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MODIFICATIONS TO THE SOIL PATTERN OF SOUTH-CENTRAL CHILE RESULTING FROM SEISMIC AND ASSOCIATED PHENOMENA DURING THE PERIOD MAY TO AUGUST 1960

By Charles Wright and Arnoldo Mella

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ABSTRACT

Genesis and evolution of soils in the earthquake region is discussed and then reviewed in the light of changes induced by the earthquakes. Those effects of the earthquake that could possibly influence soils are reported on in detail. These include many field observations on the mass movement, the tsunamis, flooding, changes in land elevation and regime of rivers, volcanic eruptions, etc. A catalogue of changes, including land lost to production completes the study.

(PStA)

Introduction

The soil pattern of Chile is an expression of the extreme youthfulness of the landscape. There is no ancient land surface, as in Brazil, and no areas are known wherein the soil processes have been able to operate consistently over a long interval of time. Moreover, on many of the older and more stable sectors of the landscape, deposition of volcanic materials has, from time to time, initiated new cycles of soil building. Even in South-Central Chile, where the combined effects of weathering and leaching approach their maximum regional intensity, there are no known examples of soil of sufficient age or stability to show the maximum impress of the forces at work. In this sense, there are few mature soils in Chile.

The soil assemblage is thus characterized by a high proportion of young and immature soils, including Recent soils of the alluvial bottomland, unconsolidated coastal and riverine dune soils, and Recent volcanic soils. An interesting feature of the Chilean soil assemblage is the presence of other kinds of Recent to immature soil whose origin can only be ascribed to catastrophic earth movements associated with seismic and volcanic activity.

Features of the soil pattern considered to belong to this category include the following:

1. A sequence of Recent, sub-Recent young, and immature soils on bench terraces along part of the Chilean coastline. These terraces have mainly a gentle surface relief and occur at various altitudes ranging from 20 to 1,000 feet above present sea level. The soils on these terraces show a degree of profile development inconsistent with the prevailing weathering and leaching enviroment: the soils are too youthful for their position in the regional landscape. It is suspected that they represent soils derived from coastal drift (and associated dune loess), elevated during Recent geological time during the successive stages of uplift of a rising coastline.

The nature of the coastal drift has clearly varied from time to time, and further study may show that the nature of the coastal drift, now preserved as soil on the bench terraces, can provide valuable information about cycles of volcanic activity in the past. Volcanic activity in the Andean Cordillera has, from time to time, loaded the rivers rising on the flanks of the volcanoes with fine ejecta of varied but specific mineral composition. On reaching the sea, much of this alluvium has been turned northward by the Humboldt Current and deposited as drift material on the coastal shelf. This is a factor that produces diversity in the altitudes above sea level of the terrace soils.

This diversity notwithstanding, there is some measure of uniformity in soil profile development among terrace soils of the same elevation: over a limited sector of the coastline, terraces of the same general altitude above sea level possess soils with equivalent leaching and weathering characteristics. Using this as a rough guide, it is apparent that the Chilean coastline north of latitude 38° 30′S has been fairly consistently rising; whereas the coast south of latitude 40°30′ has been slowly sinking. Between these two points, the lower bench terraces progressively disappear (south of latitude 39°30′, only the oldest, highest terraces remain), suggesting that the axis of depression has been creeping slowly northward.

2. Sharp discontinuities in the soil profile in the alluvial soils of the coastal plain, brought about by minor, but abruptly initiated, changes in drainage conditions. In the Valdivia area, for instance, there is a sequence of river alluvium-peat-estuarine clay repeated several times in the material of the bottom lands. This could represent periodic ingressions of the sea, each followed by the gradual accumulation of estuarine clay to the point where aquatic and bog plants can colonize the area. The subsequent covering of the bog with river alluvium may represent increased erosion of the coastal range in a landscape that is slowly rising with respect to sea level. These movements are relatively minor oscillations in comparison with the appearance and disappearance of the coastal bench terraces mentioned above.

3. Local chaotic complexity of the soil pattern, apparently the result of the development of massive landslips in former times, principally along the flanks of the main river valleys traversing the coastal range.

4. Very marked development of tumultuous fan-building along sectors of the Andean piedmont. These are of two types: one, probably associated with the sudden melting of snow and ice attendant upon the reawakening of volcanic activity but not necessarily associated with seismic activity; and, another, with a distinct and characteristic microrelief that appears to be associated with the development of massive mudflows originating in seismic movements.

5. Evidence of unusual changes in the pattern of alluvial deposition in the lower valleys of the main rivers. This is, at times, due to overloading of the rivers with volcanic material during eruptions, but, at other times, the soil data suggest change in the trend of sedimentation such as might be caused by seismic activity (continental movement or activity of tsunamis) modifying conditions at the river mouths.

Change Effected in Soil Pattern and Subsequent Developments

Seismic activity was initiated at 10:02 GMT (6:02 a.m. local time) on 21 May, when a severe earthquake, with its epicenter in the Pacific Ocean west of the Arauco peninsula, caused damage in the neighboring Provinces of Concepcion, Nuble, Arauco, Bio-Bio, and Malleco. The following day, further severe shocks, with more southerly epicenters, extended the disaster to all the remaining provinces of South-Central Chile, as far south as Chiloé. The second phase of the seismic activity was accompanied by the development of tsunamis, which brought additional distress to coastal settlements between the Arauco Peninsula and the southern tip of Chiloé Island. (Fig. 1, Map of South-Central Chile, is in pocket at the end of this number.)

Damage to the road and railroad system and to telegraphic installations virtually isolated South-Central Chile from the rest of the country, and the first assessment of damage came from the reports of persons evacuated from the zone by air. Within one week, however, it was possible for teams of assessors to penetrate the affected regions by car. The following account is descriptive of the changes observed in nine selected districts (which may be located on the index map, figure 1 in the pocket at

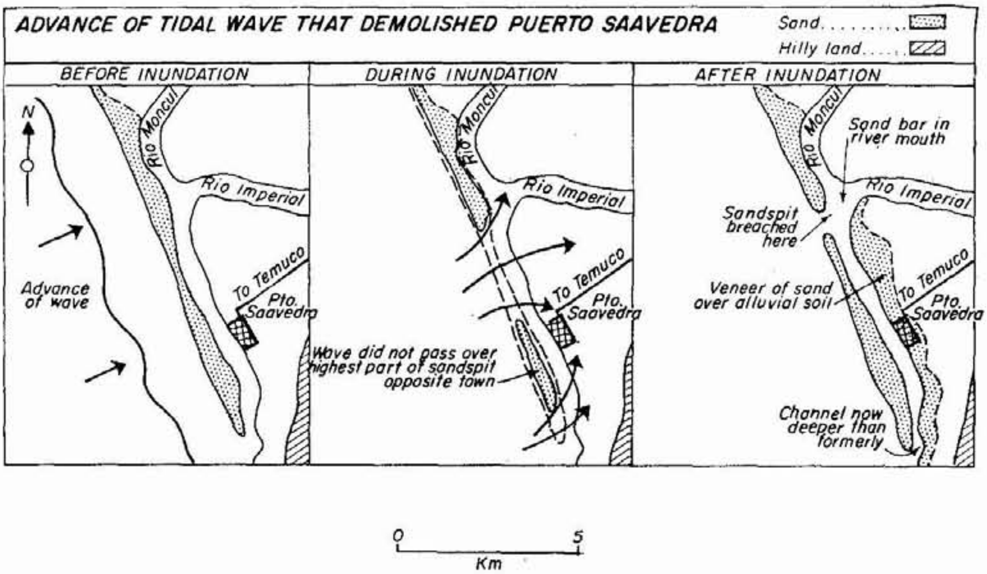

FIG. 1 (a). Advance of Tidal Wave That Demolished Puerto Saavedra.

the rear of this number), visited within two weeks of the onset of the earth movements. Further changes that occurred during the ensuing year have been added to the report.

The districts visited, and the type of modification in the soil pattern available for study in each case, were as follows:

Puerto Saavedra—flooding of lowlands with sea water; emplacement of dune sand on alluvium. (Fig. 1(a)).

Tolten—flooding of lowlands with sea water; subsidence of land caused by compaction of lightly consolidated organic substrata; possible general subsidence of coast.

Puyehue—eruption of pumiceous ash; widespread development of landslides.

Rupanco—very extensive debris avalanches; mudflow destruction caused by lake waves; subsidence of unconsolidated sediments.

Valdivia City and Southern Valdivia—subsidence of coastline; damage by tsunamis; subsidence of unconsolidated sediments; shearing of substrata rich in allophane clays.

Northern Valdivia—damage by tsunamis; subsidence of coastline; salination of of soil water table.

Central Valdivia—landslides; alluvial deposition subsequent to release of impounded waters of Lago Riñihue.

Pellaifa—landslides; debris avalanches.

Arauco—uplifted coastline.

1. *Puerto Saavedra.* The town of Puerto Saavedra, at the mouth of the Rio Imperial, was almost completely destroyed (fig. 2) at 3:30 p.m. on the afternoon of Sunday, 22 May and during the following night, by a series of waves. The main

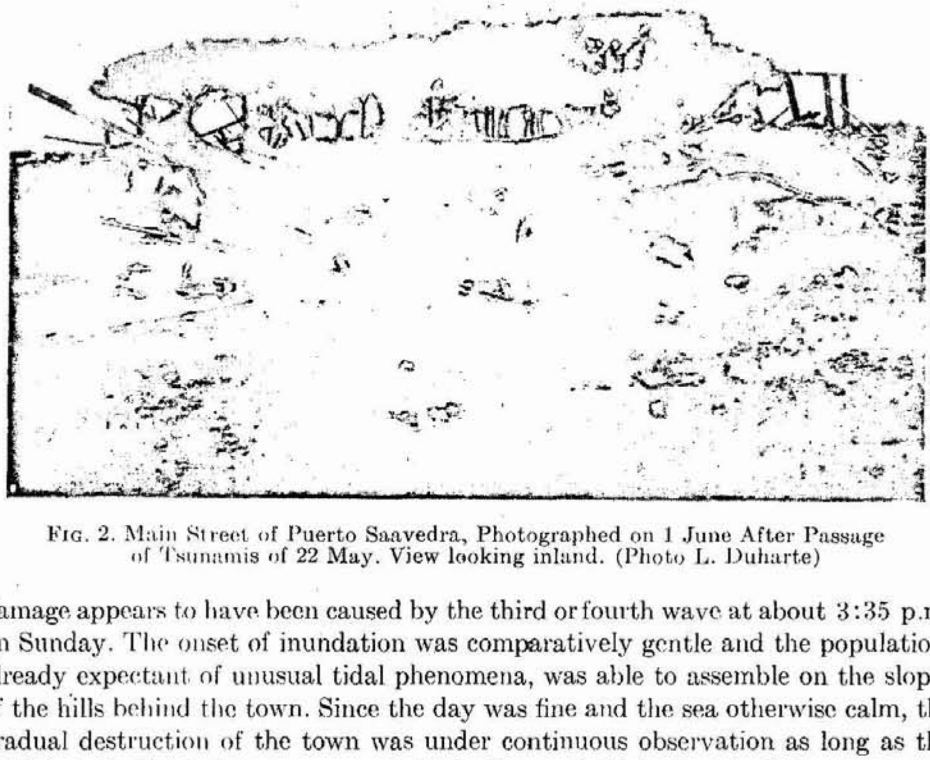

FIG. 2. Main Street of Puerto Saavedra, Photographed on 1 June After Passage of Tsunamis of 22 May. View looking inland. (Photo L. Duharte)

damage appears to have been caused by the third or fourth wave at about 3:35 p.m. on Sunday. The onset of inundation was comparatively gentle and the population, already expectant of unusual tidal phenomena, was able to assemble on the slopes of the hills behind the town. Since the day was fine and the sea otherwise calm, the gradual destruction of the town was under continuous observation as long as the light lasted. Most observers agreed that after an initial retreat of the sea water, there was a gradual flowing in and that the larger waves, which caused most of the damage, were not more than a few meters high. It appears that the town was flooded to a maximum depth of about $3\frac{3}{4}$ meters, and within 24 hours from the onset of inundation, the land was again clear of water, except for the many pools occupying the low-lying places.

Many of the buildings on the seafront were wholly or partially destroyed by direct wave action, and the single row of macrocarpa trees planted as shelter from the wind provided but little protection for the buildings. However, buildings farther away from the shore, with protection of trees, usually escaped demolition or even serious damage. Without the protection of trees, the battering action of the debris from the demolished buldings of the seafront carried inland by the waves caused almost total demolition. Since few houses had the requisite shelter by trees, almost the whole town site was eventually swept clean. The protective effect of even a few trees in in areas remote from the actual seafront was very striking. Most of the buildings were constructed of wood and were easily demolished. Some were lifted up and overturned before breaking up.

