GEOLOGICAL SURVEY CIRCULAR 639

Preliminary Report on the Geologic Events Associated With the May 31, 1970, Peru Earthquake

Preliminary Report on the Geologic Events Associated With the May 31, 1970, Peru Earthquake

By George E. Ericksen and George Plafker,
U.S. Geological Survey, and
Jaime Fernández Concha, Lima, Perú

GEOLOGICAL SURVEY CIRCULAR 639

Washington 1970

United States Department of the Interior
WALTER J. HICKEL, *Secretary*

Geological Survey
William T. Pecora, *Director*

First printing 1970
Second printing 1970

Free on application to the U.S. Geological Survey, Washington, D.C. 20242

CONTENTS

ILLUSTRATIONS

Preliminary Report on the Geologic Events Associated with the May 31, 1970, Peru Earthquake

By George E. Ericksen and George Plafker, U.S. Geological Survey,
and Jaime Fernández Concha, Lima, Perú

INTRODUCTION

The Perú earthquake of May 31, 1970, was by far the most destructive historic earthquake in the Western Hemisphere and ranks high among the world's catastrophic natural disasters. Within an area of about 65,000 sq km (square kilometers) in west-central Perú (fig. 1) the earthquake took an estimated 70,000 lives, caused 50,000 injuries, and destroyed or rendered uninhabitable roughly 186,000 buildings, representing 80 percent of all structures in the area (statistics from Comité Nacional de Emergencia del Perú, July 2, 1970).

Within the affected area many landslides and one cataclysmic debris avalanche disrupted communications and temporarily blocked ground access to many of the afflicted communities in the Andes Mountains. As a consequence, rescue and relief operations were seriously hampered, and the full extent of the disaster did not become known until weeks after the earthquake.

Much information relating to the earthquake, aftershocks, geologic effects, and structural damage is still being processed and will eventually appear in comprehensive reports. The purpose of this report is to make immediately available the results of our reconnaissance observations on the geologic effects of the earthquake, as well as some conclusions and recommendations regarding geologic hazards that should be considered in reconstruction. This preliminary report is based largely on studies of the effects of the May 31, 1970, earthquake made by Fernández Concha from June 1 to 17 and by Ericksen and Plafker between June 13 and July 4. During this investigation one or more of us visited most of the damaged cities and larger towns in the area, observed and measured ground effects, and made helicopter and fixed-wing photographic flights over the Santa Valley.

Acknowledgments

We wish to express our deep appreciation to the many persons in the earthquake-devastated area who cheerfully and informatively answered our questions about their observations of phenomena related to the seismic movement and resulting destruction. Their poise and cheerfulness in the aftermath of this cataclysmic tragedy have been truly magnificent.

Thanks are given to our Peruvian and American colleagues who supported our investigations and furnished invaluable information. We especially wish to express our gratitude to Ing. Alberto Giesecke, Director, Instituto Geofísico del Perú, and Enrique Gajardo, Director, Centro Regional de Sismología para América del Sur, for advice, information, and logistical support.

We wish to thank the Corporación Peruana del Santa for furnishing us with a copy of the report of Ing. Jaime Fernández Concha, of which we have made liberal use in the preparation of this report. We also wish to thank Ing. Gilberto Tisnado of the Instituto Geofísico del Perú who assisted us with the field investigations, logistic arrangements, and in obtaining data from various Government and private sources. The Servicio Aerofotográfico

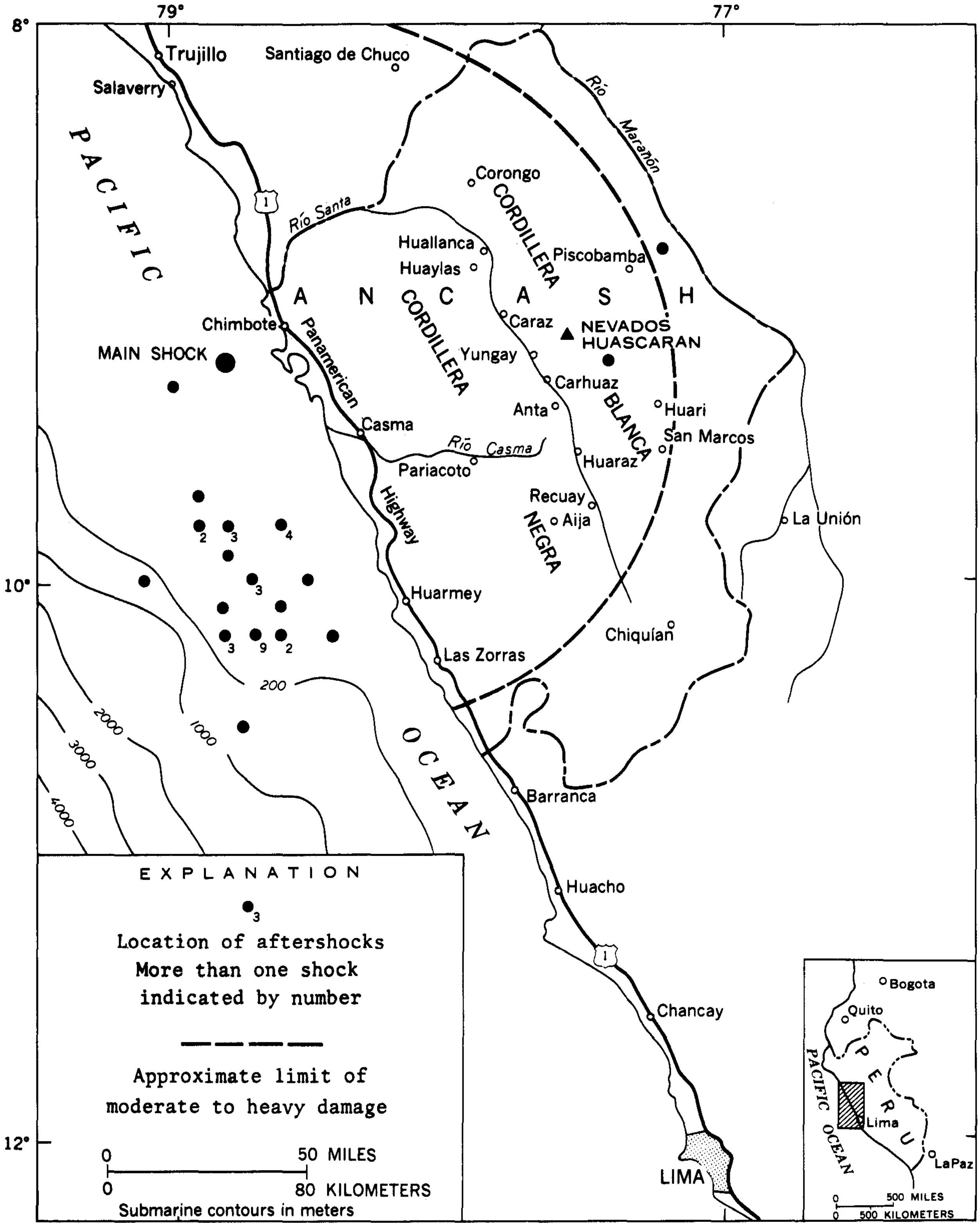

Figure 1.—Map of central western Perú showing area affected by the earthquake of May 31, 1970. Epicenters indicated for main shock and larger aftershocks are from U.S. Coast and Geodetic Survey (Mark Spaeth, oral commun., July 9, 1970).

Nacional del Perú kindly furnished the oblique aerial photograph of the Huascarán debris avalanche (fig. 2). Ing. Daniel Huaco also accompanied us during investigations in the coastal region and provided us with data obtained during his studies in the vicinity of Chimbote.

