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Potrerillos. Locality called Pastos Cerrados above Cortadera, looking southwest over matureland at elevations ranging from 12,000 to 15,000 feet (3,500 to 4,500 meters). The rocks are Neocomian shales and limestones, and in the view the strata are repeated by overthrusts three times. Deep canyon in foreground is Quebrada Asientos. Official photograph, Potrerillos Company.

STUDIES IN COMPARATIVE SEISMOLOGY

EARTHQUAKE CONDITIONS IN CHILE

BY

BAILEY WILLIS

RESEARCH ASSOCIATE IN SEISMOLOGY
CARNEGIE INSTITUTION OF WASHINGTON

WITH CONTRIBUTIONS BY
J. B. MACELWANE, S. J., PERRY BYERLY, JOHANNES FELSCH, AND H. S. WASHINGTON

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INTRODUCTION

On November 10, 1922, at about eleven forty-five p. m. there occurred an earthquake of very great energy, which literally shook the earth. The tremors which radiated from it were registered in the Americas, Europe, Africa and Asia, wherever there were instruments capable of recording them. In this respect it was not a very unusual shock, there being annually a number of so-called world shakers. But it happened violently to affect a district in central Chile where the conditions in the cities were favorable to disaster and it occasioned, therefore, a catastrophe of notable magnitude.

News of death, suffering, and need was flashed in the wake of the earthquake waves to all peoples, and there was an immediate response to the call for help. A large fund was raised to relieve destitution and to rehabilitate the communities. At the same time the earthquake aroused scientific interest in the nature of the phenomena and caused those who were engaged in seismological research to seek the means to carry out an investigation on the spot.

The Seismological Society of America had previously investigated the activity of several shocks that had occurred in California, but could not finance an expedition to Chile. It appealed to the Carnegie Institution of Washington, which secured from the Carnegie Corporation of New York a grant to defray the actual expenses of a journey to and through the region of maximum effects, to investigate the scientific and the practical human problems there presented.

Having been invited by Dr. John C. Merriam, President of the Carnegie Institution of Washington, to carry out these studies, the writer sailed from New York on January 11, 1923, and returned to that port on September 2. Seven months were spent in Chile, five of them in field work in the province of Atacama, where the earthquake had been most severe.

The conditions of travel were difficult. Atacama is a desert country. Hamlets are few and are separated by long distances where there is neither shelter, food nor water. The earthquake had destroyed some pueblos and had reduced others to great need. The traveler could expect but little, however ready the hospitality of the people, which indeed never failed him. Under these circumstances the results of the research must have been comparatively meager, if the Chilean administration had not provided facilities, which none but it could have furnished. The Government-owned railway runs the length of the northern provinces, from south to north. Free passage was given on it and a special car was placed at the service of the writer, who made it his base of operations. It was hauled some 4,000 kilometers and was always available at the point to which he might wish to return from a more or less extended expedition off the railroad.

Furthermore, it was understood that a stranger could hardly hope to solve the problems of the structural geology of the region satisfactorily without the assistance of a geologist already familiar with the rocks and their relations. Dr. Johannes Felsch, who had studied the geology of northern Chile during seven years as official geologist assigned to the duty of locating water supplies for the railroad, was delegated to accompany the writer and much of the result attained in the investigation of the geologic faults was due to his intimate knowledge of the formations.

Again, when it became desirable to extend the observations to the volcanic islands of San Felix and San Ambrosio, even at the cost of the voyage of 1,250 miles (2,000 km.) to and fro, the Minister of the Marine placed the corvette *Aguila* at the writer's disposal, under the command of Captain Hector Diaz.

To the President of Chile, Dr. Arturo Alessandri, the expedition became especially indebted for the liberal cooperation which he caused to be extended to its efforts. He fully appreciated the significance of the scientific research as well as the purpose of the more practical studies of those conditions that make earthquakes more or less dangerous, and desired cordially to promote cooperation between Chilean scientists and their American colleagues. His initiative in this respect had been anticipated by Dr. Beltram Mathieu, Minister from Chile to Washington, who both officially and personally did everything in his power to establish helpful relations between officers of the Chilean Government and the representative of the Carnegie Institution.

In official circles in Santiago, Dr. Xavier Gandarillos Matta, Director of the Bureau de Minas i Geología, and his chief, Minister Francisco Mardones, were especially cordial in giving their personal support to the purposes of the expedition. The Director General de Ferrocarriles Nacionales, Dr. Rudolfo Jaramillo, took a practical interest in the investigation and provided the special car for the convenience of the geologist, in return for which courtesy the latter made a report on the local conditions that affected the earthquake hazard along the railroad. Don Carlos Silva Vildosola, editor of *El Mercurio,* lent the aid of his great daily to the publication of such current reports of the work of the expedition as were of general interest.

A great loss to the science of seismology and a grave disappointment in the cooperation anticipated in prosecuting the earthquake studies was occasioned by the death of Dr. Le Comte Ferdinand Montessus de Ballore, head of the Servicio Sismológico de Chile. He had known of the action taken by the Carnegie Institution and had looked forward eagerly to the proposed joint scientific studies, but was stricken unconscious on the day the writer left New York and died on the day of his arrival at Valparaiso, January 31. He left no successor, either in Chile or in the world. His lifelong devotion to the investigation of earthquakes, their activities, their geographic distribution and their relation to geologic conditions had made him preeminently the master of the science. His assistant in Santiago, Dr. Carlos Bobilier, did what lay in his power to carry out the wishes of his deceased chief.

In the provinces, Don Luis Romero, Intendente de la Provincia de Atacama, was particularly helpful in securing data regarding the effects of the terremoto, and in Don Luis Sierra Vera, the writer found a most capable associate and colleague. The latter, a professor of natural history at the Lyceo de Copiapó, had long been a student of earthquakes as they occur at Copiapó and furnished precise data regarding the phases of the latest shock, which he had observed with extraordinary coolness while the city was being all but destroyed.

To many friends and helpful acquaintances whose thoughtful attentions made the journey a pleasure and a satisfaction to recall, the writer would extend his sincere appreciation of their manifold courtesies and kindnesses. Especially to the American Minister at Santiago, the Honorable Dr. William Miller Collier, and to Sir John and Lady Murray at Vallenar his thanks are due.

The itinerary of the journeys in Chile comprised a number of distinct excursions. Santiago, the center of official relations, was visited first and there contact was established with the Chilean government. Copiapó, Coquimbo, La Serena and Vallenar were visited and studied during the latter part of February, March, and part of April. The latter part of April was spent at the Potrerillos mining camp as the guest of the Andes Copper Mining Company, and great assistance was given the writer in his observations in the higher Andes by officials of the company, especially by Mr. James E. Harding, Geologist. Similar courtesies were extended at the Chuquicamata camp of the same company, in May. In the interim, April 27 to May 6, the voyage with Captain Diaz of the *Aguila* was made to the islands of San Felix and San Ambrosio, sailing from and returning to Chañaral. After further studies at Potrerillos and a visit to Chuquicamata the writer joined the party headed by Dr. Juan Felsch, official geologist, and with him made extensive trips on horseback with pack mules into the Cordillera east and southeast of Copiapó. Geologic sections were examined in the Quebrada de Paipote, in the upper Copiapó valley to the head of the Rio Manfias, on the Rio Huasco from its source to the Pacific, and also on the Rio Elqui from Rivadavia to La Serena. Winter storms prevented more extended trips in the high Andes, but the surveys reached all of the principal sections of the Cordillera, including the Coast Range, the western slopes of the Andes, and the plateaus and volcanoes at altitudes of 13,000 to 16,000 feet (4,000 to 5,000 meters).

The scientific results of the expedition may be summed up in the statement that the geologic structure of the Cordillera was determined; the occurrence of earthquakes was traced to the active development of the range; and it was found that the Andes constitute a live mountain chain which is being pushed upward and eastward on a deep-seated and probably complex fault zone or system of overthrusts. The practical studies of the destruction caused by the earthquake led to suggestions for safer methods of building with the materials available in the country, and designs of resistant buildings were published in a pamphlet entitled *La Casa Segura contra Terremotos,* which was distributed by the Carnegie Institution of Washington to the people of Chile in recognition of the cooperation they had extended to the expedition.

BAILEY WILLIS.

Stanford University, California,
September 1926.

A. Copiapó. General view of Copiapó basin and city. Area of greatest destruction lies in distant middle groun (eastern) half of city, which is on slope of alluvial cone. Hills in right (western) half of panorama are Paleozo Andes. Paipote at mouth of the Quebrada Paipote, where it joins the Copiapó valley, lies in extreme middle dista

B. Coast range between Pueblo Hundido and Chañaral. The dark rocks which form heights of distant hills are Paleozo large dike of black diabase, probably also of Paleozoic age. The vie

) right of church in center of picture. This is the area of marshy formations. There was less destruction in left
rocks and belong to Coast Range. Those on left (east) are of Mesozoic rocks and constitute foothills of the
.

lates and schists; light-colored masses are intrusive granite. High ridge in middle foreground shows outcrop of a
lustrates the characteristic structure of the Coast Range of Atacama.

SECTION I

RELATING TO EARTHQUAKES, THEIR HISTORICAL SEQUENCE AND EFFECTS IN ATACAMA

REGIONAL DESCRIPTION OF ATACAMA

Chile is extraordinarily long and narrow. Her territory extends from Cape Horn to the Bight of Arica; that is, from latitude 52° to latitude 18°, a distance of 2,400 miles (3,800 km.). Yet, clinging to the western slope of the Andes, her domain is nowhere more than 200 miles (320 km.) across from east to west.

The country may be divided into three distinct sections. The southern, from Cape Horn to latitude 41°, resembles the southeastern coast of Alaska in being a region of profoundly deep fiords margined by an archipelago of rocky islands. Glaciers occupy the heights, and the land is inhospitable. The central section, which is the heart of the country, extends from Puerto Montt in latitude 41° to Copiapó near latitude 27°, nearly a thousand miles (1,600 km.). This zone corresponds very closely with the State of California, being very similar not only in area and topography but also in diversity of climate. Remembering that the two countries are on opposite sides of the equator and that therefore north and south are reversed as regards climatic conditions, we have in southern central Chile the heavy rainfall and dense forests characteristic of northern California; whereas in northern central Chile there is a semiarid region corresponding to the irrigated valleys about Los Angeles. In the vicinity of Santiago, as in California, there is a longitudinal valley, west of which is a coast range; and in each country there is on the east the great barrier of the high Cordillera, which impedes intercourse with the interior of the continent. The northern third of all Chile comprises the desert of Atacama and corresponds in climate and topography with extreme southern California and the peninsula of Lower California. It is a region of interior basins, of salt plains and sterile mountains—one of the most utterly arid districts of the world.

The parallel with California fails when we try to compare the river systems. For there is in Chile no such great longitudinal system as that of California. In the latter State the rivers of the Sierra Nevada unite in the Sacramento and San Joaquin, and these two, joining their waters, discharge into San Francisco Bay. In Chile, on the contrary, all of the rivers flow separately from the Andes to the sea, and the divides between them are in many places mountain ranges of considerable altitude. This topographic condition has made it difficult to establish and maintain intercourse between the northern and southern sections of the country. From Santiago south to Puerto Montt, a distance of 400 miles (640 km.), the difficulties in the way of construction of a railroad line were not serious, although it required skilful engineering to locate a route with a reasonably good grade. Communication between Santiago and Valparaiso on the coast is even easier. But from Valparaiso northward for a distance of some 800 miles (1,300 km.) the topographic conditions render almost impossible the successful commercial operation of the longitudinal railway. That railway alternately ascends and descends on grades which in places are so steep as to require rack and pinion, and the capacity of locomotives is therefore limited to short trains. For miles the road climbs among barren cliffs on the sides of waterless gulches, or winds across gravel plains where the few growing plants in sight, the low clusters of desert shrubs, may easily be counted as the train crawls past. The road would never have been built except as a military necessity to bind the country together. Even though it is in operation, the cities in the irrigated river valleys depend largely on the branch railroads, which connect them with ports at the river mouths where the coasting steamers frequently touch.

The terremoto of November 10 violently affected only this northern region, the stretch of 400 miles (640 km.) between Coquimbo and Copiapó. In this area it shook the barren mountains and plains, destroying the huts of goatherds, but in general leaving no other trace. Only where the populations of little communities settled along the rivers had built their clusters of adobe houses or had laid canals along the canyon walls could the shock do any material damage to man and his works. It was thus fortunately limited in its power to harm, but the conditions were unfavorable for any detailed study of the extent and distribution of its intensity.

The first notices of disaster came from La Serena and Coquimbo. These two towns are situated on Coquimbo Bay, in latitude 30°, at the mouth of the Rio Elqui. Coquimbo is located on the rocky peninsula which forms the western side of the bay of that name, while La Serena is built on the gravel terraces of the Rio Elqui. The former is a commercial port consisting of the wharves and warehouses essential to commerce and a single street, along which runs the railway. Above the latter the residences are perched on the granite ledges of the promontory. There was also an extension of the city over the beach and marsh lands at the southern end of the bay, but that section was swept away by the earthquake wave.

La Serena is a city of gardens and orchards, girt about by high walls in the Spanish style, and is the seat of government for Coquimbo Province. It is an old city with records going back to the days of the conquistadors, and it has a long record of earthquake experiences, as appears in the historical notes.

The valley of the Rio Elqui, a large stream for this region, is narrow and precipitously walled in. The railroad line, which follows it for about 50 miles (80 km.) above La Serena, winds between the cliffs and the narrow cultivated bottom lands. Only at one point, Vicuña, does the arable land spread out to a mile or more in width. Above it rise the cliffs of dark-red volcanic rock, almost devoid of vegetation. At the end of the railroad, at Rivadavia, the main river is formed by the junction of two streams which come from the south and north. They head in many branches in the heights of the Andes, among peaks which rise to 17,000 or 18,000 feet (5,000 to 5,500 meters), and they have extremely rapid falls.

The earthquake was by no means impartial in its work in this valley. It did little harm to Coquimbo, except by the wave which followed it. It shook La Serena severely, damaging a great many buildings. It left Vicuña almost scatheless, but practically destroyed Rivadavia, which lies farther east. This peculiar irregularity

A. Coquimbo. Looking north across district swept by earthquake wave.

B. Coquimbo. Looking south to low district, swept by earthquake wave.

A. Coquimbo. Effects of earthquake wave in railroad yard; height of wave 26 feet (8 meters) above mean tide.

B. Coquimbo. View from hill south of bay, looking northeast across flat swept by earthquake wave.

of effect was chiefly due to the nature of the rock or ground on which the several towns are built, but also to the occurrence of fault lines where the shock was most violent, or where possibly secondary shocks originated.

In the generally straight coast line of Chile, Coquimbo Bay is one of a number of small indentations which are incidental to a peculiar structure of the Coast range. The range is not continuous, but is made up of many sections which lie at a slight angle, trending north by east where the coast lies north and south. They therefore lie *en échelon* with reference to one another; and at the southwestern end of each section, where the ridges run into the sea, there is a bay like that of Coquimbo. This peculiarity is due to the faults which define the blocks, as will be described later.

The idea of a continuous coast range carries with it the suggestion of a continuous longitudinal valley. But, as has just been stated, the Coast range is interrupted and the so-called longitudinal valley is also divided into separate basins by high spurs which project westward from the Andes, even to the coast itself.

These characteristics of the topography become apparent when we leave Coquimbo and follow the railway north to Vallenar, the next town of importance, about 240 miles (150 km.) distant as the crow flies. Skirting Coquimbo Bay, the line passes through La Serena and thence up the canyon of a small tributary of the Elqui to a divide about a thousand meters above sea-level. It then descends abruptly to the gorge of the Rio Choros, a small foothill stream of the Andes, climbs again up a very steep grade to an altitude of 3,300 feet (1,100 meters), and, after winding for some miles over the plateau which is a spur of the high Andes, descends over a wide gravel plain to Vallenar, in the valley of the Rio Huasco.

In this stretch of 240 miles (150 km.) there is no village of any consequence. The railroad stations consist of a station house and water tank. From them mule trails, not roads, lead off into the mountains, where there are numerous mining camps. Many of the mines are superficially worked out and the miners have left. The region is arid, but it is not salt-covered and utterly waterless, as are the nitrate basins farther north.

Approaching the valley of the Huasco, one sees only the wide gravel plains which extend beyond the view north and south and from the foothills of the Andes on the east to the ridges of the coast range on the west. The width of the basin is 3 to 12 miles (5 to 20 km.) across the gravel plain. The river lies 600 feet (200 meters) below, sunk in the channel which it has cut across the longitudinal valley and out through the coast range. It is a delightful surprise on arriving at the edge of the trench to look down upon the orchards and gardens of the city of Vallenar. The river bottom is but a quarter of a mile wide, but is a strip of rich verdure, being grown with rank grasses in its marshy sections or planted and irrigated wherever it can be protected from flood (Plate LXIX (in pocket)).

From the high gravel plain 600 feet (200 meters) above the river, one steps down over three very distinctly marked terraces to the valley bottom. Each of these terraces carries a large irrigation canal, which brings water from 10 to 30 miles (16 to 48 km.) up the river and supports a rich growth of alfalfa.

Behind the traveler is a parched, stony plain, but before him is a garden.

Vallenar was an Indian settlement before the Spaniards came, and has always been an important cross-roads at which the east-west traffic down the valley of the Huasco met the north-south lines of communication. Today it is the junction point of the longitudinal railway with the branch line to the port of Huasco on the bay of that name. The town is built on the gravel cone at the foot of a small ravine that enters the river from the northeast, the site being determined by the fact that the gravels heaped up by the little tributary constitute a foundation which has good drainage and is higher than the marsh land of the river bottom.

The valley of the Huasco is a fertile zone stretched across sterile hills and plains, and it is occupied by settlements and ranches for some 75 miles (120 km.) from its mouth to the principal forks of the stream above La Pampa, where it has an elevation of nearly 5,000 feet (1,500 meters). Throughout this stretch the little villages and the ranch-houses were generally severely shaken by the earthquake. Vallenar suffered most because it was much the largest town, but the intensity of the shock was similarly effective in all other places whose foundations and geological relations were the same. There were some curious instances of immunity, which again are to be explained by local geologic conditions.

We may here cite some of the principal facts. The town of Huasco, which, like Coquimbo, is built on a granite promontory, shivered in the earthquake, but was not shaken down. Huasco Bajo, a village 4 miles (6 km.) distant, built on alluvium and near the line of a fault, was practically leveled. Freirina, a village 7.5 miles (12 km.) farther up the valley, was very seriously damaged. It also is built on alluvium and on the line of a fault. Vallenar, 23 miles (35 km.) from Freirina, located between two faults, suffered most severely, but the damage done depended largely on the original construction and the actual condition of individual houses and on the nature of the ground on which they were built. In the gorge of the river east of Vallenar the gravel terraces are very narrow or entirely wanting, and the rocks are near or at the surface. The distribution of earthquake damage depends upon these conditions, it being least where the foundation is rock. But the intensity was even more definitely concentrated at those points where the gorge is crossed by thrust faults. Thus, on a fault 2 miles (3 km.) west of Vallenar, in the Quebrada Valparaiso, movement was renewed on an ancient landslide (Plates XXIII to XXVI). At the Quebrada Jilguero, 3 miles (5 km.) east of Vallenar, the cliff adjacent to the outlet of the stream into the gorge of the Huasco was cracked for a height of 150 feet (50 meters) (Plate XXII). The quebrada is located on a fault. Furthermore, in the little village of El Tránsito, built on the alluvial cone of a tributary ravine, which in turn is determined by a thrust fault, there were few houses that survived the shock and the church was ruined.

Extending northward from the valley of the Rio Huasco to that of the Rio Copiapó, a distance of 100 miles (150 km.), the gravel plain that begins south of the Huasco is continuous. It widens out and ramifies among the foothills of the Andes and the spurs of the coast range, thus forming one of the major basins characteristic

A. Near Coquimbo. Hut, on coast 16 miles (25 km.) south of city, not damaged by earthquake, showing weakness of shock at this point.

B. Coquimbo. Jointed Paleozoic granite near northern end of promontory.

of the series of depressions which lies east of the coast range in northern Chile. The Rio Copiapó enters this basin from the southeast through a narrow gap in the granite foothills and pursues its course in a wide flat valley westward to the coast. Just upstream from the gap the valley of the Copiapó spreads out in an intermontane basin some 3 km. wide and 10 km. long, which is a fertile oasis. (Plate I A.)

From time immemorial the oasis has been a center of population. It is the last fertile spot on the route of travelers going northward into the utterly desert waste of Atacama, and it is the first settlement at which the traveler from the desert may refresh himself. It is also the center of what was an exceedingly rich mining region. It is now the capital of the province and one of the most important towns in northern Chile.

The present town of Copiapó is built on the eastern side of the oasis, partly on the marsh land and made ground next the river and partly on the lower slopes of an alluvial cone which descends abruptly from the neighboring heights. Since every one desires flowing water for gardens, trees and drains, the upper limit of building is fixed by the very moderate altitude to which water can be carried. The city, therefore, stretches its length between the river and this upper contour, and is long and narrow. At the northern, lower end it extends into the gap beyond the alluvial plain; southward it spreads over the valley, running out into farms and adjoining the older Indian pueblo of San Fernando. The construction of the houses varies greatly, from huts of wattled twigs and mud to massive walls of adobe or framed structures covered with stucco. These resisted the earthquake quite unequally, the adobe being the weakest because of its excessive weight and little strength. There were, however, very few houses which were not seriously damaged in the interior, even though the outer walls appeared not to have suffered much; and in a large proportion of cases the collapse of the heavy roofs rendered the houses uninhabitable.

As might be expected, the destruction was greatest on the marshy ground near the river; it was less on the slope of the alluvial cone—indeed, relatively insignificant in the upper part of the city—and it was also comparatively slight in the northern end in the gap where the rocky spurs close in upon the valley. Thus the destructiveness of the earthquake at Copiapó was directly related to the character of the subsoil.

La Serena, Vallenar, and Copiapó are three important towns which lie almost in a straight line that trends north-northeast from the first named, along the inner side of the coast range. It was natural to infer, as I at first did, that they were located along a single great fault line similar to the San Andreas fault of California. This afterwards was found not to be the case. There are many faults instead of one, and no one of them has the distinction of having caused the wreck of more than a single town. Copiapó, indeed, is not situated on any fault line. There is one which passes about 6 miles (10 km.) southeast and another about 2½ miles (4 km.) west of it, but its unfortunate reputation for being a place of special and peculiarly violent earthquake activity rests rather upon the marshy character of its subsoil than upon any other condition. It is somewhat surprising, where all the region round about is utterly sterile, to find vegetation growing so rankly that it will produce thick beds of peat. But peat occurs in the valley of the Copiapó River near Monte Amargo, some 40 km.

below Copiapó (Plate L), and peat probably underlies the sands of the plain upon which San Fernando and the lower parts of the city of Copiapó are built. Water is very abundant in this intermontane basin. The latitude, 27° south of the equator, corresponds with that of the Gulf coast of Texas, but the sun is even hotter than in Texas, because the dry atmosphere of the desert allows the rays to pass undiminished in intensity. Thus, marsh vegetation grows rankly the year around. Its roots and decaying stems form a spongy mat which thickens year after year until, by some accident of flood, the vegetation is buried under sand and the sparser grasses of the plain replace the marsh. The conditions for this kind of growth are extremely favorable above the obstructed outlet of the intermontane basin, and render it most probable that the unstable condition of the foundations of the city is due to the existence of a bed of peat, which is, however, buried beyond the depth of any of the shallow wells in the plain. The remedy, of course, is to grade the slope of the alluvial cone above the present city, provide water for irrigation at higher levels, and condemn the residences on the low ground. If buildings must be erected on the unstable soil they should be so constructed as to resist its vibrations in any earthquake.

The longitudinal basin which extends from Vallenar to Copiapó ends immediately north of the latter city, where again a high spur of the Andes projects westward. The railway climbs to the pass of Chimbero, at an altitude of nearly 6,600 feet (2,000 meters), and then descends into the southernmost of the broader and more arid basins of the true desert. Pueblo Hundido is the station situated at the southwestern end of this basin, in the channel of the Rio Salado, a stream whose waters do not suffice to flow beyond the foothills of the Andes, but whose valley is nevertheless cut through to the coast at the bay of Chañaral.

Pueblo Hundido and Chañaral, 63 miles (100 km.) north of Copiapó, are the first settlements of sufficient importance to have given any record of the intensity of the earthquake. But neither of them suffered materially from the shock. Chañaral indeed was struck by the earthquake wave, but was not damaged by the temblor itself. Both places appear to lie to the west of the trend of the fault zone in which the activity was pronounced. But going eastward from Pueblo Hundido up the Rio Salado, we come in 47 miles (75 km.) to the copper-mining camp of Potrerillos, at an altitude of 10,400 feet (3,100 meters), and here the buildings were damaged to the extent of some $75,000. They were mostly long, low structures built of a specially good adobe and strengthened by a continuous band of reinforced concrete above the doors and windows. They were, nevertheless, seriously damaged by cracks. Had they been of the usual type of native adobe they would probably have been completely ruined. There is no question, therefore, that the earthquake was almost if not quite as violent at this great altitude among the rocky peaks of the Andes as it was in the lower valleys.

Potrerillos is located on a group of thrust faults, which may be seen in the neighboring canyon but which, beneath the mining camp itself, are buried by the gravel wash of an ancient valley. This gravel is thoroughly drained by a canyon 1,500 feet (450 meters) deep and, being full of air-spaces, might have been expected to absorb the earthquake vibrations. It is, however, fairly old (Pliocene or early Quaternary)

A. Vallenar. Water forced out of river bed by shaking down of alluvium.

B. Vallenar. Two-story frame and adobe house standing among ruins of one-story massive adobe houses.

A. Copiapó. Typical adobe ruin.

B. Copiapó. Good adobe ruined by heavy mud roof.

and has undoubtedly been consolidated by a great many earthquakes. It evidently transmitted the shock effectively (Plate XLVI).

We have thus described the district in which the terremoto of November 10 was of destructive violence. It extends from La Serena on the coast, north by east to Potrerillos at an altitude of more than 10,000 feet (3,000 meters). It is a zone of thrust faults, 14 of which are known to extend nearly parallel to one another at distances apart that vary from 2½ to 12 miles (5 to 20 km.). The total width of the faulted zone in the latitude of Copiapó is about 100 miles (150 km.), but these are not its limits. The ocean prevents us from arriving at anything more than a surmise as to the extension of the zone westward, and the winter season prevented the writer from exploring eastward in the high plateau of the Andes or across to the eastern slope of the Cordillera, where faults of a similar character are reliably reported to exist.

The length of the zone of maximum activity of the earthquake, from La Serena to Potrerillos, is 300 miles (500 km.). Here again, however, we are obliged to admit that the effect may have been violent beyond these limits; for south of La Serena the fault zone runs into the ocean, and north of Potrerillos are uninhabited salt plains and barren ranges varying in altitude from 12,500 to 17,000 (4,000 to 5,000 meters). If we attempt to draw an inference from the distribution of intensity, we find but little reason to limit the area of great violence by the known facts. The shock was no doubt less at La Serena and more violent at Vallenar and Copiapó. It may have been somewhat less at Potrerillos, but not enough to indicate that it was rapidly diminishing in intensity toward the northeast. Thus the area of severe vibration was large. The disturbance was nevertheless not violent, in general. Local conditions, especially the proximity of fault planes and the weakness of alluvial deposits, determined the areas of destructive violence, where the poor structures built by man were thrown down and he was buried in the ruins of his own handiwork.

History repeats itself where it depends on permanent natural conditions. La Serena, Vallenar and Copiapó have again and again been the centers of maximum damage by earthquakes in southern Atacama. The nature of the alluvial ground which makes earthquakes dangerous is the attraction that draws man to the spot, for there he can irrigate the land, raise fruit and alfalfa, and establish his home in an oasis. These advantages have overcome the fear of the terremoto. Rather than abandon their homes, the dwellers in these cities have returned each time to the ruins and have rebuilt on the old site; sometimes they took warning and built better structures, but as a rule the old ways prevailed and there has been but little change in the architectural types during 400 years. In 1922 proposals were made, as they had been made before, to move Vallenar to some neighboring, supposedly safer position. They were argued with earnest, even with heated purpose, but the arguments were based largely on self-interest. In the end, the general economic control prevailed, invested interests refused to be uprooted, and a new Vallenar was erected where the old houses had stood. It was so also in Copiapó and elsewhere. And few considered the saying of the Jesuit father who in 1665 wrote: "He who inhabits a house of adobe lives in his tomb."

EARTHQUAKE HISTORY OF ATACAMA

LIST OF SEVERE EARTHQUAKES, 1543 TO 1922[1] INCLUSIVE

1543. Tarapacá.
1604. December, La Serena.
Before 1648. Coquimbo.
1730. July 8, La Serena.
1792. November 30, La Serena.
1796. March 30, Copiapó, Vallenar, and Huasco.
1796. August 24, Copiapó.
1801. January 1, La Serena.
1819. April 3, 4 and 11, Copiapó.
1822. November 5, Copiapó and Coquimbo.
1843. December 17, La Serena.
1847. January 19, Copiapó.
1847. October 8, Coquimbo.
1849. December 17, Coquimbo.
1857. November 7, Copiapó.
1859. October 5, Copiapó.
1864. January 12, Copiapó.
1877. July 26, Coquimbo, Chimbo, and Tamaya.
1877. August 29, Vallenar.
1903. December 3, Vallenar.
1903. March 19, Vallenar.
1918. December 4, Copiapó.
1922. November 10, Copiapó, Vallenar, Huasco, and Coquimbo.

Thus the records of 400 years list 22 severe earthquakes in Atacama, distributed through a zone from Coquimbo and La Serena in the south to Copiapó in the north. The center of greatest effect is indicated by the name of the place, in each case, but none of these severe shocks was of local occurrence only. Their extent may be indicated with more or less accuracy, according to the completeness of the available data, in the following descriptions, which also indicate the severity of the shock in the place of greatest intensity. The notes are translated from the work of Count Fernando de Montessus de Ballore, cited above.

DESCRIPTIONS OF TERREMOTOS, 1543–1918 INCLUSIVE

1543. Tarapacá—A severe earthquake, which prevented the Indians from showing the Commissioner, Lucas Martinez Begazo, the founder of Arequipa, the Mine of the Sun, of pure silver, which they had previously worked. (Tarapacá lies some 200 miles north of Atacama, but not beyond the region simultaneously affected by extensive shocks occurring in the latter province.) This earthquake is therefore here noted, as it is the earliest definitely recorded and may have extended to Copiapó and other parts of the territory under discussion.

1604, December. La Serena—Concha relates: "This earthquake occurred in December 1604. There is no account of the event whatever, except some slight references in certain public documents, from which one may infer that it ruined a large part of the buildings of the city, which indeed were few in number." Thus:

"Record of the Cabildo de la Serena of July 17, 1605. The said church (the Metropolitan Church) is being built and it having occurred when the walls were high that the earthquake, which there was in this city six months

[1] Historia Sísmica de los Andes Meridionales por Fernando de Montessus de Ballore, Director del Servicio Sismolójico de Chile, Segunda Parte, 1912.

past, ruined the walls of said church, and it having been expedient to tear it down and rebuild it on account of the one-third part which, by order of H. M., is provided from his funds, it was agreed to pay to Captain Juan de Baldovinos de Leide one hundred pesos from the two-ninths pertaining to H. M., from the tithes of this year, and from those to be received until he shall have been paid the one hundred pesos, and the said Captain Juan de Baldovinos has built the said church, repairing the damage referred to, and has finished it to the height which the walls must have, and he has petitioned that he be paid the amount of the said account."

Before 1648. Coquimbo—This earthquake is recorded in the following from Bishop Villaroel. No other author has mentioned it. (Gobierno eclesiastico . . . . , Part II, Quest. XIII, Art. III, 17.)

"With reference to the earthquakes, processions have been very important: prodigious effects have been observed. I will refer only to one (446. Oriente), not because it is unknown, but rather because it can not be forgotten; and because as I have been instructed in Lima, where it quakes, and in this my Bishopric an earthquake destroyed completely the city of Coquimbo, I describe the instance in order that those who suffer from earthquakes may know the remedy."

In another passage Villaroel (p. 587) says that he had to rewrite his work in August 1648. The earthquake must consequently have occurred before that year.

1730, July 8—The great earthquake of July 8, 1730, devastated all central Chile (that is to say, the region of which Santiago is the center and which lies far south of Atacama), but although its area of destruction extended to La Serena, the damages, even though they were notable, were not of such importance as is supposed by some historians or authors, as, for example, by Francisco Solano Asta Buruaga y Cienfuegos in his *Geographical Dictionary of Chile*. This, therefore, is not the place to describe this great seismic phenomenon. (See *Hist. de los Andes meridionales*, Part IV, p. 75.)

1792, November 30. La Serena—Concha relates: There was another earthquake no less strong (than that of December 1604) which also destroyed some buildings; but its havoc was by far not to be compared with the other.[1]

1796, March 30, VI, 3/4. Copiapó and La Serena—A violent earthquake (says Sayago[2]) which did damage in the city of Copiapó, ruining the metropolitan or parish church, de la Merced, the jail, and a great number of houses. . . . . Sayago appears to have known and to have abridged an account in an administrative report, belonging to the archives of the Ministerio del Interior, preserved in the Biblioteca Nacional (vol. 656, No. 7721). It treats chiefly of estimates of the costs in order that the Government may supply the funds necessary for the reconstruction of the principal edifices. It appears from these documents that the tower and façade of the parochial church fell, but without personal injuries, and also it is indicated that Huasco and Coquimbo suffered in a manner similar to Copiapó, but nothing is said of La Serena, which was likewise ruined, as is shown by the statement which follows.

With reference to the earthquake in La Serena, Montessus quotes from J. T. Medina, Cosas de la Colonia.[3]

"On the 30th of March, 1796, at 6 3/4 in the morning, this city suffered from a very violent movement of the earth, which lasted at least 4 minutes in the first shock and was continued in others, but not as severe, for more than an hour. The damages have been very considerable, chiefly in the churches. The Church of San Francisco was partly thrown down and the tower remained in such a ruined condition that it was necessary to tear it down to avoid further injuries. The Metropolitan church lost its tiles and some adobe blocks (tapias) which had fenced the cemetery. Deaths from the falling of houses were only three in number, and among them was the twelve-year-old daughter of the alcalde, Don Francisco Soza. Many were dangerously wounded."

The Church of Paitanaz, now Vallenar, built at the beginning of the eighteenth century, was thrown down and was rebuilt in the same year.[4]

Letter of the Cura, Juan Nicolas Varas y Marin, to the Bishop Marán, dated La Serena:

"The earthquake was most severe in the districts of Coquimbo, Huasco, and Copiapó."

1796, August 24, between X and XII. Copiapó—

"Panic stricken by three consecutive movements of the earth of greater duration, though not of equal force and violence, with that of March, which completed the ruin of the little that might survive such violent disturbances, including what happened the first time, the people endeavored to fly to the hills, telling each other to their greater

[1] *Crónica de la Serena*, from its foundation down to our time, 1540-1870. Written according to the data taken from the Archivos de la Municipalidad, Intendencia, and other papers. La Serena, 1870.

[2] *Historia de Copiapó*, Copiapó, 1874.

[3] Apuntes, *Crónicas del Siglo XVIII en Chile*, Segunda serie. Santiago, 1910, p. 117.

[4] Memoria presented by the Cura and Vicario de Vallenar, Don Manuel Garcia, to the Bishop of La Serena, Don Jose Manuel Orrego, on the occasion of the visit which he made him on June 1, 1872. Valparaiso, 1872.

distress and fear a vague tradition to the effect that this city must be transformed into a lake by means of an earthquake, because it is situated in a meadow." (Letter of the sub-delegate, José Ignacio Balbontín, of September 24, 1796, forming part of the various administrative papers which constitute the report on the results of the earthquake of March 30, in the district of Copiapó. Documents of the Ministerio del Interior, Biblioteca Nacional, Vol. 656, No. 7721.)

1801, January 1. La Serena—Concha, *Crónica de La Serena,* page 208, says: "A very severe earthquake was experienced, January 1, 1801, which caused some damage."

(He quotes a letter from the subdelegate Joaquin del Pino, who writes only of the aid to be extended to the sufferers from the earthquake.)

1819, April 3, 4 and 11. Copiapó—Earthquake and earthquake wave. It would seem that this earthquake was the fourth to ruin the city of Copiapó, which was officially founded in 1744, for it is known that various edifices, particularly the church of La Merced, had already been rebuilt three times when the earthquake of 1819 occurred. The most extended account that it has been possible to secure is that compiled by Don Diego Barros Arana in his well-known *Historia Jeneral de Chile* (XII, 372). He, according to his statement, utilized the scanty data to be obtained from the few periodicals of that time in addition to two reports which were sent to the Government of the United Provinces of the Rio de la Plata by its diplomatic agent, Don Tomás Guidón.

This seismic phenomenon was characterized by a peculiarity which is sufficiently rare in general, and which, up to that date, had never been observed in Chile, so far as we know: In an interval of eight days, from the 3d to the 11th of April, three distinct shocks assumed a destructive character, each one of them causing notable damage.

Without any previous indication, at 10 o'clock on the 3d, an initial strong shock was felt throughout the entire region, which threw the people into great alarm because of the very numerous, consecutive, and repeated after-shocks that followed it, even though they were not so severe. According to Sayago, many houses and walls of adobe blocks (tapias) were thrown to the ground and the inhabitants, praying for mercy, fled to the parks, streets and patios.