The impact of the sea was not equal along the whole coastal strip. The town of Puerto Saavedra (fig. 1a) is sheltered by a long sand spit— a prolongation of the coast from near the mouth of the Rio Moncul, which lies to the north. Between Puerto Saavedra and the sand spit, there is a channel some 1 ½-km wide, carrying water from the Rio Imperial to the sea. When the great tsunami swells from the open ocean approached the shore, they engulfed all but the highest parts of the sand spit and moved on across the channels toward the mainland and Puerto Saavedra. In one place opposite the Rio Imperial, in passing over the sand spit, the sea broached the sand barrier, and the Rio Imperial can now empty directly into the sea without following its former channel past the site of Puerto Saavedra. Following the broaching of the sand spit, there was more or less free passage of waves from the open sea, and the town was subjected to wave action from two directions, southwest and northwest. Where these two systems of waves met, the action of the sea was particularly destructive.

It is important that this broaching of the sand spit and other local modification in the coastline be studied closely, because all the evidence suggests that there will be a building up of a new sand bar, or at least some depos tion of sand from the old sand spit across the new mouth of the Rio Imperial. This could have serious repercussions on the lowlying agricultural land in the valley of the Rio Imperial because in the event of heavy rain over the cordillera, it is unlikely that the river will be able to discharge the extra volume of water at its customary rate. Abnormal flooding of valuable agricultural land may be expected in this valley for some years. (This actually did happen in May and June 1961.)

There were few permanent changes in the soil of the plain adjacent to the former site of Puerto Saavedra. These soils are sandy loams or, in some places, gravelly clay loams, and their normal water table lies 80 cm to 1 meter below the surface. Below this depth, the soils are poorly drained and strongly mottled; they are fairly free-draining above the level of the permanent water table. These soils were flooded with sea water for about 24 hours, but inspection pits dug into the center of the affected area one week after their inundation showed that earthworms and grass-grub larvae were alive and well. The pastures did not seem to be greatly affected, as they were still green and putting out new leaves. Bare soils, such as in fields where the potato crops had been harvested or where sugar beets were growing, suffered some superficial erosion, but the amount of soil lost amounted to only a few centimeters. A few of the shallow drainage ditches in the area were filled in, but most of the drains are now functioning normally. By 1 June, the soil water table had almost returned to its normal level, and instead of the land now being lower, it appeared to be slightly higher than before. There was some redistribution of sand and silt from the actual coast, these materials being carried inland and deposited near the more clayey soils of the center of the plain; but, again, this amounted to only 1 or 2 cm. The chief agricultural damage was to fences and other farm installations. Soil samples collected one week after inundation showed that these soils still contained some extra salt, but it seems there had been sufficient rainfall between 23 May and 1 June to wash out most of the added salt.

From rapid examination of the coastal plain in the vicinity of Puerto Saavedra, it would seem safe to conclude that there has been no permanent damage to the agricultural potential of the soils. Attention should be drawn to the possibility of severe flooding of the lowlands between Puerto Saavedra and Nueva Imperial, 40 km inland. The new configuration of the coast at the mouth of the Rio Imperial and its implications with regard to possible change in the pattern of sedimentation at the river mouth need to be studied in detail. It is likely that the former channel of the river, which passes to the south of Puerto Saavedra, will become considerably deeper opposite the site of the former port installations.

2. *Tolten.* The town of Tolten is located near the mouth of the Rio Tolten, approximately 100 km southwest of Temuco, and near the last major bend made by by the river before reaching the sea (figure 1). The town is located on an alluvial plain and is nearly 2 km inland from the bank of the river (figure 1 b). At this point, the river channel runs inside of and is protected by a sand spit $1\frac{1}{4}$ km wide. The presence of this sand spit and the wide extent of the alluvial plain undoubtedly protected the town of Tolten from the type of extensive damage suffered by Puerto Saavedra, although the sand spit opposite Tolten is somewhat lower in elevation than that opposite Puerto Saavedra.

As in the case of Puerto Saavedra, the sea retreated and then began to rise steadily and rapidly at 3:15 p.m. on Sunday, 22 May, inundating the town to a depth of about $1\frac{1}{2}$ meters. The water then subsided and, fearing another deeper inundation, the people moved to the tallest available buildings and to trees. A second inundation began after a lapse of about 10 minutes, and the water reached a maximum depth of about 3 meters. This inundation took longer to subside, and many of the wooden houses were washed from their supporting blocks. Actually, some houses, weakened or damaged by the earthquake about 30 minutes before, probably began to disintegrate when the sea first entered the town. Unlike Puerto Saavedra, where the sea caused almost all of the damage, in Tolten the earthquake damaged many houses and produced large fissures in the soil. The inundation that followed partially filled in many of these fissures, but the damaged houses collapsed. Eyewitnesses stated that the main swell broke against the protecting sand spit and the sea passed over the sand only in the lowest part, opposite the site of Tolten. Undoubtedly, the force of the wave had diminished greatly in passing the sand barrier and was further reduced while passing the 2-km wide strip of alluvial plain. The pattern of destruction was quite unlike that at Puerto Saavedra; the arrival of the water was comparatively slow—as in an abnormally high tide—and there was little battering action by floating debris.

For a time, sea water covered all the low-lying alluvial plain between Tolten and the adjacent coastal range. The soils of the alluvial plain contain more clay than those of Puerto Saavedra. However, as in the case of Puerto Saavedra, the soils appear to have suffered little permanent damage from their brief immersion in sea water. When visited on 24 June, the earthworm population was still alive, and the only pasture plants that appeared to be dead were the clovers. The water table had returned to its normal winter level (at the top of the mottled zone), and the land in the immediate vicinity of Tolten did not appear to have altered in elevation with respect to the level of the sea.

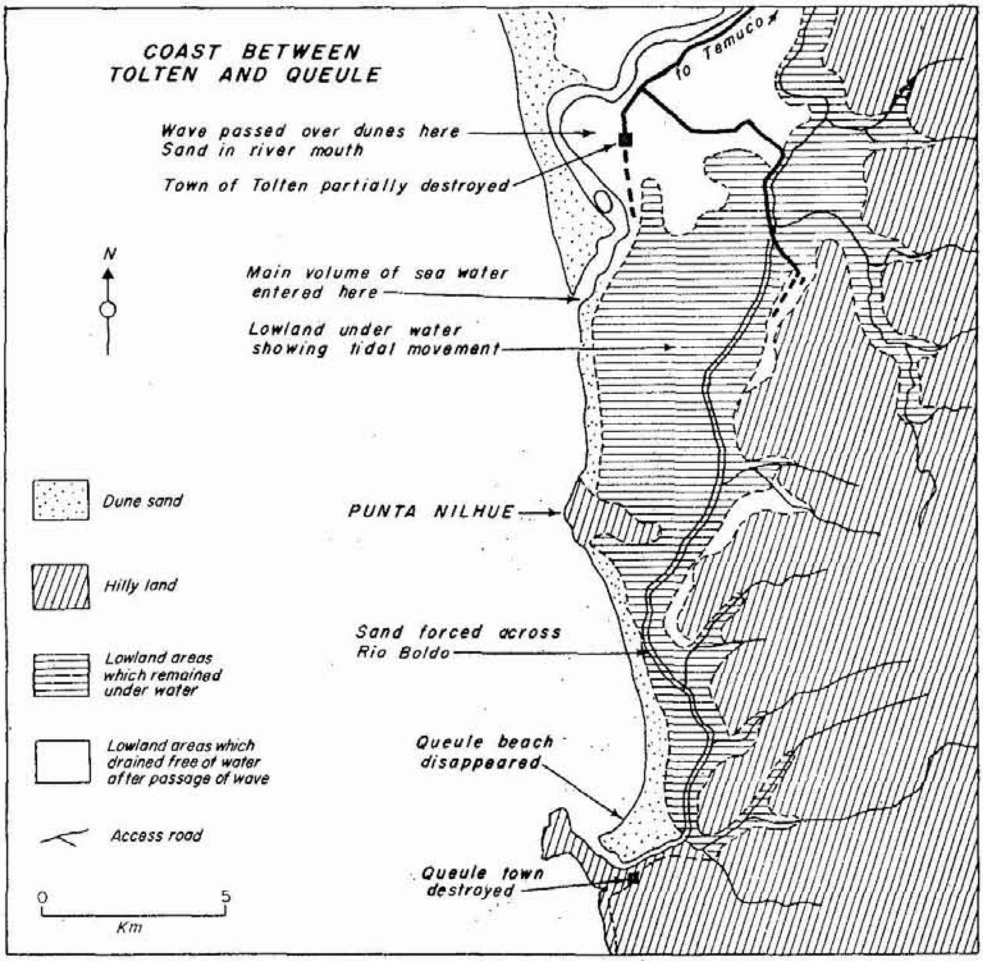

FIG. 1 (b). Coast Between Tolten and Queule.

Between the site of Tolten and the foothills of the coastal range, there is an area of low-lying land some 5 to 6 km wide, normally lying about 1 to 2 meters above the mean low tide level. On this part of the coastal plain, the soils are mottled peaty clays and peat loams. This lowland area filled with sea water at the time of the tsunamis, and after an initial flooding to a depth of 2 to 3 meters (in the deepest parts), there was only a recovery of 60 cm in the level during the succeeding 8 days. Most landowners are convinced that the land has now sunk at least $1\frac{1}{2}$ meters below its former level (figure 3). They point out that the water on their land fluctuates regularly in depth by some 30 cm with the tides. Accurate measurement of the level of this land with respect to mean tide levels is in progress, but even today, 12 months after the earthquake, the land remains beneath a lake of brackish water.

Evidence from Queule, a coastal port at the mouth of the Rio Boldo where a grotto cut in the cliff is said to be 1 meter 80 cm closer to mean sea level than before the earthquake, provides more positive indication that there was indeed a general subsidence in the level of the coastal region south of Tolten. This may be the reason

Fig. 3. Flooded Lowland Near Tolten Photographed on 2 June 1961. Twelve months later, the only differences noted were that the trees had died and a temporary access causeway had been constructed across the flooded plain.

why the Tolten lowlands are no longer draining normally. There are, however, two other points to be kept in mind. The first is that, as in the case of Puerto Saavedra, the offshore sand bars have altered their form and distribution. In one place, to the south of Punta Nilhue, the coastal dunes were breached by the tsunamis, and the sand is now partially blocking the lower reachs of the Rio Boldo. Thus, both the Boldo and the Tolten rivers are now partially obstructed by sand, and, during periods of heavy rain, further flooding of the lowland may be expected. The second possibility to be kept in mind is that, during the shaking action of the earthquake, unconsolidated sediments tend to pack closer together. A clear example of subsidence from this cause was seen 5 km northeast of Tolten, where Recent sandy alluvium of about 1 meter 50 cm depth overlies organic materials accumulated in an ancient swamp. During the shaking action of the earthquake, these organic deposits compacted, and an arcuate pattern of vertical fissures developed in the over-lying alluvial material, marking out the limit of the area of subsidence (figure 4). Much of the Tolten and Boldo plains are underlain by similar peaty materials, and some of the apparent change in the level of the land may be due to local subsidence caused by the decomposed, peaty substrata being shaken into a more compact mass.

The situation of the farmers on these inundated lowlands is serious. There were heavy stock losses on the smaller holdings, and much first and second class agricultural land has now been under water for more than a year. The heavier textured soils have suffered considerable structural damage from their prolonged immersion

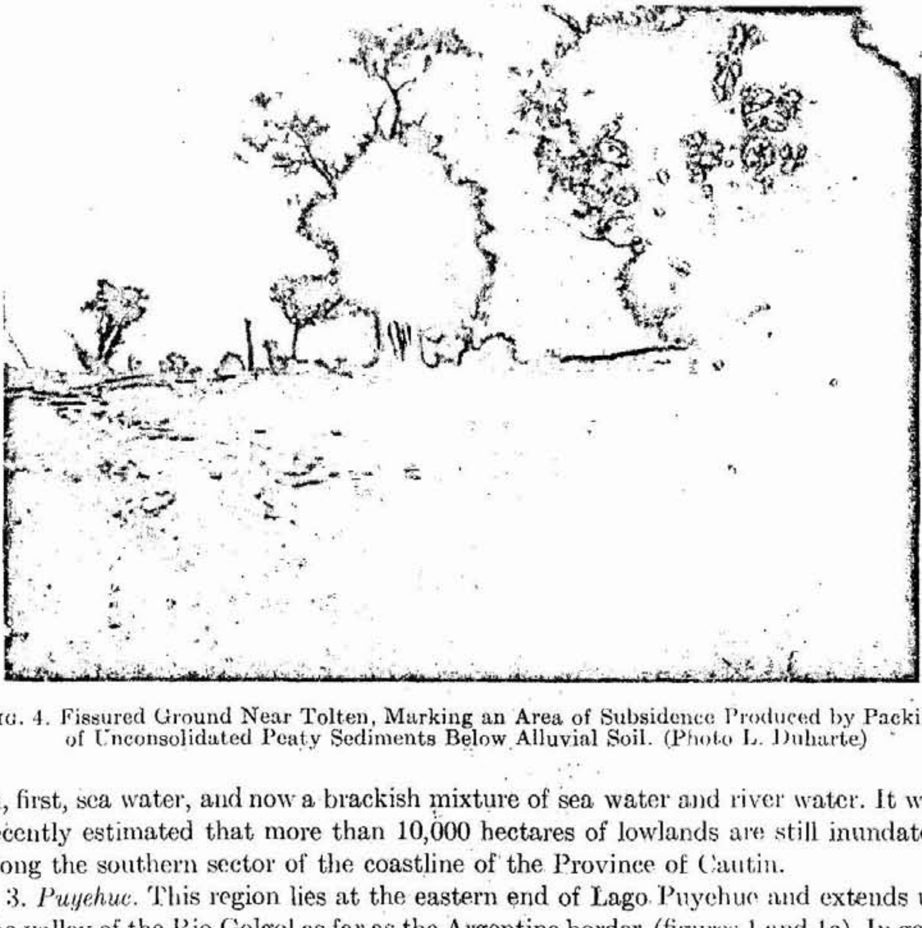

FIG. 4. Fissured Ground Near Tolten, Marking an Area of Subsidence Produced by Packing of Unconsolidated Peaty Sediments Below Alluvial Soil. (Photo L. Duharte)

in, first, sea water, and now a brackish mixture of sea water and river water. It was recently estimated that more than 10,000 hectares of lowlands are still inundated along the southern sector of the coastline of the Province of Cautin.