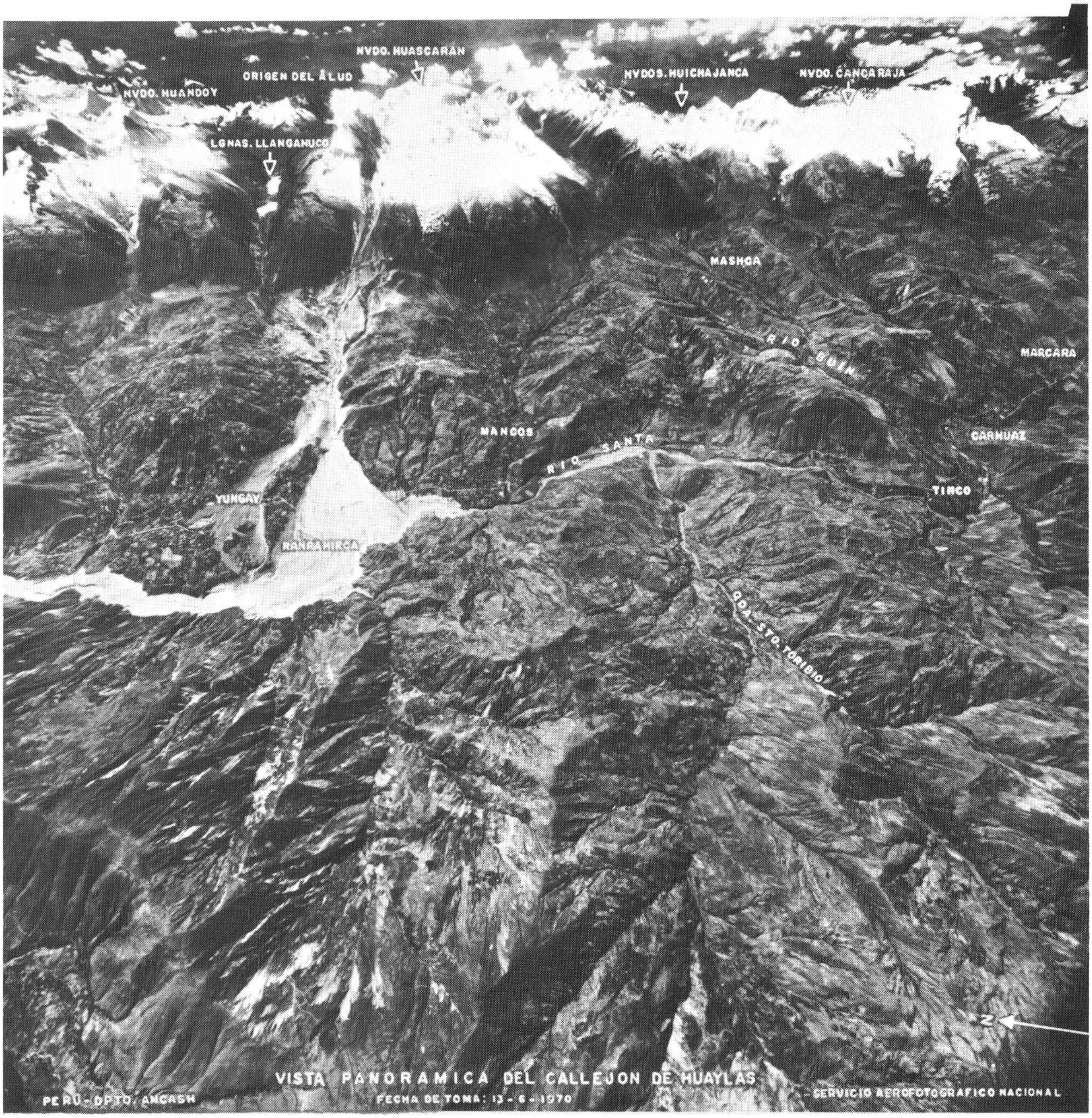

Figure 2.—Oblique aerial view of Nevados Huascarán and the Huascarán debris avalanche that destroyed Yungay and Ranrahirca.

Although Ericksen and Plafker were sent to Perú as direct representatives of the U.S. Department of the Interior, they worked as part of a special UNESCO team that was formed to make a preliminary study of the earthquake. We wish to express our thanks to our structural engineer colleagues on this team, Prof. Glen Berg of the University of Michigan and Dr. Raul Husid of the University of Chile, and to their associate Mr. John Meehan of the State of California Department of Schools for information that helped us to evaluate the relationship of structural failures to foundation conditions.

SEISMICITY

According to the U.S. Coast and Geodetic Survey (P. D. E. card, June 1, 1970), the initial shock, Richter magnitude of 7.7, occurred on May 31, 1970, at 3:23 p.m. Peruvian time (3:23 e.s.t.). The epicenter was at lat 9.2° S., long 78.8° W., or at sea 25 km (kilometers) west of the port city of Chimbote in the northwestern part of the Department of Ancash (fig. 1). Data from local seismic records in Perú (Enrique Gajardo W., Rept. to the Smithsonian Institution Center for Short-Lived Phenomena, June 23, 1970) suggest that the epicenter may actually be somewhat farther seaward than shown in figure 1, but that it would lie on the continental shelf. The hypocenter, or focus, was determined by the Coast and Geodetic Survey to be at a depth of 56 km.

According to eyewitness accounts, the earthquake began without prior warning as a gentle swaying motion that lasted for a few seconds and was followed by hard shaking variously estimated as lasting from 30 to 90 seconds (the best estimates seem to be about 45 seconds). There were no strong-motion accelerographs in the affected area at the time of the main shock, but several portable instruments that were installed later recorded some of the aftershocks. Most eyewitnesses described the earthquake tremors as having a pronounced side-to-side motion that made it difficult or impossible to walk or run, but not strong enough to throw people to the ground. In most places visited, the adobe structures reportedly began to collapse after only about 15 seconds of hard shaking.

The area of structural damage extends along the coast from north of Trujillo to slightly south of Las Zorras, and it extends inland nearly to the Río Marañon (unpub. data, American Andean Relief Expedition to Ancash) roughly 120 km from the coast (fig. 1). Our investigations suggest a maximum intensity of shaking in the coastal area between Casma and Chimbote (VII—VIII on the Modified Mercalli scale). Intensity of shaking was slightly less in the Santa Valley, attaining a probable maximum of VII on the MM scale in the region from Huaraz northward to Huallanca.

The epicenters of 37 aftershocks recorded at teleseismic distances on the Worldwide Seismograph network through June 8 are shown in figure 1. Most of these have magnitudes between 4 and 6¼ and hypocentral depths on the order of 45—66 km. Many strong aftershocks continued to be felt in the disaster area throughout the time we were working there.

The spatial distribution of the main shock and all but two of the aftershocks plotted in figure 1 suggests that the faulting associated with the May 31, 1970, earthquake occurred at depths between 45 and 66 km on a fault surface about 140 km long parallel to the coast and 65 km wide. Fault movement at depth is indicated by the absence of movement on known surface faults within the region, or of tectonic warping along the coast, as well as the lack of a tsunami (maremoto or seismic sea wave) that would suggest tectonic deformation of the sea floor. The significance of the two aftershocks having epicenters east of the Cordillera Blanca (fig. 1) is not apparent from the available data.

Neither the nature of displacement nor the dip of the fault are known, but it is reasonable to expect that focal mechanism solutions of earthquakes in this sequence will eventually provide information on the displacement at the earthquake source. The May 31, 1970, earthquake occurred in a well-defined belt of seismicity that follows the Perú-Chile Arc for 7,000 km from Venezuela to southern Chile. The high seismic activity, youthful mountain chains, volcanoes, and oceanic trenches that characterize this belt are believed by many geologists and geophysicists to result from progressive underthrusting of the Pacific Ocean basin beneath the South American continent. The nature and distribution of the May 31, 1970, earthquake and its aftershocks suggest that this earthquake also was probably genetically related to this fundamental zone of underthrusting along the western margin of South America. Although numerous large earthquakes have been recorded throughout the Peruvian sector of the arc during this century, it is noteworthy that the area affected by the May 31, 1970, event had been relatively free of destructive shallow-focus earthquakes (Gutenberg and Richter, 1954; Silgado, 1968). This is in accord with the testimony of Santa Valley residents who stated that a major destructive earthquake had not occurred in that area previously for a period of at least three generations.

GEOLOGIC AND PHYSIOGRAPHIC SETTING

The principal populated areas affected by the earthquake of May 31, 1970, include the coastal region from Las Zorras in the south to Trujillo on the north, and the valley of the Río Santa south of Huallanca (fig. 1). This part of the Santa Valley commonly is referred to as the Callejón de Huaylas (Huaylas Corridor) but in the strictest sense, the Callejón de Huaylas is only that part of the Santa Valley between Huaraz and Huallanca. The lower part of the Callejón de Huaylas is a deep, steep-walled canyon, about 15 km long, at the bottom of which is a narrow vertical-walled slot, as much as several hundred meters deep, called the Cañon del Pato.

The upper Río Santa flows between two major mountain ranges of the Andes, the Cordillera Blanca on the east and the Cordillera Negra on the west. The Cordillera Blanca has a core of granodiorite; Mesozoic marine sedimentary rocks lie on the flanks and at places cap the granodiorite in the center of the range. In contrast, the Cordillera Negra consists largely of Tertiary volcanic flow and volcanic clastic rocks, chiefly andesitic, but also rhyolitic in composition. Granodiorite and Mesozoic sedimentary rocks are widely exposed in the northern part of the Cordillera Negra. The valley of the Río Santa is partly filled with deeply dissected, fluvioglacial and mudflow material, which locally attains thicknesses of several hundred meters. A considerable part of the mudflow and debris-flow material originated from bursting of glacial lakes and from ice-rock avalanches in the Cordillera Blanca. Although this material is coherent enough to stand in near-vertical roadcuts and high streambanks, it is relatively unstable and slides readily when saturated or subjected to seismic shaking. Most of the cities and towns in the valley have been built on this type of material or on uncemented alluvial and fluvioglacial deposits.

Cordillera Blanca

The imposing Cordillera Blanca takes its name from a nearly continuous capping of glaciers and snowfields. The highest mountain in the range is Nevados Huascarán. It culminates in a glacier-covered north peak 6,663 meters (21,860 ft) high and in an even higher south peak that attains an altitude of 6,764 meters (22,190 ft) (fig. 2). Many other ice-covered peaks in the range are 5,500 meters or more in altitude. Deep U-shaped glacial valleys of the Cordillera Blanca drain westward into the Río Santa and eastward into the headwaters of the Río Marañon (fig. 1). Several of these valleys now contain morainal lakes and formerly (perhaps during the last 10,000 years) probably all contained one or more lakes. Some of the older lakes have gradually filled with sediment and now appear as flat valley floors or swampy areas. Some lakes gradually cut through their morainal dams and thus were drained. Other lakes were drained by sudden bursting of their morainal dams, probably owing mostly to overtopping of the dams by waves generated by ice or rockfalls. Sudden drainage of these lakes can result in catastrophic mudflows such as the mudflow of December 1941 that destroyed one-fourth of Huaraz.