On the following day, a little before dawn, at 5 o'clock, according to Barros Arana, or at 16 according to Sayago, another much stronger earthquake augmented the disaster, increasing the piles of débris and adding to the terror of the inhabitants. Two years later the celebrated English traveler, Captain Basil Hall, visited the region and gathered interesting details, which were still fresh in the memories of the sufferers but do not occur in other documents. According to his account, it was then that the church of La Merced of Copiapó fell, but without causing any deaths because some self-possessed person induced the people to leave the church quickly, under the pretext of carrying the sacred images outside in order to worship them there and implore the aid of heaven. This statement is not without interest, since it gives occasion to think that the hour indicated by Sayago, 4 p. m., is more probably correct than that given by Barros Arana, 5 a. m., it scarcely being probable that there would have been many worshipers in the church at so early an hour.

According to the version of various witnesses this earthquake lasted about 4 minutes and was accompanied by a terrifying noise. It threw down many houses in the cities, in the suburbs, and in the surrounding country. In Copiapó the most notable was the destruction of the two churches, La Matriz and La Merced, and about one-half of the houses. The jail and the municipal residence were ready to fall down. Of La Merced there remained erect a part of the side-walls and of the façade, but even they were shaken and badly cracked. The great buttress walls were thrown down, with the exception of one, the upper part of which was separated by 3 or 4 feet from the wall which it was built to sustain.

Two years later Basil Hall was able to observe in the neighboring orchards that cypresses had been thrown down upon the ruins, while many other trees remained more or less in a leaning position. He says that here and there one could still recognize wide cracks opened in the ground, which had not been closed, in spite of the long time that had elapsed since the earthquake. He noted that the precinct of La Chimba had suffered comparatively little.

Terrified by these occurrences and kept in constant alarm by the after-shocks, which did not diminish in intensity and frequency, the people who had fled without shelter or resources to the slopes of the adjoining hills of Chanchoquín and Rosario had not dared to return to their ruined homes; and this was indeed fortunate, since, on the 11th, at 11 of the morning, according to Sayago, or in the night as stated by Barros Arana, a much more violent earthquake completed the ruin. An hour and a half later there occurred still another shock, which was almost as strong and extremely prolonged, lasting, according to the testimony of those who experienced it, some 5 or 6 minutes.

Except for the church of La Merced, the accounts do not distinguish any of the principal edifices, as to whether they were damaged initially by the earthquake of the 4th or by that of the 11th. Be that as it may, we are also ignorant of the extent of the area damaged; but it is certain that the church of Matriz de Paitanaz, which was on the present site of Vallenar, was also ruined.

There occurred an earthquake wave, and in regard to it Diego Barros Arana says:

"Along the coast, where the earthquake was intense, it was observed that the sea retreated upon itself, but shortly advanced over the land, reaching in some points a distance of more than 600 meters beyond the line of the highest tides. This extraordinary movement of the waters of the ocean was noted at other points along the coast to as much as 200 leagues from those localities."

Without giving any more explicit details, the illustrious historian cites the testimony of the commandant of the naval vessel *La Fortunata,* which, having been anchored off the dock of La Nueva Bilbao, now called Constitución, was wrecked upon the rocks in consequence of the advance and retreat of the sea, after having broken away from her anchors. The accident occurred on the 12th at 2 o'clock in the morning.

Now, we know from other earthquake waves which have occurred on the coasts of Chile, especially from those of August 13, 1868, and May 9, 1877, that earthquake waves advance from north to south with a velocity of about 300 marine miles per hour. Hence we may directly infer that the third earthquake of Copiapó occurred at 11 p. m. and not in the morning of the 11th, in order that it should agree with the hour of the earthquake wave in Constitución.

The same phenomenon was noted in Caldera, as was natural, and Peter Schmidtmeyer relates that they later recovered ingots of copper which the advance of the sea had buried beneath great masses of sand. No other observations relating to the earthquake wave are known, and we are equally ignorant regarding the duration of the after-shocks of the earthquake.

At this period the public edifices of Copiapó were built of very heavy walls of masonry—it might be of stone or of brick—while the private houses were constructed of adobe with frames of wood, the uprights or joists of which were set deep in the earth. They resisted much better, and the inhabitants, taught by the experience of the earthquake of 1819, according to the testimony of the oldest inhabitants of the city, from that time on adopted the system of construction now in use; that is to say, to build with frames of wood, mud, and Guayaquil cane, a method which without doubt has for almost a century saved the city of Copiapó from various disasters which it could not otherwise have escaped as a consequence of the numerous violent earthquakes which have since that time shaken its unstable foundations. As a matter of fact, there has been no other real catastrophe since 1819.

This earthquake occasioned great demonstrations of charity in Huasco, and especially in Santiago, where public subscriptions facilitated giving relief to the sufferers of Copiapó in the form of money, clothing and provisions.

It was proposed to move the city of Copiapó to a safer locality, but this project was not carried out. In regard to it Sayago says:

"After several days, during which the oscillations of the earth ceased, the people recovered their poise and little by little began to return to the city to undertake in some measure to restore the ruins; it was then that the Lieutenant-Governor called together the councilmen, the cura and prelates, and the principal men in the neighborhood, and constituted an open council in the suburb of Hidalgo, situated in front of the now abandoned powder magazine at the foot of the slopes of Chanchoquín.

"The assembly was called to consider the selection of a better site for the city and the problem of rebuilding it. Many voices were raised to petition that it should be moved to some other place, where the ground might be firmer, it being argued that, since the founding of the city in 1774, the church of La Merced and many other public and private buildings had been three times rebuilt. Attention was called, however, to the fact that such a proposal must be decided by the supreme government, and the Lieutenant-Governor was charged with the duty of presenting the matter to Santiago.

"General O'Higgins replied that there was no one who could better determine the question than the Council of the city and neighborhood.

"To this end, on the 20th of July, there was held a second open Council in the Chapter Hall, which had already been repaired. Ten votes were cast to remove the city to Potrero Seco, 16 to Nantoco, 26 to Bodega, and 27 to remain on the same site. Thereupon the inhabitants began to remove the ruins and rebuild their dwellings and fences, and the Council and the Lieutenant-Governor to dictate the necessary measures. Little by little the idea of moving the city was abandoned."

1822, November 4. Copiapó—Violent shock. Many houses damaged. 20-5 Copiapó. The city was almost completely destroyed, and Coquimbo also suffered greatly.[1] Without any doubt, what-

[1] Mallet, cita Quart. Journ. Roy. Inst., XVII, 39; Perrey, Nouv. Ann. des Voy. XXV, Févr. 1825, 155; and Darwin, Trans. Geol. Soc., V, 612, according to Journ. of Sci., XVII.

ever, the phenomenon has been greatly exaggerated in all that relates to its effects, and it is probable that the descriptions relate to the damage done by the earthquake of the 22d of November to old walls and tumble-down houses.

1843, December 17, XVII, 10 or XVIII, 15. La Serena—An earthquake of notable force. A pile of stone fragments, gathered from the ruins at the church of La Matriz to build the actual cathedral, which lay in the center of the plaza where at the present time, 1870, the fountain stands, was completely thrown down almost to the level of the earth; and many houses suffered considerable damage.[1]

1847, January 19, X, 50. Copiapó—This earthquake was the strongest that has been felt since 1822. Up to XIV o'clock (2 p. m.) at least 14 shocks were counted. Many houses collapsed and many more suffered such damage that it was believed for the moment that the city would be completely destroyed. The shocks continued during three consecutive days.

1847, October 8, about XI. Coquimbo—Very little is known in regard to this occurrence, to which reference is made by Goll, and it is probable that its effects have been exaggerated. It was felt in Melipilla, Santiago, Valparaiso, and Copiapó. In Valparaiso the bells were rung. Damage is said to have been done in Coquimbo and the neighboring towns in the interior.

1849, December 17. Coquimbo and La Serena—Earthquake and earthquake wave. A short but terrifying subterranean noise, the precursor of an earthquake, in which the earth continued to move without interruption, even though slowly, during the long period of 84 seconds. A barometer hanging from the wall but separated from it by a space of 2 inches, swung from northeast to southwest, and it became necessary to hold it, as it struck hard enough to have broken it. This movement did not cause any damage to houses, but it was otherwise in the port of the city in the rise of the sea, which occurred 10 minutes later. The water rose 16 English feet higher than high tide. The first movement of the waves was in the direction from northeast to southwest, as it had been in the movement of the ground. It caused great damage and destroyed almost completely several reverberating furnaces and a canal.

1857, November 7, XI, 21. Copiapó—At the hour indicated there began a slow shaking of the earth, which had not been preceded by any sound whatever. In 3 minutes the movement increased and the earth trembled forcibly, so that buildings and trees were violently shaken and people walked unsteadily in consequence of the violent oscillation of the ground. With each second the commotion appeared to increase, and buildings were thrown out of plumb by the force of the shock. The people ran together in the streets and plazas in consternation. Many people, especially the women, kneeled imploring piteously the mercy of heaven. The earthquake continued with all its violence until XI, 23, and then gradually the movement lessened until XI, 24, when it ceased. . . . . The Intendente ordered an inspection of the city by the Director of Public Works of the Province, and it appears from his report that adobe blocks (tapias) were thrown down from 38 houses and walls, and that the water-pipes of some 10 places were destroyed.[2]

1859, October 5, VIII and some minutes. Copiapó—The principal known details regarding this occurrence are taken from the earthquake catalog of A. Perrey, of the year 1862. At the hour indicated there occurred in Copiapó various horizontal shocks, from north to south, accompanied by a terrifying noise. They lasted 4 minutes with their maximum force, and afterward decreased in violence. The train from Caldera, which should have arrived at $11^h\ 30^m$ a. m., did not reach Copiapó until 5^h p. m. In that port, where the shock lasted $2\frac{1}{2}$ minutes, it caused many ruins. The damage was considerable in Copiapó, where the Intendencia, the jail, the hospital, and the churches all suffered greatly; 115 houses were thrown down and 224 remained uninhabitable. The losses were estimated to be 930,000 pesos.

In Tierra Amarilla the first shock occurred at VII, 57, and lasted more than 2 minutes. The buildings rocked like pendulums, and several were damaged. In the mine of Carmen Alto 8 or 10 miners were buried under rock falls.

The ground was cracked in various places, and particularly in the Plaza de Armas in Copiapó, according to the statement made to the writer by an inhabitant.

In Caldera there was an earthquake wave, the sea sinking 19 feet below the level of ebb tide, thus emptying a space of 150 varas in the port and occasioning considerable damage to the boats anchored there. The after shocks were numerous.

This earthquake was felt in La Serena, but the area of its action was probably even much more extensive.

[1] Manuel Concha, *Crónica de la Serena*.

[2] *El Minero de Copiapó* of November 7 and 11.

LETTER OF THE SUPERINTENDENT TO THE DIRECTORS OF THE COPIAPÓ RAILROAD. (2d semester of 1859, p. 6. Signed Luis Lebreu. Extracted from the archives of the Intendencia of Atacama.)

"There have been no serious accidents which have occasioned either death or injury. Nevertheless, I should mention here the fearful catastrophe of the 5th of last October, in so far as it affected this corporation, for it caused an interruption of four days in the traffic. I refer to the great earthquake which, in less than two minutes, destroyed innumerable houses and properties in this province. On the railroad between Copiapó and Caldera the earth was torn from the rails for leagues. All the embankments were thrown more or less out of level. At other points embankments 20 feet high disappeared, leaving the rails and ties scattered over the flat earth. In Caldera the oven and chimney of the smelter were thrown down, the wharf was thrown badly out of level, and innumerable adobe blocks, both in the stations and in the walls along the road, were thrown down. The buildings of the company suffered less because, being built of wood and cane, they resisted the earthquake much better in consequence of their elasticity."

1864, January 12, II, 9, Copiapó. Semiterremoto—The details which follow are taken from the annual earthquake catalog of A. Perrey for the year 1864. He obtained them from *El Constituyente* and from the *Comercio* of Lima for the 25th.

The temblor lasted 1 minute. Although it was longer than that of 1859, it was not as violent, and did not do as much damage. It was accompanied by a very loud subterranean noise which began only after the earth was moving. The shocks were distinctly directed from NNE. toward SSW., but with a vertical movement from above downward (*sic*). Walls running north and south suffered little, but those which were directed east and west received great damage. At least 12 shocks were counted during the morning, and up to 3 in the afternoon frequent after-shocks and occasional subterranean noises were observed. In Punta Negra houses were thrown down. Tierra Amarilla, on account of its wretched construction, was almost completely ruined. Damage was done in the mines of Elena and Tránsito del Cerro Ojancos and extended to Potrero Grande, Chañarcillo, and Tres Puntas. Nothing occurred in Caldera, where not even an earthquake wave was observed.

The earthquake was felt in Freirina, where various persons were injured and a little girl was crushed in the street of San Fernando. A house in Colipe Street was thrown down. In El Tránsito (in the valley of the Huasco above Vallenar) 2 Argentine peons were crushed to death. (*El Minero* of Freirina, January 23.)

1868. The great earthquake and earthquake wave of August 13—The terremoto of August 13, 1868, devastated the northern part of Chile and the south of Peru. Numerous consecutive shocks succeeded one another and were followed by a terrible earthquake wave, *tsunami,* which did great havoc in the ports of both countries. The latter extended throughout almost all the immense area of the Pacific, from the Antarctic lands to California and from Australia to New Zealand, as well as in the scattered islands of Oceanica; and for the first time it was possible to gather a sufficient number of observations to study the propagation of an earthquake wave across the ocean. Polo considered this terremoto as the greatest which had occurred in these provinces of South America and even more destructive than that of 1746, although it did not have so many victims. For these several reasons we have to do with a great seismic phenomenon which deserves detailed study, for which there are available a number of scientific articles of importance and interesting original documents.

It is not appropriate to the historical list of the earthquakes of Atacama to reproduce here the full account of the effects of the earthquake of 1868 in the more northern part of Chile and the south of Peru. It will be found in the *Historia Sismica de los Andes Meridionales,* Segunda Parte, pp. 77–158. Atacama was several hundred miles south of the region of great intensity, and the shock was but a moderate one in that region. Montessus gives the following, pp. 94 and 95.

"*Copiapó*—At 5 o'clock and 16 minutes there was felt a temblor of an unusual type of movement. I first felt it in my head as a giddiness. It seemed very slow and rhythmic, like that of a hammock or of a boat, but without any vibration, so that the house did not even creak. The movement was wholly in a horizontal sense and in a direction which could be clearly observed from north-northeast to south-southwest. The interval from the time when I first noted the temblor to its conclusion was two minutes and thirty seconds, but others whose statements are worthy of credit assert that it lasted four minutes. I believe this to be quite possible, because it is evident that I did not observe it until it had already been in progress for some time." (Carvajal, Rector del liceo.)

Montessus also quotes the following:

"At XVII a temblor of 2½ to 3 minutes duration alarmed the city. The movement began gently, so much so indeed that it was mistaken for that which was produced by carriages. But by degrees it increased in strength until it was difficult to remain erect without staggering. Fortunately the oscillation was slow and nearly all the buildings were of wood and adobe. The temblor was neither preceded nor accompanied by any sound, a rare circumstance, but one quite like that which was experienced in Copiapó when Mendoza was destroyed by the earthquake of 1861." (Gutierrez, Melchor. Estadística del horrible cataclismo de 13 de Agosto de 1868. Valparaiso, 1870.)

(The great earthquake of May 9, 1877, like that of 1868, was extremely violent in southern Peru and northern Chile, but was felt only as a strong shock in Atacama. Montessus gives a full discussion of the terremoto, *Historia Sismica,* Segunda Parte, pp. 162 to 223, from which we may take the following notes regarding its effect in Atacama.)

"*Copiapó*—Strong temblor. No injuries. The first movement occurred at XX. 20 (Diario Oficial). The duration was estimated at 4 minutes.

"*Chanarcillo and other places in the valley of Copiapó*—A strong shock was experienced.

"*Puerto del Huasco*—The temblor occurred at XX. 20. It was strong and was prolonged during 3 minutes. There were no accidents either on land or sea. (Report of the Subdelegado Maritimo.)

"*Carrizal Alto and Carrizal Bajo*—The earthquake was felt at XX. 30 and the movement seemed to come from the north.

"*Freirina*—Temblor which lasted 3 or 4 minutes.

"*Vallenar*—A strong, undulating temblor without preceding sound. It lasted 2 minutes and the movement seemed to be horizontal. (Diario Oficial.)

"*La Serena*—The shocks began at XX. 31 mean time (tiempo medio) according to a clock whose exactness was frequently checked. The shock moved from north to south, with east-west oscillations. There was no sound preceding the temblor, which lasted 1 minute and 58 seconds. The movement of oscillation was slow but very strong. I did not note the sharp shocks that commonly characterize terrestrial temblors. On the contrary, the extraordinary slowness of the oscillations was comparable with the movement which may be felt when on board a vessel in a tranquil sea. (The report of the German consul.)

"*Coquimbo*—The temblor of the 9th occurred at 8^h 15^m p. m., producing a prolonged movement of the earth which lasted at least 4 minutes, according to the most general estimate. It was, however, without premonitory sound, so that many did not notice it. Most of those who felt it said that they experienced a dizziness which they could not explain until they recognized by the oscillations or movements of the lamps that there was an earthquake." (Report of the Gobernador Marítimo.)

The above notes are taken from Eugen Geinitz, *Das Erdbeben von Iquique am 9 mai 1877, und die durch dasselbe verursachte fluth im Grossen Ocean.* (Nova Acta d. Ksl.-Carol.-deutschen Ak. d. Naturfor. Bd. XL, Nr. 9, Halle, 1878.)

Vallenar—August 29, 1877, semi-terremoto; December 3, 1903, terremoto; March 19, 1904, terremoto.

[These occurrences of more or less severe shocks are listed by Montessus without details.]

1918, December 4, Copiapó [1]—This severe shock was too recent to have been included by Montessus de Ballore in the *Historia Sismica.* Fortunately, there is a complete report by a competent engineer, which we take from the *Boletín Minero.*

"Near the beginning of the current year I received from the Minister of Industries instructions to investigate the effects of the terremoto of December 4, 1918, at Copiapó.

"For this study I had at my disposal no more than 14 days. Consequently I was obliged to limit my investigations to the city of Copiapó itself and its immediate vicinity, this course being the more urgently imposed by the fact that the city had suffered the greatest damage. Nevertheless, I made an opportunity to visit the port of Caldera for several days, where I was furnished with important data relating to the great movements of the sea during the terremoto, and where I expected to find opportunity to observe any permanent elevation or subsidence of the coast.

"I must furthermore observe that this statement of facts is based in part upon reports whose accuracy it was impossible for me to check personally. However, of the many accounts received, I have used only those which came from persons who by their standing and personal qualities inspired confidence in the exactness of their observations. I owe very important and reliable data to Señor Luis Sierra Vera, who also supplied the facts regarding the hour, the duration and other phenomena of the seism which are included in the following account.

[1] Linneman, Clemens, Report of the Servicio de Minas i Jeologia. Copied and translated from the Boletin Minero de la Sociedad Nacional de Mineria, pp. 412-420, 1919.

"The principal movement was preceded during the same day by premonitory temblors of little importance. The first took place at $0^h\ 30^m$; the second at $7^h\ 43^m$. The principal movement began at $7^h\ 44^m$. It commenced with weak oscillations which gradually increased to a temblor of higher grade. The most violent shocks lasted 3 minutes. Oscillations of minor grade followed during 2 minutes and 53 seconds, so that the duration of the total movement was 6 minutes.

"No subterranean sounds were heard either before or during the temblor.

"The movement was composed of horizontal oscillations in which no particular direction predominated. Simultaneously with these oscillations, a number of vertical shocks of great violence were experienced.

"Among the effects of the terremoto, those which take first place are the damages to houses. Even a superficial inspection of the streets in which the greatest damage was done developed evidence of a vertical force. In support of this assumption we may cite:

"(1) The collapse of flat roofs, where not accompanied by serious damage to the surrounding walls which supported them.

"(2) Regular cracks extending from the roof to the ground along the dividing-lines between the houses.

"(3) Numerous cracks which extended from the corners of the doors and windows toward the roof in one direction and toward the ground in the other.

"The failures indicated under 2 and 3 are typical of irregular vertical stresses where houses collapsed, for the points in which they were manifested are the weakest with reference to such forces as those which are considered. In the course of my activity as an expert, appointed by the courts of justice to study the damage caused by mining in the densely populated coal-producing district of Rhenish Westphalia, I had repeated opportunity to observe these relations. We must, therefore, reject the statements of some persons in Copiapó that no other movements than those of oscillations of the ground were to be observed. The violence of the vertical shocks is demonstrated by the following fact: The safe in the steel vault of the municipal treasury, standing on a wooden box, was thrown violently upward and left definite holes in the paper on the wall, from the height of which one may form an idea of the violence of the movement, even after deducting the difference which would correspond to a probable subsidence of the ground.

"Nevertheless, there is no question that the principal cause of destruction was the horizontal component. In regard to the direction of the horizontal movements, there is a great diversity of observations. Some thought they had observed an east-west direction, others a movement from north to south. Señor Sierra, whose statements in regard to this point inspire the greatest confidence, describes the seism as a shaking without pronounced determinate direction. The cracks which opened in the earth during the terremoto, regarding which I shall have more to say later on, also failed to indicate a definite direction. Furthermore, the damage caused by the cracking of walls and houses was distributed equally in the surrounding walls without any predominant orientation.

"The destructive action of the terremoto was enormous in the city. Of 1,630 houses not less than 344, that is 20.9 per cent, were completely destroyed. Those which were seriously damaged numbered 349, or 21.3 per cent. The remainder, 944 or 57.8 per cent, suffered comparatively little damage, but nevertheless, not a single house escaped intact from the catastrophe.

"In order to get a definite idea of the effect of the terremoto of December 4, 1918, in the destruction of the city, it is necessary to consider, even though only in a summary manner, the different classes of buildings, the condition of the different edifices, and the subsoil of the built-up area.

"The city of Copiapó is built in large part upon the sandy clays of fluvial deposits of the river Copiapó, and stands in a very unfavorable situation, since it is exposed to inundation by the floods of the river, such as that which occurred in 1906. The houses are in large part very old, many of them dating back 60 to 80 years. Those which are not more than 10 or 15 years old are few in number and are found chiefly in the center of the city. Rented properties predominate. The number of houses in private hands is very small. In consequence of the decay of the city caused by the abandonment of the mines, the number of inhabitants has fallen off in the last decade and rentals have been correspondingly reduced. The maintenance and repair of houses has correspondingly decreased in consequence. When to these conditions we add the losses caused by the inundation of 1906, it may be understood that at the date of the terremoto of Copiapó the state of the buildings was deplorable.

"In the following description I will refer only to the principal types of construction, each one of which is linked with the others by transitional examples. The proportion of each type to be found among the buildings of the city is practically the same, as may be seen by the statistics which are appended at the close of this statement.

" The oldest and cheapest houses, which for that very reason are inhabited by people without means, are those built of *tapiales*. This type of construction is employed chiefly for interior walls. The material (mud) is pounded into blocks 1 meter high, more or less, 1.5 meter long, and 0.5 meter thick. The mud is made by the clayey sediment deposited by the River Copiapó, which is compressed in a mold. The blocks are placed one upon another to the height of 2 meters, more or less, which with rare exceptions are not tied together or held by mortar of any sort. Indeed, in general they do not even take the precaution to strengthen this material with straw, even though it is but slightly coherent, because of the large proportion of sand which it contains. Generally a number of layers of adobes of the same material are placed upon the blocks, and the rafters rest upon these. The walls are covered with a thin coating of mud which is made to adhere by means of sticks or nails placed wherever practicable in the walls for this purpose. The roof, which in most of the houses is rather low, is composed in these, as well as in the other types of construction, of a supporting frame which is covered with cane or reeds. In order to protect it from wind or rain, it also is covered with a thin layer of mud. This deteriorates, but not uniformly, and thus needs to be repaired year after year, and, as the simplest method, is covered with a new layer. Thus after a few years a very thick covering accumulates, which lessens the stability and resistance of the structure with reference to shocks.

" Of great advantage for its cheapness is the widely employed method of building with adobe brick. The material is the same as that of the tapiales, but the walls are thinner and the building as a whole is thus lighter. Beyond that, the placing of the adobes and the mud stucco is the same as in the previous case. It is, however, a general practice to reinforce the adobe brick by means of wooden beams.

" This type of construction constitutes in a certain degree a transition to the structures which are more modern but more costly and in which cane and sacking are used. The sacking is done up in small bundles and placed between the uprights, which are fairly close together. The whole is covered with a layer of mud, according to custom, and the latter adheres much more firmly.

" In those cases where Guayaquil cane is used, the canes are nailed horizontally across the uprights, one above the other. Thus two walls are produced, one inside and one outside, and the space between the two is not filled. This type of construction is very durable and, because of its elasticity, resists shocks strongly. But it is not very much used because of the high price of the cane, which is imported from Ecuador. On this account it is found principally in business houses and in the residences of persons of means.

" These four types of construction were found to be distributed in the following proportions among the 1,630 houses examined:

		Per cent
Tapiales	440	26.8
Adobes	349	21.3
Frame and sacking	405	24.7
Guayaquil cane	446	27.2

" There are some other types of construction which occur in such small numbers that it is not worth while to consider them. If we consider the damage occasioned by the terremoto in each of these different kinds of buildings, we shall see that the destruction is much the more general in those of tapiales. Already weakened by the spalling and cracking of the surfaces at the contact of the blocks, the tapiales would not have resisted a temblor of even moderate intensity, decidedly inferior to that of December 4.

" The blocks placed one upon another simply fell off and in some cases crushed the inhabitants. The resistance of the houses of Guayaquil cane was very much greater. The damage consisted almost exclusively of cracks of little moment and in the fall of plaster. In the cases in which there was grave damage or total ruin the results may be attributed to the age of the building or the defects of construction.

"A very fair, though less effective, resistance was offered by the houses of sacking. This construction also is very light and elastic. There is no doubt that if Copiapó had been built of lighter material, such as wood frames with sacking and cane, as is the case in the ports of the province, we would not have had to consider this earthquake as one of maximum grade, according to the estimates in general use.

" The number of adobe houses which were totally destroyed or which suffered severe damage is considerable. Unfortunately, as I have already indicated, it was not possible for me in the course of my investigations to distinguish between those buildings of adobe brick which were not reinforced by any structural frame and those in which a frame of wood or other material had been used; but it is quite certain that the percentage of houses of the latter class must have in a measure favorably influenced the proportion of houses in which there was but little damage as compared with those in which the damage was serious.

Statistics of Damage to Different Types

			Per cent
Tapiales		440	
	Totally destroyed	249	56.6
	Seriously damaged	138	31.4
	Slightly damaged	53	12 0
Adobe bricks		349	
	Totally destroyed	57	16.3
	Seriously damaged	106	30.4
	Slightly damaged	188	53.3
Frame with brush and adobe		405	
	Totally destroyed	54	8.4
	Seriously damaged	81	20.0
	Slightly damaged	290	71.6
Frame buildings with Guayaquil cane		446	
	Totally destroyed	4	0.9
	Seriously damaged	25	5.6
	Slightly damaged	417	95.5

" With respect to the importance to be attached to the character of the subsoil in the distribution of damage in the city, it is difficult to obtain statistical data. It would appear, nevertheless, that that part of the city which is located on firm ground suffered in general less, in spite of the fact that

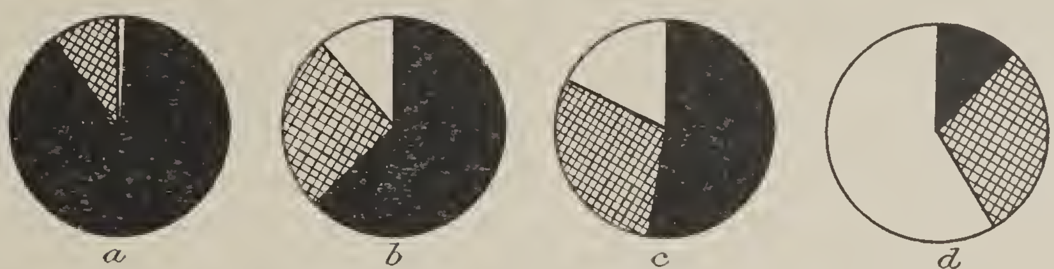


Fig. 1—Diagram showing proportion of total destruction (black), serious damage (crossed), and slight damage (white) in houses of tapiales (*a*), abode bricks (*b*), frame with brush and abode (*c*), and frame buildings with Guayaquil cane (d).

there were many houses of poor construction and many old ones. This is readily understood, for the firm ground transmits the oscillations more uniformly to the structures, while the terrane of clayey or sandy alluvium, but slightly compacted, exhibits cracks and local disturbances which indicate tension and unequal strains in the subsoil, the inequalities of which must have produced more serious damage in the edifices built thereon.

" I observed numerous cracks and local disturbances of level, which appeared to be phenomena connected with the earthquake, in the garden of the German high school and in the vicinity of the corral of the municipal inspeccion de obras publicas. In the latter place the principal crack was 100 meters in length, more or less, and 0.30 meter wide. Its course was S. 75 W. The visible depth was 0.70 meter; below that it was full of clods and earth. One of the two cracks in the garden of the German high school measured 8 meters in length, 0.20 meter in width, and 6.30 meters in depth. Its course was N.-S.

" On one side of this crack the ground was raised and had therefore experienced a very severe shock. It had nothing to do with a sinking in or faulting. I was told that in several streets there had been similar occurrences, but I was unable to verify these statements.

" With respect to the formation of cracks in firm ground I was unable to secure definite proof. It seems appropriate to mention the following interesting fact: Shortly after the earthquake a large quantity of water invaded the mines of Agustina and Bateas in Tierra Amarilla. The mine was already inconvenienced by the large quantity of water. As the amount varied with the flow of the River Copiapó according to the proportion used for irrigation, there could be no doubt that the water came from the river. The earthquake caused such an increase that it was feared that the water would flood the entire mine, but after a few days the influx returned to its normal amount. This phenomenon may be explained by the formation of a new group of cracks which provided a new outlet for the waters of the river connecting with the old cracks that had given the water access to the mine. With the formation of the new cracks the clay sediments of the river were washed down, giving to the water a muddy appearance. As the water began to diminish in volume and to recover its usual color, we may infer that the sediment which it had carried closed the system of cracks until they again became unimportant.

"I have not been able to observe any subsidence or elevation of the ground; at least, that was the result of my investigations. My observations on the coast gave a negative result. In Caldera, where the temblor was strong, I was assured by those who had seen the phenomena that shortly after the shock the sea withdrew considerably and afterward rose to 5 meters above the normal tide. This movement was repeated four or five times, but none of the observations permits us to draw any inferences in regard to even a minimum change of level of the coast.

"Herewith the data which I personally secured regarding the action of the terremoto come to an end. I subjoin in an appendix certain reports which refer to the country round about and to some points distant from Copiapó. I owe them in large part to Don Luis Sierra, Vera."

Caldera—(1) Duration of the terremoto, 6 minutes; direction N. 80 W. The cross of the church fell forward in the same direction. Heavy sideboards were moved in that direction. Almost immediately after the terremoto the sea began to withdraw and moved back and forth. The sea withdrew in Puerto Ingles. The normal advance of tide is about 27 meters, measured across the beach. The sea advanced 39 meters at the point where the beach begins at the north. The tides are generally equal in all parts of the beach, but toward the south their range at one point was 24 meters, at a second point further south 17 meters, and at the end of the beach 55 meters. In Calderilla the normal tide is 11 meters at the beginning of the beach next to the bridge, but here the sea after the earthquake rose 48 meters and at the opposite extremity to the south 141 meters horizontally. No change of level was observed in the coast. In the lawn-tennis beach cracks appeared at a distance of 200 meters from the beach and parallel to it. Damages: In the stores the window glass was broken. There were no cracks in the houses, not even in the old ones. All the houses are of wood (boards). The street lamps were shaken. It was difficult to walk during the temblor. The water in the wells remained at constant level. No subterranean sounds were heard. After the temblor low subterranean sounds were heard until January 17, 1919. The vertical movement could be felt by individuals in their own persons. There were some gyratory movements, but these were observed only in heavy objects, whereas the light ones moved in the direction already indicated. On a board covered with powder, figures and heaps were formed as if it had been hit from below upward. Three classes of movements were noted, vertical, horizontal and rotational.

(2) The wharf of the railroad was damaged by the earthquake. The sea withdrew slowly, leaving the passenger wharf high and dry, shortly after 8 o'clock. The movement was slow. The sea afterward returned, slowly inundating the beach, and almost overtopped the wharf, the height of the movement attaining 4.5 meters. The length of the wharf is about 70 meters. On board a vessel the crew experienced a vibration and were alarmed by the creaking of the beams. With respect to change of level of the coast it can not be stated whether the level is the same as before or whether it has suffered a change which is so slight that it can not be observed. On the high seas there was a strong shock which was communicated to a ship, and the passengers thought that they had struck something.

(3) The principal direction of the seism was from west to east. Vertical shocks were not perceived.

(4) There were large movements after the earthquake. The sea withdrew four or five times and returning rose to a height of 5 meters above normal tide. The waves produced by the earthquake had a N. S. direction, which is considered out of the common. There were strong movements of boats anchored in the ports, accompanied by strains in the chains of the anchors and the capstans of the boats.

Monte Amargo (between Copiapó and Caldera)—During the night of December 5-6 much strong subterranean noise was heard only in the ravines.

Potrero Seco—Moderate damage done to walls of tapiales and houses. Nothing occurred in Hornito.

Pueblo Hundido—There was a very strong temblor.

Punta Colorada—A slow temblor was experienced. The train was stopped. The oscillations were transverse and slow, as if one were in a hammock. The duration of the temblor was 2 minutes. In kilometer 530, between Almarante Latorre and Quebrada Grande, there was a rock-slide which obstructed the track. The train moved back and forth, the wheels turning a little.

Puquios—It is not possible to state with exactitude from what direction the movement came. The phenomenon began with a slight noise, but just before the beginning of the strong vertical movement was a deep, powerful subterranean sound. Afterward and continuing until February strong sounds were heard, some of them short and hard like the discharge of a cannon and others long and intermittent like echoes, but these were not accompanied by any movements. In the town of Puquios not a single edifice escaped without some damage. Several houses and walls fell into the street, some lengthwise and some across. In the works of the Dulcinea mine, including the administration building and houses of the workmen, scarcely anything remained standing. The buildings, including those of the administration, had walls of tapiales or adobe. The inclosures of tapiales fell almost without exception. They were not overthrown, however, as is commonly the case, but were completely demolished. In the works there are two wells 35 meters deep, in which the water has increased about 25 per cent. In various places small cracks or superficial fissures have opened in the meadows. The several wells in this vicinity have not shown any change. There have been no changes of level of the ground.

San Antonio i Loros—Several houses have been damaged by the terremoto, some have been destroyed, and numerous walls have been thrown down. Several irrigation canals have been completely ruined. In the hacienda El Fuerta, 2 or 3 leagues south of San Antonio, the houses were thrown down.

Tierra Amarilla—The earthquake was less severely felt here than in Copiapó and did not do any considerable damage.

Tres Puentes—Many slides obstruct the wagon road.

Vallenar—A strong temblor. People ran out into the street and patios. Many objects were overthrown. In the building of the Sección Industrial del Instituto Técnico Comercial there are cracks, among which the vertical ones predominate, almost always in the eastern or western sides. There were none in the other direction. The separation of the walls in a vertical sense is readily noted at the joint of the adobes with the uprights. They have separated so far that the light shines through and one may see through to the other side. In the first story, however, there is hardly any damage, except in the Sección Industrial, and even there there is nothing more than one floor with small cracks in the N. S. wall.

TERREMOTO[1] OF NOVEMBER 10, 1922

IMMEDIATE ANTECEDENTS

While Chile rightly has the reputation as a whole of being an earthquake region, it is nevertheless true that it may be divided into several different earthquake provinces, each of which is distinguished geographically from the others by the occurrence of shocks that are peculiar to it, both as to extent and intensity. The southern portion of the inhabited region, south of latitude 36°, of which Concepción is the central point, is comparatively free from shocks. Valparaiso and Santiago, in latitude 34°, are central in an area of extreme activity, which extends northward up the coast to about latitude 32°. Copiapó, in latitude 27°, lies in a third province of somewhat more moderate activity; and northern Chile, comprising the district from Antofogasta to Arica, is again relatively inactive. Still further north, in southern Peru, in the vicinity of Arequipa, is the most active earthquake province in all South America.

The terremoto which gave rise to this report occurred in the province of Atacama, in which Copiapó is situated, but its vibrations extended sensibly beyond Concepción on the south and northward beyond Iquique. It was, therefore, an extremely widespread phenomenon. It is possible that the conditions that led up to it may have been connected with the seismic activity of the entire coast. It is therefore desirable to note the temblors which occurred during the preceding month of October.[2]

October 4—Temblor in the south. According to advices received yesterday by the State telegraph, a strong earth tremor was felt shortly after noon in the south. It occurred at 12^h 12^m p. m., with the center in the vicinity of Constitución, where the quivering of the earth was most intense. The tremor was also felt with force at Parral, Quirihué, and Empedrado.

October 11—Washington, D. C. The seismographs in this capital registered this morning one of the most violent earthquakes of which there is record. The center is estimated to be 3,800 miles south of this city (3,800 miles corresponds to 55 degrees of latitude, and, measuring from Washington, this places the earthquake in latitude 16 south, in southern Peru). The estimate thus agrees with the advices from Peru, which follow.

October 12—Lima, Peru. An intense earthquake yesterday shook an extensive zone in the southern part of Peru, occasioning considerable damage in Arequipa and elsewhere. The railroad line between Arequipa and the coast suffered appreciably. Telegraphic communication with the south was interrupted.

October 16—Lima, Peru. Notices continue to be received regarding the earthquake in the south. The movement was confined to the department of Arequipa; Camana, Caraveli and Arequipa suffering most. In Arequipa certain buildings fell and others were seriously damaged. There were no deaths, but the number of wounded is very large. The material losses are great.

October 17—Santiago. In Constitución, according to telegraphic advices, a strong earth tremor was felt a little after 5^h 30^m p. m. It extended throughout the department. This shock was not registered by the seismographs in this capital.