3. *Puyehue*. This region lies at the eastern end of Lago Puyehue and extends up the valley of the Rio Golgol as far as the Argentine border (figures 1 and 1c). In general, it is a region of narrow, fertile valleys with steep slopes formerly covered with forest up to the snowline (at about 1,990 meters). Before the earthquake, much of the landscape had suffered severely from erosion as the result of efforts to develop agriculture in the region, and fire had damaged much of the natural forest at higher elevations.

Lago Puyehue is 212 meters above sea level, and the main valley of the Rio Golgol rises fairly gently for a distance of about 22 km. The valley floor, occupied by a narrow strip of Recent alluvium, is flanked by colluvial soils accumulating along the foot of the steep valley sides and partially burying a system of old alluvial terraces. The valley is somewhat wider in the vicinity of Anticura, 22 km east of Lago Puyehue, and, here, there is a more extensive development of alluvial fan soils. Agriculture in this valley is mostly practiced on small mixed farm holdings, ranging from 50 to 150 hectares; the total population in the valley is probably less than 800 persons. The valley of the Golgol is carved in mainly andesitic and basaltic rocks

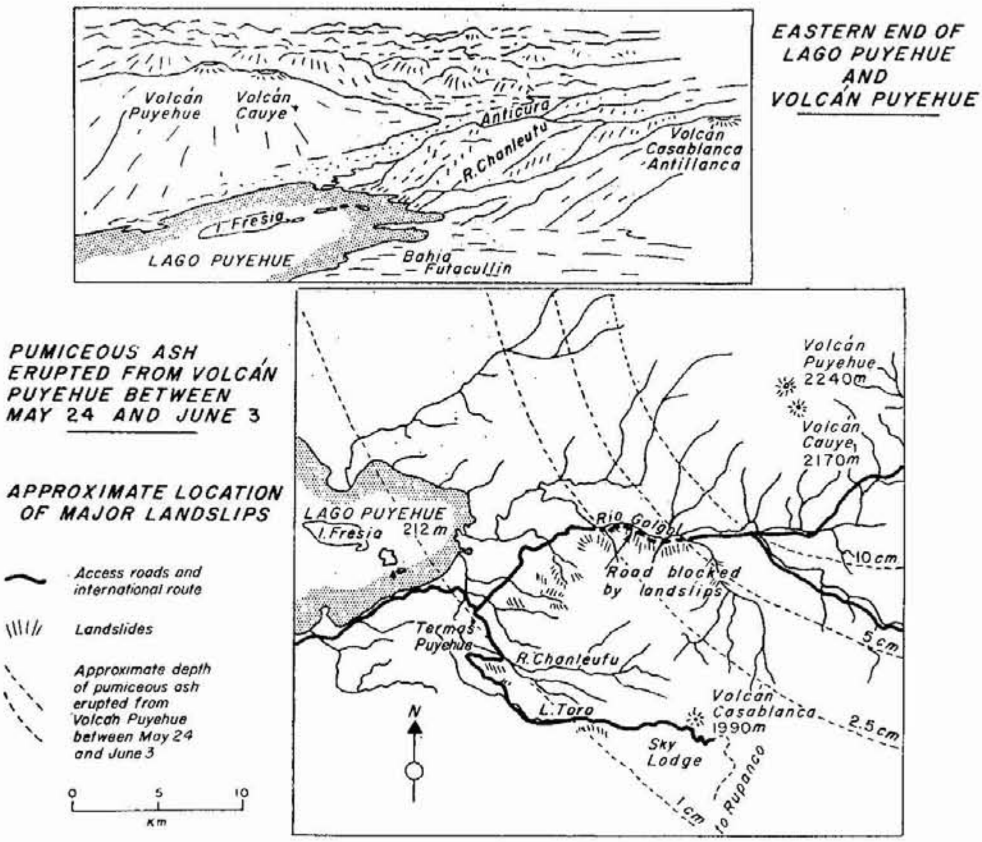

FIG. 1 (c). Eastern End of Lago Puyehue and Volcan Puyehue Covered With Pumiceous Ash.

lying between the two main volcanic centers of Puyehue and Antillanca. The mountainous landscape surrounding the valley is dominated by Volcan Puyehue (2,240 meters), about 10 km to the north, and Volcan Casablanca (1,990 meters), some 13 km due south.

The farming population was formerly served by one road, which also connected with Argentina. A few moments after the earthquake at 3:15 p.m. on Sunday, 22 May, this road was blocked by a series of landslides that engulfed sectors of the road, carried away bridges, and diverted streams so that they eroded away additional sections of the road.

The isolated valley community was further alarmed at 3:15 p.m. on Tuesday, 24 May when an explosion occurred near the crest of Volcan Puyehue, apparently located in or near a parasite cone called Cauye. The exact location of this eruption was observed from several points, for the afternoon was clear until the moment of the eruption; but there is some difference in local opinion as to whether the explosion actually occurred in, or merely near, the crater Cauye. The eruption steadily increased in violence and continued for seven days. A further brief eruption occurred in March of the following year.

Little volcanic ash fell in the Golgol area during the first day of the eruption. The sky became obscured and the air became charged with sulphurous gases, but a strong westerly wind was blowing and most of the volcanic ash was carried over the cordillera toward Argentina. Messrs. A. Delley and S. Barraclough of the Technical Assistance Mission of FAO in Chile, who were passengers on the regular LAN flight from Punta Arenas to Santiago on the same Tuesday afternoon, report that the plane flew through a wide belt of ash-filled air, and, on landing at Mendoza, the pilots found that most of the paint on the leading edges of the fuselage of the plane had been completely eroded.

The following day (Wednesday, 25 May) was calm. The column of steam and ash over Volcan Puyehue extended vertically upward to a great height. In early morning, fine black ash, and later very fine white sand, began to fall on the landscape as far west as Cudico (near La Unión) and as far south as Puerto Octay, at the north end of Lago Llauquihue. The total amount accumulating during the day, at these points (80 to 90 km distant from the vent), was only a few millimeters, but all the vegetation and buildings had a greyish color from the layer of volcanic dust. At the Custom Station near Termas Puyehue, a total depth of 7 mm was recorded. Ten kilometers nearer the volcano, in the Golgol valley, more than 1 cm accumulated, but all the material falling on landscapes to the west of the vent during this early phase of the eruption was sand, of a fine to medium texture.

The mountain became obscured by a cloud during the latter part of Wednesday and remained invisible for most of the succeeding week. Small amounts of ash fell intermittently over the landscape between Osorno and Puyehue on Thursday, but, either late on Thursday night or early on Friday morning, an increase in the frequency of earth tremors and subterranean noises heralded the appearance of a shower of coarse pumice fragments. These were mainly oval-shaped or rounded, light, porous stones between $\frac{3}{4}$ and $1\frac{1}{2}$ cm in size. These coarse materials fell over the landscape within 15 km to the west and southwest of the vent, and probably most of this coarse shower fell on the slopes of the cordillera to the east. No large pumice fragments fell at Termas Puyehue, or at any point further to the west. About $1\frac{1}{2}$ cm fell at Puente Negro, 10 km east of Termas Puyehue, while further up the Rio Golgol about 4 to 5 cm was reported. No ash fell on the landscape between Osorno and Termas Puyehue on Saturday. A little fell on Sunday, 27 May, and the activity of the vocano was apparently on the wane. During the strong easterly wind experienced in this region on 10 and 11 June, a small additional dusting of ash (less than 1 mm) was observed in Rupanco and Osorno. Thus, during the three weeks following the intial phase of the eruption from Volcan Puyehue, a total of only 1 cm was recorded by the carabineros stationed in the Customs House near Termas Puyehue, and the 7.5-cm boundary of the new volcanic ash deposit lies about 10 km west and south of the actual vent. The greatest extent of the new volcanic material will certainly lie to the east, over the Andean Cordillera, and in Argentina.

A sample of fresh ash collected by the officials in charge of the Customs House appeared to be mainly fine pumice sand. Collecting samples of the new ash from the actual surface of the soils proved to be quite difficult. Over 10 points of rain had fallen on 25, 26, and 28 May, and again on 1, 3, 5, and 6 June. This amount of rain proved to be adequate to disperse the ash on the landscape, and only very small amounts could be scraped up from particularly favorable sites, such as fissured rock surfaces, tree stumps, and horizontal logs. Samples of this type were collected

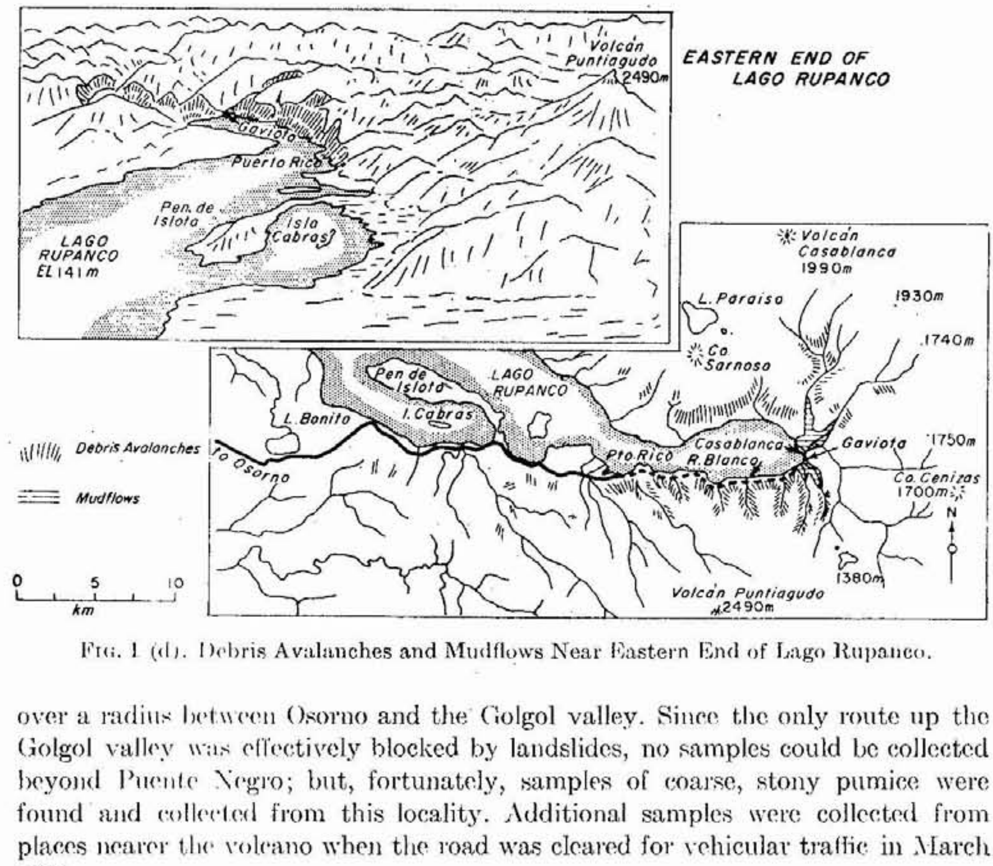

FIG. 1 (d). Debris Avalanches and Mudflows Near Eastern End of Lago Rupanco.

over a radius between Osorno and the Golgol valley. Since the only route up the Golgol valley was effectively blocked by landslides, no samples could be collected beyond Puente Negro; but, fortunately, samples of coarse, stony pumice were found and collected from this locality. Additional samples were collected from places nearer the volcano when the road was cleared for vehicular traffic in March 1961.