The upper slopes in the Cordillera Blanca are oversteepened, commonly ranging from 45° to nearly 90°; they are thus locally in an extremely unstable condition. In some areas, as observed by Ericksen in 1948—49, small icefalls take place several times a day. At other localities major ice avalanches are reported every few months or few years. Evidently the north peak of Huascarán is presently one of the most unstable ice-covered areas in the Cordillera Blanca. The northwest side of this peak, the source of the avalanche that destroyed Yungay and Ranrahirca at the time of the May 31, 1970, earthquake, also was the source of a smaller avalanche that destroyed most of Ranrahirca in 1962. The distribution of debris-flow deposits throughout the area suggests that repeated ice and rock avalanches have originated on the flanks of Huascarán during Holocene time.

Cordillera Negra

The Cordillera Negra, in contrast to the Cordillera Blanca, has a more gentle and subdued topography, and its relatively broad, gently undulating crest is generally about 14,000 feet in altitude. It lacks glaciers and snowfields. Valleys on the flanks are V-shaped, and are deeply incised in their lower parts, indicating that they were cut by streams rather than by glaciers. Small cirques and lateral moraines near the crest of the range attest to former local glaciation. Volcanic rocks on steep slopes of the Cordillera Negra are locally deeply weathered or strongly fractured and consequently are subject to sliding during the rainy seasons or in response to seismic movement.

EARTHQUAKE EFFECTS

Most of the effects of the May 31, 1970, earthquake herein described are of the kind that are characteristic of great earthquakes; they have been thoroughly documented in many reports, including reports describing earthquakes that have affected the Andean region. Because this report is of preliminary nature, we have not attempted to compare destructive effects of the May 31, 1970, Perú earthquake with other great earthquakes that have taken place along the west coast of South America. However, the Huascarán avalanche of May 31, 1970, appears to be a geologic event that, in size and destructiveness, exceeds any avalanche known to have accompanied any other earthquake.

Santa Valley

It is estimated that throughout the length of the Santa Valley above Huallanca, a distance of about 130 km, 90 percent of the buildings have been seriously damaged or destroyed. The widespread damage is due largely to (1) adobe construction (fig. 3), which offers little resistance to earthquake shock, (2) to thousands or tens of thousands of small landslides and rockfalls, and (3) to the debris avalanche that destroyed the city of Yungay and the nearby town of Ranrahirca (fig. 2). Two- and three-story adobe buildings with heavy tile roofs were the most severely damaged. In addition, some brick buildings and a few reinforced concrete buildings were damaged or destroyed. Brick or concrete-block buildings without a reinforced concrete framework offered only a little more resistance to earthquake shock than did adobe buildings, although rarely did they collapse totally. The few reinforced concrete buildings that were severely damaged were of poor construction; they either had very poor quality concrete that crumbled during seismic movement, or they lacked proper pillar support and shear walls.

An accurate estimate of deaths in the Santa Valley is not yet available, and it is doubtful that the true number will ever be known. By far the greatest number of casualties were at Yungay (320 known dead; 15,000 missing and presumed dead) and in Huaraz (800 dead; 16,000 missing and presumed dead). (Statistics of the Comité Nacional de Emergencia of Perú, July 2, 1970.) In addition to the known dead and missing inhabitants of Yungay, an unknown additional number of Sunday visitors and marketers of farm products, perhaps totaling several thousand persons, were also killed by the avalanche that destroyed Yungay.

Yungay had a pre-earthquake population of about 19,000 and Huaraz, the largest city in the Santa Valley and the capital of the Department of Ancash, had about 65,000 residents. Most deaths in Huaraz were in the older section of the city where collapse of 2- and 3-story buildings killed both occupants and people who fled into the narrow streets for safety. One area of some

Figure 3.—Destruction of adobe buildings in Huaraz as a result of the May 31, 1970, earthquake.

100 square blocks now is a mass of rubble and broken adobe walls where streets are filled with rubble to depths of as much as 10 feet. Figure 3 is a typical street scene in this area of Huaraz. At the time of our visit (end of June 1970), local authorities estimated that several thousand people were still buried beneath the rubble of collapsed buildings. In striking contrast to this adobe disaster, most of the few buildings in Huaraz that were built of brick with reinforced concrete frames, including one of four stories and one of five stories, were only slightly to moderately damaged. On the other hand, a four-story school building of reinforced concrete and brick with inadequate shear walls did collapse.

Roughly 3,100 people out of a population of 5,000 are dead or missing at Mancos where roughly 70 percent of the adobe buildings were destroyed. Ranrahirca was also destroyed by a tongue of the same avalanche that buried Yungay, and an estimated 1,800 of the 1,850 residents were killed. Other villages and towns in the Santa Valley reported deaths ranging from less than 10 to several hundred. Damage to communities on the east side of the Cordillera Blanca was relatively slight and casualties few. Although many of the adobe houses in this area collapsed, surprisingly few occupants were injured. Innumerable small landslides and rockfalls triggered by the earthquake caused several hundred injuries and an unknown number of fatalities through the region.

Nevados Huascarán debris avalanche

Yungay-Ranrahirca area

By far the most destructive and geologically fascinating aspect of the earthquake was the cataclysmic avalanche of ice and rock that fell from the glacier-covered north peak of Nevados Huascarán (fig. 2). The main part of the debris avalanche appears to have involved a slab of ice and rock about 800 meters wide that broke away from the sheer west face of the peak, at an estimated altitude between 5,500 and 6,500 meters. Our observations of the configuration of the slide source area, and on the composition, volume, and flow characteristics of the avalanche material indicate that the original slide mass probably involved a volume of ice and rock that was considerably greater than 25 million cu m (cubic meters). The amount of rock was probably much greater than the amount of ice. By means of comparison of post-earthquake vertical and oblique aerial photographs with photographs taken prior to the earthquake, we hope to be able to make a more accurate estimate of the volumes of ice and rock that fell.

As the avalanche moved down the side of Huascarán and down the Llanganuco Valley it took on the character of a highly fluid mudflow, owing to melting of part of the ice (as a result of friction and other energy release in the rapidly moving mass) and to water and water-saturated sediments picked up in Llanganuco Valley. Within a few minutes after the first tremors of the earthquake were felt, an enormous mass of rock, ice, and mud had sped 16 km from Huascarán to the Río Santa. The avalanche disrupted the Río Santa temporarily, so that it flowed upstream for a distance of about 2 km; it also lapped up onto the lower slopes of the Cordillera Negra, and flowed downstream.

An area of more than 15 sq km was devastated. Yungay was obliterated by a relatively small tongue of mud and rock several meters thick that swept over a ridge 100—200 meters high that stood between Yungay and the main stream of the avalanche, which followed the Rio Llanguanuco Valley to the south (fig. 4). Only the tops of a few palm trees in the central plaza and part of the main cathedral now protrude above the mud, and mark the site of this formerly prosperous and picturesque city.

Figure 4.—A lobe of the Huascarán debris avalanche that now covers the former city of Yungay; the avalanche flowed over a 100- to 200-meter-high ridge (arrow) between Yungay and Llanganuco Valley.

The main part of the debris avalanche, which was channeled along the Río Llanganuco Valley, buried most of Ranrahirca as well as parts or all of several smaller villages along the fertile valleys of the Río Llanganuco and Río Santa. An estimated 1,800 people were killed at Ranrahirca and an unknown, but probably large, number of additional casualities were sustained elsewhere in the extensive area covered by the debris lobe. Only 8 years earlier, on January 10, 1962, the Ranrahirca area was devastated by an avalanche that originated from the same part of the north peak of Nevados Huascarán as the recent one. According to a published account by Benjamin Morales (1966), the 1962 avalanche contained an estimated 2.5—3 million cu m of ice and rock; it wiped out nine small towns, including Ranrahirca, and killed 4,000 people. Unlike the May 31, 1970, avalanche, however, the 1962 event was not triggered by a felt earthquake, and the debris did not have sufficient velocity or volume to flow over the ridge between Yungay and the Llanganuco Valley.

According to eyewitnesses, the 1970 debris avalanche on Huascarán was triggered during the earthquake. It moved downslope at high velocity with a deafening noise and was everywhere accompanied or preceded by a strong turbulent airblast. Accounts of survivors suggest that the debris avalanche traveled the 14.5-km distance from its source to the vicinity of the cemetery at Yungay in 2—4 minutes—an average velocity of between 217 and 435 km per hr (kilometers per hour). A velocity on the order of 400 km per hr is indicated near the middle part of the course by the trajectories of thousands of boulders, many weighing more than 3 tons, that in some places were hurled more than 700 meters across the Llanganuco Valley (fig. 5). This deadly rain of rocks killed and injured many people and was extremely destructive to buildings, livestock, and vegetation. The unusually high velocity and large volume of the debris avalanche allowed it to override large topographic irregularities including the ridge between the Llanganuco Valley and Yungay. Its momentum at the Río Santa, almost 16 km from the source, carried it across the river and as much as 50 meters vertically and several hundred meters horizontally up the opposite bank, where it destroyed part of a small village.