[1] *Terremoto*, in the usage prevailing in Chile, signifies a destructive earthquake and contrasts with *temblor* which is used to designate an earthquake of less severity. Thus the earthquake of November 10, 1922, is called a *terremoto* in Copiapó, Vallenar, and other places where its effects were disastrous; but it is more appropriately described as a *temblor* in Valparaiso and Santiago, where the public was startled but no damage was done. We unfortunately have no similarly convenient terms in English; but the words *terremoto*, earth movement, and *temblor*, earth quiver, may well be adopted and used with their Chilean signification. That usage is to be understood wherever they appear in this report.

[2] The data here cited are taken from the daily paper, *El Mercurio*, Santiago.

October 22—Santiago. A strong temblor. In the midst of the play at the theater last evening, at 11^h 30^m p. m., there was felt a formidable temblor which alarmed the entire population. A panic was produced in the theater, which was fortunately only momentary. When the tremor had passed the play was resumed. Six ladies were assisted from the theater in a swooning condition. At midnight a strong subterranean noise was heard, not accompanied by a sensible movement.

October 28—Concepción. In the early hours of dawn today people were violently awakened by a terrible temblor which alarmed the entire neighborhood. The movement was of little duration, but of such intensity that if it had been but a few seconds more prolonged Concepción would probably have been reduced to ruins. The entire population ran into the streets in panic, many without clothing and others half dressed. The outcries of the people and the desperate flight of many, with the noise of falling shelves in stores and of breaking doors and windows, increased the general confusion. Fortunately, when the first moments were passed it was seen that the temblor had not caused the damage which at first was feared, the destruction being confined to the window panes of various galleries and doors, and so forth, and the show cases in the shops.

A short time after the first shock others of much less violence were felt, even though they were accompanied by subterranean noises. A large part of the people passed the night in the streets or in the patios of the houses. It is the general opinion that it is many years since there has been so violent a temblor at Concepción.

The greatest damage done consists in the cracking of walls of various houses, especially those of stucco and those which were adorned with heavy ornaments. In the jail of the Comissaria, an old building of poor construction, part of the roof of one of the interior wings fell with a wall. There were no personal injuries.

Notices from Tomé, Coronel, Lota, Talcahuano, describe a sharp shock but no damage. From Chillián it is reported that at 3^h 15^m a. m. there was felt an extremely violent temblor which greatly alarmed the people. The oscillations were determined as being from southeast to west, and it is stated as a fact that a long time has elapsed since an earth-shock of equal intensity with that which occurred to-day has been experienced.

October 31—Temuco. At 3^h 8^m on Saturday morning three temblors were felt, which caused no little alarm.

Coigüe. At 3^h 15^m on Saturday morning there was a severe temblor, which lasted about 15 seconds and alarmed all the neighborhood.

November 8—Copiapó. In the late hours of the afternoon, at 6^h 30^m p. m. today, this city experienced a prolonged temblor, that caused great alarm in the entire population. The movement was relatively gentle but of very great amplitude, so that people rushed into the streets in panic, fearing with good reason that the shock was a recurrence of one of those great earthquakes which have repeatedly devastated this region. Advices from neighboring places indicate the temblor was felt generally, but did no damage.

The preceding notices suffice to demonstrate that there was general activity in the earthquake zone of Chile and southern Peru throughout its entire length, in the autumn of 1922. The terremoto of October 11 at Arequipa, although not very destructive, was apparently severe enough to relieve the strain in that region, for there are no reports of particularly heavy after-shocks. The north-central district of Chile, comprising Copiapó, had no part in the movements until November 8, and appears to have been a locus of gradually increasing strain. In Santiago, in the south-central province, there was a strong temblor on October 22, and the southern province, comprising the area around Concepción and Constitución, was the scene of repeated though moderate activity throughout the month of October.

In each of these districts the shocks experienced during these weeks were of unusual severity; that is to say, they exceeded in violence anything within very recent experience; and they may be regarded as representing the culmination of a strain of moderate severity, in all the districts except that of Copiapó. In the latter the strain had attained proportions which could be relieved only by movements of disastrous effect.

In thus considering the terremoto of November 10 as an incident in the general activity of a zone 1,500 miles (2,500 km.) in length, we are linking together local phenomena, each of which no doubt is related to geologic conditions peculiar to the province in which each separate temblor occurred. Because of the disjointed condition of the materials, the rocks, it is impossible that there should be continuity of effect throughout so extended a mass. This is obviously true when we consider the numerous faults and volcanic intrusions by which it is divided into blocks of irregular shape. In the vicinity of Arequipa the mountain trends are northwest and southeast, departing at an angle of 45° or more from the north-south ranges of Chile. Throughout the latter there are many points of division indicated by short mountain ranges and basins that have the aspect of Basin Range structure. Volcanoes stand aligned along great fractures, several hundred miles in extent. Intrusions of various kinds of igneous rocks, ranging from granite to basalt, form a complex that is extremely heterogeneous in its capacity to transmit pressure or elastic waves; and these rocks are, superficially at least, so crushed that there are but few masses that would yield a respectable building stone.

From these facts it follows that unity or continuity of activity can not be regarded as a result of continuity of structure throughout this long earthquake region. The superficial facts would, on the contrary, lead us to expect local manifestations of the relief of strain; and yet it is evident from the wide distribution of the shock of November 10 that it was a general, not a local, phenomenon. To be sure, it did not extend to Arequipa; but throughout the north-south range of the Chilean coast, from Iquique to Concepción, a distance of 1,250 miles (2,000 km.), it was distinctly felt, with intensities represented by V or more of the Rossi-Forel scale. From southeast to northwest the diameter of the isoseismal of intensity IV or more appears to have attained 1,625 miles (2,600 km.), for Buenos Aires reported a strong temblor, and the island of San Felix, situated in the Pacific Ocean, 500 miles (800 km.) west of the Chilean coast, was notably shaken.

The vast extent suggested by these superficial linear dimensions indicates great depth of origin. It will appear in the discussion of the geologic structure of the region of maximum intensity that the pressure to which the earthquake is attributable originated beneath the Pacific Ocean, and that the shock was propagated eastward in the direction of thrust-planes lying at a low angle beneath the Pacific and the Cordillera of the Andes. With this concept in mind, we are in a position to understand how it is that the great terremoto affected the entire earthquake zone, in contrast to the many local temblors which have been recorded as distinct occurrences in separate parts of it. The great earthquake appears to correspond to movement on a very deep-seated, widespreading thrust-fault, while each of the minor occurrences may be regarded as representing the relatively superficial displacement of a segment of the general structure. This view of the relation of the parts to the whole and of the controlling structure was reached only after prolonged study on the ground.

EXPERIENCES IN THE TERREMOTO

At Copiapó

On arriving in Copiapó the writer received from Dr. Luis Sierra Vera a very accurate account of the earthquake of November 10, 1922. Dr. Sierra had experienced many earthquakes and some severe ones. He was accustomed to observe them and had formed the habit of promptly noting the times of beginning and passing of the different phases which might occur. His residence was situated in the upper part of Copiapó on the alluvial fan which descends from the high mountains on the east and which is composed chiefly of loose cobbles and sand, but is thoroughly drained. It was compact enough to constitute a fairly good foundation, and houses in that section were not materially damaged when well built, as was Dr. Sierra's. He was reading when the thunder of the approaching earthquake announced it. He rose to his feet, placed his watch on the table, took out his notebook, and wrote " Maximum grade." It was my privilege to see the notes which followed and, lacking the transcript which I had hoped to receive from Dr. Sierra, I quote the record from memory, as follows, in translation:

> Preliminary tremors 1′ 30″; violent phase 3′ 30″; diminishing 2′; two very strong shocks 30″; coda 4′. Total duration 11′ 30″.

Dr. Sierra described the terremoto as one not only of long duration but also of great violence, and this latter impression was confirmed in conversation with other residents of Copiapó who had experienced the earthquake of 1918. Nevertheless, it appears from the studies of tapiales, that is of the walls which were partly overthrown, that the actual acceleration did not exceed four-tenths of the acceleration of gravity and was in general considerably less. That is to say, the shock did not attain the extreme violence reached by some of the most severe earthquakes on record, and was probably comparable with the earthquake of September 1, 1923, in Tokyo. The great damage sustained by the cities in its path was due to its prolonged duration and to the very bad condition of many of the buildings exposed to it.

Questionnaires—It being impossible to interview personally any considerable number of individuals in the different towns or throughout the province, a questionnaire was prepared, with the aid of Dr. Sierra, and was officially distributed by the Governor of the Province of Atacama, Dr. Luis Romero. About a thousand were sent out and some three hundred were returned. The information which they contain varies greatly in character, and the labor of digesting the answers to the questions was considerable. We are again indebted to Dr. Sierra for the summary of results given in Appendix II. In the following notes, the data contained in a number of the questionnaires are arranged for the convenience of the reader, somewhat in narrative form, but with strict adherence to the facts as stated by the individual contributors.

Residents of La Serena

(1) Professor Gustavo Lagos, residing on Calle Infanta, was standing in his house facing north. He heard no premonitory sound. He perceived no other indication of the beginning of the shock than the movement. It came from the north. The hour was 23^h 50^m by city time. The dura-

tion was 3 minutes, more or less. He went out into the patio and observed that the sky was clear, the stars shining; but afterward it clouded over and there was lightning.

The movements varied in intensity. They appeared to be in a vertical direction, from below upward. They were all sharp from the very beginning and all of the same kind. There were about three strong following shocks between $12^h\ 30^m$ and 3^h a. m.

The walls of the house were not cracked, except slightly at the corners. It was built of adobe brick with wood ties and stood on a compact gravel formation. The roof was of corrugated iron on wood rafters. The furniture was not thrown down, but one vase fell from a table.

(2) Señor Eulijio Robles Rodriguez, Ministro of the Court of Appeals, was in his library and had just risen to his feet, facing east. He afterward did not remember what might have been the first indication of the earthquake, but thought there was a noise. The time was $11^h\ 50^m$ p. m. He did not note the duration. He joined his family and remained a long time in the street with his sons.

During the earthquake he observed that the movements diminished toward the middle of the shock, but only to be renewed with the same or even greater rapidity. Following the termination of the principal shock there were two very strong ones and innumerable slighter ones up to 5^h a. m., when he went to sleep.

He observed very frequent flashes of lightning. It was said by some that they proceeded from contacts of electric wires, but they continued after the light had been cut off.

The furniture of his house did not fall over. The house was built of a wood frame with adobe bricks and corrugated iron roof. It stood on compact gravel formation. Vertical and horizontal cracks appeared in some of the walls.

(3) Señor Alfredo Clausen, Defensor Público de la Serena, was in the street walking westward. He perceived a sound, simultaneous with the first shock. The movements came from every direction. The earthquake was from northwest to southeast. It began more or less exactly at $11^h\ 52^m$ p. m. by the city time and lasted about 4 minutes. He estimated that there were four vibrations per second. The movements varied in character, being rather more brusque than gentle, more rapid than slow.

Señor Clausen states that between the dates of November 17, 1922, and March 25, 1923, he published a number of articles on the phenomena of earthquakes and their relations to astronomical conjunctions, sunspots and so forth, combating the popular superstitions. Unfortunately, none of these articles, which appeared in *El Chilena* of La Serena, has been available for examination.

(4) Señor Luis F. Alfaro Varleta, empleado, residing at Calle Domeyko, No. 1, was seated in his house drinking maté (tea). According to his observation the first indication of the earthquake was the sudden shock itself. It came from below, upward, as proved to his satisfaction by the fact that all the water was thrown out of his wash-basin, without the latter being upset. The time was $11^h\ 55^m$ p. m. by his watch and by a clock which stopped at that time. The duration is estimated by some at 6 minutes.

During the earthquake he four times went down from the second story, in which he and his family lived, and returned upstairs, to carry them out, and when this was done the earthquake was still continuing. Three shocks at intervals of about a minute were experienced.

All of the glassware on the sideboard was thrown down, as well as vases, etc. The movements were long and brusque. The movements appeared the same in each impulse and seemed to last a minute.

No damage beyond small cracks was occasioned in his house of adobe brick and wood frame.

(5) Señorita Maria Lidia Pinto P., a teacher, living at Calle Vicuña 114, had retired, but was still awake. She perceived no indication of the earthquake before the occurrence of the shock, which began violently. It appeared to come from the north. The beginning was at $11^h\ 56^m$ by her watch, official time, and the duration approximately 10 minutes, followed at intervals by after-shocks

She ran into the patio and thence to the street, where she stayed to observe the heavens. They were lighted by electric flashes, which crossed each other at every repetition of the shocks. She had observed that the sky was clear at 9^h p. m. when she entered her house, but during the earthquake it was covered with clouds.

Dishes and glasses fell from the tables, but no furniture was overturned, nor was the house damaged.

The character of the shocks, especially at first, was very brusque and prolonged. The succeeding ones were shorter and less violent, but always very sharp. None which occurred that night was gentle. At first they came every 5 or 10 minutes and later every 20 or 30 minutes. The last occurred at 5^h a. m. and those which followed during the day were more gentle and farther apart.

(6) A telegrapher, Señor Bernardo Cortes, D., was in the telegraph office in communication with Valparaiso. He was seated facing south. The first shock came from behind him, from the north, at $23^h\ 50^m$ exactly by the office clock.

The impulses were violent from the beginning. The first were long, rapid and brusque, while the repetitions were of minor intensity and duration. The successive shocks appeared quite distinct, separated by intervals of a minute. There were two of great violence about 2 minutes apart.

The shocks were not preceded by any noise, but accompanying them were sounds such as would be made by a heavy truck. They came from the north and were the same throughout.

His house (or office) was built of thick walls of adobe with roof of corrugated iron. It was cracked in straight vertical fissures. Some articles of furniture remained standing, others (mirrors, pictures, lamps and table) were overturned.

Señor Costa adds the following observations: During the earthquake he observed a sudden change in the sky, which, having been clear and starlit, became overcast, clouded and lighted by lightning flashes from the north. The clouds drove rapidly toward the northeast. For some days prior to the catastrophe the sea had been very tranquil and at a slightly lower level than usual, so that the subsequent change was even more notable. There was a decided change of temperature during the same day (November 10). During several days previous he noted an uneasiness among animals (steers and cows) in the pastures near his house, particularly at night, a condition which made him cautious.

RESIDENTS OF COQUIMBO

(1) Señor Eduardo Olivares Quadra, an employe of the post-office, residing in the port of Coquimbo, was standing and at the moment of the shock was reading. He faced north. The first indication of the earthquake was an immense subterranean noise. (Coquimbo is built on a peninsula of solid granite.) The oscillations appeared to be from right to left, as if the shock came from the Cordillera of the Andes. His watch gave the hour as $11^h\ 57^m$ p. m. by telegraph time. The duration was approximately 3 minutes. He aroused and dressed his children.

There were two principal shocks at an interval of a minute apart. The first was slow (lento), strong (ipero) and longer; the second was short and sharp. The former he estimated to have lasted 90 seconds and the latter 30 seconds.

The sounds accompanying the earthquake had the character of those produced by great rockfalls in a mine. Their direction could not be determined with precision.

The house, No. 1411 Calle Aldunate, was built of light materials and stood on rock. It suffered no damage of any consequence. But tables, wardrobe and other articles of furniture were thrown down and overturned from east to west.

Señor Casandra supplies the following notes:

The night of the earthquake was one of great calm. There was only a slight breeze from southwest, with a suffocating heat. The sky was completely covered with clouds. It was about $11^h\ 52^m$ that a terrifying subterranean noise was heard and was followed in a few seconds by the earthquake, which comprised two strong shocks, proceeding from east to west, while the sky was lighted by lightning flashes.

About two hours after the earthquake came the maremoto with its three successive waves. The last was the one which did the most damage. It rose to an altitude of 5 meters and attained a distance of 2 km. in the lowest part of the coast. Elsewhere parts of the shore suffered not at all from the wave, indicating that the waters were impelled by strong currents from northwest to southeast. (Coquimbo Bay is a cul-de-sac opening toward the northwest. The wave, passing the wide entrance, was low and did not rise high along the eastern or western shores, but the waters were constricted at the southern end and attained an extreme height of 7 meters above mean level at the railroad wharf—B. W.)

RESIDENTS OF VALLENAR

(1) Señor Ivan Franulic, residing at Calle Pratt No. 1274, was standing in his bedroom, awake. He experienced no warning. The shock struck suddenly. He did not observe the direction or the time, but seized his son to escape. He could not open the door. A wall fell, suffocating them with dust. The door opened and he ran out to the street, where it seemed that the earth would open. "The earthquake was strong enough."

There were at least 3 shocks in 4 minutes. They were rapid and sharp. In the house pictures fell and furniture slid, but the mirrors did not fall and windows were not broken. Drawers opened or closed according to position. Those facing south remained closed; those facing north flew open.

(2) Señor Lacarias Rojas Veregara, a tailor, was in the Grand Hotel Vallenar. He was lying down but awake, facing north. He first perceived a noise, which appeared to come from the east. On hearing it he jumped for the key of the door and the shock struck. Grabbing his watch from the bureau, he observed the time to be 11^h 55^m p. m. He estimated the duration at 3 minutes. Seeking to escape, he fell in jumping from the veranda and landing on all fours remained in that position till the earthquake was over.

There were three shocks, the first from the east, the second from the south, while in the third it appeared that the earth would fly to the sky. The respective durations of the several shocks was 1.5 minutes, 30 seconds, and 1.5 minutes. He could take account of these details, since he had no family in Vallenar. The sound which was like subterranean thunder came from the Cordillera de los Andes, and had lasted 5 seconds when the shock struck. The subterranean sounds continued after the earthquake and resembled waves passing toward the ocean.

(3) Señor Arsenio Tapia Opuso Molina lived at Calle Pratt No. 1728. He was a merchant and agriculturist and was in his house writing. Although lying down he was awake and somewhat nervous. He faced north. He did not observe any preliminary indications, but experienced three shocks which seemed to come from the east. He remained in a doorway until the shocks ceased. It seemed as though the house must fall, to judge by the movements (somajeras?) which shook the timbers. The movements were long, rapid and brusque; each one lasted a minute and followed one upon another. There was a sound like thunder, which seemed to come from the coast. His house of adobe with wood frame was rendered uninhabitable, the walls being cracked and thrown out of plumb.

(4) Señor Guillermo Gray Lopez, of Calle Serrano No. 1357, and engaged in business as insurance and commercial agent, was in his room about to retire. He first heard an exceedingly strong noise, which seemed to come from below. The hour was almost 12.

As he ran through the first passageway of his house, which was very narrow, carrying a two-year-old daughter, the eastern wall fell upon him and threw him against the western wall, where he remained buried to the waist. The child was unhurt and was cared for by its mother, who then freed her husband and supported him to the patio. He states that although he was so injured as to be unable to move, he did not lose his sense of direction, in spite of the darkness of the night and the confusion of falling walls.

The movements were long, rapid and brusque; they came from every direction, some horizontal, some vertical, and each was of prolonged duration, a minute or more. They were preceded by a very brief interval by a subterranean noise resembling that made by a heavy cart rolling over a pavement.

His house stood on loose ground. It was built of adobe and wood frame, with some walls of tabique. Two out of three rooms in the western part remained standing, but ruined. The rest of the house was all thrown down except the party walls of adjoining houses.

(5) Señor Leonio Bardian Ovalle, cashier of the National Bank of Savings, and residing at Calle Pratt No. 1067, was standing at work in his office. He was facing north. He first observed a most powerful noise, followed immediately by the shock. The movement came from left to right, from the ocean toward the Cordillera. The time was 11^h 46^m by the office clock, which was then stopped. The duration he estimated at 3 or 4 minutes.

He ran at all speed to his room, where he remained in the protection of the door of his room during the entire earthquake.

He observed two principal shocks, without any cessation of the vibrations. The movements were all long and brusque. In the stronger ones the ground seemed to jump from above downward, but the dominant movement was from the sea toward the Cordillera. So violent were the oscillations that he was obliged to cling to the door with arms and legs in order not to fall on his face.

The building had a front and left lateral wall of tabique (wood frame); while the back and right lateral were of tapiales. The light walls of tabique remained upright, but the tapiales were thrown down and the roof with them.

(6) Señor Agustin Banaza was lying down but awake, when he heard a noise like the tearing of cloth. It appeared to come from above. The shock came from west to east, since the walls of the house fell in that direction. The hour was 11^h 55^m p. m.

He was unable to remain upright and dragged himself out into the hallway. There were three shocks, of which the second appeared the strongest. The movements were prolonged, rapid, and brusque. Each appeared to last a minute.

The house consisted of six rooms, of which four were of tabique with adobes, the rest being of adobe walls. The latter fell, but the frame house remained habitable.

(7) Señor Guillermo Gallo, living at Calle Serrano, corner of Talca, an agriculturist, was lying down in his house, awake, reading and facing east to west. He first perceived a great noise and shock,

more or less at $11^h\ 50^m$ p. m. The duration he estimates at about 4 minutes. He at once ran to save his sons, and since he was moving about constantly during the earthquake he does not trust himself to give details. But he is sure the shock came from the sea, moving toward the Cordillera. The furniture was thrown down, including sideboard and wardrobes measuring 1 to 1.20 meters by 2 to 2.50 meters. They fell forward from north to south.

The house consisted of a wood frame of 4 by 4 inch timbers braced diagonally and filled with small adobe brick. It had no rafters and was not wired. Some of the adobe brick fell out, and the plaster fell. Two rooms were crushed by the fall of the adjoining house, built of tapiales and adobe brick, which was a complete ruin.

(8) Señor Victor Arochas, a traveling salesman, who resided at the Hotel Pardo, was walking in the street. The first shock struck as a single blow from below upward. The time was $11^h\ 53\frac{1}{2}^m$ and he observed with his watch in hand that it lasted 7 minutes. He struck a light and sought to avoid being knocked down, as the street was very narrow. The shocks were brusque, rapid and distinct, each one lasting 3 seconds, according to his observation. He compares the noise of the earthquake to the breaking of great quantities of glass.

(9) Señor Rector Miranda Alvarez, of Calle Pratt No. 1490, was asleep in his house adjoining his store, it being his habit to retire early, as he is at pains to state. He lay with his head to the sea and feet toward the Cordillera. He is of the opinion that he woke before the earthquake actually began. He observed a brief noise and immediately after it a great movement of the earth, which appeared to come from the sea toward the Cordillera. The furniture was thrown in that direction. He sprang from bed and ran to place himself in the large doorway which opened into the store. After the first shock he sought his brothers and brought them to the same place. But he observed three distinct shocks, with the following details: After the first sound came a sharp movement which was followed by a calm, as if it were finished, but the movement then recommenced with almost greater force than before. The movements were distinct one from another, their direction being unlike. It did not seem possible to estimate the lengths of the shocks, but he would judge that they lasted several seconds.

(10) Señor Eduardo Wolf, a builder, living at Serrano, corner of Colchagua, was asleep in a "chalet" on Calle Serrano, lying with his face toward the east. He first perceived a violent shock. The oscillations appeared to come from all directions. He could not say in what direction the earthquake advanced, other than that it moved from east to west. By his watch it began at $11^h\ 45^m$ p. m., and lasted 5 minutes, more or less. He dressed himself, it being impossible for him to get out in the darkness. His cot having been overturned, he could not find the door. He repeats that the first shock was long and very violent, the others, which he could not count, were shorter and less violent.

Señor Wolf adds the following information regarding the ground under Vallenar, basing his statements on his experience as a builder. Between the plaza and the upper part of the city, as well as between Calle Merced and the river, the formation is gravel, which is on the average 2 meters deep. It rests on clean sand. North of Calle Merced and up to the north embankment (of the terrace) the gravel is but 1 meter deep and rests upon hardpan (or mud?) ("fango"). From the plaza to the station. the hardpan? (fango) is met at shallow depth and consequently there is water at a depth of a meter. All the houses of Vallenar tremble when an automobile or cart passes. He is therefore of the opinion that the subsoil is quicksand or fango throughout.

RESIDENTS OF FREIRINA

(1) The curé of Freirina, Padre Felix Morey Amengual, was in his house, lying down but awake. He faced south. The first indication was a sharp blow like that of a bomb exploded beneath the earth. It came from below upward. Following the first blow there came oscillations of great rapidity, at first from the sea toward the Cordillera (west to east) and afterward from north to south. The hour was 2 minutes before 12 by his watch. The destructive shock lasted half a minute. He was unable to go out by any of the doors and finally escaped by a hole between the roof and the fallen walls.

He did not clearly recall the number of shocks, but would say that there were three or four destructive ones and afterward many strong ones which followed each other very rapidly, during the night and following day. The first movements were extremely rapid and brusque. The others were not equally so, but nevertheless were rapid and sharp. He states: "I do not feel able to define the duration of the individual shocks, but in my judgment during the 24 hours following, the earth did not cease to oscillate, although imperceptibly, the heavier shocks succeeding each other at irregular intervals." No sound of any kind accompanied the first shock, which felt like an explosion. The following shocks produced a noise, which was amazing and terrifying. They all came like explosions.

His house of tapiales, surmounted by adobe bricks, standing on gravel and boulders, consisted of two wings. The north-south one fell, whereas the east-west one did not. But all the walls were cracked or thrown out of plumb.

RESIDENTS OF HUASCO

(1) Francisco Quinones Gorman was asleep in his house in Huasco with his face toward the coast. He perceived no preliminary indication of the terremoto, which struck suddenly. It appeared to him to come from northwest, and lasted several minutes. The hour was $11^h\ 55^m$. He remained in bed, hoping it would pass, but on learning of the rise of the sea he fled. The first shock was long and strong. The succeeding ones were short, but still strong and rapid. They lasted 10 seconds more or less. The sound began simultaneously with the temblor. It sounded like thunder.

His house was built on solid rock of wood frame and roof of galvanized iron. A part of the plaster fell. A jar, full of "loza," fell to the floor and rolled about.

(2) Señor Pedro 2d Ruiz was in his house, sleeping with his face to the west. He experienced a strong shock which appeared to come from in front. The terremoto advanced from south and west, to judge by the falling of objects, which was in the opposite direction. The duration was 10 minutes. The hour was $23^h\ 50^m$, official telegraph time of Vallenar.

He gathered his family in the passage of his house, preventing their running out, while he looked for matches, lighted a candle, and they dressed themselves.

There appeared to be three principal shocks, at very short intervals, but it shook continuously. The shocks were long, rapid and brusque, each lasting approximately 3 minutes. Having been asleep, he recognized only the terrible noise that accompanied the terremoto.

The articles of furniture overthrown were a center table, wardrobe and "veladores." They fell in part to the north and in part toward the west. This statement applied also to the walls of the enclosure.

RESIDENTS OF CALDERA

(1) Señor Enrique E. Ramirez, an official, was asleep in his house, facing north. He first perceived a great noise, which appeared to come from in front of him, whereas he states that the earthquake came from the south. The hour was $11^h\ 45^m$ p. m. and the duration was 7 minutes. He ran into the street with his little children. He did not distinguish separate shocks, but observed an equality in noise and vibration throughout.

He adds the following information regarding the maremoto: The first rise of the sea occurred about $12^h\ 30^m$. The greatest wave advanced between 2^h and 3^m a. m. of November 11. At Ramadas Point the advance amounted to 600 meters and to 125 meters along the harbor front. The customs house, railway station and other buildings were destroyed or moved.

(2) Señor Jorge L. Becerra, Alcaide de Aduana, was asleep in his house facing north. He was awakened by a strong noise, which came from the north, from the right, from below upward in front. The terremoto also appears to him to have come from the north. The hour was $11^h\ 50^m$ according to his watch, which kept good time. The duration he estimates at three-quarters of an hour of constant trembling. He got up and ran to the playa to see the maremoto, which destroyed the customs house and other buildings. (It is difficult to reconcile this apparently immediate action with the times given in the preceding account.)

(3) Señor Bernado Tornini, a merchant, was on board the steamer *Flora*, anchored in the bay. He was sitting in the cabin with friends, looking toward the north. He first heard the sound, which began about $11^h\ 50^m$. The duration was about 5 minutes. Of the group, which included the captain of the vessel and the harbor master, together with several others, Señor Tornini was the first to give the alarm. They went on to the deck and walked from stern to prow. They observed many lightning flashes, some of which seemed to fall on the poop of the steamer in a terrifying manner. On going ashore they encountered a warm rain, which began to fall about half an hour after the beginning of the terremoto. The sea rose several times, but without surf, and at its greatest advance attained a height of 6 meters above the highest tide.

(4) Señor Guillermo W. Lavan Rives was on board the steamer *Flora*, anchored in the bay. He was standing facing east. There was a noise which he took to be that of the winches of the steamer. He went ashore, and 15 minutes after the beginning of the terremoto he observed close at hand the initial rise of the maremoto, being at the time in the boat in which they came from the ship. While we were still at a short distance from the passenger pier the sea had begun its first slow rise. When the landing-steps were reached they could not use them, because the boat was on a level with the flooring of the dock. This first rise attained a height of 5 meters, more or less, above high tide.

The several advances of the sea which followed were greater than the first, but always gradual. The maximum attained 7 meters above the normal stage and advanced 35 meters more or less, doing much damage. It occurred about 3^h 30^m a. m.

(5) Señora Ana S. de Baez, Administrador de Correos Telegrafos, was walking in the street and did not perceive any indication before the earthquake, which began at 11^h 48^m by the official time of the state telegraphs.

After the earthquake the sea remained completely tranquil, that is, without waves, but after 30 minutes began to advance. It rose without noise and without surf. Between 12^h 30^m a. m. of November 11 and 9^h a. m. of the same day the sea advanced many times, each advance lasting 20 minutes, more or less.

According to approximate estimates, the greatest advance was 50 meters in the higher parts of the port and 100 meters in the lower part. The level reached by water is estimated at 5 meters above the level of the sea. The greatest occurred between 2^h and 4^m a. m.

These data la Señora Baez submits as in accord with the facts, while admitting that there may be some errors, since it was impossible to observe and estimate in all its magnitude a phenomenon so unfamiliar to the experience of those living on the spot.

Residents of Chañaral

(1) Señor Guillermo Zepeda was in his house on Calle San Martín, Chañaral, sitting, looking toward the northwest. He observed a subterranean sound accompanied by a sudden, brusque shock. It came from behind him. The oscillations were from the sea toward the Cordillera. The shock began at 11^h 50^m. It lasted 3 minutes with maximum intensity, and continued during half an hour of minor oscillations. He rose to his feet and would have run, but the movements of the ground made it difficult even to stand.

There were about three principal shocks at intervals of 2 minutes. The movements were long, rapid. gentle (suaves) and regular. During and after the terremoto, when the sea rose, people observed a kind of roar in the bay, which led them to think a volcano might be in eruption. The noise of the terremoto began with the first shock and resembled the noise that accompanied the maremoto. Although very much louder, it resembled that of heavy surf. The day following the earthquake it was observed that the sea had withdrawn, leaving a great extent of the playa uncovered.

(2) Señora Maria Isable T. Zeballos, Director of Primary Instruction, was asleep facing the south. The shock itself was the first indication she perceived. It appeared to come from the east, from her left, because on rising to her feet she leaned to that side. The earthquake was not alarming. She partly dressed and went into another room. The maremoto began an hour after the shock and continued about 4 hours. The sea advanced three times. It rose 9 meters, destroyed 14 blocks of houses, and swept 4 blocks inland. The movements were gentle, but prolonged. The sound preceded the shock and resembled that of a heavy cart. She did not notice any variations of the movements.

(3) Señor Oswald Fernie, engineer, though lying down was awake. The first indication was the sound, which came from the south. The terremoto began, more or less, at 12 o'clock and continued 3 minutes. He remained a minute in bed and the rest of the time in his room. He observed the movements to be almost continuous and slow and gentle.

Residents of Copiapó

(1) Professor Carlos A. Gonzales H., residing at Chañarcillo 1010, was sitting in his house facing northwest. He first perceived a loud noise like thunder from the northwest. He judged, by the direction in which the walls fell, that the earthquake came from the northwest. The hour was 11^h 55^m by his watch, which he had set that same day with the railroad time. He was unable to estimate the duration. He went out into the street with his family, not running, but pausing long enough to sense the oscillations and seek a safe place. There were three shocks at brief intervals. The first was prolonged, rapid, but gentle; the second was sharp. They were distinct and lasted during minutes.

(2) Señor Luis A. Romo Ch., Intendente of Atacama, was in his bedroom, lying down, but awake. The first indication of the earthquake was a subterranean noise of great intensity. It came from the south and very soon from underneath. The earthquake came from the south, as was demonstrated by telegraphic advices. It occurred at 23^h 55^m, by a good watch compared with the telegraph time. The duration was about 4 minutes by his watch. He remained in bed during part of the movement and then went out into the patio and remained standing, holding on to a tree to avoid falling.

He observed two shocks, a first and afterward a second, which was more violent and caused him to leave his bed. The movements he describes as prolonged, almost continuous, rapid and brusque. The movement was indeed almost equal. It was an earthquake of great intensity throughout. The sound was heard first. It suggested the rolling of a cart or of many carts of enormous weight, coming from the south; subsequently the shaking and groaning of the structure, as well as of the door and windows did not permit the earthquake sound to be heard. The furniture fell and danced. It comprised wardrobes, stands (estantes), and an iron safe, which measured 70 cm. Most of them fell toward the west. The house was a wood frame with cana de Guayaquil, the roof of wood and galvanized iron. Some of the timbers were broken, the frames were partly wrenched apart, and most of the plaster and ceilings fell. Nearly all of the adobe wall surrounding the inclosure fell.

(3) Señor Federico Melendez M., of Calle Infante 551, was at Calle Rodriquez 440; had just gone to bed and was reading. He faced northwest. The first indications were a noise and small shock which lasted a second. He thought it came from in front; that is, from the northwest. In his haste to save his children he took no note of the direction of the movement or of the time. He put on his trousers and succeeded in finding his shoes, but dropped them to pick up a child asleep near him. Having opened the door, he remained standing in it and did not run out because the child was

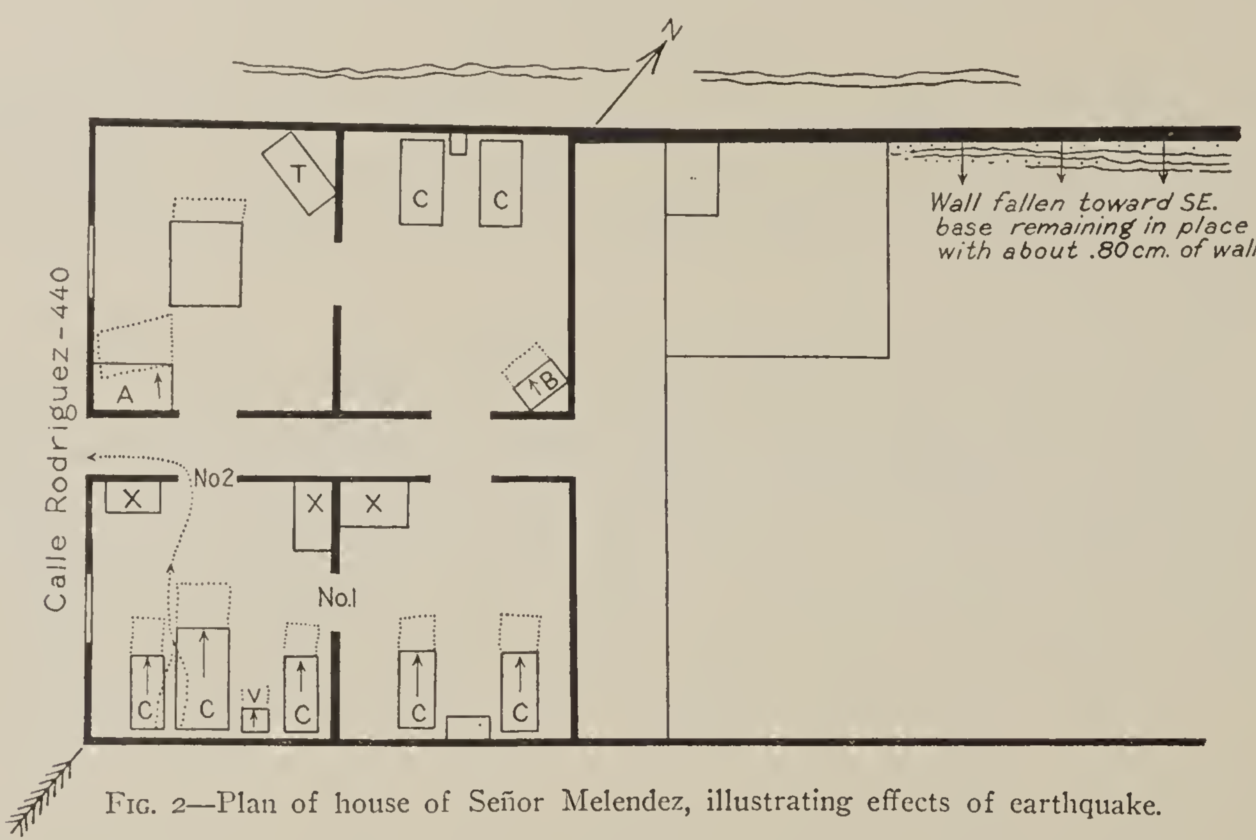


FIG. 2—Plan of house of Señor Melendez, illustrating effects of earthquake.

naked. His wife did not stop for clothes, but gathered up the baby and little boy and ran toward the inner patio. As he sought to follow her the door on the northeast (No. 1) side of the room slammed in his face, while that on the northwest (No. 2) opened. By it he ran into the hallway and so to the street. Señor Melendez gives details of the displacements of furniture as shown here:

He thinks that after the first swinging shock there was a single one, whose vibrations were intense and were maintained possibly for 5 minutes. It appeared to him that the movements began from northwest to southeast and afterward developed in all directions, with dominant brusqueness in the initial direction. He observed that the waves were long and well defined, momentarily interrupted or cut off, producing very notable horizontal shocks due to inertia in a northwest to southeast direction.