During the first few days of the eruption, most of the farmers in the valley were evacuated by helicopter or escaped on foot across the landslides. These landslides are composed mainly of ancient volcanic ash material, with boulders of andesitic and basaltic flow rocks. In their natural state, these steep valley sides are mantled with 2 to 3 meters of volcanic ash, showing clear layering, with successive layers of scoria, fine sand, coarse pumice, allophane-rich silts and loams, etc. The natural mechanism that caused this mantle of ash to peel away, and the events that followed, appear to be the same as those investigated at Lago Rupanco. In the Golgol valley, the debris avalanches (Sharp, 1938) are not as widespread or of so great an individual extent as at the head of Lago Rupanco. In addition to the destruction of the only access road, damage by landslip debris to the agricultural land in the Golgol valley has been considerable. On the other hand, deposition of ash from the Puyehue eruption appears to have occasioned little damage to the agricultural resources of of the region. The ash samples collected have been checked for toxic or other possible harmful factors likely to affect the health of livestock, but nothing of this nature was found.

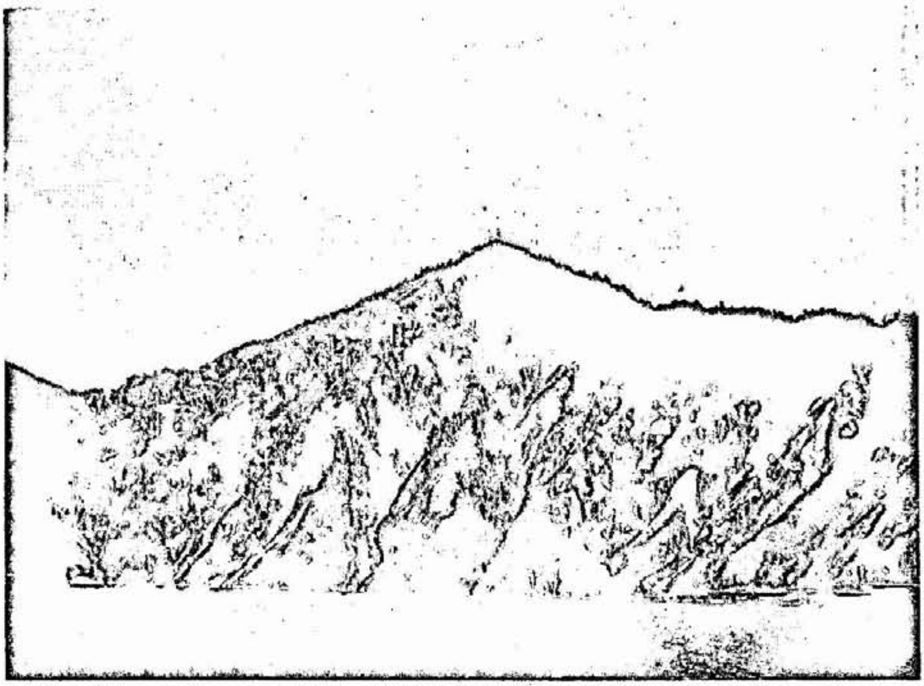

FIG. 5. Scarred Face of Slopes Bordering Lago Rupanco Where Landslides Developed During the Earthquake of 22 May. Fifteen persons were overwhelmed on the road and swept into the lake in the sector shown in the photograph. White scars indicate removal of the volcanic ash mantle to expose andesitic rock; darker scars still have some weathered scoria clinging to the steep slopes. The ancient volcanic cone, Puntiagudo, can be seen in background.

4. *Rupanco.* At the eastern end of Lago Rupanco (figs. 1 and 1d) some 125 persons perished within a few minutes during the earthquake at 3:15 p.m. Sunday afternoon, 22 May. About half this number were families belonging to the Gaviota farming settlement established by the Caja de Colonizacion, and the rest were laborers engaged in constructing a road around the lakeshore to link this farm settlement with Osorno city. Some of the victims were swept into the lake by landslides (fig. 5) from the steep slopes bordering the lake; others were enveloped in rapid-moving rivers of mud, rocks, and trees that developed wherever landslides converged.

The soils of this region (fig. 6) are formed from successive layers of volcanic ash; typically, the top 40 cm is pale colored and pumiceous while the lowermost horizon consists of 40 to 80 cm reddish-brown weathered scoriaceous coarse gravel.

Between these two thick porous horizons, there may be one or more thin layers of fine andesitic volcanic ash weathered to the stage when a high proportion of allophane clays are present. When moist, these allophane-rich horizons are slippery and greasy; when dry, they have many of the properties of very fine sand. These laminated soils, derived from alternating layers of volcanic ash of diverse origin, occur over the whole of the landscape; even slopes of 40 degrees and upwards have an ash mantle usually thicker than 1 meter. Rarely do the underlying andesitic-flow rocks protrude through this mantle.

FIG. 6. Laminated Volcanic Ash Soils Typical of the Rupanco Region. The dark colored surface soil is pumiceous sand. This is underlain by loamy fine sand of andesitic origin, followed by coarse pumice gravel and a layer of silty clay loam rich in allophane clay (level with bottom of spade). Note shown in photograph is the thick layer of weathered scoriaceous gravel that underlies the allophane-rich layer.

The rainfall of the region is abundant and well distributed throughout the year, and even the steepest slopes are able to support a forest cover. Up to about 1,200 meters, the commonest trees in the forest are olivillo (myrceugenia corraefolia) and tepa (tepulia stipularis) of the myrtle family; ulmo (eucryphia cordifolia) of the eucryphiaceae; and the chilean laurel (laurelia sempervirens) of the monimiaceae. In the volcanic ash soils of this region, all these species have very shallow rooting (figure 7). The top soil is laced through by a mass of large and small roots, often fused together where they intersect, forming a tough superficial root network, which undoubtedly helps to hold the soil in place on steep slopes. This predilection toward superficial rooting is probably connected with periodic renewal of plant nutrients at the soil surface when the neighboring volcanoes are erupting.

There is abundant evidence that this plant-soil landscape system is under tension even under strictly natural conditions. Steep slopes carrying virgin forest show the same pattern of erosion as has been observed in the fiordland region of New Zealand (Wright and Miller, 1952). In the course of time, individual trees become too large for the steepness of the slope, and on breaking away they start an avalanche of trees, soil, and rocks that cuts a long narrow scar in the forested mountainside. Trees slowly reclothe this scar, and the net result is a forest composed of communities of varying ages, with marked vertical, or "striped," patterns.

When the forested slopes are burned, either accidentally or as a stage in the process of replacing forest with pasture, the superficial root network is destroyed and marked instability of soil develops, especially on slopes steeper than 25 degrees. Actual land-clearing operations usually stop if the slope is more than 25 degrees, because the farmers are well aware of the instability of the soil; but fire employed in clearing the land frequently escapes and burns the forest on the steeper slopes nearby. Accelerated erosion is evident on much of the land wholly or partially cleared, and takes the form of small crescentic slips, land slumping, or landslides, which are usually of greater width but smaller length than those that are a feature of the normal erosion. Any abnormal seasonal condition (such as a very dry period followed by a few days of heavy rain or an abnormally wet winter season) starts the cycle of accelerated erosion on land cleared or partially cleared by farmers.

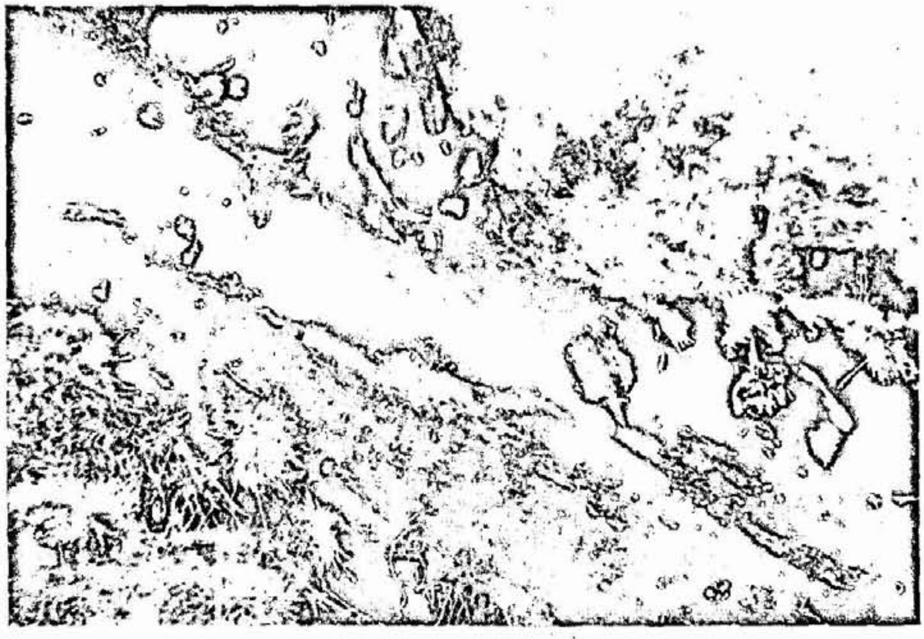

FIG. 7. Main Roots of Olivillo (myrceugenia corraefolia) Are Near Surface and Do Not Penetrate Into Gravelly Pumice and Scoria Layers of the Subsoil.

In the past, in this part of the Rupanco region, much time and labor have been lost in trying to establish pasture on the hill slopes—even wheat crops have been sown—because the strip of easily cultivated land along the lake side is far too small to permit the settler to develop an economic farm unit. Most holdings are between 50 and 200 hectares in extent, and usually less than $\frac{1}{10}$th of this area consists of land of easy relief, which can be relied upon to remain in a stable condition when the forest is removed. Under such conditions, farmers must try to get as much production as possible from the hill and steepland soils; but on soils such as these, formed from laminated ash beds, the risk involved is always extremely high.

The impact of the earthquake on Sunday, 22 May, was sudden and disastrous. The previous summer had been a dry one and the soils were in an abnormally

FIG. 8. Fissuring of the Soil and Slumping Produced by Heavy Rain Following the Mild Earthquakes of 20 May.

dry condition. On Friday the 20th, there had been a mild earthquake which, as several farmers noted, caused widespread fissuring on the soil (figure 8). Heavy rain fell all day, and one may assume that this rain quickly saturated the porous layers in the subsoil and thoroughly wetted the allophane-rich layers. Several minor landslips occurred on Friday night and more on Saturday. The main earthquake came on Sunday, causing the simultaneous development of hundreds of major debris avalanches. In areas where the forest had been burned, these landslips started from the highest crest of the slope; where the forest was in a more or less natural state, they started from the highest point reached by land clearing operations. Many avalanches fell a total distance of more than 1,000 meters, down slopes averaging 40 degrees. In some cases, whole mountainsides 5 to 8 km wide were suddenly and completely stripped of vegetation and soil. In places, this enormous mass thundered down directly into the lake, sweeping houses and people along with it. In two places, at the head of the lake, debris avalanches from several slopes converged and formed enormous mudflows (figure 9), which advanced with surprising rapidity over the intervening rolling land and then finally discharged into the lake. People, animals, houses, etc. in the path of these mudflows were engulfed and churned among the mixture of trees, rocks, and soil. Many of the largest trees were completely stripped of their bark, and some were splintered into matchwood. There is abundant testimony to the power and irresistible force of these mudflows. Eye-

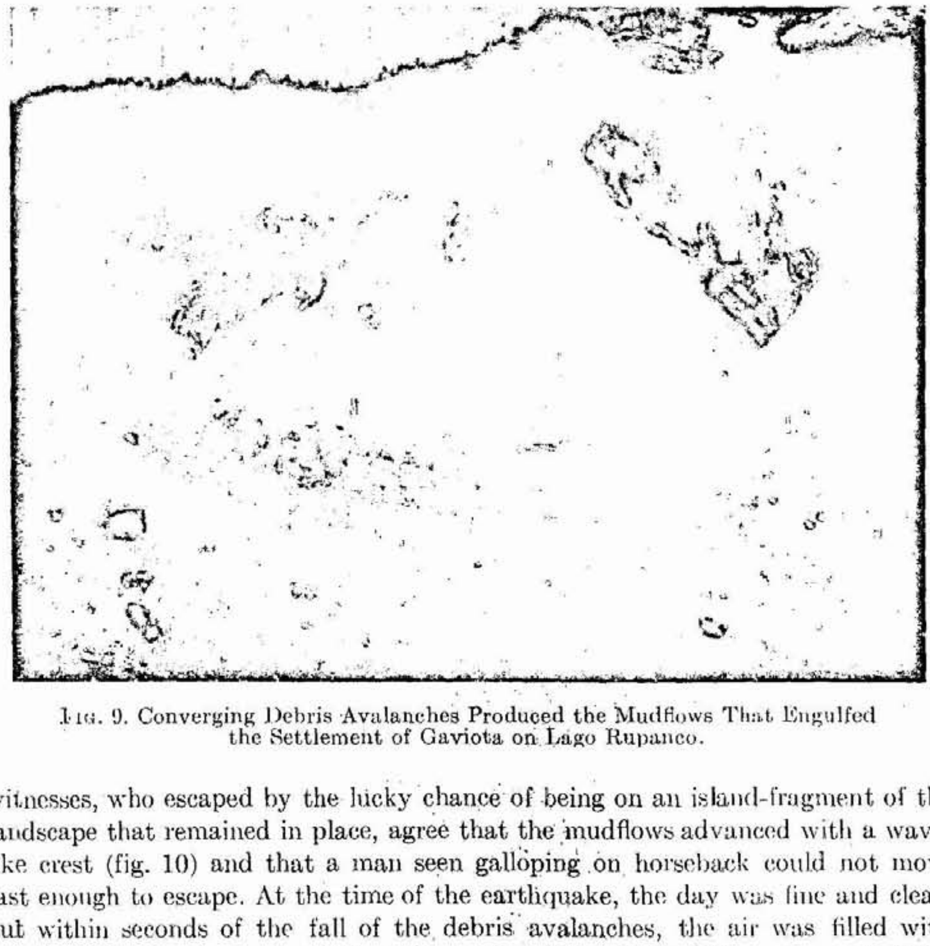

FIG. 9. Converging Debris Avalanches Produced the Mudflows That Engulfed the Settlement of Gaviota on Lago Rupanco.