The avalanche's velocity was due primarily to the combination of steep slopes (as much as 70°) in the source area and to the great vertical relief (3,700 meters) along its 16-km path to the Río Santa. In the upper half of its course the vertical drop is almost 3,000 meters at an average slope of 23° ; in the lower half the drop is only 700 meters and the slope averages 5° . Frictional resistance to sliding of the mass may have been significantly reduced by admixture of snow and ice and locally, perhaps, by entrained air beneath the debris. Air-cushioned flow near the source is suggested by the fact that the debris avalanche apparently moved across ridges of unconsolidated morainal material without disrupting them.

Most of the damage caused by the avalanche was in the populated and cultivated lower part of its course below about 2,600 meters altitude. Here, the debris spread across an area of low relief in three lobes in an area of about 9 sq km. Maximum width across this area, near the Río Santa, is 4.3 km. These lobes buried Yungay, most of Ranrahirca, and several smaller communities. They also destroyed 2.3 km of the main highway in the Santa Valley and about an equal amount of the primary electric transmission line from the hydroelectric plant at Huallanca.

The thickness of the debris deposit, as measured at a number of places along its margins and in incised stream channels, ranges from a few centimeters to 10 meters and is conservatively estimated to average about 3 meters. The thickness is about 5 meters at the site of the plaza in Yungay, as estimated by comparing the heights of four palm trees that extend above the debris surface with the overall height of palm trees from the same place that were uprooted by the debris flow. Assuming an average depth of 3 meters, the volume of debris in the three lobes alone is on the order of 27 million cu m. An additional 5—10 million cu m of debris (mainly boulders) was deposited in the upper part of the avalanche over an area of about 10 sq km, and an even larger volume of debris has been flushed down the Santa River. Thus, the total volume of solid material moved by the debris avalanche could easily be on the order of 50 million cu m.

The material deposited by the debris avalanche is mainly mud and boulders. Near the

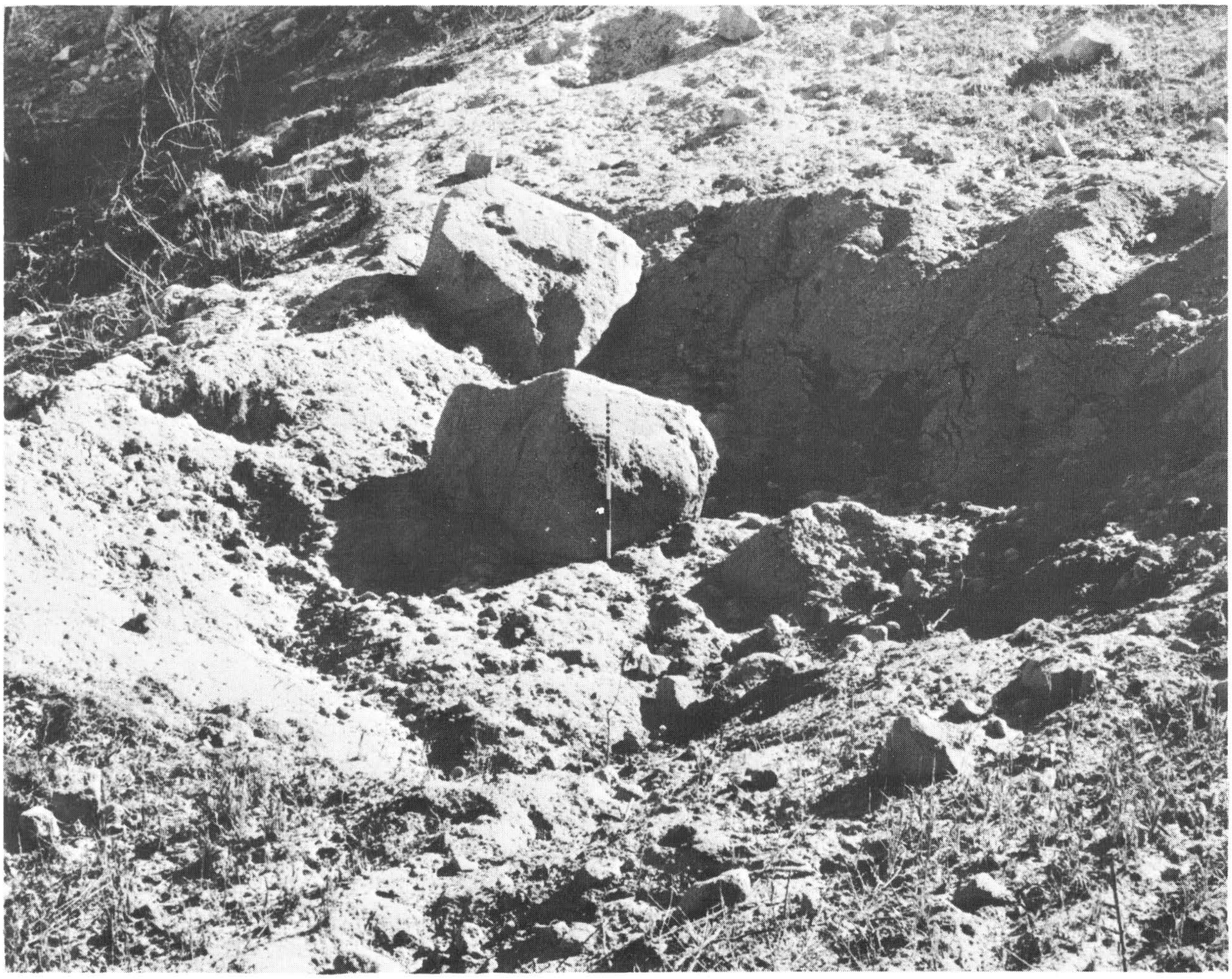

Figure 5.—Large impact crater (2.5 meters deep, 7 meters wide, and 11 meters long) in field at the south side of Quebrada Llanganuco, which was made by a huge block of rock or cluster of rocks hurled several hundred meters by the Huarascán debris avalanche. All rocks in or near crater are projectiles or fragments of projectiles from the avalanche. The two large rocks in the crater are about 2½ meters in longest dimension.

terminus, where the water content of the mass was increased by melting of incorporated ice and snow and by the overrunning of streams, it locally spread out as a viscous debris flow consisting of mud with embedded boulders. The mud characteristically is a medium-gray silt containing subordinate very fine sand. It probably contains a high percentage of glacial rock flour derived from morainal deposits along the mountain front. It is soft and sticky when wet, and very hard, with deep dessication cracks, when dry. One survivor said that the mud near the terminus was too soft to walk on until about 8 days after the avalanche. Except for a few poorly drained soft spots, the surface was generally as hard as adobe at the time of our visit 4 weeks after the earthquake. Residents of the area also claim that the surfaces of the debris lobes were covered with blocks of ice after the avalanche; numerous conical collapse pits in the mud, as much as several meters across, clearly mark the sites of ice blocks that have melted out of the mud. Some of the local soft areas that we noted on the debris lobes were said by road-construction crews to be over buried blocks of partly melted ice.

Surface features of the debris lobes, such as steep margins, grooved surfaces, mud spatters on boulders, concentrically grooved mud-covered boulders (indicating slow rolling), and depressions or "wakes" behind obstacles in the path of flow, all suggest that the mud had appreciable viscosity near the termini of the lobes. Conversely, splattering of mud on the upstream side of obstacles and far from the margins of the flow are indicative of local high surface fluidity. Areas of smooth-surfaced, boulder-free mud within the debris flow apparently represent the melting of ice and "dewatering" of fluid mud from between the coarser material (fig. 6).