His house stood on comparatively firm ground (compact gravel and cobbles of a coarse alluvial fan) near the base of the mountain (east of the city). It was built of wood frame with cane (caña de Guayaquil). It suffered no other damage than that of cracks above the doors and windows.

(4) Señor Manuel Corona, F., agent of the Sociedad de Minas i Fundación de Carrizal, was sitting in his house at Calle Infante 1060, facing north, under an electric light. The earthquake was initiated by a great noise and shock almost simultaneously. He could not state the direction. The hour was $11^h\ 50^m$, at exactly which time there stopped a large pendulum clock that was kept on railroad time. He did not note the duration, but could estimate that the strong movement lasted 4 minutes. He left his room to go out on to a porch, turning on the electric light, but it was quickly

cut off. As the movement continued to increase he ran out toward a tree and held on to it, since he had difficulty in remaining erect. The motion began to decline, but as it still continued he ran into the open toward the hill, but did not go on, as the shocks had greatly diminished. He is unable to describe separate shocks. The movements appeared long and not very brusque. A stand (estante) and bureau were thrown down and nearly all articles were moved out of their places.

His house stood on cultivated ground and was of wood frame with cane (caña de Guayaquil). It suffered no damage except loss of plaster and stucco and the breaking of some beams, which were in poor condition.

(5) Señor Luis G. Brand, C., Professor del Liceo de Hombres, was in the Liceo lying down but awake, and facing southeast. He first noticed a strong noise, but did not observe its direction. He judged that the earthquake came from southwest toward northeast by the movement and the noise of the windows. The hour was 23^h 46^m, by Santiago time. He estimates the duration at 4 minutes. He went out into the patio and there awaited the termination of the shocks.

In addition to that which he designates the terremoto itself, he noted a second and a third temblor with intervals of 4 and 2 minutes. The movements were long, rapid, and brusque. The shocks were distinctly separated. He observed the sound which preceded the shock. It resembled that made by a heavy cart.

The building stands on firm ground (compact gravel and boulders) and consists of wood frame with caña de Guayaquil. The ceiling was cracked and part of it fell.

(6) Señor Jose Escanriaza, chief of the third telegraph district, was walking in the street facing northwest. He first perceived a loud subterranean noise, followed by a temblor of moderate intensity ("regular intensidad"). It came from the south, according to telegraphic reports from Vallenar. He had no watch at hand. He ran to avoid being crushed by falling walls. There were two shocks, the first of moderate intensity, but increasing in violence almost immediately. The sound resembled that of a heavy cart.

(7) Señor Ladislav A. Arestizabal, an apothecary residing at Calle Carrevas 708, was in his house, asleep. He was awakened by a great movement accompanied by much noise. He is unable to say from what direction it came. The hour was 23^h 50^m, more or less, and the duration 6 minutes, by his estimate. He started to dress, but to save his child he was obliged to desist. Naked he ran to the balcony and jumped into the street. He received the child from his wife, whom he assisted to descend, and they ran to the plaza for safety. After the first shock, he felt many others, at intervals which he could not estimate. There was a great deal of noise, in part like thunder with detonations. Immediately on going into the street he observed a light in the north, the heavens being rosy. The stars appeared to tremble. The movements which followed the principal shock were of long duration, at least some of them, but of almost uniform intensity, like the swinging of a hammock. The barking of dogs increased the sense of tragedy in the situation. There were times when one sensed only the great noise, without movements that could be perceived without instruments.

(8) Señor Felix P. Olea, an attorney and notary public, living at Atacama No. 545, was seated in his bedroom looking toward the south. He first perceived a noise which appeared to come from in front to the right and from below. The hour was 11^h 50^m by his watch. The duration he estimates at 6 minutes. He jumped to his feet to prevent his wife and child from running out, as he had great confidence in the construction of the house. The movements were many and very continuous. They were long, especially the first, and repeated many times; some were rapid and sharp; some of those which succeeded the first occupied more than half a minute. The sound preceded the first shock by about 10 seconds. It resembled that of an automobile and appeared to come from the southwest. All of the furniture was overturned in the house, which stood on cemented gravel. It was of wood without plaster, except two interior rooms which had mud roofs; they fell in.

(9) Señor Aristides G. G. Zoraguín, professor in the School of Mines, was sleeping lightly in his house at Avenida Juan Martinez No. 128. The first indication was a noise like distant carts, followed in a few seconds by the movement. It appeared to come from the west, judging by the displacement of the furniture. The piano, wardrobes and other heavy furniture marched from east to west and reached the middle of the rooms. The hour was 11^h 47^m by railroad time. The duration was perhaps 4 minutes. He remained standing in the middle of the street watching the oscillations of the building from south to north and the wave-like movement of the earth. There were three principal shocks, the last being the most violent. They were rapid and brusque.

The house was of wood frame, filled in with small adobe brick. The section which consisted of these materials, with wire inside and out, suffered no damage whatever. The same was true of a part which consisted of a wood frame filled in with brea (brush); but in another part where the walls were filled with adobes, the frames separated at the corners. The suburb in which his house is situated is near the mountain and it is noteworthy that not a single house in it was thrown down, although some of them were of poor construction. Yet they were not damaged in the least.

(10) Señor Oscar Letchier, La., apothecary, living at Calle Atacuna 477, was lying awake in his house, when he perceived a strong shock. It appeared to come from all directions. The hour was $11^h\ 55^m$ more or less. The duration was about 10 minutes, as he would estimate. He carried his youngest son down stairs and returned for his wife and other children, who had remained, as it were, paralyzed. He recognized three shocks, almost without intervals of quiet. The movements were long and rapid, very brusque, unlike any he had previously experienced, and lasted three minutes more or less. The sound began at the same time as the shocks and resembled the discharge of heavy artillery. The noise was so great that his voice, which he describes as somewhat powerful, could not be heard 3 meters away.

(11) Professor Pedro Villagran Arrayo, living at Rodriquez, corner of Vallejo, was standing in his house facing southeast. He first perceived a loud subterranean noise, which came from the southwest. The time was $11^h\ 50^m$ by his watch. The duration was 10 minutes by his estimate. While his wife opened the doors to allow the children to escape to the street, he ran to one who was still sleeping. They then fled to a crossing of two streets, where they remained during the rest of the earthquake. He did not observe the number of shocks. The terremoto began with a rapid movement, which demonstrated the great danger. After about 3 minutes it became very violent and irregular. The earth rocked in every direction. After about 5 minutes it returned to its initial period with regard to the intensity. Very soon after the earthquake began the city lights failed, leaving everything in complete darkness. On entering the street one observed great lightning flashes in the southeast, which illuminated the tragic obscurity. That lasted a few moments. Shortly after the terremoto had ceased the atmosphere began to undergo a complete change. From having been clear it became humid and cold and 2 or 3 hours afterward began to drizzle.

(12) Señor Samuel Jenkins, an agriculturist and miner living at Calle Colipe 475, was lying asleep in his house, when he was roused by a loud and very violent noise. He faced south and it appeared to come from the right, that is from the coast. The hour was $11^h\ 50^m$ p. m. The terremoto lasted during 2 minutes of great violence and 5 minutes of less intensity. He remained in his room. There were two shocks at intervals of a minute, more or less. He noted both horizontal and vertical shocks, in alternation, the same being very hard. The noise at first resembled thunder and then became confused with that of shattering windows and falling roofs.

Residents of Tierra Amarilla

(1) The Secretario Municipal of Tierra Amarilla, Señor Juan 2d Echeverria, was sitting in his house facing the west and first perceived a great noise, together with a very brusque movement, which came from in front of him. The hour was $11^h\ 55^m$ and the strong movement lasted 2 or 3 minutes. He ran out into the street and went ahead to avoid falling. He and a friend helped each other to stand by holding hands. He estimates the number of shocks at five or six of high intensity at intervals of quarter of an hour apart. They were long, rapid and brusque. The shocks which followed the great temblor were quite distinct from it. The noise at first resembled that of a train. During the succeeding shocks it suggested a heavy cart rolling over hollow ground. Some articles of furniture were thrown down and fell toward the east. The house of wood frame filled in with brush and mud plaster was not cracked. Some cracks appeared in the roof of mud and rushes.

Señor Echeverria further observed that the railroad was damaged by the caving of fills. Pendulum clocks were stopped. Pictures and other hanging objects banged against the wall. Windows were broken. There were electric discharges, and in the mines some timbered stopes caved in.

Residents of Puquios

(1) At Puquios, the most eastern point from which the questionnaire was returned, Señor Arthur C. Cahera, a mining engineer, was sitting in the house of a friend when the terremoto began. It came from the south according to the way it felt. The hour was $11^h\ 55^m$, official time. The duration was 3 minutes. He took the time. During the movements he went out into the street and took a "pimiento." He felt four shocks separated by distinct intervals, the length of which he did not observe. The movements were long and rapid, not to say brusque. They were distinct and the last was from below upward. Each one lasted 45 seconds by his estimate. A noise began simultaneously with the shock. It resembled surf. It seemed to come from the east. Furniture did not fall over, but was moved out to the middle of the room. The house stood on compact gravel and sand. The house, consisting of wood frame with walls of caña de Guayaquil and adobe, was wrenched at the corners. The wall of adobes surrounding the inclosure was damaged throughout its extent.

Residents of Salado

(1) At the railroad station Estación de Salado, situated 35 km. inland from the coast, the station master, Señor Carlos J. Duarte, was in his room lying south to north and awake. He heard a sound like a locomotive approaching rapidly from the west; that is, from the coast. At the same time he seemed to hear the sea breaking close at hand. The hour was $11^h\ 55^m$ by railroad time, and the duration was more than 5 minutes. He observed that the sky was lighted as by the moon for the space of 5 minutes, after which darkness set in again. There were many shocks, which continued until 7^h a. m. next day. A sideboard and shelves were overturned toward the west. No damage was done to the station, which was built of wood and roofed with galvanized iron.

Residents of Potrerillos

(1) Señor Hernando Osandon D., a chemist, was in the mining camp of the Andes Copper Company. He was about to fall asleep, when he experienced a severe earthquake shock. It was 6 minutes before 12 by his watch, which was set by the mining time and presumably by that of the railroad. The terremoto lasted about 5 minutes. Awakened, he lighted a candle, looked at his watch, got up, and opening the window looked out. He then went to bed and followed the movements of the ground. There were possibly three shocks at equal intervals, but the movement appeared continuous, except that a fresh impulse was given three different times. He states that he did not suppose there was any sound except the earthquake, but what there was resembled the rolling of a heavy cart a long way off. It appeared to come from the east.

(2) Señor Hermogenes Pizarro A., was at Agua Helada, a camp northeast of the mining camp of Potrerillos, about 4,000 meters above sea. This is the highest point and the farthest northeast from which any information has been received. He was asleep facing east and was awakened by the movement of the ground. The shock came from southwest and moved northeast, at $11^h\ 50^m$ p. m. Potrerillos time. He did not observe the duration. He went out and stood on a point of rock nearby. There were two shocks about 20 seconds apart. The second one was much the more intense. Cups fell from the shelves toward the northwest, the shelves themselves extending southeast to northwest. The movements were horizontal from southwest to northeast. They were slow and gentle. The intensity was almost constant during the first 30 seconds and then increased. Each movement lasted about 30 seconds. He did not perceive any sound.

EFFECTS ON MONUMENTS

In the city of Copiapó there were three monuments which were notably damaged by the terremoto. They all stood on the Alameda, a street running from firm granite down an alluvial cone of coarse cobbles and sand to the river, and consequently differing in the character of the foundation material. The first of the monuments, dedicated to O'Higgins, stood nearest the hill on the firmest ground. It was a marble shaft standing on a pedestal and it remained intact, but was rotated at the joint of the pedestal and shaft through an angle of 3°. The bottom moved from left to right, anti-clockwise with reference to the top section.

The Matti monument, erected in honor of a local citizen, consisted of a bronze statue on a lofty stone pedestal. The statue fell toward the river, because the actual base on which it stood consisted of two stone slabs, and the one on that side gave way when the shock threw the weight of the bronze upon it. The violence of the vibration that enabled the shock to tilt the bronze may be attributed to the character of the soil, which was soft, this statue being nearer the river than either of the other two.

Between the O'Higgins and Matti monuments stood a more pretentious structure dedicated to Atacama. The pedestal was 12.6 feet (3.85 meters) high and was surmounted by a bronze figure 9.5 feet (2.9 meters) tall. The pedestal consisted of several sections. At the base was a wide concrete block representing four steps; it was followed by a segment built up of four tiers of brick, laid in weak mortar; and upon this came a concrete structure, said to be hollow and modeled with appropriate offsets. Between the pedestal proper and the bronze there was interposed a thin concrete slab, which was not seen from below, but which, as it was not fastened in place, formed a loose segment between the pedestal and the statue.

The most obvious effect of the earthquake was to throw the statue in such a way that it came to lie with its foot about 21 feet (6.5 meters) from the center of the monument and its head toward the latter (*c* in Fig. 5). It was evidently thrown with violence and its path was apparently such as would be communicated to it by rotation of the pedestal in a clockwise direction.

The pedestal of the Atacama monument showed abundant effects of rotation. The bricks between the two masses of concrete were crushed, rounded and displaced

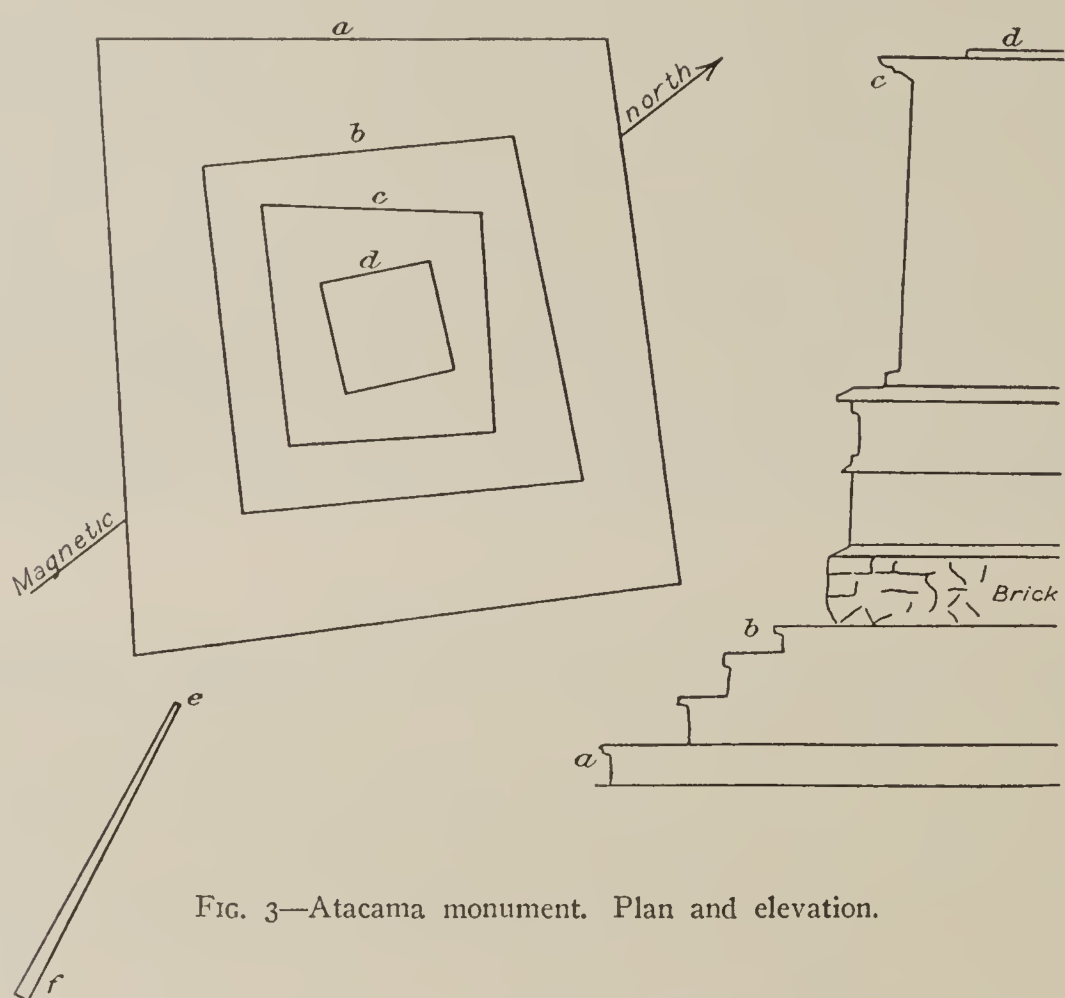


FIG. 3—Atacama monument. Plan and elevation.

as if the base had twisted about under the superincumbent weight and the shearing had been concentrated at the weak joint. Upon ascending to the top it was found that the thin slab upon which the statue had stood was twisted about on the next lower section and yet was nearly parallel with the steps of the base. It seemed as though the inertia of the statue had held the thin slab steady while the entire pedestal turned clockwise under it. This movement threw the statue. The slab appears thereafter to have remained fixed on the pedestal which stood still, while the base turned under the brickwork in an anti-clockwise movement. This may have been the case, but it can not be demonstrated, for the sides of the different sections were not originally parallel and it is impossible to reconstruct their positions before the rotation occurred.

This conclusion follows from the observations of compass courses on the several sections on all four sides, which are given below.

Section	North side	East side	South side	West side
Loose slab	N. 26° E.	N. 64° W.	N. 25° E.	N. 65° W.
Top of concrete	N. 40° E.	N. 56° W.	N. 34° E.	N. 58° W.
Brick section	Crushed			
Top step	N. 33° E.	N. 64° W.	N. 32° E.	N. 58° W.
Lowest step	N. 38° E.	N. 60° W.	N. 30° E.	N. 55° W.

The above courses are plotted in figure 3 and suffice to show that the Atacama monument when originally constructed had no two sides parallel, nor any right angle. What the original positions were or how much the parts may have rotated with reference to each other is therefore indeterminable. It follows none the less from the throwing of the statue and the crushing of the brick that a rotary movement was communicated to the structure.

SURFACE EVIDENCES OF FAULTING

Experience in California in tracing active faults leads to the expectation that similar faults in other countries may be identified by fissures, landslides, ponds, and valleys, which range along the outcrop in a line. As has already been stated, the search for such evidences in Atacama was practically vain and the failure to find them led to the conclusion that the mechanism of faulting differed in some important particulars from that which has been recognized in California.

The inquiry for fissures was included in the questionnaire that was widely distributed, and many of the responses cite instances of their occurrence. But in every case it is demonstrated by the evidence of the location or was found on examination that the cracks which were described were produced by superficial landslides and were controlled by the slope of the basement-rock surface beneath the alluvium. The fissures of this type were not connected with earthquake faults.

Two occurrences were found, however, which appear to have had more deep-seated relations. Both occurred near Vallenar, in the region of highest intensity, one being at the mouth of the Quebrada Jilguero, the other in the bluffs of the Arroyo Valparaiso.

QUEBRADA JILGUERO

The Quebrada Jilguero enters the Rio Huasco about 3 miles (5 km.) east of Vallenar from the northeast. It is characterized by the peculiar feature of a narrow canyon in hard rock, through which the Jilguero runs in the last few hundred yards before joining the main stream. Its valley above the canyon is wider and lies between high banks of gravel. The facts are, perhaps, best explained by considering the Huasco and the lower section of the Jilguero as superimposed on the firm rock by the gravels that formerly filled the entire valley. The streams meandering over the aggraded surface assumed their present courses and were hung up on a spur of hard rock, in which they have cut their actual channels.

The rock on the western side of the Jilguero canyon, which is about 150 feet (45 meters) high, was riven from bottom to top by a movement which is reasonably attributable to the earthquake. It was broken and spalls, which showed fresh fractures, fell from the cliff. The crack itself, however, did not show any displacement. The two sides appeared to fit, practically as before. It was traceable only by freshly broken surfaces and by the opening of old joints, which it traversed. Its strike was north 45° east, magnetic, and the dip was 60° northwest. (See photograph, Plate XXII B.)

VALPARAISO SLIDE

The Arroyo Valparaiso enters the Huasco about 2 miles (3 km.) east of Vallenar by a valley cut in the gravel formation. The latter is somewhat firmly cemented and stands at a steep angle of rest, but the valley is none the less wider than others like it, and there is a narrow bottom-land along the stream. The bluff on the east rises 165 feet (50 meters) above the brook and in its upper part exhibits a distinct fault scarp, below which there are masses of the gravel that have slid down. (Plates XXII-XXVI.)

The scarp is 42 feet (13 meters) high. It is straight in a north 35° east magnetic direction and dips 75° west toward the valley. In these respects it conforms to what would be expected in an ordinary landslide. But the surface is hard, when scratched with a knife, and exhibits striations that dip 55° from the horizontal, downward toward the north. These details appear to distinguish it as a shearing plane on which there has been compression. If so, it is older than the erosion of the valley, since the shear could not have developed except in a continuous mass of gravels.

The slide below the scarp is a large body of the gravel formation, which shows transverse fractures and displacements in a gravitative direction, downstream. Their positions can best be appreciated by inspection of the photographs. They were fresh fractures and demonstrated notable movements in the recent shock, but the slide as a whole is much older. It originated in some much earlier earthquake and has been repeatedly shaken, as is evident in the contrast of weather slopes and fresh fractures.

The scarp may reasonably be regarded as a fault scarp, the outcrop of a deep-seated compression fault which here traverses the gravel deposits. Definite proof of the extension of the fault plane into the rocks is, however, lacking, as they are not uncovered.

DISTRIBUTION OF INTENSITIES

It is generally assumed that a study of the apparent intensities of an earthquake shock, as indicated by the degree of damage suffered at various points within the area of vigorous activity, will define a central tract of maximum effect, surrounded by zones of less and less vigorous action, diminishing outward. The central tract is

A. Copiapó. Adobe wall of large building intact, tied with timbers; tapiales thrown down, temporary shelter of rushes.

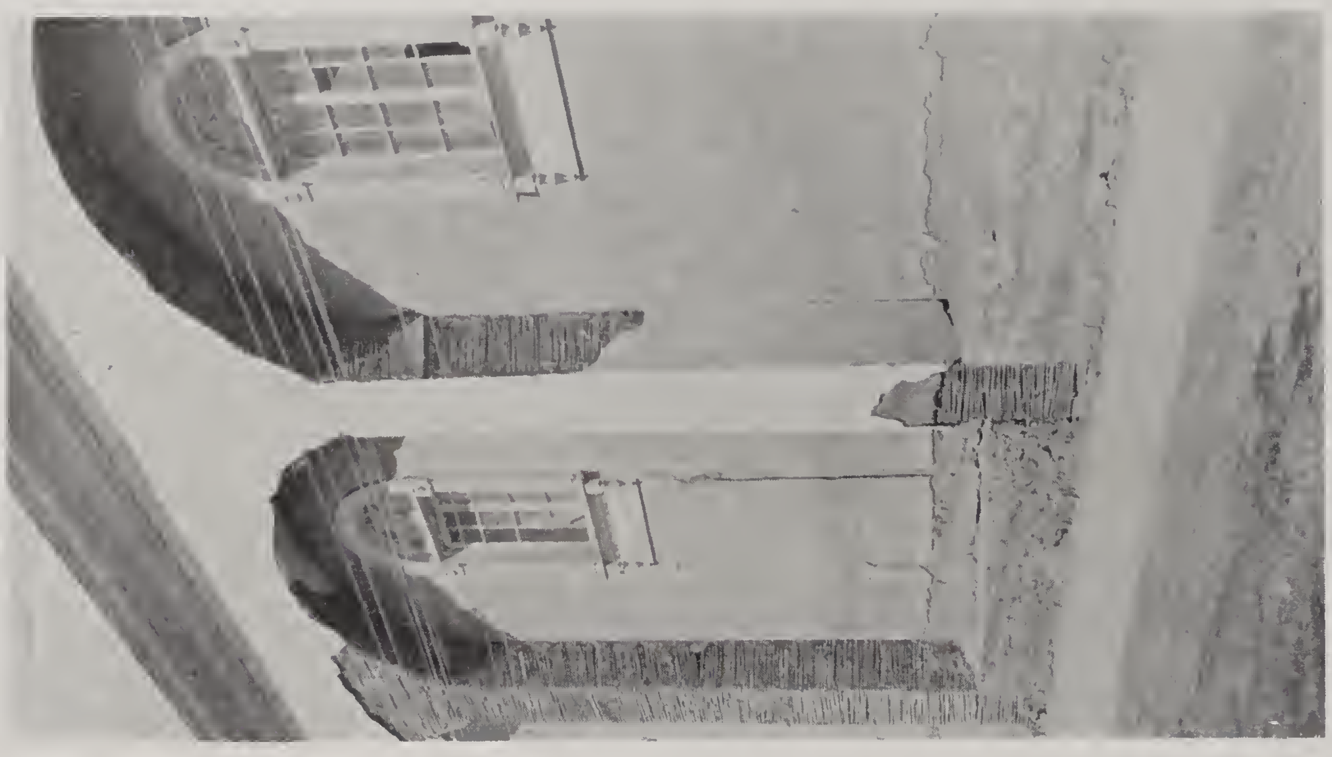
B. Tatara. Estancia west of Vallenar, near fault line; adobe buildings wrecked.

A

B

A and B. Vallenar (12.5 miles (20 km.) southwest of). Examples of effect of the earthquake upon massive structures of dry stone walls; located on gravel plain above fault.

A. Vallenar. Church tower intact.



B. Vallenar. Walls of church, showing columns and walls of caña de Guayaquil on frame construction.

A. Copiapó Church in Plaza Godoy. Frame structure, interior walls and plaster crushed.

B. Smelter chimneys at Huasco. Note twisting effect at node of vibration.

A. Copiapó. Destruction of tombs of massive masonry.

B. Vallenar. Ruins after the removal of the dead and wounded, victims of ignorance and carelessness, who numbered 1,300, nearly one-third of the population.

A. First class construction of frame and "brea" or brush; to be plastered with mud.

B. Average construction of frame, caña de Guayaquil, and adobe; to be plastered with mud.

A. Upper Copiapó valley, San Antonio. Rebuilding a wall of tapiales.

B. Upper Huasco valley, La Pampa. Very old adobe house with mud roof.

A. Vallenar. Wall of tapiales; two high, partly thrown.

B. Vallenar. Typical ruin of adobe house with heavy mud-covered roof; front wall pushed out by rafters.

A. Upper Copiapó valley, San Antonio. Looking northwest, showing general destruction of adobe houses.

B. Upper Copiapó valley, San Antonio. Looking southwest, showing general ruin and a new wall of tapiales.

A. Upper Copiapó valley, San Antonio. Cemetery walls standing on east, west, and south, on gravel cone inside canyon; white rhyolite dike in Jurassic sandstone.

B. Upper Copiapó valley, San Antonio. View up valley, showing broad, marshy fill on which village stands.

A. Upper Copiapó valley, Potrero Seco. Walls of tapiales thrown down, gate columns standing: typical view of wide canyon.

B. Upper Copiapó valley, at La Suretá. A primitive plough consisting of a tree-trunk and roots.

A. La Pampa on Rio Elqui. Wall thrown and column standing.

B. La Pampa on Rio Elqui. Columns and roof free to sway but not overthrown.

A. Copiapó. Atacama monument, showing statue thrown 16 feet (5 meters) from its pedestal.

B. Copiapó. Base of Atacama monument, showing detail of brick layer sheared by rotation of upper structure.

A. Copiapó. Overthrow of Matti monument by failure of pedestal.

B. Vicuña. Monument in park, not disturbed.

A. Vallenar. Rock fall on track up Huasco valley, near Quebrada Jilguero and fault line.

B. Vallenar. Railroad up Huasco valley, showing displacement of track.

A. Vallenar. Quebrada Jilguero, 3 miles (5 km.) east; view of cliff at outlet of the Quebrada into valley of the Rio Huasco, showing earthquake cracks opened in last shock.

B. Vallenar. Quebrada Jilguero, looking through canyon by which it enters Huasco. On left is cliff which was fractured by earthquake, and in foreground is reinforced concrete bridge that was not injured.

A. Vallenar. 2 miles (3 kilometers) west of, Quebrada Valparaiso, general view of big slide.

B. Vallenar. Quebrada Valparaiso, view of quebrada showing position of big slide with reference to terrace level as seen across Huasco valley.

A. Vallenar (2 miles (3 kilometers) west of). Slide in Quebrada Valparaiso, in Pleistocene terrace gravels, looking north.

B. Vallenar. Slide in Quebrada Valparaiso, looking north from near middle of slide.

A. Vallenar. Quebrada Valparaiso, details of big slide showing old mass shaken down in previous earthquakes and view across terraces of Huasco valley.

B. Vallenar. Quebrada Valparaiso, view of old slide, showing breaking down of mass in last earthquake.

A. Vallenar. Slide in Quebrada Valparaiso; near view of striated surface in Pleistocene gravels.

B. Vallenar. Looking south across Rio Huasco from Quebrada Valparaiso, along fault line.

assumed to contain the epicenter. These conditions have not been realized in the investigation of the Atacama shock under discussion. The field observations show that the apparent intensity of the movements was similarly violent at widely separated points and depended in large measure upon local conditions.

Apparent intensity is here distinguished from the actual force with which the earthquake vibrations are transmitted through the outer crust of the earth. The latter passes through the dense and highly elastic rocks where the pressure due to superincumbent load is high. Where the vibrations emerge at the surface of the earth they produce effects which vary greatly, the amplitudes and periods changing according to the resistance offered by the relatively inelastic materials at the very surface. The destructive action on buildings also varies with the nature of the superficial materials that support the foundations. Inasmuch as the observed effects are thus independent to a notable degree of the original force, the apparent intensity deduced from them is not a satisfactory indication of the real intensity. This subject was discussed at length in the report on the earthquake in northern California in 1906.[1]

Four facts stand out as controlling conditions which make it impracticable to draw lines of equal intensity, isoseisms, according to the surface evidence: (*a*) The earthquake produced almost no visible effects upon the landscape of the plains and mountains. There is, therefore, no evidence of intensity, not even that there was a shock, except where structures had been built by man. (*b*) The region is so inhospitable that habitations are very sparsely and irregularly scattered over it. The evidence that may be found in their damage or destruction is consequently exceedingly meager. (*c*) Where buildings exist or existed the nature of the foundation was in most cases the controlling factor. Structures built on rock suffered little or no damage. Those on gravel terraces were severely shaken, but often not with destructive violence. Those which stood on river alluvium or other soft material, especially when it was filled with water, were generally wrecked. (*d*) The geologic condition of faulting also determined lines of high intensity, which fixed centers of destructive violence at the points where they crossed the alluvial fills that occupy the valleys. From these considerations it follows that what we may observe on the surface in this and similar cases is the *apparent local intensity,* a result of several strictly local, unsystematic conditions.

In the course of a journey that covered the area of material damage to structures, the writer observed evidences of very high relative intensity at Vallenar and vicinity, at El Tránsito on the Huasco, at San Antonio on the upper Copiapó, at Copiapó itself, and at Potrerillos. These places are scattered over a distance from south-by-west to north-by-east of 175 miles (280 km.). The east-west diameter of the area is about 47 miles (75 km.). Within an oval of these dimensions lie the severest effects. But within that same area are villages, built essentially like the others, which suffered little or no damage. Investigation shows that they owe their immunity to the character of the material on which they are built or to the distance that sepa-

[1] State Earthquake Investigation Commission, Report, vol. I, part 1, pp. 160-162 and 200, 1908.

rates them from a fault or to good construction, whereas the examination of the damaged buildings led to the conclusion that the causes of failure were to be found in the weakness of the foundation material or in the proximity of a fault or in the construction of the building or in a combination of all of these conditions.

A valuable group of data bearing on the local effects of the shock is contained in the answers received from those who experienced it and who courteously sent in answers to the questionnaires which had been distributed. The answers were studied by Dr. Luis Sierra Vera, of Copiapó, an assistant to Count Montessus de Ballore and a seismologist familiar with earthquakes in this region. His digest of the questionnaires will be found in Appendix II. From it we extract the following estimates of intensity at various places. To complete the list some places that are not included among the questionnaires, but which were visited by the writer, are included. They are marked by an asterisk. The data are arranged from south to north by latitude and for each latitude they are stated in the order from east to west.

Intensities deduced from questionnaires

Latitude	Longitude	Place	Intensity, R. F.	Local conditions
	° ′			
27° to 27° 50′	70 50	Caldera	VII–VIII	Rocky coast
	71 20	Copiapó	IX–X	Marshy fill
	70 17	Tierra Amarilla	VIII–IX	Near fault; river gravels
	70 08	Tres Puentes		
	70 05	Loros		
	70 03	San Antonio	X	On fault and marshy fill
28° 30′ to 29° 00′	71 15	Huasco	VII–VIII	Rocky coast
	71 14	Huasco Bajo	IX–X	Marshy fill
	71 07	Freirina	VIII–IX	On fault; gravel terrace
	70 46	Vallenar	IX–X	Near faults; marshy fill
	70 16	El Tránsito	IX–X	On fault; gravel cone
	70 12	La Pampa	VIII	Gravel terrace
30°	71 20	Coquimbo	VII	On fault; rocky coast
	71 14	La Serena	VII–VIII	Gravel terrace
	70 42	Vicuña	VIII	Do.
	70 32	Rivadavia	IX	On fault; gravel terrace

Examination of the preceding table shows that the maximum apparent intensities were observed in the vicinity of Vallenar (at Vallenar itself, at El Tránsito east of the city, and at Huasco Bajo west of it). Similar effects were noted at Copiapó, 140 km. north-by-east from Vallenar. The surface materials beneath the two towns are much the same and the apparent intensities may fairly be compared. No material difference can be distinguished. We may conclude that the destructive force was equally violent at these two cities and they were similarly situated with reference to the fault or faults on which it originated.

We may next inquire whether the initial release of elastic strain occurred nearer one or the other place; in other words, where was the focus of the earthquake?

The direction of movement of the longitudinal wave being outward from the focus it affords a means of locating the latter when determinable. In the absence of more exact data we have to fall back on the human testimony, which, unreliable though it is, is significant when a number of observers agree.

From the answers to questionnaires we find that at La Serena four persons recognized the approach of the earthquake from the north, while two observed east-west oscillations. The latter were, presumably, the lateral vibrations that succeed the longitudinal. At Vallenar two persons noted the first shock as coming from the east and two from the west. Another put it down as from the south. Two others perceived it to be from below upward. These last observations suggest that the city was not far from the epicenter and the violence of the movements in the neighborhood would confirm the inference. It happened that on the day following the great earthquake the direction of movement of the after-shocks was noted by telegraphy. Telegraph operators at Vallenar communicating with those at Copiapó wired: "It shakes." And those at Copiapó perceived the shock a few seconds later.[1] Thus the testimony adduced indicates that the origin of the shock lay to the north of La Serena, presumably at some considerable distance since the shock was weak at that place, and somewhere on the further side of Vallenar from Copiapó; that is, to the south or southwest of Vallenar. Observations of rock falls in the mountains southwest of the city and the statements of goatherds, whose stone huts were utterly leveled (plate VIII), would suggest that there was a locus of high intensity perhaps 12 miles (20 km.) from the town in that direction.

These deductions from the field evidence do not accord closely with the determinations of origin which have been calculated from seismograms. As is stated in Appendix I, Messrs. Macelwane and Byerly locate it about 85 miles (140 km.) southeast of Vallenar. This is near El Tránsito, where the shocks were extremely violent. They also cite the calculations of Sieberg and Gutenberg who place it 37 miles (60 km.) northeast of the city in an uninhabited region. It is evident that the approximate assumptions from which the results are determined do not permit of accurate conclusions. The movements of the elastic rockmasses, slipping and snapping back on the fault plane or planes, were exceedingly complex. The assumption that there was some initial point of rupture, which could be taken as the instantaneous focus, appears doubtful in the light of the above cited evidence.

STUDIES OF TAPIALES

Among the earliest efforts of the writer on arriving in the area shaken by the earthquake was to discover effects from which the intensity of the shock at any particular point might be deduced. The conditions in the towns were most unsatisfactory. The wrecked buildings were of so many different types and conditions, the foundation materials were so unequal in character, the evidences were so confused, that no definite estimates were possible. Nevertheless, the general impression was that the weak structures had failed because they were weak and not because they had been subjected to very violent forces.

In the course of the field work attention was soon riveted by the mud walls, which occur everywhere. They are built by tamping mud into a frame so as to produce a large block, which is called a tapiale, from the Spanish *tapar,* to tamp or pound

[1] Oral statement of the chief telegrapher at Vallenar.

down. They are of uniform size, being 1 meter wide, 2 meters long in the direction of the wall, and 0.5 meter thick. They thus offer blocks which have approximately the same resistances to oppose to any force that tends to overthrow them, a condition which, on the average, gives an indication of the relative intensity in different areas. By the application of West's well-known formula one might also arrive at some indication of the acceleration of the force; that is, of the intensity. (Plates XXVII-XXX.)

A little study soon showed the necessity of considering some qualifying conditions. A perfect tapiale, being half as thick as it was wide, would be overthrown by a force having an acceleration of 4.8 meters per second per second. But perfect tapiales are rare. Moisture rising from the ground causes the corners to slough off and reduces the width of the base. Similar effects are produced by hand, since it is often convenient to take dirt from a tapiale in cultivating the fields or mending the roads. The value of the tapiale as a seismometer is thus grievously and inconsiderately diminished.

Furthermore, it became evident that an impulse which had not been strong enough to overthrow a tapiale in its first effect had sufficed to break off the corner on which the weight was to a greater or less extent concentrated. The subsequent overthrow might then be the effect of forces distinctly inferior to that which would have been required if the tapiale had been strong enough to bear its own thrust upon the corner.