witnesses, who escaped by the lucky chance of being on an island-fragment of the landscape that remained in place, agree that the mudflows advanced with a wave-like crest (fig. 10) and that a man seen galloping on horseback could not move fast enough to escape. At the time of the earthquake, the day was fine and clear; but within seconds of the fall of the debris avalanches, the air was filled with fine droplets of water and a thick mist enveloped the whole of the upper end of the lake for the rest of the day. The impact of the debris avalanches produced a shock-wave that caused some houses to jump several meters into the air. A wall of water rose from the northeast corner of the lake, swept across the settlement of Gaviota on a terrace 12 meters above normal lake level, and then ricocheted from side to side down the lake until its force was expended in the vicinity of the peninsula of Islota. In the center of the lake, this wave and succeeding backwash waves produced nothing more than a sharp swell; but along the lake shore where the waves broke with great force many small houses and many of their occupants were washed away. This was the catastrophic erosion and associated phenomena that practically obliterated the settlement of Gaviota on Sunday, 22 May, 1960.

There remains the scientific inquest (Wright and Mella, 1961). In the first place, the layer formation of the soils themselves, with an allophane-rich layer sandwiched between two porous water-holding layers, provides a basic element of instability. The history of land slipping in the region confirms this instability. The pattern of

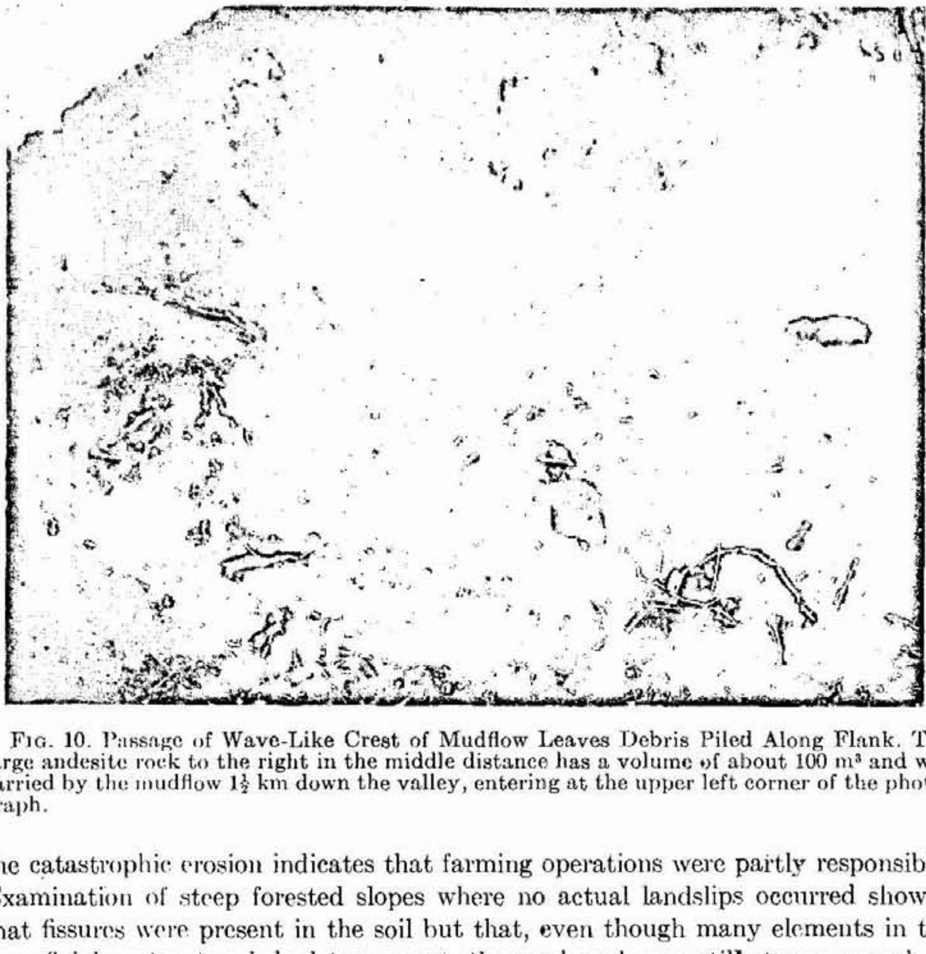

FIG. 10. Passage of Wave-Like Crest of Mudflow Leaves Debris Piled Along Flank. The large andesite rock to the right in the middle distance has a volume of about 100 m³ and was carried by the mudflow 1½ km down the valley, entering at the upper left corner of the photograph.

the catastrophic erosion indicates that farming operations were partly responsible. Examination of steep forested slopes where no actual landslips occurred showed that fissures were present in the soil but that, even though many elements in the superficial root network had torn apart, the meshwork was still strong enough to hold the soil mantle in place. Further examination of the upper zone of deforested slopes, which only slipped a short distance, confirmed that the initial fissures were quite shallow, penetrating through topsoil and pumice horizons and ending in the allophane-rich layer. The examination was carried out during heavy rain, and care had to be taken not to set off further landslides since much of the soil's mantle was still highly unstable. It is not difficult to reconstruct the origin and development of the debris avalanches set off by the earthquake.

The phenomenon of the mudflows is even more interesting. At first sight, it is difficult to understand where an adequate volume of water came from to provide the great mobility of the mass of earth, trees, and boulders. There is only one likely source for this water: within the porous pumice and scoria that made up at least 70 % of the material involved. Under pressure of the downward slipping mass, water

FIG. 11. Trees Near the Lakeside That Survived the Passage of a Mudflow. Note the bruised bark and mud-splattered trunks.

would be squeezed out from the porous fragments, and as the mass gained volume and speed the expressed water would provide additional lubrication, so that near the foot of the slope the whole mass would have the consistency of a liquid mudflow. Several such flows, coalescing in a narrow valley, would easily form a surging wave such as was observed at the time. As the main flow passed and the water drained out of the mass, the wave-like frozen billows of mud, which now remain as a characteristic feature of the landscape, would be formed. The edge of the mudflow has a characteristic upturned rolling form, solidified at the point where the water was inadequate for the journey onward into the lake. The mist that developed in conjunction with the landslips may also have been due to droplets of water forced under great pressure from the porous pumice and scoria gravel.

When the mudflows began to lose impetus as they traveled across the flat land, a few large trees managed to remain in place. The lower part of their trunks are still buried in debris, but their bark is bruised and mud-splattered (fig. 11) far

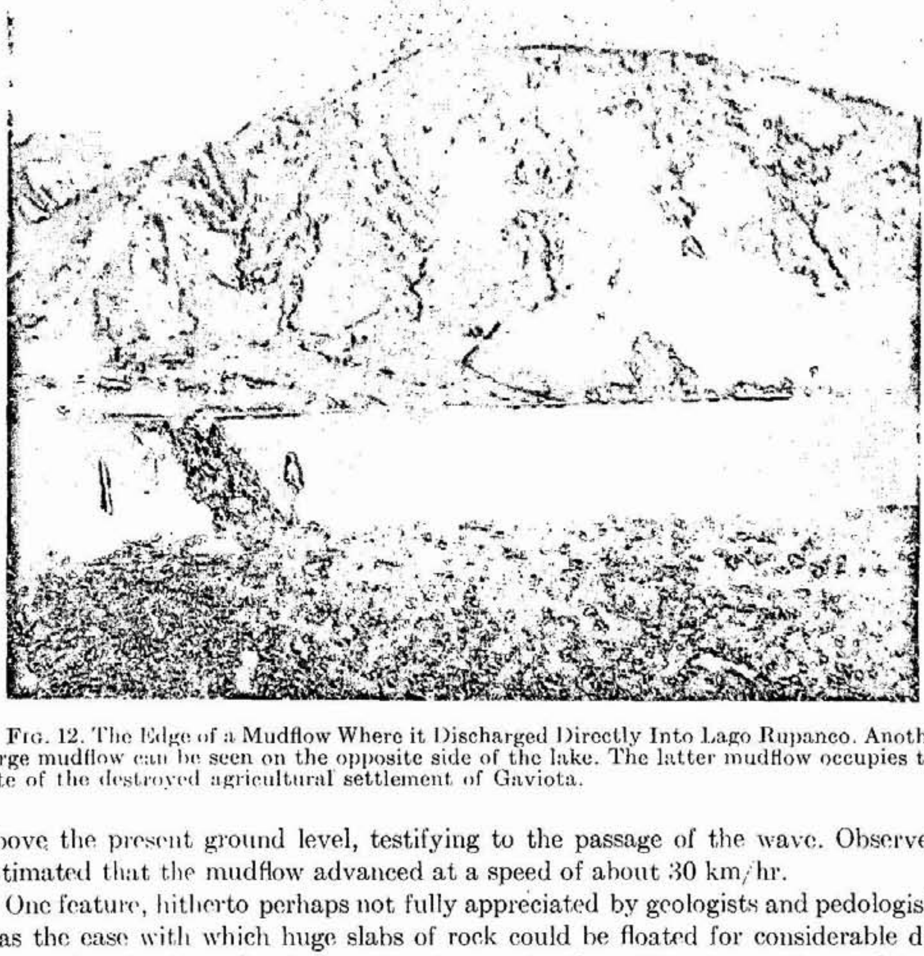

FIG. 12. The Edge of a Mudflow Where it Discharged Directly Into Lago Rupanco. Another large mudflow can be seen on the opposite side of the lake. The latter mudflow occupies the site of the destroyed agricultural settlement of Gaviota.

above the present ground level, testifying to the passage of the wave. Observers estimated that the mudflow advanced at a speed of about 30 km/hr.

One feature, hitherto perhaps not fully appreciated by geologists and pedologists, was the ease with which huge slabs of rock could be floated for considerable distances. One boulder of andesite, of a size greater than 100 m^3, was observed from the time it emerged from a lateral valley to the time it reached a new resting place near the lakeshore, having traveled a distance of 1½ km from the point of its first appearance.

Much of the debris from the disaster surged directly into the lake (fig. 12) and created a wave that extended the damage around the lakeshore far beyond the area most seriously affected by avalanches and mudflows. Narrow sandy beaches and sandspits at the mouths of streams disappeared at this time. Along other sections of the lakeshore, before the arrival of the waves, the oscillations of the ground during the earthquake caused unconsolidated materials at the edge of the lake to slide into deep water. This caused displacement of one or two houses and farm buildings before the shockwave arrived to finish the destruction.

5. *Valdivia City and Southern Valdivia.* The city of Valdivia and the coastal region to the south of the city (fig. 1) suffered severely from a number of causes.

In South-Central Chile, by far the worst affected town was Valdivia, where at least 60% of the buildings in the center of the city were destroyed or severely damaged. Valdivia is located a short distance inland from the sea at a point where the Rio San Pedro, carrying the effluent waters from a system of large inland lakes, breached the coastal range. The site is a gently undulating one, ranging from 10 to 50 ft above sea level, near the bank of the Rio Calle-Calle (the name given to the lower reaches of the Rio San Pedro) opposite its confluence with the Rio Cruces. The substrate on which many city buildings have been constructed is, in part, Recent alluvial material; in part, Quaternary sediments consisting of weathered gravels, sands, and clays; and, in the higher parts, weathered mica schist. Undulations in this terrain have been filled in with soil and other debris to form the almost level foundation of the city.

Internal packing and lateral sliding of the filled in areas, and also similar movements in the weakly consolidated alluvial sediments near the river, were responsible for most of the displacement of buildings in Valdivia (Doyel, Maraga, and Falcon, 1960). Indeed, this observation applies widely in towns throughout South-Central Chile. In some localities, even the partially weathered Quaternary gravels underwent considerable displacement, particularly when located near steeply sloping margins of rivers or lakes. In many cases, instability was clearly associated with the presence of ground water at levels near the surface; but in other cases, instability appeared to be caused by the presence of beds of weathered volcanic ash interbedded among the gravels. These ash layers have weathered to the stage in which they are rich in allophane, a type of clay that is fairly stable when dry but can absorb a very large amount of water, which is subsequently expressed when shaken under pressure, producing a remarkable phenomenon resembling liquefaction. During the earthquake, the material in these ash layers became liquefied, thus permitting the gravel beds above to fracture and blocks of the gravel to slide laterally *en masse* into gulleys, rivers, or lakes. Movements of this type were particularly noticeable in towns sited on dissected terrace landscapes composed of gravel beds interlayered with ash beds; for instance, the town of Rio Negro, where the damage to buildings was very severe.