Quantities of boulders and angular blocks of rock vary considerably from place to place, generally constituting an estimated 10–50 percent of the total volume of the debris lobes. Cobble- and pebble-size rock fragments seem to be relatively sparse in the material covering Yungay and Ranrahirca. The overwhelming majority of the rock debris consists of massive granodiorite of the type that makes up Nevados Huascarán. The largest block observed is a 14,000-ton giant that was transported by the avalanche and deposited on the Ranrahirca lobe near the site of Ranrahirca. The largest boulder measured on the Yungay lobe was about 7,000 tons. Most of the rock fragments are angular and fresh as though recently derived from the outcrop; such an angular block, estimated to weigh about 700 tons, is shown in figure 6. A number of them, however, were previously transported by earlier debris flows and (or) glaciers, as indicated by adhering soil, weathering of one or more surfaces, or multiple glacial faceting and striations. A few of the fragments consist of weakly cemented Quaternary gravels and deeply weathered granodiorite. The presence of large blocks of such semicoherent material in the debris flow

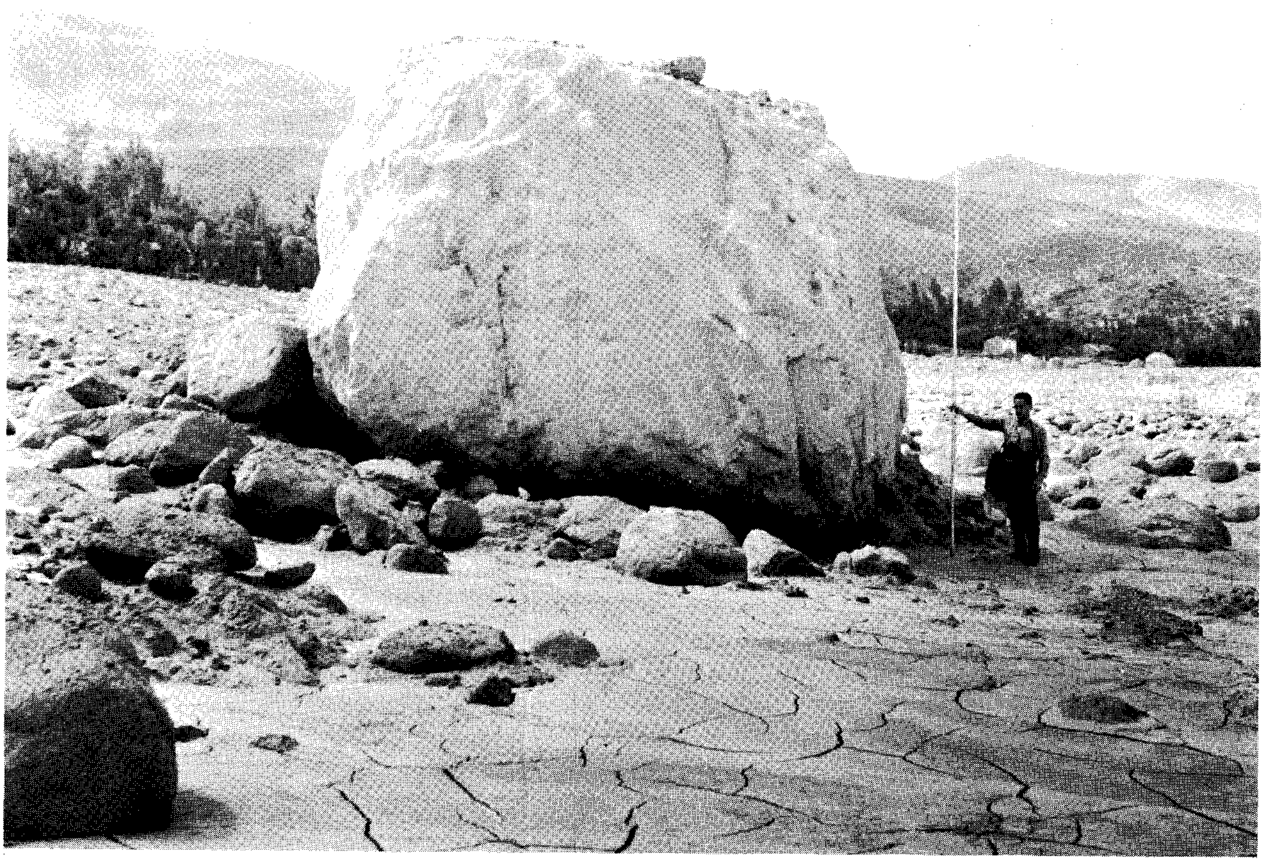

Figure 6.—Block of granodiorite (estimated to weigh 700 tons) that was transported by the May 31, 1970, Huascarán debris avalanche, located near the site of the former town of Ranrahirca. Layer of mud showing polygonal cracks resulted from seepage from the avalanche after it had come to rest. Top of block is covered with mud and rock fragments deposited by the avalanche after the block had come to rest.

and the general absence of percussion marks suggest that the boulders did not abrade one another significantly within the moving avalanche. Many of the larger boulders now rest directly on the original ground surface beneath the debris lobes or are embedded in a layer of mud that is thin relative to boulder height. However, such boulders are covered with mud and commonly have smaller rocks on their upper surfaces (see fig. 6), implying that the mud was thick enough to cover them at some stage during the debris avalanche.

The debris avalanche probably moved as a high-speed wave pulse or slug that picked up and moved even the largest boulders at its front while dropping others out behind. Such a mechanism would be consistent with eyewitness accounts of a "wall of debris as high as a 10 story building," with the pronounced airblast that accompanied the avalanche, with the great disparity between the height of the mud coatings on boulders and other objects in the path of the debris avalanche, and with the relatively thin residual layer of mud over much of the area traversed by the debris flow. Furthermore, a large destructive slug of muddy water is known to have passed on down the Río Santa to the sea. A thorough ground and photogeologic investigation of the debris flow deposits and extensive interviews of eyewitnesses to the event undoubtedly would shed light on the intriguing problem of the transport mechanism of this debris mass.

Effects downstream from Yungay

The flow of muddy water and rock debris continued down the Río Santa, causing extensive damage to structures, transportation routes, and communications networks downstream from Yungay. According to eyewitness accounts, the flow reached Huallanca, 52 km downstream from Yungay, at about 5:00 p.m. This rate of flow indicates an average velocity of roughly 35 km per hr. This approximate velocity is consistent with information that the flow reached the Mirador railroad station, 100 km downstream from Yungay, at 6:00 p.m. and Tablones, a distance of 130 km from Yungay, at approximately 7:00 p.m.

Eleven kilometers downstream from Yungay the debris flow overflowed the Río Santa's channel and inundated the Caraz airport, much of the highway, and extensive tracts of agricultural lands. Caraz itself was not damaged by the flow. However, the Río Parón, which flows through Caraz into the Río Santa, did have a minor debris flow that locally overflowed its banks and damaged small areas of the town. From aerial inspection, it appears as if this debris flow originated in an extensive area of surficial earthflows and rockslides just a few kilometers east of Caraz.

Between Caraz and the Cañon del Pato, the highway was locally covered by mud where the debris flow overflowed the Río Santa channel. The highway bridge across the Río Santa at Choquechaca was destroyed.

The hydroelectric plant at the mouth of the Cañon del Pato near Huallanca, having an installed capacity of 100,000 kw (kilowatts) and an ultimate capacity of 150,000 kw, was not damaged by the earthquake or debris flow. Safety gates at the tunnel intakes were shut in time to prevent entrance of debris into the turbines. However, the diversion dam at the tunnel intake was destroyed and the access road through the precipitous Cañon del Pato was largely buried or swept away by landslides. Also, the railroad bridge that provided access to the powerplant at the lower end of the Cañon del Pato was destroyed by the debris flow.

Low-lying parts of the town of Huallanca and the camp of the hydroelectric company (Corporación Peruana del Santa) immediately below the Cañon del Pato were damaged by the debris flow, and five persons in one of the homes were swept away. The Río Santa has a channel that averages about 100 meters wide at Huallanca. According to residents in Huallanca, the river dried up for about an hour after the earthquake and prior to the arrival of the debris flow. Upon arrival of the debris-laden waters, the river rose 20 meters above its prequake level, and reportedly ran full for 2—4 hours before beginning to subside. Residents describe the front of the flow as a dark-colored, noisy, turbulent wave, containing abundant blocks of ice, that was competent enough to carry off "room-size" boulders from the town site. After the main part of the debris flow passed, dozens of corpses, and vehicles and other manmade materials were deposited near Huallanca.

In addition to the damage from the flooding, most adobe structures in Huallanca and the camp at the hydroelectric plant were extensively damaged by the earthquake, and a few were struck by boulders shaken loose from the steep valley walls. Two or three people were reportedly killed in houses that collapsed.

The part of the Santa Valley between Huallanca and the coast could not be visited during our reconnaissance investigations, but was examined from the air. Large segments of the railroad line between Huallanca and Chimbote are covered with debris deposits or were washed away by the debris flow, and railroad stations were destroyed by the shaking or by inundation by the debris flow.

Landslides

Landslides of all types ranging from several tens of feet to a few thousand feet in diameter or maximum length are found throughout the steep slopes both of the Cordillera Negra and Cordillera Blanca. Such landslides were triggered by the combination of lateral and vertical accelerations imparted to the slide masses during the seismic shaking. Most of the rockfalls and soilfalls are on steep, relatively dry slopes. Some larger rotational slides and surficial slumps, particularly those near the bottom of the Santa Valley and intermediate slopes of the Cordillera Blanca, are in water-saturated ground where dynamic ground-water loading in the pores and joints of the affected materials probably increased the susceptibility to sliding. A record rainfall during the past wet season, which included unusually heavy rains as late as May 17, probably contributed significantly to the amount of landsliding observed.

In general, the larger landslides were concentrated along the lower courses of the Río Santa and its tributaries, which commonly are deeply incised into unconsolidated Quaternary fill. In this area, many landslides were clearly related to roadcuts and to the terraced and irrigated cultivated fields on steep hillsides. These landslides can be classified according to the type of failure, and each of the many classes can be correlated closely with the nature of material involved and the slope inclination.