In addition to these considerations, it was necessary to take account of the long-continued action of the earthquake, which could not have failed to produce coincidences between the earthquake vibrations and the oscillations of the walls, and must thus have had excessive effects.

Somewhat careful studies in the area of maximum effects, that is, from Vallenar to Copiapó, resulted in certain general conclusions that remain uncontradicted by other evidence of equal validity and are probably sound, namely:

(1) Some tapiales out of any wall remained standing wherever they were observed. Hence we conclude that nowhere did the acceleration attain the maximum of 4.8 meters per second per second, which must have overthrown them all.

(2) Measurements of a large number of tapiales which had been overthrown showed that their bases varied from 40 to no more than 25 cm. in thickness. The force required to overturn them, therefore, did not surpass 4 meters per second per second, and in the case of the narrower bases need not have exceeded 2.5 meters.

(3) The large proportion of tapiales which had bases near 30 cm. thick and which had been overthrown indicated that an acceleration of 3 meters per second square had generally been attained.

(4) These observations were made, as a rule, upon walls standing upon the widespread gravel fill of the broad valleys or river terraces. The deduction is therefore to be applied only with due consideration of the foundation coefficient characteristic of dry, partly consolidated gravel masses.

To elucidate these general statements, the specific observations are given in the instances described below, and the reader is referred to the photographs of tapiales which illustrate typical conditions.

A. Copiapó. Detailed view of tapiale wall, which runs NW.-SE.

B. Copiapó. General view of tapiale wall running NW.-SE. and of distant wall at right angles to it, showing effect of earthquake.

A. Copiapó. Field in valley, southwest of city; wall of tapiales extending southwest.

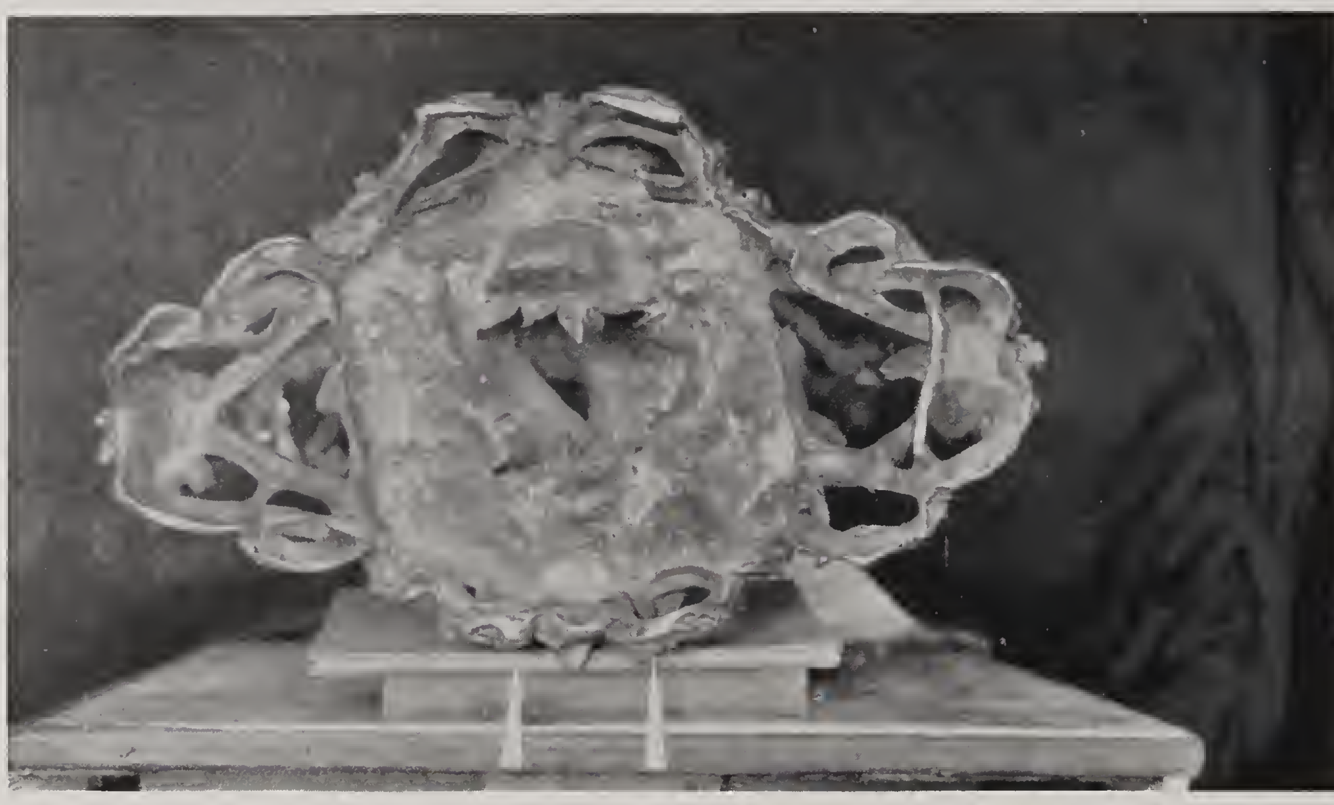
B. Copiapó. Same field as in upper view; wall of tapiales extending southeast.

A. Copiapo valley, above Copiapó near Tierra Amarilla. Showing standing and fallen tapiales; looking south parallel to longitudinal earthquake waves.

B. Copiapó valley, below Copiapó at Ramadillas. Showing wall of tapiales running N.-S. parallel to longitudinal earthquake waves.

A. Vallenar. Wall of tapiales near the city, extending east across the line of longitudinal vibrations.

B. Vallenar. Narrows in the valley of the Rio Huasco caused by a fault-ridge of Paleozoic rocks; looking west, down stream toward the city.



A. Copiapó. Fruit dish, showing the two hind legs, indicated by white points, on which it danced on sideboard as shown in B.

B. Copiapó. Matta sideboard and fruit dish which made record of gyrations shown in plate XXXII B.

A. Copiapó. Matta sideboard, the fruit dish that danced.

B. Copiapó. Matta sideboard; the record it wrote in zig-zagging on the polished surface and in sliding straight down and off.

A field situated about 1 km. southwest of Copiapó was surrounded by walls of tapiales running south 63° west and south 27° east. Large sections of the former were thrown, whereas in the latter only occasional blocks had been overturned. A road ran parallel with the south 63° west course, along the northwest side of the wall, and the tapiales had been undermined on that side by the removal of dirt, as was shown by the hoe-marks on the lower corners of the blocks. They had generally fallen in that direction, *i. e.,* toward the northwest. Some had broken off at the foundations, which consisted of stones placed in two rows, with the outer edge slightly raised, but no wider apart than the width of the wall. Others had broken at the first joint above the base. The wall running at right angles to this one remained standing, almost intact. Its stability may have been due to the proximity of solid rock under the gravel plain, since that side of the field was close to the hills. On the other hand, the directions of the two walls may have been a factor in the difference of effects. The course of the standing wall, south 27° east, made an angle of about 35° with the longitudinal waves of the shock. The course of the overthrown wall, south 63° west, made an angle of about 55° with the same waves. The difference of angle may have been sufficient to give the impulses an effective component in the one case and not in the other. If so, it was the longitudinal, rather than the transverse, waves that overthrew the one wall. The initial impulse advanced from south to north and should have thrown the blocks toward the south. They fell toward the northwest, toward the side on which they were undermined. Hence, the initial impulse did not throw them, but the elastic return did. The destructive component of the force had an acceleration between 3 meters and 4 meters per second per second, according to measurements of the bases of the blocks. The impulse in the direct course may then have approached 5 meters as a maximum, but probably did not exceed 4 meters.

In the vicinity of Vallenar observations were made on many walls of tapiales, and always with the same general results as to the probable intensity of the forces. It is probable that the acceleration reached 4 meters per second per second, and may have exceeded it, but it often was less, the foundation coefficient being a very important factor. Walls of tapiales two blocks high had been built around the railroad yards and also around some inclosures on the larger estancias. They had generally stood fairly well and furnished a check on the lower walls. A good example was photographed at the estancia de Buena Esperanza. (Plate XIV A.)

The following is the analysis of the reactions in this case (see figs. 4 and 5):

The dimensions were as given in the figures. Taking the two blocks as a whole, the center of gravity falls at *C* (fig. 4), and the force required to start a turning movement around one corner of the base would have an acceleration of 2.3 meters per second per second. If the two blocks were one, that force would suffice to overthrow them. They were, however, not attached, and the impulse acting upon the lower would cause it to turn, while the upper remained still, in an upright position. The weight of the upper would thus be thrown upon its corner and the center of gravity would be transferred to *C* (fig. 5). The effect is to stabilize the system and to raise the acceleration to 4 meters per second per second, in the case examined, if both blocks are to be overthrown. This rarely happened, and is attributable to special weaknesses where it did occur. When the upper block was thrown, it was obviously due to the to-and-fro oscillations of the lower block, as a result of repeated impulses.

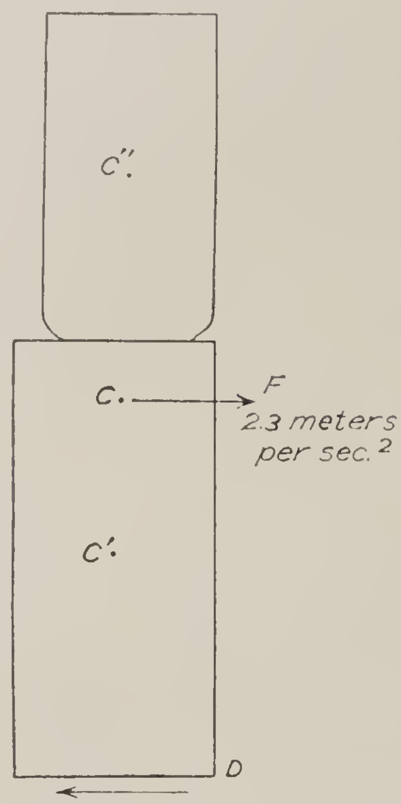


FIG. 4—Effect of earthquake force on wall consisting of two tapiales. If the two acted as a single body, a force acting at C with an acceleration of 2.3 meters per second per second would overthrow the wall.

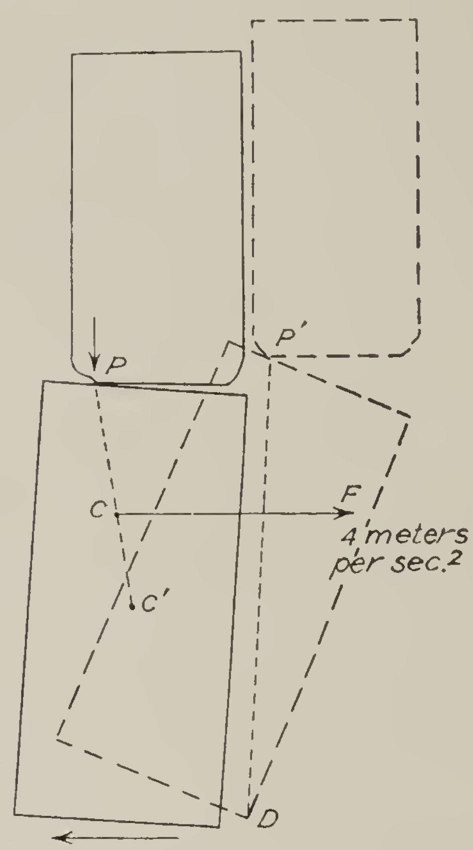


FIG. 5—If the two tapiales separated, then the initial tilt of the lower would throw the upper on to its corner P and a force of 4 meters per second per second applied at C would be required to overthrow the wall. The lower block could not be overturned until the line DP' passed the vertical.

Hence it would appear that the force in this case, as in others similarly studied, probably did not attain an acceleration of 4 meters per second per second, but very probably exceeded 2.3 meters.

A. Copiapó. Adobe house 70 years old, wrecked by collapse of roof: outer walls suffered but little, being held together by bean

B. Copiapó. Adobe house of one story with light roof, built around a square patio, showing shearing

f ceiling which may be seen projecting through. Foundation material is river gravel, but bed-rock lies not far below surface.

walls on vertical lines. House was rendered uninhabitable by general fall of plaster walls and ceiling.

SECTION II

GEOLOGIC FACTS, THEIR HISTORICAL DEVELOPMENT AND THE DYNAMIC HISTORY OF ATACAMA

ROCKS OF ATACAMA

The following table of formations in Atacama is based upon a paper contributed to the report of the Carnegie expedition by Dr. Johannes Felsch, who had spent seven years in studying the region under the auspices of the Chilean Government. The description of the geologic facts observed by him is contained in the report which he prepared for this volume. See Appendix III.

PALEOZOIC:	
Metamorphic Rocks:	
Quartzite.	
Mica schists and slates.	
Gneiss.	
Plutonic Rocks:	
Granite	Both intrusive in the metamorphic rocks.
Plagioclase granite	(Both intrusive in the metamorphic rocks.)
Black diabase	Intrusive in the granite in very large dikes, accompanied by a great deal of metamorphism.
MESOZOIC:	
Porphyries in dikes	Possibly Paleozoic. They cut the Paleozoic gneisses and granite and are regarded as probably Mesozoic by Felsch.
Rhetic:	
Sandstones and conglomerates with coal beds	Locally developed.
Lower Jurassic, Lias:	
Calcareous sandstone and gray limestone, interbedded.	
Middle Jurassic, Dogger:	
Reddish gray limestones.	
Labradorite porphyry	Occurs in thick beds overlying the middle Jurassic limestones on the western slope of the Andes from Santiago in latitude 34° to 26°, as observed, and still farther north and south. The zone of eruption was over 600 miles long and the bedded porphyries are many hundred feet thick.
Upper Jurassic, Tithon:	
Black limestones and black, calcareous slates.	
Melaphyres or pyroxenic breccias.	
Neocomian:	
Greenish gray sandstones and calcareous shales and limestones.	
Diabase in dikes and flows.	
Post-Neocomian; chiefly Tertiary and Quaternary:	
Quartz diorite.	
Diorite without quartz.	
Andesite.	
Pyroxene andesite.	
Trachytes and liparites.	

According to Felsch the andesites are more recent than the diorites and older than the trachytes and liparites. Liparite flows on the upper slopes of the Western Cordillera cover gravels that fill Tertiary gulleys. There is nothing more recent among the volcanics, so far as present information goes. Active volcanoes do not occur in the area discussed, although they rise in the Andean plateau adjoining on the east.

DYNAMIC HISTORY OF ATACAMA

POINT OF VIEW

The preceding enumeration of the rocks which occur in Atacama expresses time and force. The expression of time is in the usual terms of geology: Paleozoic, Mesozoic, etc., apply to great eras; Rhetic, Jurassic, etc., designate periods that are distinguished within an era. The latter are names which were first applied to certain groups of strata occurring in Europe or England, but which have come to signify the period of time in each case during which certain species of marine shells existed. Upon the discovery of those species anywhere in the world the strata in which they are found are regarded as having been deposited contemporaneously with those in the type locality and are assigned to the same period. The terms Rhetic, Jurassic, etc., thus serve to indicate the chronologic relation of events which occurred in Atacama to contemporaneous conditions in Europe or England.

The terms and the comparisons are the commonplace usage of geologic correlation. In this particular case they rest upon the identification of fossils by Dr. Felsch.

The expression of force is less commonly read into such an enumeration of rocks. Each rock type is, however, the result of a reaction involving the expenditure of force, which is indicated in the crystalline structure or mineralogical composition of igneous rocks or in the nature, extent and thickness of sedimentary rocks. The succession of rocks thus expresses a sequence of dynamic reactions, which concern us in this inquiry because earthquakes also are effects of a force that is presumably related to the dynamics of the past.

The formation of the rocks has not been a continuous or continuously similar process. It has been intermittent. Periods of rest have alternated with much shorter episodes of activity. Ebb and flow of forces are expressed in superficial results. At times quiet conditions favorable to the deposition of strata in shallow seas have prevailed. At other times enormous masses of igneous rock have risen into the outer crust and have even appeared on the surface as extensive volcanic flows.

We proceed to consider in historical sequence the dynamic effects recorded in the rocks of Atacama.

PALEOZOIC ACTIVITIES

The earliest geographic condition of which there is record in this region dates probably from the late Paleozoic and was that of a sea coast on the site of the actual coast range of Atacama. Sand and silt were then deposited there to form extensive and thick accumulations of strata. They were washed from a rising land and gathered upon a subsiding sea bottom. The thickness of the strata indicates that the subsidence was notable and continued for a long period of geologic time. The elevation of the land was commensurate with the subsidence, since it sufficed to furnish the large body of sediment.

Thus the earliest effects which can be deduced from the visible rocks are those resulting from the action of vertical forces which caused one zone of the earth's crust to rise and an adjacent zone to subside. The effects were gradual, the process was one of long duration, and though not steady was persistent.

Changes of level of the earth's surface, whether positive (that is, in the direction of uplift) or negative (that is, in the direction of subsidence) are and have been of general occurrence all over the world and during all recorded geologic ages. They have been peculiarly characteristic of shore zones, indeed the existence of a shore implies the establishment of a land on the one hand and a basin on the other. The areas of land and sea have always been liable to greater or less modification. Thus the oldest known aspect of Atacama is simply that of any shifting shore. But the normal changes remain difficult of explanation in terms of the forces that cause the positive and negative movements.

The action of unusual or extraordinary developments of energy is not to be assumed to produce these normal, though local, changes of level. The effective forces must be those which are universally available when called upon for action, but which remain inactive unless special conditions incite them. When in operation they must work through a mechanism that is capable of very long-continued action without fatigue or exhaustion. And they must eventually almost cease to act, leaving that relatively fixed condition of the earth's surface which is recorded by peneplanation.

The group of forces which we may invoke comprises gravitation, the molecular and atomic activities of mineral substances, and the exciting effects of changes of temperature or heat. The mechanical effects involve the gradual transfer of rock material at a considerable depth in the earth from beneath the area of a subsiding trough to that of the rising land, to supply the waste that is superficially carried from the land to the sea. Geologists have developed several theories to explain this movement either as a flow of molten, fluid rock, or as a kind of plastic flow of solid rock under excessive pressure and at high temperature, or as molecular, chemical metamorphism due to the effect of heating in the presence of an unbalanced elastic strain at considerable depth. This is not the place to discuss the various theories. It suffices to point out that the Atacama region had at the close of Paleozoic time long been the scene of a gradual change of levels in two adjacent zones, presumably under the moderate action of the forces of gravitation, molecular reaction, and heat.

The rocks which were produced during the late Paleozoic were the sediments which now occur in metamorphosed condition as quartzites, slates, mica schists and gneiss. They are now highly tilted, folded and contorted, as is usually the case when strata have been crushed up in the formation of a mountain range. A very large body of material has been eroded from above the masses which are now exposed in the coast range of Atacama. They have therefore continued to be elevated during subsequent ages. The present coast range is the successor of other ranges which have risen along that zone from time to time during the Mesozoic and Cenozoic eras.

The sequel to the prolonged movements of subsidence and elevation in the zone of the coast range, either during the late Paleozoic or immediately following it, was the intrusion of granite. The rock occurs as larger and smaller bodies cutting across and intruded into the older sediments, which are metamorphosed accordingly. It does not appear as large batholiths, there being no great mass of granite like that of the Sierra Nevada of California or those which constitute the coast ranges of British Columbia. In this respect the occurrences in Atacama resemble those which are described by Bowman [1] for that portion of the Cordillera that lies in southern Peru. They are perhaps not so great in volume as the batholiths which I have observed in the Patagonian Andes, though the latter also are smaller than the masses in North America. Even so the volume of granite intruded into the coast range of Atacama is very impressive, and sporadic outcrops of the rock further east indicate that it underlies some areas of the extensive Mesozoic rocks.

The intrusion of granite into the sediments which had been accumulating quietly in the Paleozoic waters was the beginning of activity in the coastal region of Chile. Earlier episodes of vigorous orogeny there no doubt had been, but they had been succeeded by the period of quiet recorded in the fine sediments. A new chapter of mountain making began. An active force had entered the crustal strip along the continental margin. We are concerned with its nature and origin.

The granite was intruded as a molten rock. It carried a large amount of heat energy, which was either inherent in it from some earlier time or which had been introduced into it shortly before it was forced out of its deeper site. The alternative presents two diverse views regarding the state of masses within the outer shell of the earth. The first, which is the older, is a corollary of the assumption that the interior of the earth is molten or contains large bodies of rock that have remained molten since some primordial stage of general high temperature. The theory is discredited in general by the evidences of prolonged stability of very extensive areas of the earth's crust as well as by the high degree of rigidity demanded by tidal and seismological observations. In this particular case the supposition that a large body of molten rock formed part of the lithosphere for an indefinite lapse of time preceding the rise of the granite into the outer shell is negatived by the evidences of very gradual changes of level while the sediments accumulated. The very moderate movements of the surface which are indicated by the fine products of erosion and the steady conditions of sedimentation are inconsistent with the instability of a floating crust. I conclude that the lithosphere had been solid to an indefinite depth beneath Atacama during the accumulation of the strata.

The granite, although not aggregated into great batholiths, occurs in numerous bodies and constitutes a notable part of the rocks as they are now exposed. It also must have been solid if the lithosphere as a whole was solid. It must also, apparently, have been granite. Petrologists maintain that the process of differentiation may yield the siliceous rock and a more basic facies, provided that a mass of intermediate composition remain liquid long enough for the appropriate chemical and gravitative reactions to occur. Whatever the validity of the reasoning may be on chemical and physical grounds, the geologic evidence is opposed to the assumption of immediate

[1] Isaiah Bowman, *The Andes of Southern Peru,* Amer. Geographical Society, New York, 1916, pp. 241-243.

A. Near Toledo, 2 miles west of Copiapó. Looking S. 62° E. on line of shearing, showing crushing, probably on a fault.

B. Vallenar (19 miles south of). Paleozoic granite, showing jointing but not crushing, being off any fault line.

differentiation prior to the intrusion of these granites. The argument which has already been presented for the stability of the crust seems to preclude the presence of a liquid body beneath Atacama or closely adjacent to the coastal zone for a period of time sufficient to have accomplished the required segregation before the granite rose.

I conclude that the rocks were solid and, as both granitic and basic intrusions occurred, solid bodies of these diverse facies must have existed in some relation of juxtaposition. We are not here concerned with their antecedent evolution. The episode of geologic history which we are considering was a very recent event if we take account of the great age of the earth. During the eons that had preceded, the processes of fusion, segregation, and intrusion had been repeated many times and it is rather to be expected that they would have accomplished whatever separations of mineral aggregates were possible than that a magma capable of being segregated had escaped the reactions.

If the proposition be accepted that the rocks beneath Atacama were solid before they were intruded into the outer shell, then the question arises as to why they melted. It is a problem in dynamics and immediately concerns this discussion. Two explanations are current in the modern theory: first, there may have been relief of pressure; second, there may have been rise of temperature. The alternative rests upon the basic deduction that pressure and heat are opposing forces which operate within the globe to promote rigidity or mobility, respectively. If their tendencies happen to be nicely balanced the state of the rocks will be critical. Assuming solidity, a slight relief of static pressure or a slight increase of temperature will result in melting. If the balance be not critical a greater change of pressure or temperature will be required to alter the state.

Let us first consider the relief of pressure as a possible cause of melting. It is a facile assumption, too often made without regard to the amount of relief required or the possibility of adequate relief.

We observe that cold rocks are solid at and near the surface. We have not been able to penetrate the earth anywhere to a depth where they became liquid. We infer from evidences already cited that as a whole they continue to be solid to an indefinite depth under normal conditions. Both pressure and temperature increase, but the effect of pressure in promoting solidity is normally superior to the effect of heat in producing liquidity. What is the margin of superiority? No relief of pressure will melt rocks at surface temperatures. A rise of temperature of more than 1,000 degrees centigrade is requisite to that end. From the surface toward the center there are rising gradients of both pressure and heat. The normal relative rates of rise are unknown, but the long-continued solid state implies that pressure maintains the superiority by a safe margin. The critical state at which a slight relief of pressure would produce melting is not the normal condition. We may compare this conclusion with the evidence of geologic facts.

North America and northern Europe were repeatedly loaded and unloaded during the Pleistocene by accumulation and dissolution of ice sheets. The weight was sufficient to cause submergence, as evidenced by drowned shores, and the unloading was adequate to cause emergence, as shown by raised beaches. In the current state of opinion some may attribute these effects to isostatic adjustments, but even on that vague assumption there must have been elastic compression and elastic expansion resulting in corresponding elevation and lowerings of temperature. The variations have continued during a fairly long period, probably a million years or more. The lateral strains induced in the outer shell have been unbalanced. These conditions would have favored the extrusion of molten rock, if any had formed, but none has appeared in the extensive glaciated areas. The presumption is strong that none formed. We may conclude that the variations of pressure resulting from the waxing and waning of the ice sheets were inadequate to disturb the normal superiority of pressure over heat in maintaining solidity.

We may continue this line of reasoning by considering the case of the complete development of the topographic cycle, which comprises the elevation and erosion of a mountain chain and results in the removal from the surface of a load corresponding to the mountain masses. There are many illustrations of the process and effect, but none perhaps is more significant than that of the Appalachian province of eastern North America. After having been the scene of pronounced mountain growth during the late Paleozoic and early Mesozoic the region was reduced to one of the most perfect peneplains known to us and remained in a low featureless condition during the later Mesozoic and early Tertiary. It was thus for a very long time an unloaded region, beneath which pressures must have been notably less than during the preceding ages. Yet there has been no eruption of igneous rocks, either as plutonic intrusions or volcanic outpourings. We do not overlook the Triassic diabases. They were erupted outside of the Appalachian zone, in an area of subsidence and loading.

This reasoning could be extended to other districts of the earth's surface, but the argument already advanced appears sufficient to justify the conclusion that superficial changes of load do not directly modify the solidity of the subjacent sections of the earth's crust.

We turn to the consideration of another phase of this problem of relief of loads. It being observed that portions of the earth's surface are up-arched, the inference is sometimes drawn that the arch must be self-supporting, at least to a notable degree, and that the underlying rocks are thus relieved of pressure.

One type of broad arches or domes comprises those which are produced at the earth's surface by vertical, upward-directed pressure, which may be due to changes of form of underlying rock masses or to the intrusion of an igneous mass. This condition of arching, however, does not lessen the load upon subjacent bodies, since the upward pressure must react from the resistance of a firm base. Arches of this type are therefore excluded from the argument.

Arches or anticlines due to horizontal compression are known as competent folds. They rise only in case the up-arching strata are competent to lift the superincumbent load. They thus do relieve the underlying rock of the weight that they lift. They develop in stratified beds having thicknesses up to 3 miles (5 km.), and possibly up to 5 miles (8 km.). There is, however, no fusion within the anticlines. If it be argued that the temperature is not high enough to cause melting in these superficial sediments we may accept that explanation and proceed to consider some deeper zone beneath the sedimentary mantle and therefore composed of interlocking metamorphic and igneous rocks. We shall then be dealing with the outer shell or crust of the earth.

"Folding of the earth's crust" is a concept not uncommonly entertained by geologists, but it is one which will not withstand mechanical analysis. A solid may yield to compression by bending or by shearing. It will yield in the manner which meets with least resistance. Bending implies the rise of a competent anticline, if it is to relieve the pressure on an underlying mass by lifting the load, and it is evident that an increase of load makes bending more difficult. As we descend into the earth we should encounter at some no very considerable depth a zone where the superincumbent load is so great that bending will be more difficult than shearing and deformation will take on the latter form. Hence it follows that competent folding is a relatively superficial mode of deformation. It can not occur at a depth sufficient to sustain the temperature at which rocks may melt in large masses.

It seems necessary to conclude that relief of pressure which might occasion melting can not be produced by so-called folding or up-arching of the earth's crust.

Another condition which may be postulated as lightening the load on any deeply buried mass is the outflow of already molten material by channels leading out laterally. Of the efficacy of this process to induce melting by relieving pressure there can be little doubt. The volume of rock thus removed represents in many cases a very material change in the length of the column resting upon rocks from 20 to 100 miles (32 to 160 km.) or more below the surface, as may be inferred by the profundity of oceanic deeps. Furthermore, the temperature of the solid rock which underlies a molten mass must be so high that the solid is near the critical temperature for the original pressure and will pass readily into a molten state with diminution of that pressure. This would seem to be a probable condition of sequential or secondary melting. It can, however, not be the cause of the first melting, which is an essential prerequisite. The initial cause of change of state must be sought in some other modification of the conditions that had imposed solidity.

From whatever point of view we consider the general proposition that relief of pressure has been the cause of melting, we encounter insuperable objections: either the relief affects strata too near the surface and too low in temperature; or the relief is not mechanically possible as postulated; or the relief occurs only as a sequential effect of previous melting and the melting has still to be explained.

I conclude that relief of pressure can not be regarded as a cause of the passage of rock from the solid to the liquid state in the solid earth.

Relief of pressure being eliminated as a cause of melting, a rise of temperature is the only alternative cause under the postulated conditions. It is an efficient cause, but there are obscurities in the manner of its development and concentration which call for discussion.

A major cause of the release of energy as heat within the globe is gravitation and resultant compression. A concentric distribution of temperature would result from this cause in a homogeneous globe. At any given depth the temperature would be the same, or in other words the isogeotherms would be concentric spheroids. This is the ideal physical concept. Among its consequences would be the conduction of heat outward along radii from the heating nucleus to the surface. Chamberlin has pointed out that the resultant distribution of temperature would depend upon the relative rates of conduction at different depths and that there would be a rising temperature within any relatively non-conducting outer shell. The postulates are: (1) That the heat energy is released most vigorously in a deep, interior zone; (2) that the material of the globe is densest in depth and becomes less dense from within outward toward the surface; (3) that in general denser materials are better conductors than are the less dense. Hence it follows that heat must be conducted to some outer zone faster than it could be conducted away and must accumulate.

The effect would be to raise the temperature to the melting point, melting would be followed by extrusion of the melt, and lowering of the temperature would ensue in the melting zone. The process would be periodic.

In a globe composed of homogeneous layers this process would result in epochs of vulcanism over the whole surface at the same time and the alternate periods of inactivity would similarly affect all the continents and ocean basins simultaneously. Some such alternation of conditions may be recognized in a gross analysis of geologic history. The Tertiary and Pleistocene, for instance, have been periods of extensive orogeny, in contrast to the inactivity of Cretaceous time in general. It is only in the gross analysis, however, that the periodicity holds true. Local departures from the conditions characteristic of any period have been of common occurrence and pronounced degree. There is some cause of variation, which affects both time and place of heat accumulation under this process.

If we turn from the deductive reasoning to the inductive and examine the facts of distribution as indicated by the evidences of heat in the outer crust, we note that ocean basins and mediterranea differ from continental masses in that contemporaneous activities characterize the opposite shores of basins, whereas diverse conditions have occurred simultaneously on opposite coasts of large land masses. For example: Geologic events have run parallel in Great Britain and eastern North America across the north Atlantic to a remarkable degree. A similar parallelism of occurrences characterizes Africa and South America across the south Atlantic, as has most recently been elaborately developed by Du Toit and Reed.[1] The histories of the Asiatic and American shores of even the vast Pacific basin are characterized by similar dynamic events. The same is true of the Mediterranean, Caribbean and of other minor basins.

On the other hand, the histories of opposite coasts of continents have been dynamically different. The fact needs no elaboration. It is well known to all who have compared them, as the history of Appalachia, for instance, with that of California, at any period since the Pre-Cambrian.

[1] Alex. L. Du Toit and F. R. Cowper Reed, *A Geological Comparison of South America with South Africa*, Carnegie Inst. Wash. Publ. No. 381, 1927.

The likenesses of dynamic histories occur between closely contiguous deeps, as among the deeps within the Mediterranean, or in the Antillean area, or around the margin of the Pacific. The differences are functions of remoteness from one another as the Atlantic and Pacific, separated by the Americas. Common histories indicate common sources of energy. Distinct histories indicate distinct sources of energy. Thus the geologic records sharply contradict assumptions of a homogeneous earth or of an earth composed of concentric homogeneous shells, of shells which shall be chemically, physically, potentially, dynamically homogeneous, each one throughout its spherical extent and radial thickness. Observation teaches that no such shell extends over the surface of the globe. The distribution of dynamic activity in time and geographic position demonstrates that homogeneity does not characterize any interior shell, at least to that great depth from which energy ascends.

We are concerned at the moment with heat energy only (or of energy capable of transformation into heat) and with its concentration in a certain superficial segment in the transition zone between a continent and an ocean basin. We have assumed conduction in diminishing degree from within outward. We have also to recognize periodicity as a characteristic of the temperature changes.

A variety of hypotheses might probably be framed to meet these requirements if we knew more about the organization of the interior of the globe and the physical characteristics of its constituent parts under intense conditions of temperature and pressure. Our knowledge is avowedly limited, but with the partial understanding we possess we may frame an explanation as follows:

Heat is generated by compression or other cause deep within a deeply heterogeneous globe. The rate of generation is a function of variables (the physical properties of heterogeneous matter) and is itself unequal in different masses. The rates of conduction away from the sources are unequal, both along radii which diverge through unlike sectors and along layers that differ in conductivity. The evolution of heat is very gradual, its transfer very slow. Changes of temperature toward a higher degree (which alone could produce a change of state) would be correspondingly long in developing. Wherever, however, in its long and tortuous journey of two or three thousand miles from the deep interior toward the surface the heat energy accumulated, there melting would ultimately occur and the molten body would carry out its latent and sensible energy in erupting to a higher level. Thus the outward progress of an accumulation of calories would be *per saltum* and the effects manifested in the melting and intrusion of the igneous rocks of Atacama toward the close of the Paleozoic would be only the final incident in a long sequence of similar movements by a mass of heat energy.

There we may leave that speculation and return to the facts of the region, which at once confront us with another problem. Granite was the first rock intruded from below into the outer crust and it was followed after a geologically brief interval by basic intrusives. It would not be necessary to discuss this particular sequence of melts in order to describe the dynamic history of Atacama, but I have elsewhere argued that basalt would melt before gneiss (or granite) unless gases were present,[1]

[1] B. Willis, *Discoidal Structure of the Lithosphere,* Bull. G. S. A., vol. 31, p. 296, 1920.

and it is desirable to correct that statement. In the passage cited there is a numerical error by which the conductivity of gneiss was given as 0.0005 instead of 0.005. By correcting this error the relative rates of heating of basalt and granite are changed from the calculated ratio of 4:1 in favor of basalt to 1:2.8 in favor of granite.

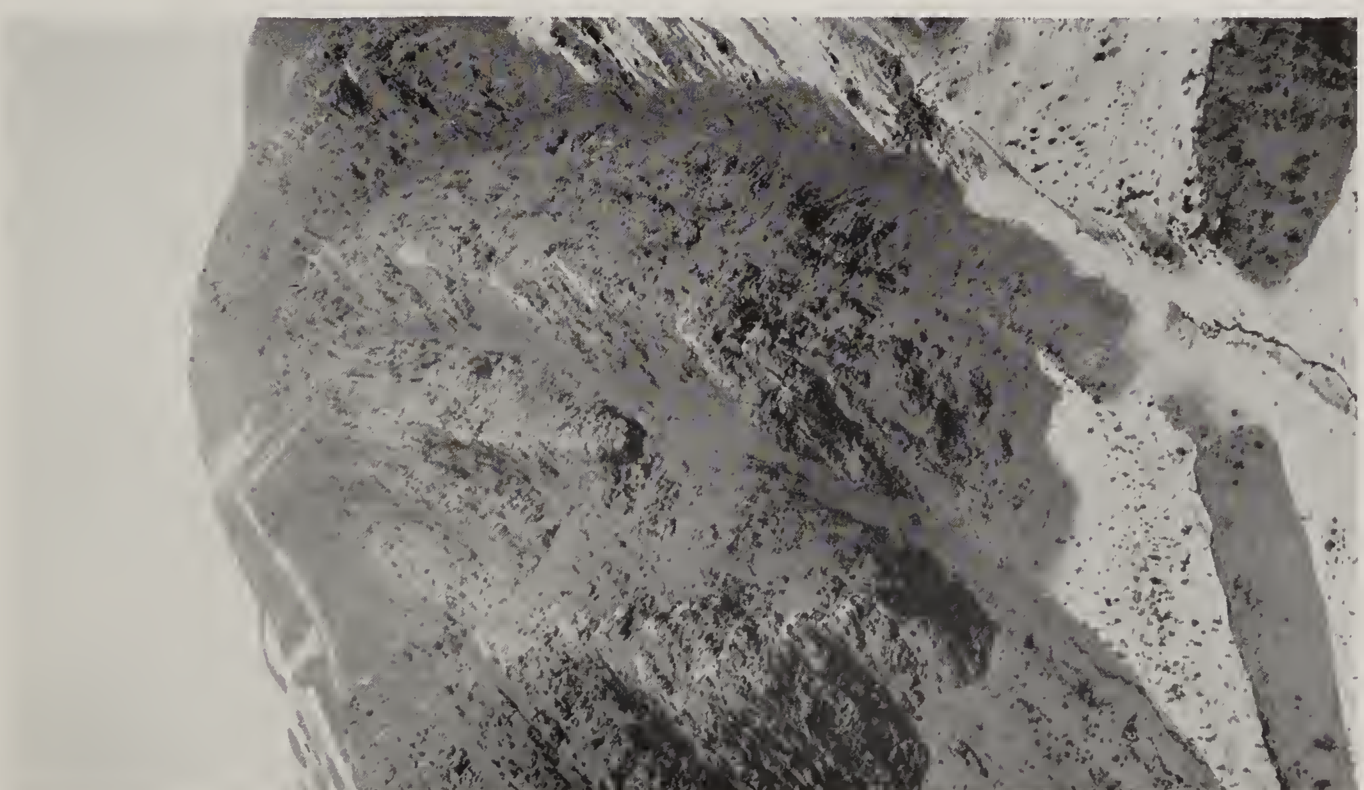
There are certain additional considerations to be taken into account in reviewing that statement. The calculated ratio is of value only in the case of a dry melt, as was then recognized, but it is now becoming more evident that gases are rarely if ever absent in igneous rocks and that the conditions described would be improbable of occurrence. Gases are known to lower the melting points of all rocks and promote liquidity of the melt, but their relative effects on unlike magmas are not yet determined in a manner to permit synthetic discussion.