On the other hand, the same beds (weathered gravels interbedded with volcanic ash) generally proved to be stable where they occurred in relatively poorly dissected landscapes, presumably because there was less scope for lateral movement. Younger, fresh gravels, consisting mainly of loose and rounded materials, seem to have absorbed the earth shocks more successfully. In some places (e.g., Los Pellines, on the west side of Lago Llanquihue) heavily and unevenly loaded storage barns survived with only minor damage. Beds of sand generally proved to be fairly stable as building sites if the sands were in a dry condition at the time of the earthquake; but in cases where the lower levels of the sand beds were saturated with water, quite severe damage occurred.

The newly constructed, cement-paved sections of the Pan-American, or Longitudinal, highway which follows the general route of the main north-south railroad) resisted damage fairly well, and road traffic was interrupted by the earthquake mainly because of the collapse of sections of earth-fill used to form approaches to bridges The bridges themselves usually escaped serious damage. A few short sections of road were actually thrown out of alignment, but the cause was, in almost every case, the displacement and further consolidation of filling material that was either deficient in gravel or contained too high a proportion of clay soil with allophane. In some of the worst examples, the filling material consisted almost entirely of a type of volcano ash material that is exceedingly rich in allophane clay, a material which thus demonstrates its unsuitability for highway construction purposes. The permanent way of the railroad was seriously displaced, and rail traffic in Llanquihue Province had to be suspended for several weeks.

Flat land in the vicinity of Valdivia suffered invasion by sea water. At this writing, one year after the disaster, this land remains under water—no longer so salty as formerly, but still subject to tidal fluctuation. It is by no means certain that the submergence of this low-lying land was due solely to a general sinking of this part part of the continent. Some deep borings, made before the earthquake, showed that in the subsurface materials there were several layers of buried peat interspersed with layers of alluvial and estuarine clays. It is likely that the lowest and most decomposed organic layers suffered sudden compaction during the earth shocks, thereby causing most of the subsidence of about 1 meter 50 cm, observed on these lowlands. The nature of these underlying sediments is of some interest, for it implies that the sea has flowed in over the area on more than one occasion in the past. Reemergence of the land has apparently been brought about by estuarine sedimentation with a gradually increasing amount of river alluvium, until the water became shallow enough to allow a swamp vegetation to develop and build up a layer of organic residues, which finally raised the land above the water. In view of this history and and of the general instability of the region, it would seem more logical to try and hasten the reemergence of the land by measures to control and promote alluvial sedimentation (by a modification of the technique of "warping" such as is used in the eastern counties of England), rather than trying to seal off the area and pump out the water.

Coastal regions south of the city of Valdivia suffered great damage from tsunamis. A visit was made to the small coastal settlement of Pucatrihue 10 days after the tsunamis had passed. Here, the coast had only minimal protection sand barriers, and when the tidal wave arrived at about 3:15 on Sunday, 22 May, it swept directly over the foreshore and surged up the coastal cliff to a height of about 12 meters. The strip of flat sandy soil along the coast, nowhere more than ½ km wide, was momentarily engulfed under about 6 meters of sea water, most of which rapidly drained back into the sea. Most of this land is now covered with 6 to 30 cm of sand, but within a short time this land was again growing grass.

The wave entered the small estuary of the Rio Trufun and increased in height slightly as it moved up the narrow valley, sweeping the bushes and trees on the valley slopes to a height of about 7 meters above normal river level. Almost all the farms and holiday residences (and the local police post) within the estuary were swept up river, and the effects of the wave are clearly visible $4\frac{1}{4}$ km inland from the river mouth. White sand was deposited on valley slopes wherever the wave passed. The mouth of the river now has a new sand bar, much larger and closer to the coast than formerly. The steep slopes of the valley are mainly covered with natural forest, but none of the indigenous species seem to have been affected by their brief immersion in the mixture of sea and river water, although some trees were undermined and swept away, and in a few places landslips are blocking the only access road.

A similar sequence of events is reported from Huiecolla, (10 km up the coast from the Rio Bruero) but in this section there were very few permanent habitations. In this locality it is reported that there was a single big swell that passed over the sandy flats, surged up the cliff to more than 10 meters above mean sea level, and traveled for a considerable distance up the valley of the Huiecolla stream. No accurate bench marks are available in the area, but it is generally agreed that the sea now rises to a maximum tide level of about 1 meter 50 cm more than formerly. Certainly, even at low tide, some of the forest-covered flatland bordering the estuary at Pucatrihue is now submerged, although this could be due, in part, to the blocking of the river mouth by the sand bar in its new position.

6. *Northern Valdivia.* The largest settled area along this stretch of the coast is at Mehuin (figure 1), and, as in the case of Queule, Tolten, and Puerto Saavedra to the north, the town was swept almost entirely away by the tidal wave of Sunday, 22 May.

The earthquake in Mehuin was felt as two distinct shocks. The first and smaller was followed a few minutes later by a heavier shock that caused some structural damage. The sea was observed to recede shortly afterwards and then the tide advanced more rapidly, flooding the town to a depth of about 2 meters. By this time, most of the population were on their way to nearby high land, sitting on roofs, or perched in trees. The sea then retreated to about normal high-tide level, and then rose again and the crest of the second inundation arrived about 5 minutes after the earlier one, but flooded the town to a depth of about 7 meters. Most of the damage and loss of life was caused by this wave, which set many wooden houses adrift, and the floating debris destroyed other buildings. A third large wave followed quickly after the second, and for some time afterwards smaller surges were experienced.

On the open coast, the highest point reached by the sea was about 15 meters above the former mean sea level. The waves entered the valley of the Rio Lingue and swept inland with diminishing force for 6 km. Farm buildings on the alluvial bottom lands were flooded and many such were destroyed, along with livestock trapped in the meadows. A thin covering of sand was left on the soil wherever the wave passed. When the water became more tranquil, it was noticed that all the lower lying land (a strip 4 km long and averaging $\frac{1}{2}$ km in width) remained flooded with sea water. This area represents the more fertile part of the alluvial soils of the valley bottom land originally from 50 cm to 1 meter 80 cm above former hightide level. The sea water now occupying this part of the valley has a tidal range of about 80 cm.

The force of the wave at Mehuin seems not to have been so great as at Pucatrihue or Bahia Mansa, and the inundation took place over a longer interval of time; but since the Lingue Valley is wider and occupied by fertile alluvial soils of greater agricultural value, the damage to soil resources has consequently been greater. Agricultural damage is largely confined to the lowlands that now are permanently flooded by sea water. The soils of the margins of the valley, which were only briefly flooded by the wave and subsequently drained fairly quickly, have suffered little permanent damage although they now have a brackish water table at a depth of 20 to 40 cm. So far, their soil structure seems to be unchanged, and above the water table, worms are living normally. The thin veneer of new surface sand will make little difference to the fertility of these soils.

Considerable changes have occurred in the disposition of the sand masses in the vicinity of the river mouth, but the presence in the valley of salt tidal water indicates that the inundation is due to subsidence of the level of the land relative to that of the sea, and not primarily due to sand obstructing the outlet of river water.

7. *Central Valdivia.* The central part of the Province of Valdivia suffered slightly from minor landslips, which disrupted road communications and produced some damage on farm properties. The most seriously affected farming districts were those located among the foothills of the Andean Cordillera. The population of Liquine District, southeast of Lago Pellaifa (figure 1), was isolated for many weeks, and food supplies had to be dropped by air. The worst affected districts were those with soils composed of alternating layers of porous volcanic gravel and fine, allophane-rich ash, similar in many respects to the soils at Rupanco. The landslides took the form of massive debris avalanches, but with only minor development of mudflows, and also simple landslips caused by the collapse of steep sections of a valley wall.

The most serious of these landslips occurred in the San Pedro Valley near the egress of this river from Lago Riñihue. In this lightly populated region, no lives were lost at the time of a massive displacement of material in the cliffs along the north side of the river valley, but, as had happened 386 years earlier, the waters of Lago Riñihue (and all the water in an extensive system of intercommunicating inland lakes) were impounded behind a gigantic debris barrier, thus forming a constant threat to the people in the San Pedro Valley below and the more heavily populated Valdivian lowlands. The valley wall collapsed in three places, and the blockage was thus in three sections, that furthest downstream being the largest and nearly a mile in length. After an initial survey to establish levels, engineers labored valiantly (through 2 months of atrocious wet weather that augmented the water impounded in the lake until it reached to over 35 feet above normal level), digging through the debris in order to release the impounded water under some sort of control. At the end of July 1960, this task was completed. As a precautionary measure, population and livestock were evacuated from low-lying parts of the San Pedro Valley and from the lower sectors of the city of Valdivia before discharge of the water began. During the discharging process, severe flooding occurred in these lowlands, but the amount of silt left behind when the waters receded was comparitively small. In the upper reaches of the valley, almost no material was deposited. Deposition of silt and sand was probably very heavy during the first three days of the discharging period (the stage when the earth barrier was crumbling), but, during the last three days, the swollen river was charged mainly with lake water, almost free of sediment, and the speed of the current was such that much of the sediment deposited earlier was swept away. Indeed, during the final phase, considerable erosion of the river bed occurred and former islands in the river disappeared. Farmers in the valley suffered more from erosion and from destruction of fences and outbuildings than from heavy deposition of alluvium.

The cause of the giant Riñihue landslips is not known for certain, but it is noteworthy that the thick beds of glacial outwash, which here are mainly sands and gravels, also contain layers of volcanic ash, weathered to the stage where they are rich in allophane clays. Thus, one of the same elements of instability is present here as was found in the case of the major landslip areas of the cordillera.

8. *Pellaifa*. Extensive landslides occurred on the steep slopes bordering the head of Lago Calafquen and on the whole of the steep land around Lago Pellaifa (figures 1 and 1c). These landslides completely severed the road passing along the north of Lago Pellaifa, resulting in the isolation of farming communities in the valley of of the Rio Llizan—a district usually referred to as Liquine. Between 3,000 and 4,000 persons (including those isolated as a result of the Pellaifa landslide and those of of the Liquine district) had to be supplied by air for several weeks. Part of the debris from the landslips fell across the effluent stream connecting Lagos Pellaifa and Calafquen, and the water of Lago Pellaifa stood some 5 meters higher than formerly, so that many portions of the former road around the lake, if not actually buried in landslide debris, were under several meters of water for about 2 months. The job of reopening this road involved not only removal of landslip debris, but also the clearing of debris from the lake effluent. About 80 persons actually perished in in the area affected by the landslides, and most of these were small farmers—some being indigenous Indian (Araucarian) families.

As in the case of the debris avalanches at the head of Lago Rupanco, the Pellaifa landslips occurred on slopes mantled with coarse, porous volcanic ash. At Pellaifa, the underlying rocks are more varied than at Rupanco and include sedimentary rocks, granitic rocks, and acid volcanic rocks in addition to andesite and basalt. The ash mantle is thinner than at Rupanco and is composed almost entirely of fine and coarse pumice erupted long ago by Volcan Villarrica. This pumice forms almost the entire subsoil; the topsoil is formed from more Recent fine sand and very fine pumice, also probably originating mainly from Volcan Villarrica.

Originally, the slopes of the hills bordering the southern side of the head of Lago Calafquen and both sides of Lago Pellaifa were forest-covered. The flatland between the village of Conaripe and the western end of Lago Pellaifa has been settled for many years. At first, the settlers were engaged in exploiting timber, but as the lowland became gradually cleared, farming developed on the flatland and on the lower slopes of the hills. Two large agricultural estates (Culan and Aniques) and five indigenous farm settlements (Reductos Llancatillo, Cafrilat, Antimilla, Lemonas, and Antiques) were affected by the landslides. Cleared land is used mainly to provide grazing for livestock, and only very small areas are plowed and sown in wheat. Timber extraction is still the main source of income for the local settlers.

and farming is carried on mainly to provide for the subsistence of the local population.