Most of the landslides observed were loose rockfalls and soilfalls or slides along the steep valley walls and roadcuts. Thousands of landslides of this type occur throughout the region. They are particularly numerous along the steep valley walls in the Cañon del Pato area and in an area of particularly unstable volcanic rock and steep slopes in the Cordillera Negra downstream from Huallanca. Several small slides downstream from the Cañon del Pato were observed during our overflights and visits to the area on June 26 and 28, and visibility was often seriously impaired by the dense dust clouds arising from these slides. The great abundance of soilfalls and rockfalls, as well as loose individual rocks that tumbled down the hillsides during the earthquake, caused many injuries and a substantial, but unknown, number of deaths throughout the Santa Valley. Rockfalls reportedly also accounted for most, or all, of the casualties sustained on the east flank of the Cordillera Blanca. Rockfalls and soilfalls have blocked road and railroad routes at many places and they constitute a continuing hazard, as many are likely to be reactivated during the next rainy season.

A large rotational slide was observed along the east bank of the Río Santa at Recuay (fig. 7). This slide involves a block of fluvioglacial sediments about 1 km long and 100—200 meters high above river level, and has a headwall scarp estimated to be as much as 15 meters high. At its northern end, the toe of the slide extends across the Río Santa, which is about 50 meters wide at this point. The rotational movement thrust the river bottom upward about 5 meters, thereby blocking flow of the Río Santa. This landslide-dammed lake is described below.

Landslide-dammed lakes

As described in the preceding section, a small lake was formed on the Río Santa behind

Figure 7.—Rotational slide in unconsolidated fluvioglacial sediments, east side of Río Santa at Recuay; a small lake formed behind toe of slide. Headwall of slide (arrows) is as much as 10—15 meters high.

the rotational landslide at the town of Recuay. At the time of our visit on June 25, this landslide-dammed lake was about 300 meters long and 150 meters wide. The lake had been somewhat larger previously but in order to remove the hazard of flooding, Cía. Minera Alianza, a mining company headquartered at the nearby town of Ticapampa, lowered the level about 2½ meters by two trenches 6 meters long that were cut through the dam.

A rockslide dammed the stream draining upper Llanganuco Lake, causing the lake level to rise 7—8 meters between the time of the earthquake on May 31 and the end of June. The lake more than doubled its length as it flooded the nearly flat alluvial plain at its head. This slide was first observed by Fernández Concha 2 days after the earthquake. Still later the Corporación Peruana del Santa started to cut a trench through the slide to limit the rise in lake level to about 8 meters instead of an estimated 15 meters that was expected if such a trench were not cut. This trench was completed in early July.

Faults and fissures

Many faults exist in the Santa Valley, but apparently none moved during the May 31, 1970, earthquake. The most prominent recent faults of the area are along the foot of the Cordillera Blanca. They are marked by an en echelon system of fault scarps, as much as 20 feet high, that cut Holocene glacial moraines. Although it is evident that these faults have moved recently (perhaps at some time during the past few hundred years), there is no evidence of movement during the May 31 earthquake. We were able to examine a strand of this fault system on the ground in Quebrada Querococha, to the east of Ticapampa, and to observe other scarps near Huaraz during a helicopter flight.

Fissuring related to incipient landsliding or differential compaction of unconsolidated sediments is extensive in the Santa Valley. Fissures are most clearly visible in the main road through the valley. Most of these are parallel or subparallel to the road and to the Río Santa, and most were evidently opened by incipient sliding and slumping of unconsolidated sediment toward the Río Santa. Such open fissures are as much as a foot wide and several feet deep. Some are due to differential compaction of the unconsolidated sediments. Fissures related to lateral extension and incipient sliding were also observed at many places in relatively flat fields near the bottom of the Santa Valley and on moderately inclined to steep hillslopes on the sides of the valley.

Geologic foundation conditions and related earthquake damage

Nearly all the cities, towns, and villages in the valley of the Río Santa are built on unconsolidated to semiconsolidated fluvioglacial material and debris-flow deposits in which the ground-water table is generally less than 5 meters below the surface. During the earthquake this foundation material locally was subject to differential compaction and to downslope slumping. In some places, damage to structures is clearly related to foundation failure, whereas in others the pattern of damage is somewhat variable and seemingly unrelated to geologic foundation conditions. For example, some villages were almost totally destroyed, whereas nearby villages of apparently similar construction and geologic foundation show only moderate damage. Similarly, parts of Huaraz were leveled, whereas other areas in the city were only moderately damaged or are undamaged. We have no explanation for the cause of these striking variations. Subtle variations in composition and (or) water content of the foundation material could be an important factor, but slight differences in construction and the pattern of seismic wave propagation may be equally important. Detailed studies of damage distribution by teams of geologists, structural engineers, and seismologists are needed before firm conclusions may be drawn regarding the cause for this erratic damage distribution.

Coastal region

Severe earthquake damage occurred in the coastal region of Perú from Trujillo (lat 8° 10' S.) on the north to the village of Las Zorras (lat 10° 17' S.) on the south, a longitudinal distance of about 260 km. Throughout this area there has been major damage or total destruction of adobe buildings, which constitute a large proportion of the residences. New brick houses that lack reinforced concrete pillars, such as are found in some communities and particularly in one entire subdivision of Chimbote, have been seriously damaged or destroyed. Well-constructed houses and buildings, consisting of reinforced concrete pillars and connecting stringers with brick wall panels, generally show little or no damage, although they may be entirely surrounded by demolished adobe structures. The few woodframe buildings in the area were virtually unaffected by the earthquake.

Damage of large reinforced concrete or concrete and brick structures varied from negligible to total collapse depending upon the design and quality of construction. In Chimbote, some of the tallest buildings of this type (to five stories) were undamaged. Others that have extremely heavy concrete roofs and inadequate resistance to lateral forces were subject to shear failure of pillars and bearing walls. In a few structures, damage is attributable to poor-quality concrete in the bearing members.

Because the earthquake occurred on a Sunday afternoon, when school was not in session and businesses were closed, the number of deaths in the coastal area was low, probably about 1,000. Of these casualities, about 700 were in Chimbote and resulted from collapse of structures on their occupants or on people who fled outdoors into the narrow streets. The total number is small considering the regional population of close to 200,000, and the extent of destruction. By rare good fortune, Casma, which formerly had a population of several thousand, and which was almost totally destroyed, recorded only 70 deaths.

Ground effects

Surficial cracking, compaction, and differential subsidence

Fissuring, slumping, and differential ground subsidence are extensive in swampy areas and areas of near-surface ground-water table in the valleys and along low-lying coastal segments. Although such areas are of rather limited extent in this desert region, virtually the entire population and most engineering works along the coast are concentrated in them. In these areas, fissures as much as 50 cm (centimeters) wide, settlement of roadbeds relative to bridges, and cracking and slumping of roadway embankments caused damage and temporary disruption of transportation routes (figs. 8 and 9). Fissures also formed in foundation materials of cities and towns owing to differential settlement along the junction of filled areas and natural deposits and to lateral spreading of water-saturated sand. At the Port of Casma and in near-shore areas of Chimbote, lateral spreading caused by liquefaction of deltaic and beach deposits produced many extension cracks in the ground as much as 20 cm wide that literally tore apart all the structures they intersected (fig. 10).

In some areas of near-surface ground-water table, seismic compaction of the surficial deposits lowered the land surface sufficiently to cause flooding. A large flooded area formed in this way extends over nearly a square kilometer of a residential area in eastern Chimbote. Houses here were almost totally destroyed, and water

Figure 8.—Slumping and fissuring of paved road near the bay shore in western Chimbote due to liquefaction and lateral spreading of water-saturated beach sediments.

Figure 9.—Chimbote-Huallanca railroad damaged as the result of differential compaction and lateral spreading of water-saturated unconsolidated sediments.

covers house floors to depths of as much as 30 cm. The entire area has been abandoned. Surficial compaction and consequent flooding also has affected a large segment of the Port of Casma.

Sand boils and water ejection

In a few areas of near-surface ground-water table, sand boils are numerous and large. These resulted from squirting of muddy and sandy water from fissures that opened during earthquake shaking in response to compaction and cracking of the saturated surficial deposits. At some places, eyewitnesses report that water was ejected to heights about a meter above the ground surface. The sand boils are commonly marked by a central hole a few centimeters to a meter in diameter, surrounded by a mound of ejected sand and silt as much as 15 meters in diameter (fig. 11).

Soil slips and fragmentation

Throughout the region from Huarmey to Chimbote, seismic movement caused small landslips (no large landslides were observed) on steep slopes and rockfalls on hillsides and steep roadcuts. The intensity of shaking was sufficient to shift rock fragments and boulders, ranging from a few centimeters to about 40 cm in maximum length, from their original position on flat surfaces, or to cause them to slide a few centimeters down very gentle slopes. In these areas, the soil surface commonly is covered with a weak evaporite-cemented crust, a few millimeters thick, which crumbles easily in the hand. The seismic shaking caused these crusts to be widely fragmented on gentle to steep slopes and to form a network of fine cracks on many level surfaces.

Figure 10.—Concrete-block house, Corporación Peruana del Santa housing development, Chimbote, which was torn apart by liquefaction and lateral flow of beach sediments that constitute the foundation material.