It seems desirable at this point to direct attention to the probable source of the granitic and later igneous rocks. It may be possible that they came from a position immediately beneath the superficial zone, into which they were intruded, that is, from beneath the zone of the coast range. This is, however, improbable. If it be assumed, as is reasonable, that surfaces of rupture in the earth's crust follow surfaces of maximum shear and that the pressure producing the shear is predominantly horizontal, then the ruptures must be inclined at angles approaching 45 degrees. Igneous rocks rising along these surfaces would thus come from a deep zone adjacent to that in which they appeared at the surface. Morever, the horizontal travel distance would approximate that of the vertical rise, which may be estimated in excess of fifty kilometers and up to several hundred when we take account of long-continued drafts of material from the asthenosphere. When we further consider that the surface of more facile rupture and intrusion is probably governed by the curve of elastic stress, which flattens out to horizontality in its deeper section,[1] we may well recognize that the sources of the observed igneous rocks lie at considerable distance to one side of the zone of their appearance at the surface. The writer regards it as more than probable that the igneous rocks of the Andean cordillera were ejected from beneath the deep trough which borders South America on the west and is known as the Atacama deep.

Two early phases of the dynamic activity of Atacama have been presented. The one was the slow changes of level during the late Paleozoic, involving both uplift and subsidence and thus requiring the exertion of a force or forces competent to overcome gravity to the extent that the continental margin was elevated. It was a slow, gradual and prolonged process. The other was the gradual heating of a great volume of rock to the point at which it eventually melted. It also was a slow, gradual and prolonged process. The latter went on simultaneously with at least the later period of the former under the same narrow strip of the earth's surface. Both processes came to an end with the rise of the granite, or more properly speaking, both passed into more vigorous phases.

Following the intrusion of the granite into the zone of the coast range of Atacama there was undoubtedly an interval of comparative inactivity, during which the gran-

[1] Bailey Willis, *op. cit.*, 1920, pp. 280-284.



A. The Andes southeast of Santiago. Valley of Rio Vulcano, showing Jurassic lavas upturned to vertical dips.

B. The Andes southeast of Santiago. Valley of Rio Vulcano, showing Jurassic lavas in horizontal position.

ite and the metamorphosed sediments were subjected to tectonic pressures of sufficient intensity to shear the granite. This conclusion follows from the fact that subsequent intrusions entered along shearing planes. The interval was, however, short. It has been established by the observations of Cloos in Germany that granites may be jointed by tectonic pressures, at least in their upper cooled portions, even while the acid magma is still so fluid in some lower part as to give off aplite and pegmatite.[1] The same relations had been independently observed by the writer in certain granites of the Coast range of California.[2] Similar occurrences of aplite are common in the granites of the coast range of Atacama and they point to the conclusion that the inequilateral pressures which caused the jointing had already developed or had been continuously active when the granite had solidified superficially but was still molten below.

While the aplite veins are of small volume and by their chemical composition belong to the granitic magma, it is quite otherwise with the great dikes of black diabase, which were next intruded. They are inferior in volume to the granite, but are nevertheless very numerous and thick. They contrast sharply with the granite in color, being black against a light ground, and resemble strata of black shale interbedded with sandstone when viewed from a distance. They occur in all parts of the zone in which the granite was intruded. The association is so constant that it seems to imply a genetic relation. The sequence is moreover of common occurrence in the coast ranges and islands bordering the Pacific basin. A discussion of it pertains, however, rather to the province of the petrographer than to that of the structural geologist.

MESOZOIC ACTIVITY

The activities described can not have occurred without producing an uplift of the coastal zone in which the intrusions are now found. We may, therefore, consider the Triassic period which followed as having opened with a range of mountains located along that zone. The coast district appears never again to have been submerged. No remnants of younger strata have been observed in it and it is properly characterized as the Paleozoic coastal belt. The evidence of Triassic conditions is, however, exceedingly meager. In this region it is limited to very local occurrences of coarse sandstones and conglomerates, which contain small lenses of coaly substances with plant remains of Rhetic age. In the latitude of these observations there is but one such deposit. It lies in the foothills of the Andes, 150 kilometers east of the coast, where it may have been spread as the wash of a river flowing down the eastern slope of the coast range of that period. The cobbles of the conglomerate lenses, the cross-stratification of the sandstones, and even the lenticular form of the coal beds suggest such an origin. The evidence is thus consistent with the inference that there was a mountain range to the west along the present coast. The record which was made in that zone was therefore one of erosion and has been destroyed by the subsequent activities of atmospheric agencies.

[1] Hans Cloos, cited in Robert Balk, *Primary Structure of Granite Massives,* Bull. G. S. A., p. 686, vol. 36.
[2] Bailey Willis, *La Force Sismique en Californie,* Livre Jubilaire, Soc. Géol. de Belgique, p. 432, 1927.

The Jurassic record was made in fine-grained sediments. Fine calcareous sandstone is the coarsest deposit; sandy shales are intermediate in grain and limestones represent the finest material. All of them indicate the presence of a shallow sea immediately bordered by low lands. Any monadnocks which may have survived from the earlier stages of the topographic cycle must have been at some distance from the shores.

The Jurassic sediments are widely distributed on the western slope of the Andes. They are not found in the narrow coast range of Atacama. They appear to have been deposited in such a sea as now extends between the islands of Japan and the coast of Asia, the coast range corresponding to Japan and the continental mass of South America representing Asia. That mass is now completely buried by post-Jurassic formations, but presumably existed as a land area.

The thickness of the Jurassic formations does not appear to be considerable. They are to be measured in hundreds rather than in thousands of feet. Apparently thick sections were found to be repeatedly overthrust. Hence we may infer that the subsidence of the zone of sedimentation was moderate, as was also the amount of uplift of the areas exposed to erosion. On the whole, the orogenic activity during the Jurassic period was exceedingly moderate. The forces which had caused the great intrusions of the late Paleozoic had apparently become exhausted during the Triassic. There are, however, two episodes in the Jurassic history which, though they may be considered as relatively brief, present a catastrophic character in their tremendous activity. They are represented by the eruptions of labradorite porphyry in middle Jurassic times and of melaphyres toward the close of the Jurassic.

The labradorite porphyry occurs in very extensive lava flows which are sometimes hundreds of feet thick. The basic character of the rock and its large volume imply the absorption of a very large amount of heat energy in the process of melting. We are here again faced with the alternative assumptions that the rock had existed either as an originally melted mass or as a solid body which became molten immediately prior to its eruption. The depth from which it rose is an indeterminate factor in these speculations, but in either case the dynamic activity of the outer crust was temporarily speeded up in the development of the eruptions.

The eruption of the labradorite porphyries was a definitely limited episode. It was followed by renewed quiescence, as is indicated by the deposition of the limestones of the upper Jurassic. A second episode of eruptive activity occurred during the latest Jurassic time and is represented by the melaphyres. The rock appears in dikes of considerable size, but of very small volume as compared with the labradorite porphyry flows. It may be inferred that the forces involved were relatively of slight intensity and duration.

The Cretaceous period is also represented by fine-grained sediments. The eroded products of the lava flows and volcanoes of the Jurassic might be supposed to be represented in the sediments either of the late Jurassic or Cretaceous, and they probably are, but they were not recognized by me during this reconnaissance. The Cretaceous sediments are greenish-gray sandstones in calcareous mud deposits, again indicating shallow seas and low lands.

A. Upper Copiapó valley. View of minor upthrust or ramp in Mesozoic eruptives. Beds dragged up.

B. Chuquicamata. View of footwall of ore deposit showing horizontal striæ on footwall fault. The ore body in front of footwall moved to right.

Again there intervened a minor episode of intrusive and presumably extrusive igneous activity, which resulted in diabase dikes and flows. They cut lower Cretaceous strata and are regarded by Felsch as having been erupted at the close of the Neocomian period. In view of the fact that later Cretaceous sediments are lacking, no definite date can be assigned to them.

Summing up the dynamic history of the Mesozoic, we recognize that on the whole it was an era of moderate orogenic activity. The conditions which determine the uplift of broad areas or the subsidence of geosynclinal troughs were apparently lacking. They had been replaced by conditions favorable to stability. Yet eruptions of molten masses occurred at three different times, and they represent the intrusion of already molten magmas or the temporary activity of energetic forces, accompanied by a rise of temperature sufficient to produce melting, into the outer crust beneath this area.

TERTIARY AND LATER ACTIVITIES

The sedimentary record closes in Atacama with the lower Cretaceous strata. It is possible that future more intensive surveys may discover upper Cretaceous or early Tertiary sediments within the area, but none are at present known, and they certainly are not extensive if present at all. Hence we conclude that not only the coast range but the western slope of the Andes corresponds with a land surface which has been persistent since the middle Cretaceous. Whatever sediments originated from it have been deposited in the adjacent Pacific basin or in the troughs of the Amazon and Paraná watersheds.

The absence of sedimentary strata indicates that landscapes of early Tertiary time, or possibly even of the upper Cretaceous, may still survive in some elevated remnants in the coast range or Cordillera. While this may probably be so, they have not been recognized. It is doubtful if they can be in the Cordillera, where the uplifts have been great and erosion has resulted generally in sharp divides. It is more likely that the oldest landscape remnants are to be found in the coast range, which not infrequently presents broad, subdued profiles, assignable certainly to a pre-Pliocene and probably pre-Miocene date.

The very powerful and intensely active forces which have raised the Cordillera of the Andes thus began their effort at some time subsequent to the middle Cretaceous. It is difficult to distinguish stages of erosion in the effects which we recognize in the actual mountains. The great heights are sculptured to a stage which represents something past vigorous maturity. The divides are all sharp. There are no remnants of an earlier topographic cycle. The salt basins of the high plateaus are wide. Portions of them probably may be identified as valleys of erosion, others are unquestionably aggraded tectonic valleys. The stage of erosion is therefore not accurately recognizable. It is clear, nevertheless, that the surface is to be described as mature rather than old.

The lapse of time required for the development of mature topography from a previous stage of old age topography is not measurable in terms of any chronologic units. We can only proceed by comparison with mountain areas where sedimentary strata, lapping up on the lower slopes, indicate a recent time limit within which the uplift must have begun. For instance, on the eastern coast of the United States the volume and character of Miocene sediments, as contrasted with the Eocene and earlier, indicate that the uplift of the existing Appalachian mountains began shortly before or during the Miocene period. I am inclined to regard the oldest mountain forms to be seen in the Andes as more advanced in their development than the Appalachian ranges. The disparity of conditions of development may not have been so great as might at first glance seem probable, for the older Andean ranges were sculptured at an altitude far below that which they now have. If the comparison is valid the more advanced topographic forms have been longer exposed to the erosive agencies and consequently their topographic cycle would have been initiated in some pre-Miocene time.

This line of reasoning leads me to think that the uplift of the Cordillera began possibly during the late Cretaceous, but more probably during the early Tertiary. It was a dynamic beginning of the first importance.

The dynamic activity which we thus assign to the greater part of Tertiary time and to the relatively brief section of the Quaternary including the Present has been a consistent if not a continuous activity. The slopes of the Andes are scored with young canyons, which represent later Tertiary and Pleistocene erosion. In the river valleys there are voluminous coarse fluviatile deposits, which probably go back to the Pliocene and which have been tilted, greatly elevated in some areas, and profoundly eroded. They record intense erosional activity, which exhibits phases of aggradation and corrasion, probably because of changes of climate rather than because of pauses and renewals of movement during the uplift.

Thus the physiographic evidence, which is described and discussed more in detail in another chapter, indicates that orogenic forces have been active in Atacama since the early Tertiary. The effects of their activity are among the most stupendous, even among those of the great young mountain ranges of the world.

Volcanic eruptions have constituted an important phase of the orogenic activity throughout all its later stages and probably from its beginning. Both acid and basic igneous rocks have been extruded in great volume in the western slope of the Cordillera and along its crest. According to Felsch diorites constituted the earliest facies, and they have been followed by andesite, pyroxene andesite, acid trachytes and liparites, in the order named. This may be the dominant sequence, but the inference rests upon reconnaissance work over but a small part of the mountain chain, and can not be accepted as a fact upon which to base petrologic theories. The outstanding fact is that the igneous rocks comprise a wide range of facies and consequently indicate variety of effects or of origins in the deep-seated zone of fusion.

An eruption of igneous rock represents an invasion of the region by heat from a subterranean source. The heat energy may have been contained in rock masses buried at very great depth, which struggled up to the outer crust, bringing their heat with them. Or it may have been conducted in successive waves from sources where other forms of energy were transformed into heat. Or again it may have been developed by chemical or physical changes in the asthenosphere at a moderate depth below the surface. However widely speculation may range among these and other possible hypotheses, the outstanding fact which must be considered is that heat energy has been supplied to a zone subjacent or adjacent to the Cordillera at a depth from which the igneous rocks have come. The process has been continued during many millions of years. Impressive though these terms appear in our measures of time, a million years is but a brief interval in geologic ages. Yet the aggregate, which covers Tertiary and post-Tertiary eras, is indeed long continued. The inflow of heat has been a geologic process, not merely in the conditions of its origin and in the character of its effects, but also in the duration of its action. We must recall also that similar effects were produced during three episodes in the Mesozoic and during one greater activity at the close of the Paleozoic. The earlier history is unknown.

The extrusion of igneous material is a local phenomenon. It is characteristic in Atacama of a belt which is but a hundred miles in width and which borders the Pacific basin. The eruptive activity thus represents that well-established relation of location in the margin of an ocean basin which has been recognized throughout the world. We may fairly draw the conclusion that in this marginal zone, where the ocean basin meets the continental plateau, there exists a condition favorable to the accumulation of heat energy which results in the melting and extrusion of rock; that this condition is a permanent one which has survived the various changes resulting from the activity; but that the heat supply is more or less intermittent and decidedly variable in concentration and amount.

In what has preceded we have spoken of the uplift of the Cordillera and of the extrusion of igneous rocks from some deep-seated source as though we were dealing with a simple vertical movement in either case. The great overthrusts which are found to characterize the Cordillera oblige us to recognize horizontal displacement as well as vertical elevation. The horizontal component of movement on the upthrust faults appears to be large as compared with the vertical component, judging by the manner in which masses of older rocks are superimposed upon younger. The observations are not conclusive on this point since we have no exact measurements, but even if the vertical should prove to be the larger effect on the upthrust faults the horizontal is a notable displacement. The thrusts are steeply inclined at the surface in many places, but dip toward the west. Where the deeper canyons are cut across them they are seen to assume gentler dips in their lower exposures and to extend downward and westward toward the Pacific. The evidence indicates that they are minor thrusts of a great overthrust structure of the Scottish Highland type.

There are many of these minor thrusts, which, even though they be called minor in relation to the whole stupendous structure, would each one be considered a thrust of notable extent in any mountain range of less magnitude. Fourteen of them were observed in the comparatively narrow zone covered by our reconnaissance. In their spacing and parallelism they resemble the overthrusts that have been mapped in the Paleozoic belt of eastern Tennessee, and are probably of similar dimensions.

The structures in Tennessee are relatively very ancient, and any evidence that may once have existed as to the sequence of their development has been eroded. That is not the case in Atacama. The topographic surface developed in the process of thrusting is still recognizable and presents differences of aspect as we go from west to east. It is older in the west and very young, indeed actively developing, in the east.

To state the evidence of this important fact: the coast range of Atacama presents deeply eroded fault scarps, which are recognizable only with difficulty and would not surely be identified as effects of faulting without the stratigraphic evidence of displacement. Moreover, these faults have not been active since the period of aggradation when the rivers deposited the gravels that filled their older valleys and now constitute the terraces bordering their recent channels. These terraces extend with unbroken evenness across faults that bring Paleozoic to rest upon upper Mesozoic strata. Since the gravels are in part at least as old as early Pleistocene, the faulting in this region may fairly be considered to have become inactive by the close of the Pliocene. Subsequent deformation has taken the form of a more general uplift of the coast range belt.

In the higher Andes the topographic expression of the fault scarps is more obvious. The scarps are younger than they are farther west. The gravel terraces extend evenly up to 11,000 feet along the Rio Salada and presumably elsewhere, but they are seen to be greatly displaced by faults in the elevated section of the watershed of the Rio Elqui, and this condition probably exists farther north and south. Thus the thrusts which outcrop in the high plateau region are younger, or have continued to be active longer, than those of the western foothills and the coast range.

According to personal communications from Felsch and Keidel, active overthrusts appear at the eastern side of the Andes down to the base where the alluvial slopes of the Chaco begin. The descriptions indicate structures even younger than those which may be recognized in the high plateaus.

Thus, as we go from west to east we recognize evidences of a progressive development of horizontal displacement. It is similar to the progressive thrusting produced by Cadell in his experimental investigations of Highland structures.[1] The development has been from the Pacific basin into the continental plateau. The effect has been to shear off the margin of the continent and push it eastward.

GENERAL GEOGRAPHIC RELATIONS

We have recognized that the Cordillera of the Andes is composed in large part of igneous rocks extruded from some deep-seated source. Their volume is great. As piled up on the earth's surface it is a great mountain chain. The space from which it came must now be represented by a depression of similar dimensions. Such a depression constitutes the adjacent section of the Pacific basin and is known as the Atacama deep. We have seen that the movement of the overthrust masses of solid

[1] H. M. Cadell, *Experimental Researches in Mountain Building,* Trans. Roy. Soc. Edinburgh, vol. XXXV, p. 342, fig. 2, 1887.

A. Quebrada de Paipote, near Puquios. Th

B. Quebrada de Paipote, La Puerta. Massive flows of t

: faults in Jurassic limestone and intrusives.

ıdorite porphyry of Jurassic age upturned to steep angle.

rock was from the Pacific toward the continent. The relative positions of the deep and the mountain chain indicate the migration of molten igneous rock in the same direction.

The consistent testimony of all the structural relations and successive developments which have been traced in this review of the dynamic history of Atacama shows that the source of energy lay to the west of the continental margin beneath the adjacent zone of the oceanic basin; that heat and pressure differences have there been effective agents to bring about changes of a very active character during certain intervals and of a less active, more gradual character during intervening periods; and that the effect has been to bring toward the surface rocks, which either cooled and crystallized at some subterranean depth or took on a crystalline state after having been extruded. Crystallization is thus seen to have been the characteristic tendency of the rocks in transition states, and may be supposed to have occurred not only in course of solidification from a molten condition but also during the progress of metamorphic changes resulting from unbalanced pressures and rising temperatures in solid rocks. The solid masses lying in their deep habitat must have gone through wide ranges of temperature in passing from the solid to the molten condition. Only that portion could become molten which possessed the most favorable conditions for melting, namely, high conductivity, low specific heat and lowest melting temperature in the presence of gases. The balance of the complex must have remained solid and have been altered by recrystallization in adjustment to stress environment.

The dynamics of the great eruptive activity which has characterized Atacama at intervals since the Paleozoic as well as of the great displacements in consequence of which the Andean cordillera has been upthrust are therefore to be explained as originating in conditions that existed and continue to exist beneath the Atacama deep. Heat has been the disturbing energy and it has brought into play the otherwise inert molecular forces. Gravity and its tangential resultants have been the directive forces.

The Atacama deep and the Andean heights have had a concurrent and coordinated development.

INVESTIGATION OF THE EARTHQUAKE MECHANISM

METHOD OF ATTACK

It is assumed in earthquake research that the shock originates from a peculiar mechanical structure, which will be found in the rocks of the affected region. The geologist expects to distinguish certain mountains, or masses equivalent in magnitude to mountains, which may be regarded as mechanical or structural units in the sense that each one would vibrate or move as a whole, if it were caused to vibrate or move at all.

Furthermore, it is established that *tectonic* earthquakes, that is to say, earthquakes that are related to the structure of the region and not to volcanoes, are very definitely connected with crushed zones or *faults,* as they are called. A crushed zone is produced where two mountain masses rub past one another in slipping or turning under great pressures that develop in the earth's crust; and when we find such a fault we have discovered that place where earthquakes have occurred and perhaps are occurring. In the latter case the fault is still active.

Thus the geologist who would locate an earthquake looks for crushed zones or faults, which bound or sometimes cut through mountain masses.

In the ordinary practice of geologic investigation, as it has been carried on for a hundred years or more, a fault is recognized by evidences of movement, by disturbance of the orderly relations of rocks. To understand this, it is necessary to recognize that in any region some rocks are older, some are younger, and they occur in orderly relations unless disturbed. If we know what the order of the rock deposition is we can trace it as far as it has not been disturbed, and so may determine the extent of a structural unit. Or, *per contra,* we can trace a fault by that lack of orderly relations among the rocks, which is peculiar to a zone of crushing or displacement.

In the last 40 years there has been developed another method of identifying active faults, which consists in tracing the extent of a structural unit by the continuity of its landscape surface and detecting the fault zones that bound it by the interruption of that continuity. This may best be made clear by an example.

The Sierra Nevada of California is a structural unit which is some 600 miles (850 km.) long and 75 or more miles (120 km.) wide. We recognize it as a unit because its western slope is practically an unbroken plane, if we conceive the recently eroded canyons to be filled up. The plane surface can actually be seen by connecting the gentler slopes across the deeply cut ravines or canyons, and can be traced throughout the length of the mountain block as well as from the Great Valley to the crest of the range. That this plane surface was originally a plain that stretched nearly level over the site of the present mountains, and that it has been tilted westward with the upheaval of the Sierra, is an inference that is justified by the reasoning of physiography, the science of earth-sculpture.

At the summit of the Sierra Nevada, however, the long slope that rises from the west is cut off by the abrupt eastern face. Standing on the crest and looking east one looks down on Nevada, whose desert basins lie at one's feet, but 3,000 to 10,000 feet (1,000 to 3,000 meters) below. One is looking down the eastern face of the structural unit, of the Sierra Nevada block. At its base is a crushed zone where the block comes in contact with other masses, and along that zone or fault earthquakes occur from time to time.

Thus the existence of the great fault may be recognized at a glance, even though the details of the crushed and shifted rocks are hidden in the foothills. It is an exhilarating experience, as many a climber knows, to ascend to a mountain crest and let the eye sweep over the distant view. It is no less inspiring intellectually to have a vision of the structure of a mountain range and to read its history as recorded in its landscape features.

Active faults were first recognized by G. K. Gilbert and I. C. Russell, early geological explorers of the desert basins and ranges of Nevada and eastern Oregon. There the mountain blocks are forced up like arctic ice flows in the pressure ridges described by Peary, and their fractured faces stand as great escarpments, several thousand feet high and tens of miles long, overlooking the desert plains. Beneath the latter lie buried the depressed edges of tilted blocks or of blocks that have not shared equally with the general uplift of the whole crushed, faulted mass of California, Nevada and Oregon.

The observations of Gilbert and Russell in regard to what is known among geologists as "Basin Range structure" were long questioned by their colleagues, who were familiar only with the mountains of the eastern United States or of northern Europe, where the existing faults have so long been inactive that their surface features have been eroded and they can no longer be distinguished in the landscape. Incidentally, we may note in passing that these are regions where earthquakes are few and far between. But it is now established and widely recognized that these two pioneers in the geology of the West saw with a clear vision and correctly interpreted the facts of Basin Range structure as displayed in the relations of the rocks and also in the escarpments and slopes of the mountain blocks.

The year 1906[1] recorded an impressive confirmation of the view that active faults are marked by recognizable details and by larger elements of the topography of a region in which they occur. The earthquake which shook the coast ranges of central north California and caused the great conflagration which destroyed San Francisco left its trace in the surface of the ground in such unmistakable fractures that it could be followed accurately for some 200 miles (320 km.), sometimes as a single line of displacement, sometimes as a wide zone of complicated breaks in the soil or rocks. Subsequent studies have developed the method of physiographic or landscape investigation with a view to tracing active earthquake faults, and it now holds a recognized position as a means of identifying them. Since it requires only the intelli-

[1] A. C. Lawson, *The San Andreas Rift as a Geomorphic Feature; the California Earthquake of April 18, 1906*, State Earthquake Commission, Report of. Carnegie Inst. Wash., Pub. No. 87, vol. I, Part I, p. 25, 1908.

gent comparison of the surfaces and slopes of hills and valleys, as one passes them in traveling, it can be carried out over an extended area far more rapidly than would be possible in making a geologic survey of the rocks. But because the causes of landscape features are often capable of more than one interpretation, the physiographic method is suggestive rather than conclusive, and its indications should be checked by studies of the rocks wherever possible.

The writer, having received many early suggestions from Gilbert, had used the physiographic method to identify active faults in regions as widely separated as China, the western United States, and the Alps; and more recently, in the investigation of the earthquake districts of California, he had gained considerable familiarity with the peculiar characteristics of the live mountain ranges, that is ranges which are actively growing at the present time. It was therefore a natural consequence of his experience that he should approach the study of the earthquake regions of Chile through the physiographic method, especially as the rock geology of those regions is but little known and local geologic maps are entirely lacking. It must be recorded, however, that he met with a decided setback and found it necessary to revise his assumptions in this unfamiliar region.

HYPOTHESIS OF EARTHQUAKE ACTION

In the course of the first weeks of work in Chile, in February and March 1923, the writer's ideas regarding the origin of earthquakes in that country underwent a change, because he failed to find the kind of evidence necessary to sustain the hypotheses with which he had come prepared by previous experience. In order to make clear the evolution of his conclusions, it is necessary to state as a background the conditions which are known to govern earthquakes in California.

It is most natural to compare California and Chile from many points of view. They are similarly situated with reference to the deep ocean basin of the Pacific and to the high cordillera that marks the margin of the continents. Each country is commonly described as presenting a coast range and a longitudinal valley west of the major mountain-chain; and there is enough basis of fact for this item of the comparison to give it color, although the longitudinal valley in California is much larger and more continuous than the basins which form the corresponding but interrupted zone of depressions in Chile.

These geographic similarities extend to the geologic history. In both regions the earliest recognizable disturbance of the stability of the crust was by the intrusion of masses of granite. In both there was a sequence of more basic intrusions and also of great changes of level. The movements continue in both countries in a somewhat similar manner and earthquakes result from the displacements of mountain blocks. In view of these likenesses it seemed probable that the mechanical structures of the mountain ranges of Chile would be found to be similar to those which had been observed in California and that earthquakes would be traced to instantaneous displacements on faults, such as occur in the latter State. This expectation was not realized.

In California the earthquake faults are vertical planes. From the line by which they may be traced on the surface they extend vertically down into the earth's crust, as may be seen in the small exposures where the dislocated rocks come in contact in cliffs. How far down into the earth the fault planes maintain this vertical attitude we do not know. It is the common practice of geologists to draw them as though they extended indefinitely toward the center of the earth, but there is reason to believe that they curve and are features of a superficial shell which may be not more than 50 to 100 miles deep.

In moving on these vertical fault planes the mountains of California slip upward and also horizontally past each other. In any individual earthquake movement either the vertical or the horizontal displacement may be the greater, but the sum of horizontal displacements added up during the ages is represented by miles, while the vertical offsets may be measured in hundreds of feet. Thus the horizontal movements are materially larger than those in a vertical sense.

The movements described in the last paragraph are in active progress in California today, and the features of the landscape to which they give rise, being persistently renewed, are not obliterated by erosion, although they are frequently modified by it. They can therefore be seen. Where the vertical element of movement has been notable the upraised mountain block presents a steep, straight face. Where the displacement has been chiefly horizontal there is usually a long straight valley. If the fault is a simple fracture the mountain slopes on either hand may rise from it with curves that are distinctly convex upward, looking like a pair of compressed lips. Or it may happen that the fracture zone is very wide and includes within its crushed belt masses of rock which have been squeezed out as one would squeeze an apple seed between fingers. Such masses may have the dimensions of large hills or even of smaller dependent ranges, where the fault branches and encircles them. There are many subsidiary topographic features of the active fault zones of California which might be looked for in Chile, provided the faults there were equally active. That they are so probably no geologist would doubt, in view of the very pronounced earthquake activity of the country—but there are material differences.

In my three days' journey from Valparaiso to Copiapó, I recognized in the landscape some similarities with California and I expected to find in the valley of Copiapó the evidences of a great earthquake fault similar to the well-known San Andreas fault. But I looked in vain for the corresponding long, straight features of the landscape, either of mountain scarp or valley. Copiapó lies in an oval basin, surrounded by mountain ridges which are everywhere sculptured to a greater or less degree, according to the softness or the hardness of the rock, but which nowhere exhibit the characteristic profiles or contours produced by recent faults. After spending a couple of weeks in vain search for the features which I expected to find, I returned southward to Vallenar and Coquimbo, but was there equally baffled.

It is true that to anyone who is looking for evidence of faulting in the mountain ranges of northern Chile certain long straight ridges appear suggestive. They trend rather uniformly from south by west to north by east and they seem to represent elongated fault blocks, especially where they border the depressions of the longitudinal valley. In some views, such as the one which may be seen looking southwest from above Vallenar across the valley of the Huasco, there is in the distant sky-line of the coast range the profile of an elevated plateau that slopes toward the ocean. It awakens the thought that the wide mountain block of which it is the summit has been tilted westward like the Sierra Nevada and should be bounded on the eastern side by a steep face, a fault scarp. There are many other similar suggestive features, but when they are closely examined it is found that erosion has progressed so far in its work of destroying the original mountain-face that its character as a fresh fault scarp has been carved away.

Thus throughout the landscape of Chile I found suggestion but no proof of the existence of those vertical faults which I had learned to recognize in California by their landscape features. It looked as though the region had once been the scene of energetic active faulting, but that it had passed through the stage of activity in which California now is and had become quiescent; and yet there was the fact of frequent and severe earthquake movements affecting this apparently dead structure.

I was greatly puzzled and anxious lest the investigation should prove inconclusive on this vital question of the origin or structural location of the earthquakes. Eventually, however, it occurred to me that I might have to deal with a type of structure which is well known to geologists and which consists of a gently inclined fault. It can best be described perhaps by comparing the fault with the bottom of a platter. The edge of the platter represents the outcrop of the fault at the surface of the ground, and the under surface of the platter corresponds with the fault surface, which, after descending somewhat steeply into the earth, soon curves toward the horizontal and assumes a gentle inclination.

We must not be deceived by the simile of the platter into thinking of something of small dimensions. We are talking of mountains, of mountain ranges, and even of mountain chains like the Andes. Such a fault, then, might well extend for hundreds of miles along the earth's surface, might have its upper edge in the heights of the Cordillera, and prolonged downward might extend far out under the Pacific. Such was the concept which came to me one March morning in Coquimbo.

Assuming such a flat fault plane, the more nearly vertical faults that I seemed to have seen and that I believed existed could be accounted for as minor features of an enormous structure, which branched from the great underlying plane and curved upward to the surface. Such a compound structure, consisting of a great major fault, or thrust as it is called, and of minor thrusts, was first recognized by the English geologists Peach and Horne as existing in the northwest highlands of Scotland. It has therefore come to be known as Highland structure. But the Scottish example is fossil. It was once active, but geologic ages have passed since it vibrated to an earthquake. Knowing this, it was a peculiar thought to realize that I might be studying a similar but vigorously active structure.

If the earthquake region of Chile were really underlain by a great major thrust, the displacements which caused the earthquake shock took place some miles beneath our feet and could not be seen. The elastic vibrations would, however, be transmitted with peculiar intensity up the minor thrust planes to the surface, and would therefore be most severely felt along the lines of outcrop of these faults. They might or might not be accompanied by visible local displacements. My observations indicated that in general they were not.

There were obviously two things to be done. One was to search for the outcrop of the major thrust plane, which might be supposed to emerge along the crest of the Andes, that is, along the edge of the platter. The other was to prove the existence of the minor thrusts by discovering evidence of faulting in the rocks in relation to the suggestive features of the landscape. It may perhaps be asked why I had not already attempted to apply geologic criteria to the solution of the fault problem. I had indeed made the attempt, but unsuccessfully, because I did not know the relative ages of the various kinds of igneous rocks of which the ranges of this part of Chile chiefly consist, and minute crushing is so general a phenomenon among them that the dynamic evidences of faulting are greatly obscured. It was only with the assistance of Dr. Johannes Felsch, a Government geologist who afterward accompanied me, that I was able successfully to attack this part of the problem.

Realizing that the more promising field of observation was to be sought high up in the Cordillera, I accepted an invitation to visit the Potrerillos copper mine. It lies at an altitude of 12,000 feet above the sea, about 80 miles northeast of Copiapó, in the general direction taken by the earthquake wave in its passage from Coquimbo to Vallenar and Copiapó. The buildings in Potrerillos had also been severely shaken. The place therefore lay in the earthquake track which, beyond it, passed into the salt basins of the high plateaus of the Andes, where it left no trace.

At Potrerillos, thanks to the cordial assistance given by the officials of the mining company, and particularly by James E. Harding, geologist, my search was successful. Among the rocks of the neighborhood there is a thick series of marine limestones and shales of late Jurassic or early Cretaceous age, and many faults traverse this stratified mass. They are thrust faults; that is to say, they are dislocations produced by compression, and they divide the strata into sections which have been pushed over each other until they lie like scales on a fish. One could see the same strata repeated in each separate section and the sections lying above one another, although when originally deposited each stratum had been a continuous bed.

From the geological point of view the opportunities for observation in the Andes are superb. Cold and aridity combine to reduce vegetation to a minimum; the wind blows away the soil; there is bare rock everywhere. In general, one can ride a mule where one pleases, the long slopes being covered with broken rock. This is to a certain extent a drawback to observation, but the jutting ledges and cliffs are sufficiently numerous, especially in the deeply cut canyons, to indicate geologic relations.

I spent ten days at Potrerillos and fully verified the initial observations. It was demonstrated to the satisfaction of Mr. Harding and later on of Dr. Felsch that we had to do with a structure of the Highland type. It appeared, however, that the faults which traverse the range at Potrerillos were still minor thrusts. We could not reach the outcrop of the great major thrust at the bottom of the structure, which probably skirts the eastern base of the Cordillera in the foothills along the edge of the pampas. Its existence there has been recognized by Dr. Johann Keidel, of the Argentine Geological Survey, and also by Dr. Felsch, both of whom subsequently described it to me.

From Potrerillos I went some 200 miles (320 km.) north to Chuquicamata, the other great copper-mine of the Andes Copper Mining Company, where also I was received as a guest and given every opportunity for geologic study. Flat-lying thrust planes were found to traverse this region also, and it became apparent that here, as at Potrerillos, the conditions governing the formation of the ore deposits were intimately related to them.

Returning from Chuquicamata to Potrerillos, I was there joined by Dr. Felsch, and in his company, assisted by his intimate knowledge of the rocks of the country which had been gained during seven years of geologic exploration in this region, I spent six weeks in tracing out the system of minor thrusts along which the vibrations of the earthquake had been transmitted with greatest intensity.

Thus the investigation resulted in the development of an hypothesis materially different from that with which I had approached the problem. Without reviewing the steps of its development, we may state the well-established conclusion: The earthquakes of Chile are of the tectonic type, that is to say, they originate in and are transmitted according to the geologic structure of the country. They are independent of volcanoes, although they may affect the latter. The particular structure with which they are related is of the Scottish Highland type, consisting of one or more gently inclined major thrusts and a large number of minor thrusts. The major thrust or thrusts are surfaces of rupture which originate beneath the Pacific Ocean basin and rise gently to their outcrop in the eastern base of the Andes. They are of great extent, underlying some unknown part of the ocean basin, the zone of the coast ranges and longitudinal valleys, and the mountain chain of the Cordillera. There is reason to think that their area is to be measured not merely by tens of thousands of square miles, but may extend to several hundred thousand. Such would be the indication of the transmission of earthquake shocks of marked intensity over so vast an area as that in which the terremoto of November 10, 1922, was felt. It alarmed people from Iquique in the north to Concepción in the south, a distance of 1,600 miles (2,500 km.). It did damage to buildings at an elevation of 10,000 feet (3,000 meters) in the Andes, and it shook the volcanic island of San Felix, 850 km. off the coast, in the Pacific. Within the area of this effect, however, there appear to be several earthquake districts. The historic record suggests separate structures since they do not snap simultaneously. Their distribution indicates that there is an equal number of major thrusts, each one of which is independently active. Valparaiso, for instance, suffered from a severe earthquake in 1906; Copiapó in 1918 and again in 1922. On each date the shock was smartly felt at the other place, but not with that effect which would have been experienced had the particular shock originated on the local fault.