During the three consecutive very dry summers of 1942, 1943, and 1944, several forest fires occurred in the district, and one big fire (originating near Curacautin)

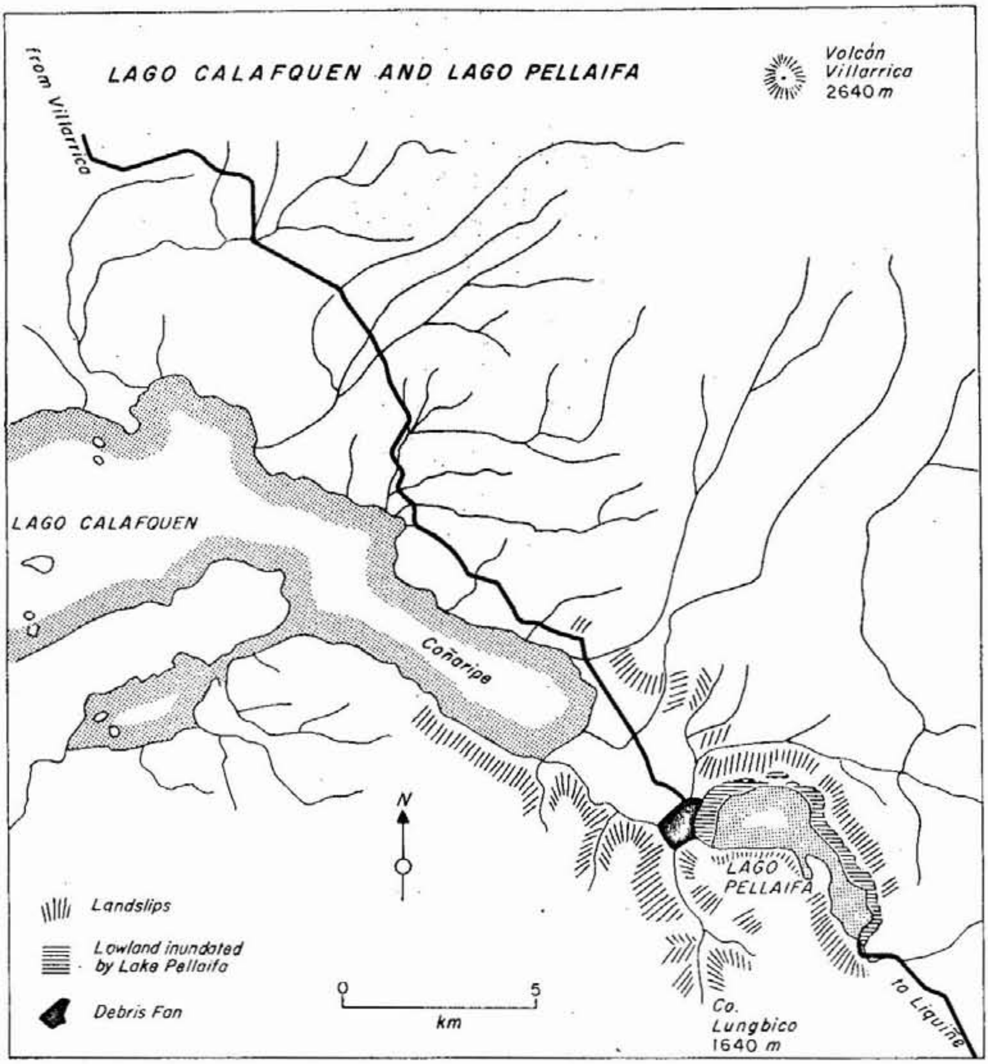

FIG. 1 (e). Landslips and Inundated Areas in the Lago Calafquen and Lago Pellaifa Section.

swept through most of the upland cordillera forests. On the lower and middle parts of the steep hillside, much of the original forest has been replaced by fern wasteland. This covering of fern is burned, in part, almost every year by fires that spread from land-clearing operations on the flat and rolling land at the foot of the slopes.

As in the case of the debris avalanches of Lago Rupanco, the steep slopes occupied by grass and fern slipped away, almost totally. Steep slopes occupied by burned-over forest were slightly more stable, but here, too, in many cases, the plant and soil mantle slipped away completely, over a whole mountain face, leaving only a few forested ridges (where Coigue trees are dominant) still in place. Of the less disturbed forest at higher levels a good part still remains, but this upper area is badly scarred by the path of debris avalanches, which developed mainly along the stream pattern. The pattern of erosion from the steep slopes is therefore different and more varied than at Rupanco, but, in contrast, the Rupanco-type mudflow failed to develop.

The reason for the absence of mudflows may be that the soils in the Calafquen-Pellaifa area are composed of a smaller proportion of porous, water-holding material and, at the time of the earthquake, they were in a much drier condition than those at Rupanco. In the Calafquen-Pellaifa region, there had been a very dry spring, a normally dry summer, and a fairly dry autumn; moreover, the only period of heavy rain occurred during one week in March. The week preceding the earthquake had been without rain. During very wet autumns and winters (i.e., as in 1959), small landslides are a normal feature of the deforested slopes in the region.

As in the case of Rupanco, the valley became filled with a fine mist immediately following the landslides, but the amount of water pressed out of the pumice seems to have been insufficient to lubricate the mass of debris and convert it into a mudflow. The only exception seen was in the case of the debris that accumulated in the narrow valley of the stream draining directly from Lungaico Peak. This valley filled completely with debris from landslides for a distance of some 4 km, and the whole mass was ejected as a spate of debris, entering the main valley near the point of origin of the stream joining Lagos Pellaifa and Calafquen. The mass flowed out from the side valley, across the effluent stream from Lago Pellaifa, and, reaching the opposite wall of the valley, formed a debris dam 4 to 5 meters high at the lowest point. This barrier now partially contained the waters of Lago Pellaifa, and a new outlet has developed at the northern end of the barrier. However, this feature seems to be unique in the area—most of the landslides merely accumulated as a rubble at the foot of the slopes or plunged directly into either of the two lakes. The total area affected was about 11 km long by 3 km wide.

Landslide areas of smaller extent are reported further inland from the valley of the Rio Tranquil and the slopes below the upland Lago Calafquen, which lies to the east of Liquine. Landslides are also reported from the vicinity of Millahuehuin in the Trancura Valley, southeast of Pucon. The steep land soils in this area, like those of Pellaifa, consist of pumice layers on very steep slopes that become unstable if the natural forest cover is molested.

On both Lago Pellaifa and the upper end of Lago Calafquen, a large wave swept the shoreline almost simultaneously with the descent of the landslides, and for some time afterwards smaller secondary waves ricocheted back and forth across the lakes.

9. *Arauco.* The coastline between Lebu (in the Province of Arauco) and Dichato (in the Province of Concepcion) (fig. 1) rose between 75 cm and 1 meter 80 cm

during the first seismic activity on 21 May (Galli and Sanchez, 1960). No subsequent uplifting or depression occurred during the earthquake on the following day. A brief visit was made to this part of the coastline soon after the earthquake, but because of heavy rain all the lowland areas were partially inundated and little of interest could be observed. Some of the headlands showed that mussel beds were now exposed to the air except during the highest phases of the tides, and it seemed beyond question that some coastal uplift had taken place.

A much more prolonged visit was made to the area in the following December and January (1961), and ample confirmation of an uplifting was obtained, both from the condition of wave-cut platforms on the headlands and from the lowland soils in embayed sections of the coastline. Not only were many of the wave-cut ledges now accessible only to very high storm waves, but, in many rocky sectors of the coast, slightly elevated boulder beaches were in the process of being wave-cut to a new base level. In general, the amount of elevation was insufficient to put former beach materials out of reach of the largest waves, and all the recently elevated deposits of drift materials were in the process of undergoing intermittent resorting; some were gradually being swept entirely back into the sea. There was, as a consequence, no really good site for the study of soil formation in coastal drift materials. Examination of several areas of swampy flatland along less rocky sectors of the coastline provided undisputable evidence that the mean water-table level had been lowered; soils that formerly were subject to strong reducing conditions in all horizons now showed a deep surface zone where oxidation had begun and had been consistently in progress for some time. In this horizon, the normal gray colors were on the wane and the pattern of mottling was changing. It is thus possible that for many of these potentially valuable flatlands drainage schemes could now be devised; formerly they were regarded as being too expensive to drain owing to their proximity to mean sea level.

Damage to Soil Resources

Damage to the soil resources of South-Central Chile resulting from the seismic disturbance of May and June 1960 is thus of several types and has resulted in the total loss of some soils, partial destruction or severe modification of other soils, and minor modification of a third group of soils.

Soil Resources Totally Destroyed: These include lowland soils of the coastal region from Tolten southward, which are now permanently inundated by sea water. Most of these soils are considered as being totally lost to agriculture because the cost of poldering and maintaining an efficient mechanical drainage system, even for small areas, will almost certainly exceed the return obtainable from agricultural production on the reclaimed soils. There is also the strong likelihood that, from time to time, in the distant future, further seismic movements will occur. Schemes for controlled flooding to accelerate and localize the build-up of alluvial sediments may be applicable over part of the inundated area, but there is little in the way of a general scheme that can be suggested for the whole affected region; certain areas might eventually have to be employed for fish and frog production. As part of the natural soil resources of Chile, most of these soils will almost certainly have to be considered a total loss. The total area involved is about 40,000 hectares.

The regions most affected by inundation of this type extend southward along the coast from Tolten to Puerto Montt, mainly pockets of flatland between the coastal dunes and the foothills of the coastal range, and the alluvial land bordering rivers, where they approach the coast. A high proportion of fertile alluvial soils are involved. On about 30% (12,000 hectares) of these, agricultural development had achieved a comparatively advanced level through milk production and the growing of market garden crops, potatoes, and root crops. About 50% (20,000 hectares) of the drowned farmland was in an earlier stage of agricultural development, where, because of insufficient capital, access difficulties, land-tenure problems, or other problems, farmers had not yet achieved a high level of production. About 20% of the drowned land (8,000 hectares) was occupied by natural forest or second-growth vegetation at the time of inundation, but probably less than half of this category represents soils of good potential quality that might one day have been developed for agriculture.

A different class of soil, which was totally destroyed during the seismic disturbances, consisted almost entirely of steep land soils that plunged, in the form of landslides, debris avalanches, and mudflows, directly into the depths of various lakes. The total area involved is probably in the neighborhood of 20,000 hectares. Practically none of this land was well adapted to agriculture, although about 10% (2,000 hectares) of the lower slopes had been partly cleared by farmers living along the lake margin, in an effort to provide additional grazing for the livestock on their small farms. In their downward plunge into the lake, the debris avalanches and mudflows destroyed some 700 hectares of better-class farmland and about 200 people from the various farming communities.

Two main regions were involved: the upper (eastern) end of Lago Rupanco in the Province of Osorno; and Lago Pellaifa, with part of the upper (southeastern) end of Lago Calafquen in the Province of Valdivia. The Osorno debris avalanches cover about one and a half times the area of those in Valdivia, and were far more impressive in that, in many cases, the face of the whole mountainside was stripped clean of vegetation and soil. Individual avalanche areas have measured up to 800 hectares in area. Whereas the debris avalanches of Rupanco cleared whole mountainsides, those of Pellaifa and Calafquen were more of the character of landslides, less well lubricated, confined to narrower paths, and they did not give rise to mudflows in their terminal phase. Both regions had in common a history of periodic forest fires.

The loss of these national soil resources is, therefore, not unconnected with past land-use policy, which has permitted the development of farm settlements in proximity of slopes carrying a type of soil that is highly unstable even under natural conditions. Such areas should be reserved for forest development or developed for carefully selected grazing areas under very carefully controlled management.

In all, some 60,000 hectares of the natural soil resources of Chile have been completely lost; but of this total, probably only 36,700 hectares represents soils of real, or potential, agricultural value (see table 1).

Soil Resources Partly Destroyed: This includes soils transported (but not irrevocably lost) through landslides, slumping, mudflows or other forms of mass movement and also includes some lowland soils immediately adacent to land inundated permanently by the sea. These latter soils were formerly well drained. In some cases, the new ground-water level is dangerously close to the surface of the soil (i.e., at depths of less than 30 cm).

The main areas where widespread transportation of soil occurred are Rupanco,

TABLE 1

APPROXIMATE AREAS OF SOILS LOST OR MODIFIED AS A RESULT OF SEISMIC AND ASSOCIATED DISTURBANCES OF MAY–JUNE 1960

Soil condition	Total area affected, hectares	Portion of total area affected suited to agricultural production, hectares
Totally Destroyed		
Permanent inundation by sea water		
In advanced stage of agricultural development	12,000	12,000
In process of agricultural development	20,000	20,000
Undeveloped	8,000	4,000
Plunged into deep lake water		
Mainly steep land soils unsuited to agriculture, but total includes some partially developed hill soils	20,000	700
Total	60,000	36,700
Partially Destroyed or Considerably Modified		
By landslides, debris avalanches, slumping, etc.	15,000	1,500
By mudflows	500	400
By development of saline water-table surface	1,500	1,200
Total	17,000	3,100
Slightly Modified		
By salinization during temporary immersion in sea water	23,000	11,500
By addition of veneer of coastal sand	800	700
By addition of pumiceous volcanic ash		
between 1 and 5 cm deep	35,000	18,000
more than 5 cm deep	22,000	3,000
By permanent rise in level of ground water	17,000	10,000
By temporary flooding by lake waters	13,000	8,000
By minor displacement (slumping, minor slips)	3,000	900
Total	113,800	52,100

Calafquen, Pellaifa, and Panguipulli; but small isolated examples occurred in the Trancura Valley and in the Tranquil and Liquine districts. All are in the precordillera or cordillera zone and all involve steep land soils that are pumiceous or scoriaceous in composition or are derived from ash minerals which, at one stage of weathering, form a high concentration of allophane clays. The latter, when dry, have properties akin to fine sand, but when wet they become exceedingly slippery. The combined effect of heavy rain following a very dry summer, repeated disturbance of the natural plant cover by burning and grazing, and finally the severe earthshocks, were the main factors responsible for the widespread landslides. At least 15,000 hectares of steep land soils were dislodged and transported rapidly to a new location on the valley floors at the foot of the slopes, where they now form a rumpled heap of soil and forest debris of far lower agricultural value, for the moment, than the original valley soils that they overwhelmed. In some places, the debris is spread out more evenly and in time may rapidly be developed into useful farmland. Some of the area damaged by this type of transportation was of little real agricultural value formerly, but of the total area involved, some 10% (or 1,500 hectares) represents useful agricultural land now buried under debris.