Tectonic deformation

Active tectonic faulting was not observed, and, to judge from the location of the epicenter and major aftershocks offshore from the coast, would not be expected on shore. There was no significant vertical tectonic warping along the coast or observable seismic sea wave (tsunami or maremoto) of the type that have accompanied some previous great coastal earthquakes in Perú. This suggests an absence of shallow dip-slip faulting on the sea floor.

GEOLOGIC HAZARDS AND RECONSTRUCTION

Huaraz

Huaraz, the major city of the Santa Valley, is estimated to be 90 percent destroyed. Foundation conditions are as suitable for reconstruction at the present site of the city as they are at any other locality in the Santa Valley. However, some of the rubble of former buildings will have to be removed from the

Figure 11.—Sand boil in water-saturated unconsolidated sediments of the Casma Valley; during earthquake jets of muddy and sandy water squirted from the two pits. The mound of ejected sand is more than 1 meter in diameter.

townsite and the remaining material carefully leveled and compacted before reconstruction. If reconstruction is to include hillslopes near Huaraz, as has been suggested in some preliminary plans for reconstruction, a careful engineering geologic study should be made of the potential for fissuring and sliding in these areas.

Two small lakes exist in the Cordillera Blanca at the head of Quebrada Cojup which drains through Huaraz. One of these is a remnant of the morainal lake that burst in 1941 and partly destroyed Huaraz. The remnant of this lake is small and is reported to be in no danger of future rupture. The other lake is in a rock basin carved by a glacier, and also is reported to be in no danger of rupture (Benjamin Morales, oral commun., Corporación Peruana del Santa, June 1970).

The glaciers and snowfields in the Cordillera Blanca east of Huaraz are less extensive and in an area of less relief than those at the Nevados Huascarán and northward in the Cordillera Blanca. Thus, the potential for development of ice-originated avalanches or debris flows that could damage Huaraz is considered to be slight to nonexistent.

In summary, there are no geologic conditions precluding reconstruction of Huaraz at its present site. The main preoccupations in reconstruction should be the widening of streets and limiting of height of unreinforced adobe buildings to one story.

Santa Valley south of Huaraz

Recuay, the major town in the upper Santa Valley, was moderately damaged by seismic shaking. Several other smaller towns and villages in this area show variable damage, ranging from about 25 percent to almost 100 percent destruction. Geologic foundations of these settlements consist of alluvium or fluvioglacial material that is suitable for reconstruction. In general, hillslopes in this part of the valley are more gentle than they are to the north in the Callejón de Huaylas, and consequently are more stable.

The only potential geologic hazard in the southern part of the Santa Valley is the Laguna Querococha. This lake, in Quebrada Querococha east of Ticapampa, is impounded behind coalescing alluvial fans from the north and south sides of the Quebrada. The resulting earth dam is broad, and because of its mode of formation, is more stable than the more typical morainal dam in the Cordillera Blanca. However, during the May 31, 1970, earthquake, fissures were opened in alluvial and morainal material at the northwest side of the lake. These fissures extended into the alluvial fan that forms the northern part of the dam (Emilio Caballero, oral commun., General Superintendent, Cía. Minera Alianza, June 1970). Ing. Caballero also reported that the surface flow at the lake outlet had diminished since the earthquake, which indicates an increase in ground-water flow into the alluvial dam. Such infiltration is potentially dangerous for it might lead to destruction of the alluvial dam due to piping and (or) sliding of newly unstable water-saturated material. As a means of evaluating the potential hazard of the Laguna Querococha, the lake discharge should be kept under close observation and the fracture system studied to determine whether incipient sliding continues. The slide area should be surveyed and a permanent triangulation net established for periodic resurvey. The most critical period for observation of the slide will probably be during the next rainy season.

Yungay and vicinity

Further data are required before the danger of future debris avalanches at Yungay can be properly evaluated. Because there is a "protective" ridge between the site of Yungay and the main path of debris avalanches from Huascarán down the Llanganuco River valley, only enormous, high-speed avalanches such as the one of May 1970 are likely to pose a threat to the Yungay area. Conceivably, such an event may not occur again for thousands of years. A detailed geologic study is required to determine whether catastrophic debris avalanches have overrun the protective ridge in the past and, if possible, the approximate frequency with which such events have recurred. In an overflight of Nevados Huascarán, we did not observe any major fractures that would indicate a possibility for other avalanches in the near future. Nevertheless, the near-vertical west face of the north peak of Huascarán is a potentially unstable feature, and other rockfalls and icefalls may be expected to take place here in the future.

Ranrahirca was in a more hazardous position than Yungay because it was in the direct path of any slide or fall from the north peak of Huascarán. It was largely destroyed in December 1962 by a debris flow which originated on the north peak of Huascarán, at the same site as the debris avalanche of May 1970. It is reasonable to assume that renewed accumulation of snow and ice in this area will result in other avalanches in the future, perhaps within 10—20 years.

Other villages near Ranrahirca also are in the paths of potential avalanches from Nevados Huascarán, and consideration should be given to moving inhabitants to safer areas. Potential areas for reconstruction of small towns are on terraces of the Río Santa just south of Ranrahirca and north of Yungay. However, before reconstruction in these areas, an evaluation of potential avalanche paths should be made to determine the safety of the sites.

Caraz

Caraz, estimated to be 70—80 percent destroyed, is on an alluvial fan at the mouth of Quebrada Parón. The geological foundation is similar to that of Huaraz and is suitable for reconstruction. However, Caraz potentially is in one of the most hazardous locations of any of the larger towns or cities in the Santa Valley. Laguna Parón near the head of Quebrada Parón, the largest lake in the Cordillera Blanca, is partly dammed by a glacier and partly by a moraine. The lake drainage is entirely by subsurface flow through the morainal dam (Benjamin Morales, oral commun., June 1970). Furthermore, this lake and the Quebrada are between Nevados Huascarán on the south and Nevados Huandoy on the north. Extensive glaciers and snowfields overhang the valley on both mountains, and ice avalanches or rockfalls into the lake could cause it to rupture and to form a debris flow even larger than that of May 1970.

Relocation of Caraz a short distance up or down the Santa Valley would place it in an even more hazardous position than its present one. To the south at lower altitude, the town would be subject to destruction by any debris flow that originated upstream in the Santa Valley. For example, the airport at the south edge of Caraz was partly covered by the May 1970 debris flow. The area immediately north of Caraz, however, would be in the direct path of a debris flow originating from Laguna Parón.

A possible solution to the problem of Caraz is the partial draining of Laguna Parón. The Corporación Peruana del Santa currently has plans to effect this drainage by driving a 1.2-km tunnel in rock, starting downstream from the lake and intersecting the lake at a depth of 40 meters below the present surface. Drainage to this level would largely eliminate the danger of rupture of the lake and consequently the danger of destruction to Caraz by a debris flow. A second alternative would be to relocate the city on the west bank of the Río Santa.

Chimbote

Chimbote had 70—80 percent serious damage or destruction to buildings. Various parts of Chimbote have been built on beach and deltaic deposits, mudflow deposits, and slope debris. In some places, the ground-water table was at or near the surface before the earthquake, and at others it was at depths of several meters or more.

At several places, differential compaction and (or) incipient slumping and sliding of foundation material were major causes of damage in Chimbote. Among structures and areas that were affected by foundation movement are the following:

1. At the steel plant in Chimbote, differential compaction of dry-slope debris and mudflow material on which the plant was constructed resulted in severe damage to some reinforced concrete structures, by causing breaking and partial settling of heavy concrete floors and by differential settling of units of a newly built rolling mill. The differential compaction in this area ranged from less than an inch to about a foot.
2. The Corporación Peruana del Santa housing development in Chimbote was built in part on an inactive beach or berm that is backed by a lagoonal swamp, near the bay shore in the westernmost part of Chimbote. The back slope of the beach surface and row masonry houses on it were severely cracked during the earthquake; some houses were torn apart as shown in figure 10. The nature of the cracking suggests that it was caused by liquefaction of the sand and lateral spreading toward the adjacent swamp.
3. Mudflats, roadways, and artificial seawalls near the dock of the Chimbote steel plant subsided as much as a meter because of compaction and seaward spreading. The massive concrete dock itself did not settle because it was built on piers driven down through the soft, unconsolidated surface deposits. However, reinforced concrete supporting pillars on the shoreward side of the dock were broken and apparently tilted gently seaward.
4. A residential area in eastern Chimbote built on low-lying lagoonal and swamp deposits subsided during the earthquake. In this area the ground-water table was near the surface before the earthquake, but seismic shaking resulted in compaction and settling of the

unconsolidated deposits, and as a consequence a low-lying area of about a square kilometer is now partly flooded with water a few inches to about 30 cm deep (fig. 12).

5. In the business section of Chimbote bordering the bay and near the Hotel Chimú is an elongate zone subparallel to the bay shore, several blocks long, where many open fissures cut across paved streets and through buildings; some 2- to 4-story buildings in this area have settled differentially as much as a foot, relative to nearby streets and buildings. This is evidently an area of liquefaction and incipient seaward spreading as well as of differential compaction of foundation material.

