Reventado River problem (Informe sobre el problema del Rio Reventado): Inst. Constarricense de Electricidad, San Jose, p. 170-193.

Instituto Costarricense de Electricidad, 1965, Report on the Reventado River problem (Informe sober el problema del Rio Reventado): Inst. Costarricense de Electricidad, San Jose, 312 p.

Murata, K. J., 1966, The 1963-65 eruption of Irazu Volcano. Costa Rica (the period of March 1963 to October 1964): Bull. Volcanologique, in press.