Where mudflows developed (such as those at Gaviota at the head of Lago Rupanco) almost all the destroyed land was agriculturally valuable. Of the total of 500 hectares devastated by mudflows, some 400 hectares represent land that was formerly producing meat or subsistence crops for the farming community. The new soils of the mudflows are mixed with about 40% (by volume) of forest debris, but they are already fairly well consolidated; successful efforts were made in some cases to resow them with grass and clover seed while the surface was still free from weeds. Owing to the protruding forest debris, the soils are too difficult to work with machinery, and the only alternative to the costly method of sowing by hand would have been to seed them by airplane. Unfortunately, no suitably equipped plane was available. The soils are fertile and only very slightly acid in reaction. Gaviota was formerly the site of a farm-colonization scheme, but so widespread has been the destruction of the soil resources in this area that it would now be more logical to transfer the survivors of this colonia to a more favorable and less perilous location.

The soils that have acquired a saline water table near the surface are to be found in many of the narrow coastal valleys, and, in some cases, extend as far inland as 5 km from the coast (e.g., in the Lenga Valley near Mehuin). They occur usually in narrow strips or in depressed areas close to the inundated area, but the total area may amount to as much as 1,500 hectares. Of this total, probably 1,200 hectares represent land normally used for cereals, potatoes, root crops, or dairy pastures. In the case of sandy soils, salt may be expected to concentrate in the topsoil during dry summer conditions and cause the loss of part of the crop. In the case of heavier soils (clay and clay loams), some additional loss of structure and deterioration of aeration may be expected. The total area of soils partly destroyed, or radically modified, as described above, amounts to about 17,000 hectares, of which some 3,100 hectares represent land formerly well adapted for agricultural production.

Soil Resources Slightly Modified: This includes the soils that were briefly immersed in sea water during the abnormal tidal surge that followed the earthquake of 22 May; soils that received a thin veneer of dune sand carried inland by the tide soils that received a top-dressing of volcanic ash during the eruptions from Volcan Puyehue; soils that have suffered deterioration of drainage owing to the rise of the water table (possibly permanent in the case of areas with general depression of the land surface but temporary in the case of some lakeside soils); and soils displaced by minor slumping or slipping.

Of the soils temporarily or briefly inundated by sea water, some 23,000 hectares were affected, and about 800 hectares were found to have a thin surface layer of sand when the water receded. Of the total area washed by sea water, some 11,500 hectares represented valuable agricultural land; practically all the land receiving extra sand also belongs in this class. However, there is no evidence that these soils have seriously deteriorated after their brief (usually only a few hours duration) immersion. When the soils of Puerto Saavedra and Tolten were examined early in June 1960, the measurable salt content of the sandy and other light textured soils was already almost back to normal; while in the case of the clay and clay-loam soils, salinity was only slightly above normal. By the end of August 1961, all the affected soils returned to their normal salt content. Earthworms, larvae of insects, and other important soil organisms appeared to remain alive and vigorously active despite the flooding with sea water, and grasses soon put forth new shoots. Of the pasture plants, only some of the legumes suffered. In parts unprotected by a close vegetation cover (for example, fields with potato and sugar beet crops), there was considerable erosion of surface soil, but this soil material was usually transported only short distances across the flat plain.

A modification of a slightly different type was experienced by the soils near Lago Puyehue in Osorno Province, where the eruptions from Volcan Puyehue provided a dusting of pumiceous sand over a wide area. During the period of the most violent eruption (24 to 29 May), the wind blew consistently from the west, and most of the volcanic ash was deposited over the central Andean Cordillera or fell in Argentina. At Osorno, less than 2 mm accumulated over a 10-day period, and a similar amount was recorded at Rupanco. A faint film of fine ash could be found as far west as Pucatrihue during the eruption, but even at Termas Puyehue, only 15 km from the seat of the eruption, a total depth of just over 1 cm was recorded during the most active period of eruption. In the lower part of the Golgol Valley, the depth of fresh pumice sand varies between 1 and 5 cm and includes some larger fragments of fusiform pumice gravel. Rain fell intermittently during the most active phase of the eruption, and, as a result, most of this ash in the lower valley was resorted and dispersed by flotation. At the upper end of the Golgol Valley, within 10 km of the vent, the new material is mainly pumice gravel and is generally more than 5 cm in depth.

The total area in Chile receiving pumice sand and gravel from the eruption to a depth of over 5 cm was about 22,000 hectares, but of this, less than 3,000 hectares represent land of gentle relief suited to agricultural production. Beyond this central zone extends a wide area of soils that received from 1 to 5 cm mainly of fine pumice sand. The total area affected is in the region of 35,000 hectares, and, of this area, some 18,000 hectares represent land actually used for agricultural production.

Samples of the fine and coarse material were collected and analyzed. They appear to be of a remarkably pure siliceous type of ash, which will probably make little if any significant difference to either the fertility, structure, or water-holding capacity of the soils of the region.

The sinking of the land south of Tolten, in the coastal region, will unquestionably increase drainage problems over some 17,000 hectares; and, of this total, at least 10,000 hectares are land that is currently contributing to the national total of agricultural production. The magnitude of the potential drainage problems varies from place to place and with different kinds of soil, but, in general, all can be expected to flood more readily, and flood water will be more difficult to remove than formerly. There may be a gradual deterioration in subsoil aeration during the ensuing farming year; cereal crops sown before May suffered a marked decrease in yield.

In a somewhat different class are certain lakeside soils in the Riñihue, Panguipulli, and Calafquen region, which suffered temporary inundation caused by the blocking of the outlet of the Lago Riñihue by the slumping of the valley walls along the upper reaches of the Rio San Pedro. There is a similar, but much smaller, area of temporarily inundated alluvial soil around Lago Pellaifa, whose waters were also impounded behind a mass of fan debris discharged from a lateral valley,

SUBSIDENCE OF UNCONSOLIDATED RECENT ALLUVIAL SEDIMENTS AT BORDER OF LAGO LLANQUIHUE

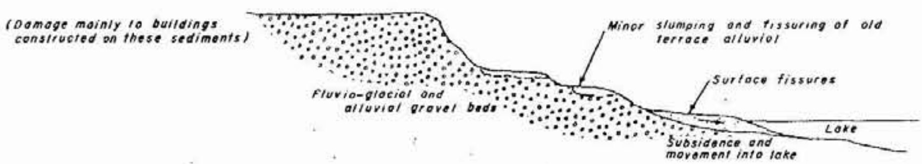

FIG. 1 (f). Alluvial Sediments at the Border of Lago Llanquihue.

blocking the effluent stream draining Lago Pellaifa into Lago Calafquen. These temporarily flooded soils have suffered no serious damage. Lake levels have not quite returned to normal, and a very small part of this inundated soil has been lost to agriculture. At their greatest extent, some 13,000 hectares were under water, of which at least 8,000 hectares represented land in agricultural production.

Minor displacement of soil resulting from slumping and slipping has occurred at many points around Lagos Llanquihue (figure 1f), Rupanco, Calafquen, and Ranco, and also near terrace margins in the Villarrica and Collipulli-Angol regions, farther north. The soils were not seriously displaced and probably a total of not more than 1,300 hectares was so affected, about 900 of which represent valuable productive agricultural land.

To this list of slightly modified soils should be added some of the alluvial bottomland of the San Pedro and Calle-Calle valleys. The release of the water impounded in Lago Riñihue produced two kinds of change in these valley soils. Those of the upper reaches at first received a thick deposit of fresh alluvium, but as the earth barrier crumbled and an increasing volume of sediment-free lake water poured down the valley, the initial period of sedimentation was followed by a period of scouring, which removed most of the new alluvium and further destroyed some of the original alluvial soils in the valley bottom. Lower down the valley, in that part known as the Calle-Calle section, almost all the alluvial soils received a deposit of fresh silty to fine sandy alluvium, ranging from 3 to 25 cm in thickness. Because measures had been taken to bring about the release of the impounded waters under control, remarkably little damage was done. Only about 500 hectares of the original valley soils were severely scoured; an additional 700 hectares received a top-dressing of stony and gravelly material scooped out of the former river bed; while some 1,500 hectares received a varying depth of fresh fine alluvium. The farmers who heeded the advice to sow the new alluvium immediately in clovers and grasses readily established excellent pastures and secured heavy yields of forage during the ensuing years. Established orchards (mainly apple and pear) were not seriously affected by the layer of new alluvium.

Recent Modification to the Soil Pattern: The new features of the soil pattern of South-Central Chile fit readily into the Chilean soil assemblage, thus testifying, in some measure, to the consistent nature of seismic activity in this part of the South American continent.

Modifications in the soil, caused by improved drainage that is occasioned by continental uplift, are evident along the coast from Tolten northward. It is precisely from this latitude northward that young soils on coastal terraces appear in the Chilean soil assemblage. On this particular occasion, the amount of uplift was slight, and few of the elevated drift deposits rose clear out of reach of the sea. On former occasions of seismic activity, much greater elevation has occurred in a single earth-shock, uplifting portions of the coastal shelf with its layer of coastal drift detritus into a new position where soil can begin to form (Fitzroy, 1836). Darwin (1837) records, "At Valparaiso, although in the 220 years before our visit the elevation cannot have exceeded nineteen feet, yet subsequently to 1817 there has been a rise, partly insensible and partly by a start during the shock of 1822, of ten or eleven feet." (The maximum elevation recorded in 1960 reached to 9 feet, on the island of Guafo, southwest of Chiloé.) The further north one travels in Chile, the greater the altitudinal interval between successive coastal terraces: in the vicinity of Tongoy (300 km north of Valparaiso), in the Province of Coquimbo, there is evidence of one abrupt uplift amounting to about 150 feet with remains of current marine organisms still easily identifiable in the terrace soils.

By contrast, all the evidence for drowning of landscape occurs from Tolten southward. In the Recent activity, this was in part due to the same process of continental depression that has produced the conspicuously "drowned coastline" of southern Chile, and, in part, due to consolidation of weak sub-strata rich in organic residues. In many cases, these organic residues are the product of former swamps, more or less identical with the swamp accumulations of the coastal lowland of the present time. They are to be expected to occur under cool, humid climatic conditions wherever vegetation establishes itself in areas of high water table. The fact that many of these strata are overlaid directly by layers of estuarine or marine clays implies that subsidence has been in progress for a considerable time. The return of vegetation to such areas may be explained by a small recovery in the continental position, but in many cases is clearly due to gradual building up of alluvial sediment in the area. There is little doubt that the soil changes observable in the Valdivia region during the recent seismic period are but a part of a long-continued landscape building process.

With regard to landslips and the gravitational transportation of soil and soil-parent materials, the events of May 1960 make more certain the explanation of several unusual landforms found in the Chilean lakes region. There is one kind of slumped, hummocky type of landscape, dotted with large angular boulders, often found near the head of the larger lakes. This has more than once been ascribed to a late phase of glacial activity. It is now apparent that this is a landform created by catastrophic mudflows in this region. The positioning of huge boulders in a landscape can apparently be achieved by mudflows as readily as by ice. Likewise many chaotic soil patterns of the piedmont areas are now explicable as being the product of ancient debris avalanches.

Even the damming and subsequent release of impounded water from Lago Riñihue has a historical parallel in the very same area. As recorded by Captain don Pedro Marino in *Cronica del Reino de Chile*, the embryo city of Valdivia suffered from earthquakes and tidal waves on 16 December, 1575. Four months afterwards, in April, 1576, the population were surprised by a sudden inundation coming from upstream in the San Pedro Valley. Subsequent investigation showed that Lago Riñihue had been blocked by a huge landslip near its mouth, the remnants of which can be seen to this day and are located only a little distance downstream from the side of the landslip of May, 1960.

Of the other types of changes in the soil pattern (those of a more temporary nature) little trace now remains of changes that occurred during previous cycles of seismic activity. However, with knowledge gained from recent events, we can assess more accurately the type of change that is likely to have occurred in certain soils during their formation, and this, in turn, may help to explain certain anomalous features of the existing soil profiles.

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