A. Quebrada de Paipote, near La Puerta. Conformable sequence of Jurassic sediments and lava flows.

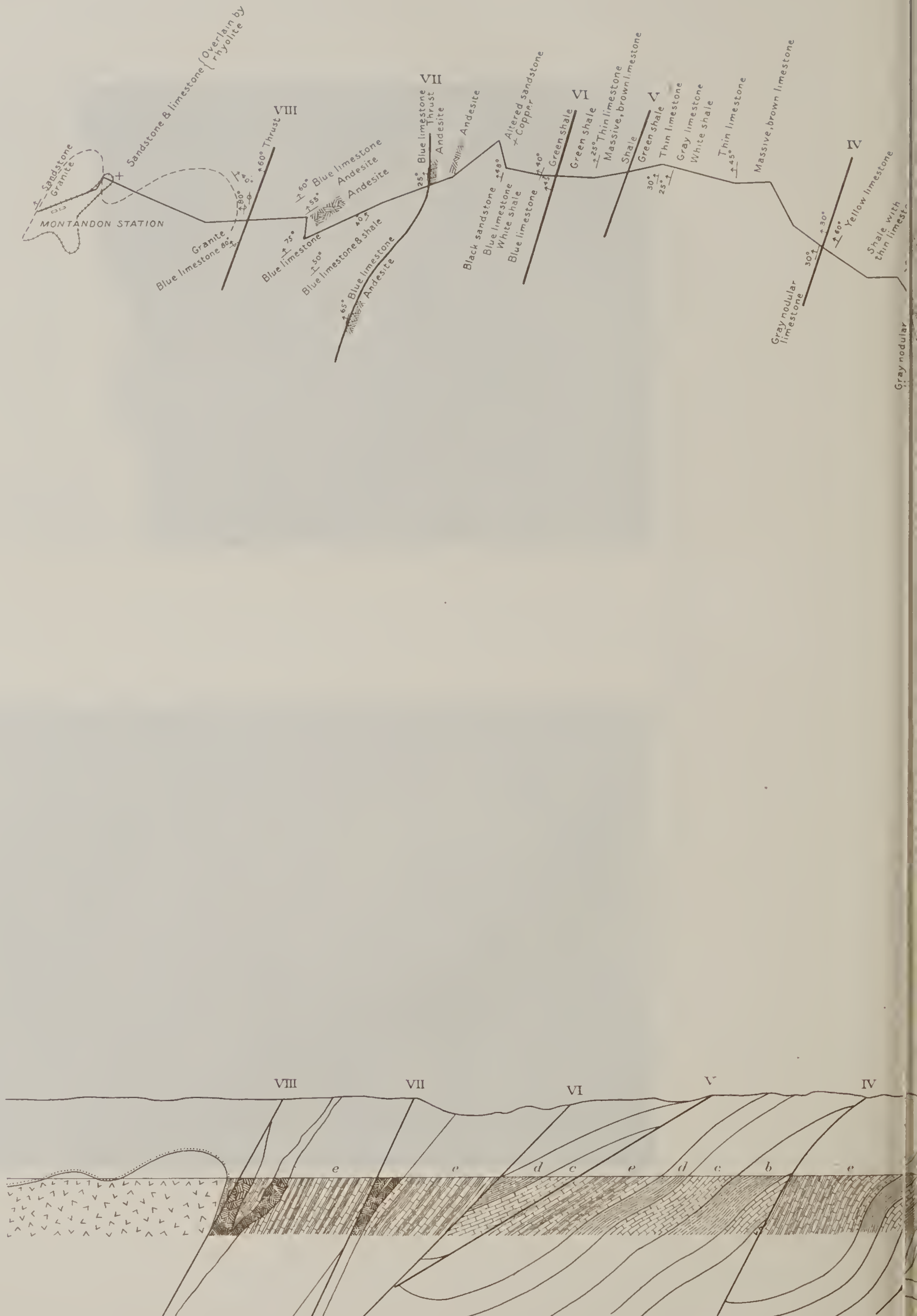
B. Quebrada de Paipote, near La Puerta. Faulted Jurassic sediments with ravine developed on fault zone.

Potrerillos, Quebrada Asientos. Overthrust in Neocomian limestone and shale series.

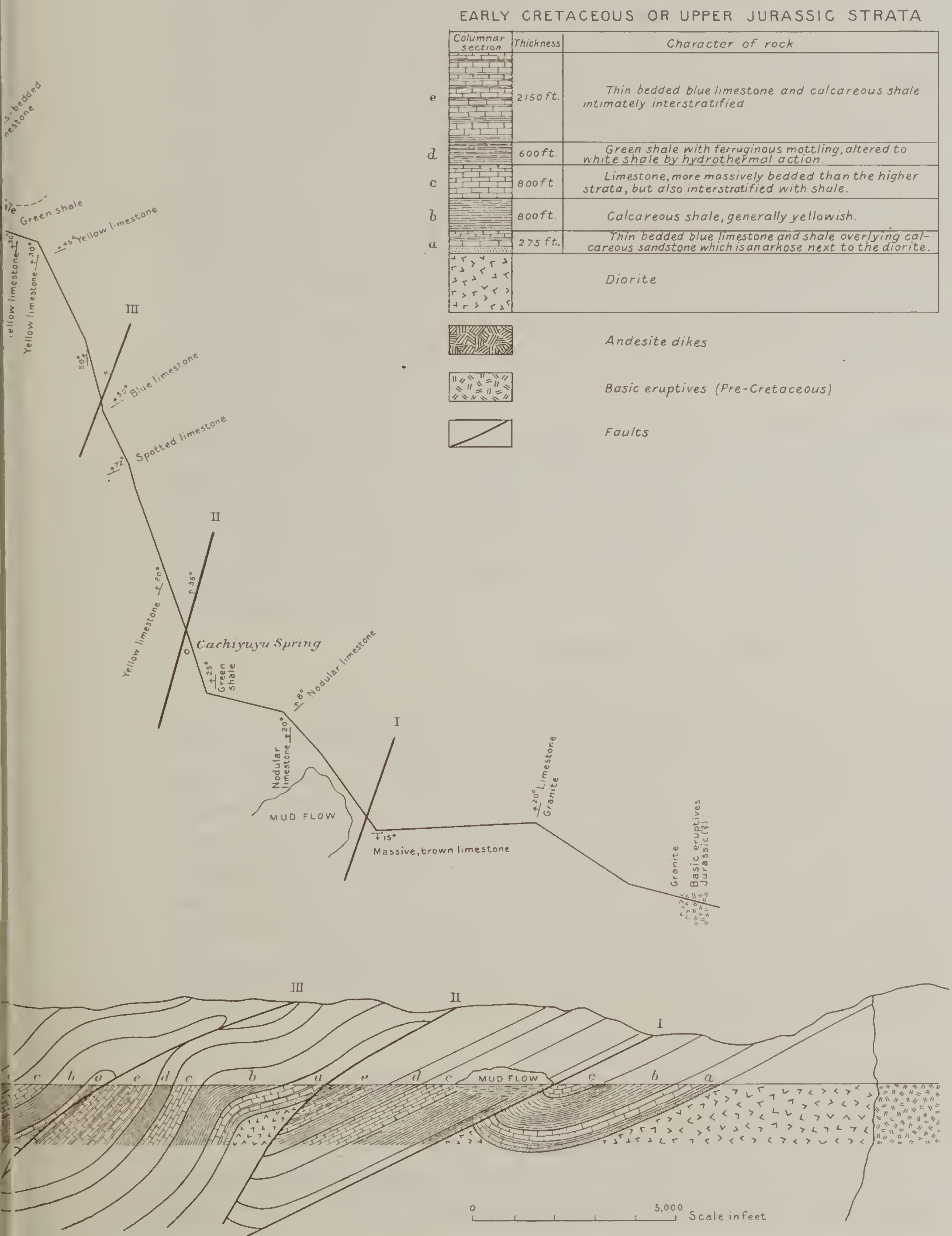
A. Potrerillos, Quebrada Asientos. Normal sequence of Neocomian limestone and shale; cross-bedded limestone.

B. Potrerillos, Quebrada Asientos. Neocomian limestone deposited on granite with basal layer of arkose sandstone.

A and B. Potrerillos, Quebrada Asientos. Views of Neocomian limestone in the zone of thrust faults.



GEOLOGIC TRAVERSE AND SECTION OF THRUSTS EX



'SED IN THE QUEBRADA ASIENTOS, POTRERILLOS

In the region north of Coquimbo and La Serena the minor thrusts constitute a parallel system and occupy a zone about 100 miles (160 km.) wide, so far as is known. In this zone 14 of them have been identified. There may be others within it, and there certainly are others to the east of it in the more inaccessible districts of the high plateau. This system of parallel minor thrusts trends north-northeast and extends beyond the limits of my observations in the Andean plateau. At its southern end it changes its course, but I was unable to satisfy myself definitely regarding the continuation of the faults. They may swing out toward the southwest and pass out under the ocean, as I had at first supposed from the suggestions of the landscape near Coquimbo and because of the distribution of earthquake intensities, which die out abruptly south of that place. But there are some indications in the trends of the ranges and valleys which afterward led me to think that the fault system south of Coquimbo may turn south-southeast, and might extend through the great heights of the Cordillera to the vicinity of Santiago and beyond. The question remains altogether indeterminate for lack of time to pursue the studies in the stretch of 250 miles (400 km.) between Coquimbo and Santiago and because exploration in the heights of the Andes is impracticable in winter.

The recognition of this unexpected relation between earthquakes and thrusts of the Highland type does not modify the concept of an earthquake as an effect of elastic rebound. It merely supplements the observations made in 1906 in California, which established that explanation as the correct one. It connects the rebound, however, with flat-lying thrusts which were not previously known in an active state, and thus advances our understanding of the possible conditions under which earthquakes may develop.

EVIDENCES OF PRESSURE

General Statement

The elevation of the Andes is in itself evidence of pressure exerted from one or both sides of the mountain range to uplift the corresponding zone of the earth's crust. Our knowledge of the mountain chains of the world, and particularly of coastal ranges, leads us to anticipate that we would find in such a cordillera evidence of severe compression expressed in the jointing of all massive rocks and the folding of stratified beds. Such is, indeed, the fact. Wherever one goes, whether in the coast range of Chile or in the Andes themselves, all classes of rocks exhibit jointing and marine sediments are uptilted, folded and also repeatedly overthrust. The facts of jointing and folding have often been noted, but the evidence of overthrusts, although perhaps observed, has, so far as I know, not hitherto been published.

Overthrusts at Potrerillos

Potrerillos is situated in the Andes, in latitude 26° 30′, 80 miles east of the port of Chañaral, at an altitude of 10,400 feet (3,100 meters) at the mining camp and 12,000 to 14,000 feet (3,500 to 4,000 meters) above sea in the mountains in which the mine itself is situated. The mining camp is located on a broad gravel slope, the upper part of the old valley floor of the Rio Sal and its tributaries. In this slope a canyon 1,500 feet (450 meters) deep has been cut by a stream that flows from the eastern heights westward and passes north of the camp to join the Rio Sal somewhat lower down. In this canyon the rocks are well exposed, and it is there that overthrusts were first seen in the course of my studies. The upper part of the canyon, to which we shall chiefly refer, is known as the Quebrada Asientos or Asientos Gulch.

The rocks of the region comprise (*a*) granite or diorite of pre-Jurassic age; (*b*) Jurassic or lower Cretaceous (Comanche, Neocomian) shales and limestones, which rest unconformably upon the granite; (*c*) rhyolite and andesite dikes; and (*d*) younger volcanics. The field relations show that the granite and marine shales and limestones are older than the faulting, whereas all the later igneous rocks are younger. Thus the faulting is placed in the Tertiary and may be regarded as pre-Pliocene.

The section that I studied in detail may be observed in Asientos Gulch, between Montandon station of the Potrerillos railway and a point some 10 miles (16 km.) up the canyon. The traverse of the canyon and the observed structural facts are given in Plate XLII, which is drawn according to a paced traverse oriented by compass sights.

The relation of the upper Jurassic (Tithon) limestones and shales to the granite is the first item in the geologic record to be established, especially because it is not the same as that of the granite at Chuquicamata and farther north in Peru, as described by Lindgren.[1] In that northern region the granite is intrusive in lower Cretaceous limestones, as is demonstrated by the contact metamorphism of fossiliferous beds. At Potrerillos the unconformable contact of the upper Jurassic terrane with the granite can be observed immediately below Montandon station and again 10 miles up Asientos Gulch, at both ends of the section. In each locality the dip is in the neighborhood of 20° toward the west. The basal strata of the sedimentary series in contact with the granite are arkose sandstones derived from the underlying massive rock by weathering, and the fact of unconformable deposition is clearly demonstrated. The sequence of sediments upward from the base consists of thin limestone strata alternating with earthy shales, which vary in color from the predominant yellow beds to green and red. The total thickness of the series is probably 2,000 feet, but it is difficult to be precise, because the strata are frequently repeated in the section with isoclinal dips. Although the degree of dip varies from 5° to 80°, it is nevertheless so persistently inclined down toward the west, that one gets the impression of a continuous conformable sedimentary series in the first examination of the Asientos section. A careful reconstruction of the structure, on this assumption, showed that the shale and limestone series would have the preposterous thickness of 30,000 feet (9,000 meters). This impossible result confirmed the inference, which I had drawn from preliminary observations, that the series was repeated by overthrusts. It was not, however, until I had passed over the section three different times that I realized how numerous the thrust faults are, and I am not sure that the seven which I identified in the 10-mile section represent the total number.

[1] Personal communication.

The criteria used to identify the locations of thrust faults were:

(*a*) The abrupt termination of limestone cliffs. As may be seen in the photographs, the limestone ledges contour the walls of the canyon, rising with the dip from the bottom of the gulch to some more or less distant point, where they terminate in a talus slope. The latter consists of fragments of crushed limestone and shale. Near their end, that is, immediately above the fault, the strata are sometimes abruptly overturned, but not infrequently there is no change of dip, even where the juxtaposition of unlike strata shows that there is a fault between them.

(*b*) The overturned dips just referred to. These are most commonly seen where the thinner beds of limestone are caught immediately above the thrust. Where the latter traverses the shales the fracturing has been so great that it is completely buried in talus, and where it cuts through the heavier limestone beds they have been too rigid to be bent over by the friction on the fault plane.

(*c*) The sudden steepening of the western dip, a peculiar feature, which I came to recognize as evidence of the location of a thrust. This effect is found immediately above the thrust plane and is the reverse of what we ordinarily expect, for we commonly consider only the forward overturned limb of an anticline in relation to the thrust plane. If, however, we prolong the latter downward across the anticlinal axis, it passes under the adjacent syncline, the advanced limb of which is not infrequently bent backward so that it has a very much steeper dip than the limb through which the pressure is being transmitted. This relation is a common one in Asientos Gulch and may perhaps be better understood by reference to the section.

(*d*) The repetition of beds is one of the best evidences of thrust faulting, provided there is some distinctive key bed or other criterion by which one may be sure that an apparent duplication by faulting is not in fact a repetition of similar sediments of different horizons. In studying the section of Asientos Gulch, I found the base of the sedimentary series only at the two ends, where the strata rested on the granite, as described, but in the sequence above the immediate base there was a mass of green shale which did not seem to be repeated at higher horizons in the regular sequence and which I regarded as duplicated by faulting where it occurred in other parts of the section. There were two massive limestone beds separated by a thin shale stratum, and also a heavier mass of limestone which I thought I could identify in the higher portions of the section. These were used as key horizons.

(*e*) The strata are greatly altered in places on the fault planes, and considerable masses of ferruginous spring deposits occur on the outcrops of the fault. Where this occurs the fault plane is completely obscured and the inference has to be based upon the occurrence of the spring deposit, although it may be confirmed by duplication of the strata or other structural evidences at a little distance from the plane.

(*f*) At various points the fault planes otherwise identified as such by the evidences already described are found to have been occupied by intrusions of rhyolite or andesite. In following out such a fault it is, then, reasonable to infer that it exists where andesite dikes occur in the proper orientation along the strike. While it is true that there are other structures, such as persistent joints, transverse faults, or irregular fractures, which have guided molten intrusives in their course toward the surface, yet it is a fact that thrust faults have frequently acted as the planes of weakness which have directed the movements of such masses. This phenomeon is so marked that there is reason to consider the thrust faults as the principal structural condition which has determined the location of ore-bearing, intrusive masses in the coast ranges and Andes of Chile.

Through the application of the above-cited criteria, seven thrusts were identified in the 10-mile section of Asientos Gulch. They are shown in the accompanying drawing (Plate XLII) and require no special description beyond what has already been stated. Their dip is westward and varies from 35° to 65°. They are accompanied by a great deal of fracturing, and this fact, taken in connection with the high dip that many of them exhibit, indicates that the strata were not heavily loaded. In that part of the section which we now see these thrusts were approaching the surface. They undoubtedly extended to it at the time of their development.

These relations are interestingly illustrated in the structural relations of Potrerillos copper deposits. The copper occurs disseminated in a body of monzonite porphyry which is intruded into faulted limestones and shales. The geographic relation of the ore deposit to the system of thrusts identified in Asientos Gulch is such that thrust-planes pass on both sides of the mine and one would pass through it if its position had not been taken by the intrusive porphyry.

One of the upper thrusts of the Asientos series is characterized by intrusions of andesite. Followed along the strike with appropriate allowance for dip and difference of elevation, this thrust can be traced west of the ore deposit, where andesite again occurs along it. Another thrust, which crosses Asientos Gulch at Cachiyuyu Spring and the line of which is closely followed by the trail from Cachiyuyu Spring to Potrerillos mine, passes east of the mine through Potrerillos Gap. Between these two thrusts, which can be traced respectively west and east of the mine, there are three other thrust faults and the ore-body lies on one or more of them. Since the copper-bearing rock is an intrusive porphyry, and since the thrusts have guided other intrusives, a genetic relation between the porphyry and the thrusts on the strike of which it occurs is strongly suggested, and there are also local conditions at the mine which explain the volume and form of the particular deposit. These consist in the strike and dip of the overlying limestone described in the next paragraph.

One of the heavier beds of upper Jurassic limestone lies above the Potrerillos ore-body, but not immediately upon it. The intervening space is occupied by shale. The limestone northwest of the mine has the usual strike of the series, about N. 25° E., and dips to the west. In approaching the mine it bends sharply toward the southeast and east and takes on a steeper dip. This is the overturn which characterizes folded strata immediately above a thrust fault, but in this case the pitch of the overfold is very steep and the fold plunges abruptly toward the southwest. It is plain that the dislocation was caused by pressure from the northwest, was accompanied by horizontal movement and dragged the edge of the limestone over.

This effect may be simulated by placing the finger-tips of the right hand on the palm of the left hand and moving the right hand forward over the left. It will be seen that the fingers of the right hand bend and a hollow is formed between the palms. The palm of the left hand represents the thrust plane, while the right hand is the limestone stratum.

As has already been indicated, there is evidence in the fractured and open condition of the strata next to the fault plane that the limestone bed at the Potrerillos mine was competent to lift some part or all of the superincumbent load as it arched up in dragging along the fault plane. The result was that the shales underneath it were loosened and space was provided for the intrusion of the porphyry. The latter, rising on the fault plane in its deeper extension, reached the cavity and assumed the pear-shaped form which was determined by the bending of the competent limestone.

These facts seem to bear very directly upon the form and size of the ore-body. The fold within which it is located is a local feature, but is one of such size that it gives reason to expect a large and rather deep hollow within the arch. The thicker rounded portion of the intrusion would occupy the higher southwestern part of the arch, while the porphyry mass would thin out toward the north in a horizontal section and also in depth in a vertical section where the limestone approaches the thrust plane. The foot-wall of the ore-body would be flat and the hanging-wall concave downward. It would have been advantageous had the mechanical structure of the ore-body been understood at the time that it was drilled to determine the amount of the ore reserves, but at that time the existence of the thrusts had not been recognized and the interpretation of the mechanics of intrusion had not been suggested.

Structural Conditions at Chuquicamata

Chuquicamata is situated in latitude 22° 18′ south, about 85 miles (135 km.) east of the coast of Chile at Tocopilla, and at an altitude of about 10,000 feet above sea (3,000 meters). In the accidental relations of distance from the coast and altitude, Chuquicamata and Potrerillos, the two great mining camps, are similarly placed, but there is otherwise very little resemblance between them in their topographic situation. Potrerillos lies near the summits of high mountains, Chuquicamata on the side of a broad valley.

Coming north by rail, one gets out at the station Calama and drives by automobile some 10 miles (16 km.) north to the mining camp of Chuquicamata. The road skirts the foothills of a range of mountains on the northwestern side of the valley, and ascends a long alluvial slope which occupies a reentrant angle between the mountain spurs. The hills are rounded, their bases are buried in wash, and the aspect of the landscape is that of the matureland which is so widely recognizable as the oldest topographic feature of the Andes. One may note immediately that the profiles of the mountains descend toward the valley and pass under it in such manner that the lowest of the foothills form peninsulas and others project like islands out in the valley floor. The first impression, which was subsequently confirmed by more extended observation, was that the valley is one of those downwarps or synclinal depressions beneath which the old matureland lies buried in the débris of later cycles of erosion. The maturity of the landscape has a bearing upon the enrichment of the copper deposits, as will appear later.

The ore deposit at Chuquicamata is a mass of crushed granite, which forms the floor of the wide reentrant angle in the foothills and of the low pass in which the angle ends. It is obvious that the angle in the hills was eroded because of the crushed condition of the granite, which rendered it relatively weak in contrast to the somewhat more massive rock of the spurs on either side of it. Thus the ore deposit is related to a mechanical condition of the rock which is expressed in the topography.

I was looking for physiographic evidences of thrust faults such as had been found at Potrerillos, but they were not to be detected in these long, débris-covered slopes. The thrusts are there, but they were not to be seen, because erosion had completely obliterated all surface evidence.

By courtesy of the Andes Copper Company, I was enabled, during my three day's stay at Chuquicamata, not only to examine the mine, but to ride far afield, and was accompanied by A. B. Motta, the resident geologist. I was furnished with the unpublished report by Lindgren on the geology of the mine, and Mr. Motta gave me all the information which his familiarity with the ore deposit could make available.

The primary object of my studies was to detect any evidence of overthrusts which might be connected with the earthquakes occasionally felt at Chuquicamata. Since the general structural trends of the region as manifested in the synclinal valley and the mountain ranges are northeast and southwest, I inferred that any overthrust structure might be crossed in going northwest. Accordingly, in our first ride Mr. Motta and I went north to Aralar, some 16 miles (25 km.) from Chuquicamata, and then rode in a wide circuit toward the west and south till we struck the Tocopilla road, by which we returned. Our route took us up over the mountains back of Chuquicamata and down into other basins which are widely filled with débris and everywhere show the characteristic features of the Andean matureland. The landscape lacks structural expression; that is to say, elevations or depressions caused by faulting have been so deeply eroded in the one case or filled in the other that their structural origin is obliterated. Certain long, straight lines of hills suggested faulting of one type or another; but on the whole the observations of that first day were inconclusive, since the evidence was not of a kind to demonstrate the fact of faulting.

In returning along the Tocopilla road, at a high point 7 miles (11 km.) west of Chuquicamata, I observed that we were riding on granite which formed the ridge top, whereas the ravines were cut through the granite into red and green sedimentary rocks which had a strike of N. 20° E. magnetic and dipped 50° northwest. Answering my question as to the relation of the higher granite to the underlying sedimentaries, Motta said the granite was intrusive in the sedimentaries and that the latter in this locality formed an included mass. He justified his explanation by the fact that elsewhere the granite is seen to be intrusive in fossiliferous sediments, and the intrusive character is clearly demonstrated by the contact metamorphism of the limestone. This fact had been established by Lindgren and is one of the well-established conditions of the geologic sequence. It was therefore most natural to assume that the same condition existed at the locality over which we were passing.

On the following day we returned to the point on the Tocopilla road where the granite may be seen overlying sediments, and made a careful examination of the contact, together with a transit survey by which to determine the form of the contact-surface. We found that the sediments are not metamorphosed in this locality; that there are no dikes of granite penetrating them. There was therefore no evidence of the intrusion of the granite into the sediments nor of the inclusion of the mass of sediments in the granite. By means of the transit survey by which the relative elevations and horizontal positions of five points on the contact were determined over a distance of 600 meters, it was found that the surface of contact between the underlying sediments and the overlying granite was a nearly flat plane having a strike of N. 16°, 17°, or 24° E., according to three different solutions of the graphic problem, and a dip of 8° toward the north of west. The variations in the several determinations of strike are such as might be expected, since the exact position of the contact-plane could not be observed because of the talus on the slopes, and the plane itself is probably not perfectly flat. The form of the surface and its attitude correspond with those of a flat-lying shear plane, and, in view of the fact that the evidences of an intrusive contact were entirely lacking, it was clear that we had to deal with such a thrust.

The fact of the occurrence of overthrust faulting in the vicinity of Chuquicamata having thus been established, the purpose of my visit was accomplished, so far as the earthquake study was concerned; but I was interested to ascertain to what extent, if at all, the ore deposit owed its existence to these thrust faults. I therefore made a study of the jointing of the granite, with a view to ascertaining the direction of the pressures which had crushed it, and took observations of the direction of striation on the footwall fault as an indication of the direction of movement of the mass. The general conclusions are as follows.

The crushed mass of granite which constitutes the ore-bearing rock of Chuquicamata lies between a major thrust fault, whose general strike is about N. 20° E. and which dips very steeply, probably 80° or more, toward the west, and a branch of that fault which strikes west of north and thus forms an acute angle with it. The major thrust is the hanging-wall, the minor thrust the foot-wall. Neither of them is very well defined, as they are zones of crushing which developed near the surface rather than clean-cut, deep-seated shears. They serve, however, to delimit the ore-body.

The foot-wall forms an acute angle with the hanging-wall, both in plan and in section. The mass between them is therefore wedge-shaped and the edge of the wedge points northeast and pitches steeply southwest. The latter is the direction in which the mountain spurs on either side open out toward the valley. The striæ observed on the fault surfaces of the foot-wall are gently inclined. They rise at an angle of 12° to 18° toward the southwest. Thus the movement on these planes has been outward and upward from the northeast toward the southwest; that is to say, the whole mass of shattered granite has been squeezed out between the two faults in the direction in which a wedge of that particular form would move under the great compressive stresses which caused movement on the thrust-planes.

With this general concept in mind, we may essay to trace the steps of concentration of the copper minerals. Lindgren reached the conclusion that the copper was indigenous to the granite, and I see no reason to question the correctness of that view. Lindgren also determined that the granite is intrusive in early Cretaceous limestone, and we may note in passing that it is therefore younger than the pre-Jurassic granite of Potrerillos.

At some time during the Tertiary the region was subjected to compressive orogenic stresses, which resulted in shearing the massive granite and overthrust it. It is apparent from the attitude of the thrust plane on the Tocopilla road that those pressures came from a direction of west-by-north, but the major thrust, which is the hanging-wall of Chuquicamata, was a steep upthrust, not a flat-lying thrust plane like that which we measured.

The development of a minor branch fault in front of a steep upthrust is a mechanical result which we have observed in the similar structures in California and which is readily explained according to mechanical principles. Thus the foot-wall fault of the ore-body is genetically connected with the hanging-wall fault.

The episode of active faulting undoubtedly gave rise to the major features of the topography in the vicinity of Chuquicamata, but it was followed by less active displacements on the fault planes and by the erosion of fault scarps to the point where they are not readily recognizable as such in the landscape.

The wedge-shaped mass contained between the hanging-wall and the foot-wall was completely shattered, as is evident from the jointing by which it is now traversed. In this shattered condition it was peculiarly liable to percolation by atmospheric waters, and the copper minerals contained in the granite were superficially dissolved during the prolonged period of erosion that followed the active faulting. Thus the deeper portions of the shattered ridge were secondarily enriched, as they are now found to be. The copper minerals at Chuquicamata are carbonates and secondary sulphides which are concentrated upon the joint planes of the crushed granite.

The percolation of the atmospheric waters that accomplished the concentration appears to have been facilitated by the opening up of the wedge of granite as it was squeezed upward and toward the southwest. That this was the direction and effect of movement is evident on examination of the striæ on the fault planes. It is clear that the squeezing-out of the wedge was made possible by the fact that it lay immediately beneath the surface, under little or no load of superincumbent rock, and also that it came in time, as the Calama valley developed, to lie on the hillside above that valley in a position in which it met with no resistance as its mass moved in a southwesterly direction. It is thus evident that this great ore-deposit owes its existence as a concentrated ore-body chiefly to those mechanical conditions of structure which have facilitated the entrance of atmospheric waters to the innumerable joint fissures in the copper-bearing granite.

EVENTS OF POST-CRETACEOUS TIME

PHYSIOGRAPHIC INTERPRETATION

The facts of geologic history, so far as they can be read in the rocks of central Chile, are restricted to the ages before the close of the Cretaceous. The beginning, like the beginning of human histories, is lost in the mists of the past. Some ancient sedimentary rocks, believed to be of late Paleozoic age, are intruded and metamorphosed by granite. The intrusion has destroyed all earlier evidence, except the fact that limestones and clastic sediments had been deposited along a coast in this vicinity when the eruptions appeared.

From that event on through the Mesozoic age the record of changing conditions is found in continental sediments of the Triassic, in marine sediments of the Jurassic, which are associated on a large scale with basic lava flows, and in Cretaceous marine sediments. These rocks are sufficiently described in the chapter on the geology by Dr. Felsch and in the geologic notes.

The Cretaceous strata occur in the heights of the Andes and are of Neocomian, lower Cretaceous age. From then on to the present the marine record fails, except in the case of the Pliocene and Pleistocene deposits of Coquimbo Bay. We are thus thrown back upon the records made by subaerial agencies, which are written in what we may call physiographic script. I use the word *script* designedly to express the idea that the post-Cretaceous history is written in the landscape, in the forms of the mountains and of the valleys engraved on the surface of the land.

The record is made by winds and waters which sculpture more or less elevated lands, according to their elevation above sea, the inclination of the surfaces, and the climatic conditions. In general, the elevation of the land mass is that condition which determines its physiographic expression. If the mass is being actively upraised, the features sculptured upon it are young canyons, whereas if it has for a long time stood nearly at the same level the sculptured forms will have reached maturity. These terms signifying youth and maturity are here used in a broad general sense, as applying to the features of a landscape during a considerable lapse of time in either case. There are a great many lands of youthful topographic aspect, that is, lands which exhibit the effects of recent sculpture by streams. They are cut by canyons of greater or less depth and more or less precipitous walls, between which extend surfaces that invariably present an older aspect. A young landscape is therefore a composite in that the youthful canyons are associated with older surfaces which owe their forms to some previous stage of elevation.

Maturity, on the other hand, when applied to the landscape, describes a phase which has been reached as the result of prolonged erosion, without material change of elevation except in so far as the height of the land surface above sea has been lowered by degradation. In maturity a landscape is simple, not composite, all of the features belonging to one and the same phase of sculpture. Maturity is reached when youthful canyons have widened to valleys and valleys to broad flood plains; and when the interstream areas, which in the youthful stage exhibit the features of an older topography, have been reduced to sharp divides in which that older stage can no longer be identified.

In the effort to reach precise definitions, youth, adolescence, maturity and old age, as applied to topographic forms, have sometimes been given more exact characteristics than those implied in the preceding general description. An effort is made to fix the exact instant or the precise form in which one phase passes into the next. But such refinements are not practicable where one is dealing with a great variety of conditions and resulting forms. The terms are therefore used in a broad descriptive sense in this report, as indicated above.

Physiographers have long since become accustomed to the use of the terms introduced by Powell, Gilbert, and Davis to describe the conditions of a land surface which had reached extreme old age, namely, base-level plain or peneplain. The older term, base-level plain, once covered the condition described by peneplain, but the latter was coined to describe surfaces which, though advanced toward the ultimate stages of erosion, still retain a degree of relief inconsistent with the idea of a base-level or grade plain. The latter term has almost gone out of use, except as a theoretical concept. Peneplain, on the other hand, has been stretched in application to designate surfaces where the relief was still so great that the term plain could in no sense be applied to them. This misuse of the term has been particularly conspicuous in the writings of those who have described Pacific Coast landscapes, and arises from the fact that there are no peneplains in the mountains around the Pacific, while yet there are old surfaces for which some designation is required. These surfaces present features of mature topography, often of advanced maturity, but rarely, if ever, of that extreme age to which the term peneplain may properly be given. In describing these mature landscapes of Pacific regions, I find it convenient to use the word *matureland*, which will appear frequently in the sequel.

As already indicated, the distinction between the term peneplain and a matureland is one which has a regional distribution. Remnants of peneplains can be identified in North America and northern Europe, on both sides of the Atlantic, and it is there that the term has found its proper application. The fact follows naturally from the inactivity of orogenic forces around the north Atlantic basin since the Triassic. During the Jurassic and Cretaceous periods eastern North America and Europe were reduced by erosion to a very low level. By the close of the Cretaceous a peneplain was very widely developed and it was extended during the early Tertiary. Since the Miocene there has been a gradual elevation and the peneplain has been eroded, but not destroyed beyond recognition.

Lands around the Pacific, on the contrary, have not come to rest for a time sufficient to develop a peneplain landscape at any time in their recorded histories. Possibly the late Carboniferous seas, in which the sediments appear to have been predominantly calcareous, may have been bordered by extensive plains. But local intrusions

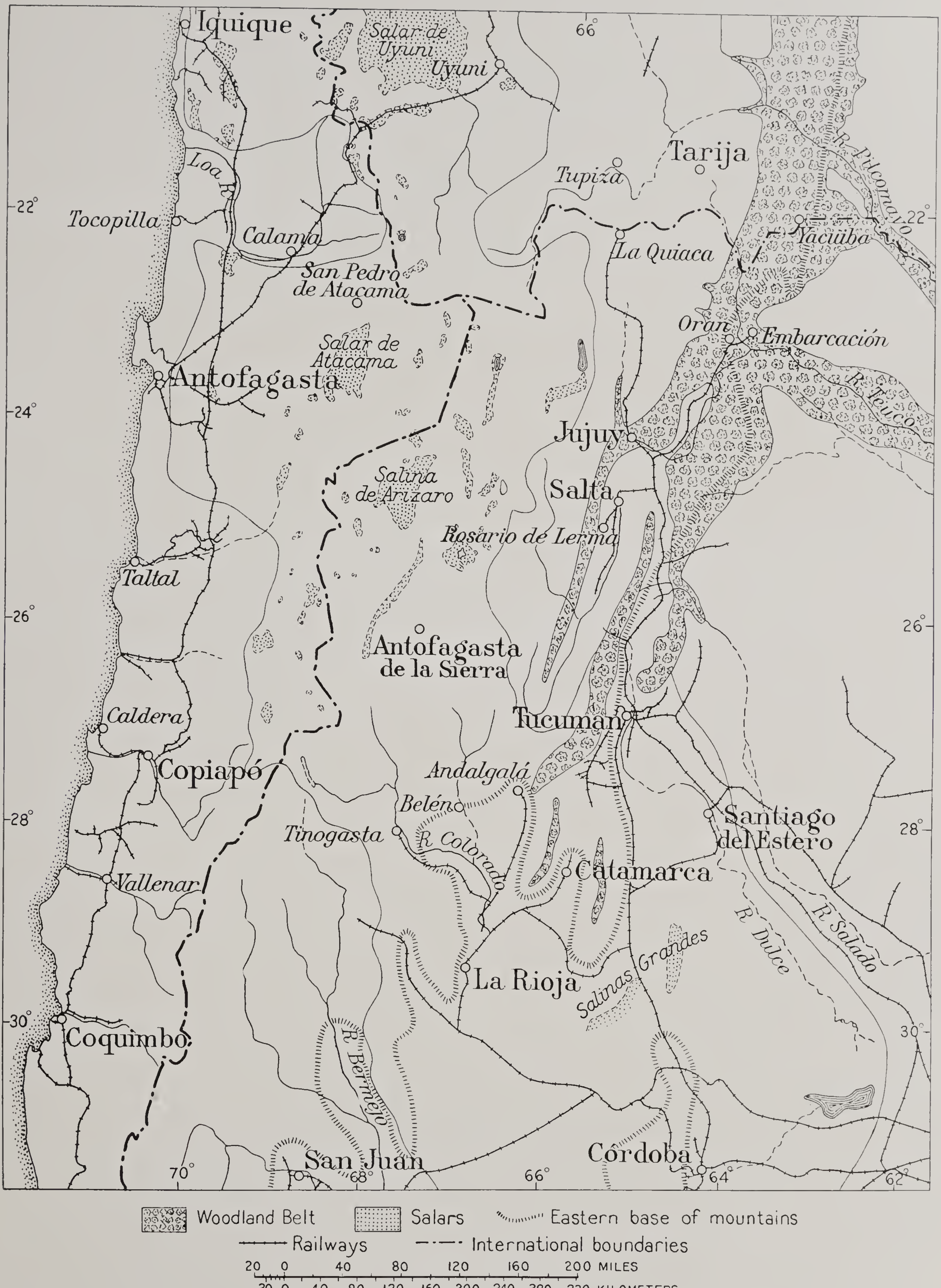
A. Salar de Infieles. Salt basin on fault zone northeast of Potrerillos: elevation about 13,000 feet (4,000 meters): Cerro de Infieles (16,570 feet), looking north.

B. Salar de Pedernales. Large salt basin occupying wide valley in Andean plateau, northwest of Potrerillos: elevations 11,500 to 13,000 feet (3,500 to 4,000 meters) looking south.

A. Potrerillos (matureland northeast of). 11,500 to 13,000 feet above sea; Pliocene (?) volcano, Doña Ynez, 16,630 feet (5,070 meters), in left center.

B. Potrerillos, Quebrada Asientos. Fringing gravels, cemented; elevation 10,000 feet (3,000 meters).

Desert and Puna of Atacama (after Bowman).



Puna of Atacama. Pacific slope, plateau of the high cordillera, and woodlands of the eastern slope (after Bowman).

Potrerillos. Elevation, 10,400 feet (3,100 meters). Terrace of fringing gravels which slopes down, unbroken to Pueblo Hundido, elevation 2,500 feet (790 meters) at the western base of the Andes, 40 miles (60 kilometers) distant. Official photograph Potrerillos Company.

Copiapó. Wind-fretted pebbles from highest terrace west of Paipote in the Copiapó basin.

A. River silt in the Copiapó basin, unusually well jointed for unconsolidated Pleistocene deposits.

B. The Andes, 20 miles southeast of Santiago. Granite pinnacle in center with Jurassic lava flows abutting on right.

A. Huasco valley, 7 miles west of Vallenar. Looking north up longitudinal valley; Coast Range of Paleozoic rocks on left; mantling gravels (Pliocene?) in bluffs.

B. Rio Huasco (headwaters of). Cliffs of gravel (Pliocene?) above Laguna Grande; height 1,000 feet (300 meters) estimated; lower slopes are slides, effect of active fault.