6. A few kilometers northeast of Chimbote, the narrow-gage Chimbote-Huallanca railroad passes through farmland in which the ground-water table is near the surface. Differential compaction during the earthquake caused irregular settling of the railroad bed in such a manner that the once straight rails are now undulating; highs and lows show differences in elevation of as much as 1–2 feet in distances of 100 feet (fig. 9). Furthermore, slumping and lateral spreading of water-saturated ground resulted in several feet of horizontal displacement of the rails in some areas.

Chimbote can be rebuilt at the same site, but certain residential areas should probably be

Figure 12.—Destruction of houses in a residential area of southeastern Chimbote where the ground settled due to compaction of water-saturated sediments; flooded area was dry before the earthquake.

abandoned. One of these areas is that in the eastern part of the city, now flooded because of soil compaction during the earthquake. This area would be subject to additional compaction and flooding during future earthquakes. Inasmuch as the central part of Chimbote is virtually at sea level, the city is in potential danger of destruction by tsunamis originating at almost any place in the Pacific region. Although it would be unreasonable to consider relocation of the city because of this danger (Callao is in an equally or even more dangerous position for tsunami destruction), it is not unreasonable to consider reconstructing the destroyed part of the city on higher ground.

An evaluation of the danger of a destructive tsunami to Chimbote may show that the configuration of the Chimbote bay may greatly reduce the danger of widespread inundation. On the other hand, the tsunami associated with the 1960 Chilean earthquake produced the highest waves yet recorded in the bay, and there is no guarantee that even higher waves might not be generated by closer earthquakes or by earthquakes in the western Pacific.

Casma

Casma was almost completely destroyed, and after the earthquake appeared as though it had been bombed; few building walls of heights of more than a meter or two were still standing. The town had only a few reinforced concrete buildings, most of which show little or no damage. A large one-story school building of reinforced concrete and cement block, apparently of good construction, collapsed. Had the earthquake been during school hours, hundreds of school children would surely have been killed or injured. The extensive destruction of adobe buildings in Casma is partly due to the extremely poor quality of the adobe bricks and mortar used in their construction. The adobe and mortar were made of a local silty sand, low in clay. Further, the bricks lack the usual straw binder which is essential to good adobe, as it increases bearing strength and resistance to shear.

The foundation material at Casma is suitable for reconstruction at the present site of the town. The site is not in danger of flooding, debris flows, or landslides.

The fishing port north of Casma shows evidence of lateral extension and settling. The town is on a former tidal and deltaic mudflat and has a near-surface ground-water table. Some streets that were dry before the earthquake now are covered with 2 feet of water, evidently due to differential compaction of water-saturated soil during the earthquake. By measuring open cracks in walls of a fishmeal plant and concrete sewage pipes, as well as slipping of wooden timbers in a nearby pier, we were able to establish that the seaward side of the area moved seaward approximately 1.4 meters in a distance of 300 meters.

Huarmey

Huarmey appears to have been 70-80 percent destroyed; as in other towns in the affected area, the major damage was to adobe buildings. The town has been built on alluvial sediments that offer no particular danger to reconstruction at the present site.

Trujillo

Trujillo was less damaged than the above-mentioned coastal cities. Serious damage or destruction was probably on the order of 10-20 percent and almost entirely limited to adobe buildings. Towers of the Cathedral on the Plaza de Armas were seriously damaged and the center part of a dome fell, although the dome itself remained in place. A huge and apparently unstably mounted statue in the Plaza de Armas remained intact during the earthquake, which indicates that the shaking was relatively mild there.

Like Chimbote, part of Trujillo is very near sea level; it consequently is subject to damage or destruction by a tsunami.

The port of Trujillo, Salaverry, shows little damage, chiefly because most buildings are of wood construction. Small churches and a few adobe buildings were damaged. An area at the port slumped, causing cracking of a cement platform near the major port warehouse.

CONCLUSIONS AND RECOMMENDATIONS

The extensive destruction effected by the May 31, 1970, Perú earthquake to cities, towns, and villages was due largely to poor construction of buildings, chiefly adobe, which had little shear resistance to lateral forces imposed by earthquake shock. The degree of destruction, however, was affected in some areas by differential compaction of geologic foundation material, generally unconsolidated sediments and rock debris of varied origin. In some areas the damage was enhanced by incipient slumping or sliding of foundation material down hillslopes or by lateral extension of liquefied sediments toward free faces with attendant surficial extension fissuring.

The major catastrophic geologic result of the earthquake was the debris avalanche that originated on the north peak of Nevados Huascarán. This avalanche buried the towns of Yungay and Ranrahirca, killing at least 17,000 inhabitants, and damaged or destroyed several other small settlements and farms in its path. As it moved down the Rió Santa, it swept over farms and small settlements, caused extensive damage to road and railway routes, destroyed the diversion dam and access bridge to the important Huallanca hydroelectric plant near the north end of the Cañon del Pato, and damaged power tranmission and communication lines.

No evidence of displacement was found on any of the exposed faults within the region or of tectonic warping along the coast.

The following recommendations are made regarding reconstruction of cities and towns damaged or destroyed during the May 31, 1970, earthquake.

1. The geological environment favors reconstruction of cities, towns, and villages at their present sites, except for the following:
   - (a) A low-lying swampy and flooded zone in eastern Chimbote should be abandoned as a residential area. Because of the ever-present danger of tsunamis associated with earthquakes of this region, preference should be given to relocating new residential areas on higher ground north and northeast of Chimbote. In future construction of multistory buildings in Chimbote, attention should be given to foundation construction to avoid problems due to differential settling and liquefaction of water-saturated sediments during seismic shock. Furthermore, the hazards of seaward sliding of sand deposits along the shore need to be considered in any future construction along the waterfront.
   - (b) Yungay probably should not be rebuilt. However, more study is required to properly assess the potential danger of another debris flow at Yungay (see page 8).
   - (c) Ranrahirca definitely should not be rebuilt at its previous site because of the danger of other debris avalanches originating from the north peak of Nevados Huascarán. Other small settlements along the lower part of the Rió Llanganuco that were destroyed by the Ranrahirca lobe also should not be rebuilt. Potential safe sites for small towns can be found on the alluvial terraces just south of Ranrahirca and north of Yungay.
   - (d) Caraz, at the mouth of Quebrada Parón, is in great potential danger of being destroyed should Laguna Parón burst. Two possibilities for reconstruction exist: (1) relocate the town in a nearby area at the west side of the Santa Valley or (2) drain Laguna Parón, as has been proposed by the Corporación Peruana del Santa (Benjamin Morales, oral commun., 1970), in which case the town can be rebuilt at its present site.
2. An engineering geologic appraisal should be made of cities and towns to evaluate systematically the foundation conditions and to serve

as a guide for reconstruction. Such appraisals should be made by experienced personnel as soon as possible.

3. The systematic hydrologic and geologic study of lakes in the Cordillera Blanca should be continued on a permanent basis, at about the present level of endeavor, to anticipate and correct potential flooding hazards.
4. An appraisal of distribution and stability of glaciers and snowfields in the Cordillera Blanca should be made.
5. Geologic research is needed into the distribution and ages of prehistoric debris flow deposits in the Santa Valley to (1) delineate areas subjected to destructive debris flows in the past, and (2) to determine their recurrence interval as closely as possible.
6. A coordinated program of geological and geophysical research should be undertaken to study active tectonic features in the region in order to gain an insight into the nature of deformation now in progress, regional variations in the strain accumulation pattern, and possible recurrence intervals of earthquakes. As a minimum this study should involve (a) mapping known Holocene faults and establishing monuments, (b) regional strain measurements by precise triangulation and leveling, (c) investigation of the coastal and river terrace sequences, and (d) detailed seismologic studies of the spacial distribution, focal mechanism, and frequency of earthquakes.

These investigations, as well as research into other phases of the May 31, 1970, earthquake, such as a detailed study of the Yungay-Ranrahirca debris avalanche, study of seismic characteristics of the earthquake and aftershocks, engineering construction study, and other research investigations should be coordinated and ultimately be the subject of a symposium leading to a publication that would place upon permanent record the characteristic features of the earthquake. Such a symposium would lead to better understanding of earthquakes, not only in Perú but in the world as as whole, and would be of aid in better preparing for catastrophes of this kind.

REFERENCES CITED

Gutenberg, Beno, and Richter, C. F., 1954, Seismicity of the earth and associated phenomena (2d ed) Princeton, New Jersey, Princeton Univ. Press, 322 p.

Morales, Benjamin, 1966, The Huascarán avalanche in the Santa Valley, Perú: Belgium Internat Symposium on Scientific aspects of snow and ice avalanches: L'assoc int. d'hydrologie scientifique pub. 69, p 304—315.

Silgado F., Enrique, 1968, Historia de los sismos más notables ocurridos en el Perú (1515—1960) Inst Panamericano de Geografía e Historia, Comité Panamericano de Ciencias Geofísicas, Bol. Bibliográfico de Geofísica y Oceanografía Americanas, v 4, p 191—241

☆U S GOVERNMENT PRINTING OFFICE 1970 O - 408-518

ERICKSEN AND OTHERS—GEOLOGIC EVENTS ASSOCIATED WITH THE MAY 31, 1970, PERU EARTHQUAKE—GEOLOGICAL SURVEY CIRCULAR 639