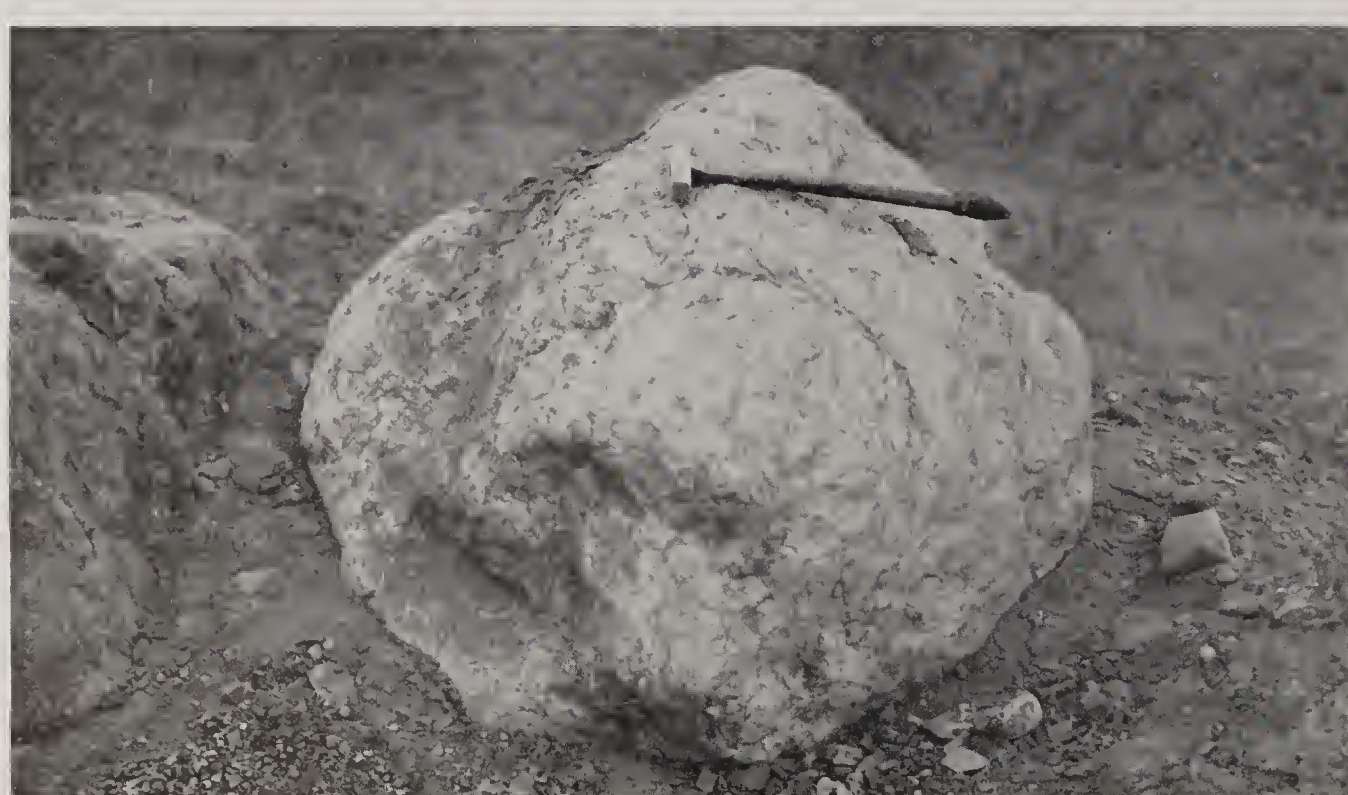
A. Copiapó valley, near Monte Amargo. Interbedded sands and peat beds in river valley.

B. Copiapó valley, near Monte Amargo. Peat digging.

Bed of Potrerillos glacierette, on railroad above mining camp, elevation 11,000 feet (3,300 meters). Official photograph, Potrerillos Company.

Potrerillos. Bed of Potrerillos glacierette, near view. Official photograph, Andes Copper Company, Potrerillos.

A Vallenar. Close view of gravels exposed in road-cut, showing steeply inclined stratification.



B. Quebrada de Hielo, 50 miles northeast of Copiapó. Limestone erratics lying on plain of Tertiary tuff, elevation about 3,600 feet (1,400 meters); rocks show glacial striæ and indicate former existence of glaciers on high peaks farther east. They may have been transported to their present position by floating ice or by cloudbursts.

A. Coquimbo. Looking east from Coquimbo point past La Herradura to Pliocene terraces along Coast Range; jointed Paleozoic granite in foreground.

B Coquimbo. Looking northwest from Coquimbo point, showing broad, wave-cut bench and cliff facing Pacific.

of granite batholiths at one time or another, from Permian to Jurassic, and the subsequent activity of orogenic forces, have prevented the erosion of any part of the Pacific Coast to a peneplain condition, so far as the writer has been able to observe or to ascertain. The oldest landscape surfaces present mature topography, that is, they are maturelands.

The term matureland, as used in this report, is intended to describe a landscape which is characterized by broad valleys, sharp divides, a degree of relief which may amount to several thousand feet, and the survival of acute peaks that rise above the ridges and are mountains of circumdenudation. The degree of relief is not an essential characteristic, but the sharpness of divides and the acuteness of peaks are typical.

With this preface we are prepared to take up the post-Cretaceous history of the Andes of Atacama.

TERTIARY MATURELAND

A matureland has been widely recognized in the Andes. It is a general feature of the Cordillera. Bowman described its characteristic aspects as they are to be seen in northern Chile.[1] The following quotations are here pertinent:

From the earliest descriptions of the mountain chains of the Andes one might suppose that they were as rugged as they are lofty and that great peaks and canyons are the rule. The frontispiece of von Tschudi's travels in South America is an almost glorious piece of misrepresentation in its attempt to show everything connected with the Andes or its borders in one composite view.[2] This is not to say that canyons and peaks are lacking. Some of them are larger than any we have in North America, that of the Apurimac in Peru being in places 10,000 feet deep. The Huatacondo in Chile, on the eastern border of the Desert of Atacama, is 3,000 feet deep, and the Calchaquí valley at the eastern edge of the Puna de Atacama has almost the proportions of the Grand Canyon of the Colorado but without its amazing architecture. The Andes contain also the highest peaks of the western hemisphere: Aconcagua, 22,868 feet; Sajama, 21,385; and Mercedario, 21,877. Such figures of peak heights are of no value whatever unless we know how frequently we encounter them and at what elevation stands the platform from which they rise.

In view of this special character of the Andes a brief explanation of their land forms is given at this point that the subsequent narrative and description of the Puna and its settlements may be better understood. The coastal belt has already been described; the present concern is with the interior chains and plateaus that form the Puna de Atacama, the southernmost unit of the Central Andes.

After repeated crossings of the Andes in widely different latitudes I should say that it is not their height and ruggedness that is their most surprising feature but rather the wide extent of high-level plateau fragments and lava fields which form the platform upon which the highest peaks stand. East of Iquique the sky line of the western summit of the Andes for at least forty miles is almost unbroken. The top, seen from the west, is as even as if cut by a knife drawn along the edge of a ruler. The elevation of the top averages about 12,000 to 14,000 feet. From this lofty platform the snow-capped Cordillera Sillilica rises several thousand feet, but it is only in this small elevation that the Andes are able to show a mountainous appearance. Their whole elevation above the sea has no expression in the relief of today. In the Puna de Atacama the average height of the basin floors is over 12,000 feet, and peaks and ridges rise to heights of only 1,000 to 5,000 feet about them. The Salar de Uyuni, at the southern end of the great basin of western Bolivia, is 12,000 feet above sea level, and there is little scope for the volcanoes on its border to make their distance above sea count in the relief.

The volcanic features of the Central Andes were preceded in their development by a land surface modeled to mature and even old forms over a vast extent of mountain country. There ensued

[1] Isaiah Bowman, *Desert Trails of Atacama,* Am. Geogr. Soc., Special Publication No. 5, 1924, pp. 252-255 and map, p. 259.

[2] J. J. von. Tschudi, *Reise durch die Andes von Süd-Amerika,* Leipzig, 1866-1869.

wide and great uplift in the late Tertiary and Pleistocene periods. The elevation of the whole surface to higher levels was accompanied by the dissection of the mountain border as the draining streams had their gradients increased; and on the floors of the valleys the most striking features are the marks of recent and continuing dissection. Turbulent streams flowing over steep gradients dislodge and transport great quantities of waste, which is strewn over all the basin and valley floors. These marks of erosion at lower levels make more impressive the even crest lines of many plateau masses and the open and parklike character of the landscape. Grassy swards abound, and gentle, beautifully graded slopes. One's imagination rather pictures the wilder mountain scenery of the lower level culminating in bold peaks, whereas quite the contrary is the case. The top of the country has in many cases the gentlest relief. Where even crest lines are lacking there is at least a succession of graded mountain slopes showing late maturity of form. In other places all but fragments of older surfaces may be buried under lava flows. Neither the Coast Range of Chile nor the so-called Pre-Cordillera along the eastern front of the Andes of northwestern Argentina is noted for its volcanic material but rather for its sedimentary and intrusive material modeled on smooth lines.

Were these generalizations limited to a small area they might have correspondingly small significance. On the contrary, they are characteristic of the whole Central Andes. More than that, the studies that Willis has made in northern Patagonia and others have made in Peru, Ecuador, and Colombia reveal in effect a similarity of topographic features throughout the whole Andean realm.

Willis[1] described the matureland of Patagonia as it occurs in the relatively low and deeply dissected section of the Cordillera in the humid, strongly glaciated region. On page 738 he says:

"In ascending from the rivers or lakes of the southern Andes one encounters a change of slope and passes from the steep canyon side into a gentler valley or on to a mountain spur at an elevation which varies from 1,200 to 1,600 meters above the sea. Standing at this level the observer recognizes two distinct topographic phases. The one below him is that of the immature canyons. The one above him is that of the mature valleys and divides of the region above the canyons. The latter is the older. . . . . The characteristics of the mature topography of the upper zone are broad valleys, sharp ridges, acute peaks and sometimes fairly extensive plateaus.

The matureland, having been recognized south of central Chile and also in northern Chile immediately adjacent to the region under discussion, was looked for. It was also realized at the beginning of the geographic study that the matureland is a feature which by the very conditions of its origin must have antedated the uplift of the Andes and should now be found at great altitudes as well as in the lowlands of the coast ranges.

The matureland was found to be developed and preserved in the vicinity of Valparaiso, where it lies at an average elevation of about 650 feet (200 meters) above sea. It is a flat upland, which supports hills and ridges of acute relief and is dissected by the younger valleys of the Limache and Aconcagua. The rivers have cut down to grade-level and are widening their valleys. The decay of the rocks to a notable depth is a condition which marks the surface as one that has long been exposed to atmospheric agencies while standing at an altitude so low that the streams could not carry off the products of decay. It did not escape the acute observation of Darwin, who says:

"It is worthy of remark that nowhere near Valparaiso above the height of twenty feet, or rarely of fifty feet, I saw any lines of erosion on the solid rocks, or any beds of pebbles. This, I believe, may be accounted for by the disintegrating tendency of most of the rocks in this neighborhood."

In Darwin's day, of course, the effects of secular decay of rocks had not been emphasized by Pumpelly, nor had the criteria for the recognition of maturelands and

[1] Bailey Willis, *Physiography of the Cordillera de los Andes between the Latitudes of 39 and 44 South,* Compte Rendu, XII Congrés Géologique, Toronto, 1912, pp. 733-756, with map.

peneplains been interpreted. Otherwise his logical reasoning would have found in the disintegrated state of the rocks additional evidence in support of the proposition that he maintained, namely, that the land had risen from a lower to a higher elevation.

Going northward from Valparaiso, as did Darwin, I was interested to study the features which he had examined nearly a century earlier. He had the advantage, however, of going on horseback, whereas I went by train and could observe only at distant points what he traversed slowly and continuously. North of Vallenar, however, I was privileged to penetrate the Cordillera on horseback and thus to enjoy opportunities similar to those of Darwin's time, and I had the advantage of his work and of a hundred years of research.

Calera, the junction station 43 miles (69 km.) northeast of Valparaiso, at which the northern longitudinal railroad leaves the Valparaiso-Santiago line, was the first place which offered a convenient opportunity to examine the structure and physiography of the outliers of the Andes. The town is situated in a valley which is from 1.5 to 3 miles wide and trends in a general way north and south along the contact between the pre-Mesozoic diorite and metamorphic rocks which form the immediate coast range and the bedded porphyrites of Jurassic age that constitute the higher mountains on the east.

The origin of the Calera Valley may be attributed to either one of two conditions. It may be a zone which has remained low while the ranges on either side of it have been uplifted and is in that case homologous with the larger valleys of this type farther north, as, for instance, between Vallenar and Toledo. On the other hand, the Calera Valley may be regarded as a valley of erosion controlled in its course by the zone of decayed granodiorite at the contact with the Jurassic porphyrite. It is not impossible that both conditions have had a part in developing the valley, but I am inclined to think that erosion has played a larger rôle than warping in this locality.

From Calera I took an afternoon ride into the mountains on the east, toward the conspicuous mountain peak El Caquis (altitude 7,000 feet; 2,132 meters). I did not reach the peak itself, since evening came on, but I ascended to a spur from which I could overlook the broad upland upon which it stands. El Caquis is a sharply sculptured monadnock rising boldly above a matureland. The reason for its survival as a height is found in the fact that it lies at the northern end of a broad syncline which pitches southward from it. The syncline is composed of the Jurassic porphyrites and of sedimentary rocks, including the lower Cretaceous (Neocomian) limestones, which are quarried for cement near Calera and Quillota. The peak appeared to be a remnant of the limestones, but of that I can not be sure.

The matureland is to be seen as a narrow but well-developed upland, extending over all the long spurs of the ranges at an altitude of about 4,500 feet (1,400 meters) above sea. It is evidently the oldest topographic feature in the landscape of this immediate region, and since it compares closely with similar maturelands observed throughout north-central Chile, I regard it as probably of the same age. We shall hereafter find reason to attribute to the Quaternary the great terraces which rest upon this erosion surface. It may therefore be regarded as having developed during the later Tertiary, presumably from the late Miocene on into and through the Pliocene.

Opinions may differ as to whether the height on which El Caquis stands should be regarded as an inner part of the Coast range or as an outpost of the Andes themselves. I incline to the latter as the more correct statement of the relations, since the divide between the water-sheds of the Aconcagua River on the south and the Rio La Ligua on the north is continuous from east to west and descends from the summit of Potrero Potrillo (13,000 feet; 3,965 meters) on the main crest of the Cordillera to the sea, without interruption by any longitudinal valley. The matureland is continuous from the highest altitude to the coast itself, and the east-west courses of the Aconcagua and La Ligua Rivers are consequent upon its westward slope. Their valleys and those of their tributary streams appear to be attributable exclusively to erosion and not to any local warping of the matureland.

The valley in which Santiago lies and which extends southward from a point south of the Aconcagua River is so wide that it can only be interpreted as an area which has remained relatively low, while the ranges east and west of it have been uplifted, producing both warped and faulted surfaces. But that depression terminates a short distance north of Santiago, no doubt for good structural reasons. It is possible that the great fault which bounds the valley of Santiago on the west trends northeast up the Putaendo Valley and continues northward in the region of the headwaters of the Rio Colorado, a branch of the Calindasta, which flows to the Atlantic. I was unable, however, to test this inference, which rests upon a study of the maps and the possible continuation southward of the fault systems observed north of La Serena. In any case, the western slope of the Andes in the vicinity of latitude 32° may be regarded as continuous from the crest to the sea, and as scored simply by the canyons of the consequent streams which have grown upon it and have sunk deeply into it during the process of uplift.

At Combarbala the railroad reaches an altitude of 3,000 feet (900 meters). The immediately surrounding landscape seen from the station is a hilly upland, the gentle profiles of which may be followed up into the heights of the Andes toward the east and also to the north and south. The deep canyon of the Rio de Combarbala, in which the city itself lies, is easily overlooked in the view northeastward, and the still deeper canyon of the Rio Guatulame on the west is not in sight. Both of these are much younger gorges as compared with the matureland which is obviously a continuation of that seen near El Caquis and in the heights of the Cordillera.

Combarbala is in latitude 31° 11′ S. Thence northward the railroad descends to Ovalle, on the Rio Limari, and then winds northward through the coast range to Coquimbo Bay. Following it, I did not again see the heights of the Cordillera until in the vicinity of latitude 28°. But the matureland is recognizable in the coast range and in the foothills of the Andes, and is without doubt continuous as a feature of greater altitudes throughout the stretch of 210 miles (336 km.) between the areas at which it was observed. It was found again in latitude 28°, on the headwaters of the Rio Manfias.

Having followed up the Copiapó River to the point where it receives the Manfias from the south, I ascended into the mountains between the Manfias and the Montosa and proceeded south to the upper Manfias, the detour being necessary in order to avoid the impassable canyon of the lower section of the Manfias. The divide between the Manfias and the Montosa lies close to the latter and is formed by a high range carrying the peaks of Cerro de la Iglesia (12,600 feet; 3,840 meters), Cerro Crespo (13,600 feet; 4,150 meters), Cerro Berraca (14,660 feet; 4,470 meters), and Cerro del Toro, of the same altitude as the last named. This ridge has a length of about 25 miles (40 km.) and rises boldly probably 3,000 feet (1,000 meters) above a group of upland valleys. Its abrupt face is probably a deeply eroded fault scarp. The elevated valleys are distinguishable by their deep soil and gentle grades from the rock-walled canyons that are sunk far below them. I regard their area as representative of the matureland seen elsewhere, both north and south. Its topographic aspects are repeated on the headwaters of the Manfias, where Cerro Pircas Blancas and Cerro Cantaritos, rising to approximately 18,000 feet (5,500 meters), overlook extensive uplands of gentle relief. The same features are continued in the upper valley of the Rio Laguna Grande and its immediate tributaries. The occurrence of extraordinarily thick and heavy gravel deposits which form cliffs above Laguna Grande indicates that the valley in which that little lake occurs is probably of post-Pliocene date, since the gravels themselves may be assigned to that period or to the early Quaternary. But Laguna Grande itself lies in a canyon about 3,000 feet (900 meters) below the level of the passes which represent the matureland.

A little farther north, in latitude 27° 50′, and some 30 miles (48 km.) west of the last-described region, is the Chañarcillo mining district, which is well known for its very large production of silver. The altitudes in that vicinity range from about 2,500 to 3,000 feet (750 to 850 meters), but there is, nevertheless, the same type of mature topography to be seen in these hills and valleys as in the heights of the Andes. The type is one of mature relief, with broad, aggraded valleys and deep soil, except where the wind has carried it away. At Chañarcillo, moreover, we have the evidence of prolonged activity of the atmospheric agents in the enormous amount of secondary enrichment of the mineral deposits. It is to the widespread occurrence of the matureland that Chile owes the great concentration of silver ores which have yielded so much wealth.

In going north from Copiapó, the longitudinal railway turns first to the southeast to Paipote and then winds up a long, steep grade to the pass of Chimbero, where it reaches an altitude of 6,500 feet (1,978 meters). The lower part of the ascent is up the aggraded younger valleys of Quaternary age, but after passing Carrera Pinto one is again in the upland which represents the matureland and on which is situated the well-known Dulcinea mine and many others. From Chimbero the matureland descends toward the depression that lies to the north and east of Pueblo Hundido beyond the Quebrada del Rio Salado. This is the first of the wide basins in which the nitrates occur.

The physiographic unity of the western slope of the Andes is well exhibited in the ascent from Pueblo Hundido eastward to the great copper-mining camp of Potrerillos. The distance in a straight line is about 50 miles (80 km.) and the difference of elevation is about 8,000 feet (2,400 meters), Pueblo Hundido being 2,500 feet above sea and Potrerillos camp 10,400 feet. The ascent is made up the canyon of the Rio Salado and then by a winding grade along the canyon wall to the mining camp, which is situated on a gravel plateau at 10,400 feet (3,100 meters). From the camp the eye may sweep the entire western slope and may follow the long grade of an old early Quaternary or Pliocene river terrace down the unbroken incline to the basin at Pueblo Hundido. Behind one toward the east the hills and valleys rise somewhat more steeply to the old valley levels at 12,000 to 14,000 feet (3,600 to 4,200 meters), which represent the old surface of mature topographic erosion that we have traced from above Valparaiso and the vicinity of El Caquis. (See Plate XLVI.)

When one rides north and east from Potrerillos to the Salar de Pedernales and thence north to the Salar de los Infieles one is on the high plateau of the Andes among peaks that reach 18,000 to 20,000 feet (5,400 to 6,000 meters). The old erosion surface persists at altitudes of 14,000 to 16,500 feet (4,200 to 5,000 meters) in the form of wide valleys separated by low maturely eroded divides. It is, however, displaced along fault-lines and is to a considerable extent buried beneath the débris from volcanic peaks that stand along the faults. Since the volcanic activity goes far back into the Tertiary and comes down to the present there is every possible relation of age between the different volcanic formations on the one hand and the matureland on the other. But the latter is nevertheless recognizable as an extensive feature of the high Cordillera. (See Plates XLIII, XLIV.)

From Potrerillos I returned to the longitudinal railway at Pueblo Hundido (lat. 26° 23′) and thence went north by rail to Calama and the great copper mine of Chuquicamata (lat. 22° 25′). The railroad skirts or crosses the nitrate basins, wide, flat surfaces of gravel and soil impregnated with nitrate of soda, from which rise the characteristic hills and peninsulas of a buried topography which, in its profiles, is identical with that of the landscape of the coast range itself and of the high Andes. Everywhere are the signs of the mature phase of erosion. The nitrate basins lie at elevations of 3,000 to 7,000 feet above sea (1,000 to 2,500 meters), with a somewhat higher coast range between them and the ocean and the very much higher basins and summits of the Andes east of them. The nitrate basins now lie at an elevation such that rivers flowing from them, if there were any, would cut deep canyons and the process of erosion would be destructive of their present form and also of the mature forms that are buried beneath the débris with which they are deeply filled. It is obvious that the sculptured mature surface now stands high above its original position; that is, it has been elevated, not depressed, with reference to sea-level. Nevertheless, we constantly refer to these basins as depressions because they lie at a lower altitude than that of the more vigorously uplifted mountain ranges which border them. Although they have shared in that upwarping of a wide zone of the earth's crust which has formed the Andes, relatively to the mountain ranges they are downwarped.

The railroad journey afforded no opportunity for specific local observation, but on arriving at Chuquicamata I was able to make extended excursions in the valley of the Rio Loa and the adjacent mountain region. The country exhibits the same characters of mature erosion marking the landscape of the oldest surface to be seen, and I concluded that the earliest phase of physiographic history which could be identified in the coast ranges, in the Cordillera, and in the basins and valleys between them was one and the same from Valparaiso to Calama, a distance of about 750 miles (1,200 km.) from north to south.

EPOCH OF CANYON DEVELOPMENT

The cordilleran matureland which has thus been identified by Bowman and myself as a characteristic feature of Andean physiography, from latitude 44° in Patagonia to latitude 18° in southern Peru, belongs to a long topographic cycle which began with the elevation of the Andes above the Neocomian sea-level. That early uplift and the minor steps by which the land reached its greatest elevation of that time, at the close of the Mesozoic or during the Eocene, are not recorded. They were lost as the matureland developed and it remains as the oldest general feature of the Cordillera.

The matureland is now found underlying the nitrate basins and other wide depressions of the Coast ranges and is also identified in the salt plains of the high Cordillera, as well as in their surrounding divides. It can be traced from the lowest to the higher elevations as an erosional surface, which is now entirely out of harmony with its environment; that is to say, it not only could not have developed in the altitudes and at the elevations where it still exists, but is either being buried or dissected by the activities of aggradation or corrasion. A great change has occurred in the zone of the Cordillera since the age when the matureland extended its hilly and somewhat monotonous landscape over the Pacific coast of South America, and that change is nothing less than the elevation of the Cordillera itself.

The elevation of the matureland resulted in the corrasion of canyons, typical of the youthful phase of topography thus initiated. There was, of course, a drainage system already established on the matureland. It had become adjusted to the structural trends of the land, except in so far as it had been disturbed and diverted by the concurrent volcanic activity, which was both widespread and persistent, as is shown by the Tertiary eruptives. But the adjusted drainage must have had predominantly north-south trending valleys in the matureland, connecting with the sea by short transverse courses. Thus the early Tertiary stream-pattern was of the grape-vine type, somewhat like that of the Appalachians, but less regular in general plan and locally very irregular.

The growth of the canyon system modified the older, adjusted drainage by extending the water-sheds of the transverse courses and by capturing the adjusted valleys in favor of the vigorous master-streams. The predominant effect was to produce such rivers as the Limari, the Elqui, the Huasco, the Copiapó, and the Salado, which flow from the junctions of their main tributaries in rather direct and simple courses to the ocean. They are to a considerable extent consequent on the western slope of the Cordillera and independent of structural control.

The headwaters of these streams show remnants of the older system and exhibit signs of capture. Thus the Rio Hurtado, a branch of the Limari, makes a right-angle bend just south of the Portillo de Tres Cruces (30° 20′ south latitude), through which it once flowed to the Elqui. The stronger Limari here captured the tributary of the Elqui, which is represented by its beheaded lower course, the Quebrada Pangue.

A similar capture is found on the Rio Elqui (just north of latitude 30°), where both the Rio Claro and the Turbio change their courses sharply from northwest to west and southwest. They may formerly have run to the truncated Rio Choros.

The captures thus effected by the Limari and the Elqui are such as would occur if the captured headwater tributaries had been slowed up by faulting while at the same time the grades of the southwest-flowing streams had been increased by the elevation of the Cordillera de la Punilla on the north. It will be observed that there are two thrust-faults which we saw at Rivadavia and Paiguano and which define the zone of capture in such a way as to sustain this suggestion.

The headwaters of the Rio Huasco, comprising the Carmen and Tránsito, do not betray their former courses to simple inspection, if indeed they have undergone material change. At the point where the Tránsito turns west (near latitude 29°), the wide valley is appropriately called La Pampa, and a very narrow gorge just west of La Pampa is known as El Portillo. These local features are probably due to the fault that crosses the valley just west of El Portillo, but the plan of the stream is, nevertheless, that which may reasonably be credited to the old adjusted, grape-vine system.

The Copiapó River gathers its waters with both hands, so to say, at a point within the zone of faulting in the high Cordillera. The Jorquera and Pulido from the north and the Manfias and Montoso from the south meet in pairs after the fashion of grape-vine drainage. Their united waters, however, take a peculiar northwest course, in lieu of flowing west by the shortest route to the sea. It is possible that they formerly did run west across that now arid basin whose center is by contrast with its general sterility called Yerba Buena (latitude 28° 5′), and were diverted northward and westward at an early stage of the general uplift and accompanying faulting. The basin alluded to is characterized by the features of the matureland and by deep oxidation of the ores, as at Chañarcillo. It is an area which has not undergone any considerable erosion since the early or middle Tertiary. In these and other stream systems interesting problems are presented. They require careful study of the topography and structural geology. They also have a bearing on the distribution of valuable mineral deposits, since the latter are most likely to be found where the matureland survives unchanged.

The object of this description and suggestion is to call attention to the epoch of canyon development which ensued upon the beginning of the uplift of the Cordillera. It is an occurrence which must necessarily be recognized as one of the phases of the topographic cycle that is recorded in the features of any mountain range. It dates from the beginning of the uplift and it can not be said to have come to an end until the topography passes into the phase of early maturity. That is very far from being the case in the Andes. The mountain chain is still very young; nevertheless, there are episodes which are superimposed upon the record of canyon development and which demand consideration here, because they bear directly upon the earthquake problem in its relation to the structure of the mountains. I refer to the gravel deposits that now fill the valleys and canyons and which by the continuity of their surfaces demonstrate that active faulting long ago ceased to be expressed at the surface, even where earthquake shocks are violent.

The epoch of canyon development probably dates from the middle Tertiary and extends down to and beyond the Present. The reason for assigning the date of beginning of the epoch is found in the occurrence of Pliocene deposits along the present coast in positions that had been shaped by the uplift and erosion before that period. The Miocene, on the other hand, appears in very slight develoment, if at all, as marine sediment. The single fossil from Coquimbo is the only local evidence, and it is found in a faulted stratum in such relation as to indicate that it had been disturbed before the Pliocene. We shall therefore not be far from the truth if we assign the uplift and faulting of the coast range in this section to the late Miocene and Pliocene. This is the early part of the stage of canyon development, corresponding with the excavation of the river gorges as they now exist. But they have since been partially filled with gravel deposits of unusual character.

GRAVEL DEPOSITS

The river valleys of the coast range and of the Cordillera to its highest plateaus are filled with voluminous deposits of sands, gravels, and cobbles, which are so omnipresent that they form one of the most impressive features of the geologic record. They are paralleled in other lands under different conditions. For instance, the terraces along the Columbia River in British Columbia and the northwestern United States are similar in magnitude to those along the Huasco between Vallenar and the sea. The terraces of the Loess district of China are equally striking. The desert plains of Nevada stretch across deposits of the same order of magnitude, but not yet terraced because the basins are still inclosed. Thus the accumulations of fluviatile sediments are found where rivers, glaciers, or winds have worked. The three agents have always worked together, but sometimes one, sometimes another, has been predominant. The texture, internal structure, or environment serve to distinguish the different types of deposits, but they have in common the character of great volume and wide distribution.

The condition precedent to the accumulation of voluminous deposits of this character was the deep decay of the rocks during a prolonged period of relatively humid climate and comparatively low level. Pumpelly first observed and described this essential prerequisite.[1] It is so directly essential to the gathering of great alluvial

[1] R. Pumpelly, *The Relation of Secular Rock-disintegration to Loess, Glacial Drift, and Rock-basins,* Am. Jour. Sci. (3), 17, pp. 133-144, 1879.

deposits that one may fairly assume the previous existence of a matureland or peneplain in any now mountainous province in which they are found. This inference is fully justified in Chile, as has been described.

Darwin was very much impressed by the gravel formations of the Patagonian plateaus and of the Cordillera in central Chile. He described them in his Geological Observations with his usual keenness and accuracy.[1] It is to be regretted that the state of geologic opinion and theory in his early days leaned unduly toward the idea of marine erosion, and he attributed the extensive river deposits to the action of marine currents. Ingenious as is his reasoning in defense of the adopted hypothesis, one can not help wondering whether it was wholly satisfactory to his logical mind. It appears that he was influenced by observing at Coquimbo and La Serena the intimate association of marine and fluviatile continental formations, where the deposits naturally meet, just as the river naturally flows into the ocean.

The gravel deposits are now recognized as an effect of river action, it being established that climatic changes have occurred and that the arguments which prevailed with Darwin are not valid. While it is true, as he stated, that the rivers are incapable of forming the terraces under present conditions, it is beyond question that they have in the past had the appropriate volume to carry and the moderate fall on which to deposit the detritus. We recognize the agent. It remains to distinguish the combinations of conditions which enabled it to do the work. Climatic changes constitute one important group, modifications of slope another.

My own observations accord entirely with Darwin's. On the Rivers Elqui, Huasco and Copiapó the canyons in the western slope of the Andes are fringed with narrow terraces, as he has described them. The depressions that lie between the Cordillera and the Coast range are floored by the gravels, and the valleys by which the streams flow through the Coast range to the sea are also deeply filled and in part reexcavated, forming terraces.

A somewhat different condition exists on the Rio Salado, in latitude 26° 30′. The canyon through the Coast range is not conspicuously terraced, although its valley is a gravel plain. At Pueblo Hundido, where the depression at the foot of the Andes forms a desert basin at an elevation of 2,600 feet (800 meters) above sea, there begins a long slope which rises to Potrerillos at 10,400 feet (3,100 meters). It is a gravel slope, which fringes the canyon of the Rio Salado and all of its tributaries, covering the rocks deeply, except where occasional pinnacles protrude through the mantling deposit. The gravels are thus continuous from a comparatively low altitude to the heights where the salt plateaus and volcanic peaks form the summit of the Cordillera. They furthermore extend not only along the canyons between the precipitous walls, as on the upper stretches of the other rivers named, but also over the interstream areas of the old matureland.

The contrast between conditions on the Rio Salado and the rivers farther south serves to emphasize the fact that the terrace deposits occupy two very different posi-

[1] Charles Darwin, *Geological Observations in South America,* first edition, London, Smith, Elder & Co., 1846, pp. 62-67.

tions, even where the upper surfaces are confluent. This is but one suggestion of the complexity of their constitution and of the diversity of age to be found among them. Thus on the Elqui, Huasco, and Copiapó the gravels which fringe the canyons were deposited necessarily after the canyons had been eroded, at the close of the period of canyon development. This was long after the beginning of the uplift to which the canyons are due. On the other hand, where the gravels cover the floors of the extensive depressions, burying the matureland as they do in all of the longitudinal valleys, they must have begun to accumulate as the basins were formed, that is during the process of uplifting. Thus the lower formations in the basins are materially older than the terraces in the canyons.

It is desirable to distinguish these two groups of terrace deposits or gravel formations, and to do so I shall refer to the older, which covers the matureland, as the *mantling* gravels or formation, and to the younger, which occurs along the canyons, as the *fringing* deposit or formation.

It might, perhaps, be suggested that a geographic term should be used as a name to designate each of these formations, but it does not appear appropriate to do so in this report because of the brief and generalized character of the description, which is all that my observations justify. The terms " mantling " and " fringing " are here used, not as names, but as descriptive adjectives, which may serve adequately to distinguish the gravels of the basins from those of the river valleys.

The mantling gravels were first recognized in the longitudinal valleys. They cover the matureland. A typical occurrence may be studied in the wide downwarp, in which Vallenar is the principal pueblo, and in the valley of the Huasco, where it is cut 200 meters deep in the deposits.

The downwarp extends 125 miles (300 km.) from north to south and is about 5 to 12 miles (8 to 20 km.) wide. The actual surface is a broad gravel plain, which is locally scored by shallow ravines. Around the margins of the plain the latest of the mantling gravels merges into alluvial cones of relatively recent deposition or rests upon the decayed rocks of the matureland. It is thus a transgressive deposit, which overlaps upon the old landscape surface. In some cases the old gravels abut against freshly exposed rocks, as if along a fault scarp, but that is exceptional. Thus it appears that the deformation by which the downwarp was formed was accomplished by flexure, rather than by fracture, at least in the later stages. The transgression upon the matureland is well shown around the basin of the Rio Totoral, west of the rich mines of Chañarcillo.

If we assemble into a moving picture the sequence of events connected with the deposition of the mantling gravels, we first review the aspects of the matureland in its last stage of erosion under the normal conditions of a humid climate, favorable to rock decay and soil accumulation. Warping ensues. The area of the downwarp becomes a basin, which, even though it be raised as it is warped, is nevertheless aggraded by the loaded streams that flow from the adjacent upwarps. Alluvial fans grow, coalesce and form a plain. Humid and arid climates, warm or cold may alternate; any phase of the activities of rivers, lakes, cloudbursts, or even of distant glaciation may be represented in the basin deposits.

The latest of the mantling gravels are naturally sought in the highest terrace-levels around the basins. They are very well preserved along the Copiapó River in the southern part of the basin in which the city is built. The gravels consist of coarse fluviatile material from which the sand has been blown away, leaving a surface of large pebbles and cobbles. The stones are largely of Mesozoic porphyries, quite dark in color but also darkened by desert varnish. They are very commonly pitted by wind erosion, a typical characteristic that is significant of their age and is wanting on the lower, younger terraces. (See Plate XLVII.)

Within this oldest terrace of the Copiapó Basin there are relatively recent river deposits consisting of sands that are remarkably well jointed, as illustrated in Plate XLVIII A. They belong to a much later activity than the deposition of the mantling gravels and may be related to some recent phase of the fringing gravels.

The continuity of the highest and oldest terrace of the mantling gravels around the basin of Copiapó is a striking fact. About a mile and a half (2 km.) southwest of the city a long, low ridge of rock rises from the river plain to a height of 30 feet (10 meters) above it, and the slope is carried back westward to the hills by an old alluvial fan. Where the latter is cut away by erosion younger fans have developed at a lower level. The rock ridge and the old fan belong to the epoch of the highest terrace and can be followed around the western and southern sides of the valley to the Quebrada de Paipote. Along the eastern side erosion has cut more deeply into the old terrace. It is, however, nowhere dislocated by faulting. The age of the highest terrace deposits in this vicinity is indicated by the pitted, wind-eroded pebbles. (Plates XLVII, XLVIII.) They reach far back into the middle or possibly early Pleistocene. Whatever their age, they are younger than the latest notable displacement by faulting in the Copiapó Basin. This conclusion banished the expectation of finding recent earthquake rifts by which to explain the severity of the shock of 1922, or of others which have given Copiapó the distinction of being an earthquake center.

The mantling gravels exhibit a very interesting distribution. In the vicinity of Coquimbo they are confined to the valleys immediately adjacent to the seacoast, if, indeed, they are present as gravel deposits, or they are represented by the Pliocene marine formations of Coquimbo Bay. Farther north, about Vallenar, the mantling gravels have their typical development in the longitudinal valley, both north and south of the Huasco. Still farther north they fill the basin in the vicinity of Pueblo Hundido, but extend thence eastward up the slope of the Andes to an altitude of more than 10,000 feet (3,000 meters), filling the ancient valley of the Rio Salado and its tributaries. The terraces along the Salado extend for 50 miles (75 km.), from near Pueblo Hundido to Potrerillos, without a break, but their present inclination is such that the river has cut a canyon 1,600 feet (500 meters) deep through the gravels into the underlying bedrock.

In the section on the Rio Salado the gravels are thick in the lower basin, but comparatively thin higher up on the slope. They thus appear to represent the accumulations in the downwarp in the one case and in the ancient river valley in the other.

The distribution and thickness of the mantling gravels thus affords in general a means of tracing out the ancient topography on which they were first laid down and the subsequent changes of level that have favored their deeper accumulation in the basins. Should they ever yield vertebrate or other fossils, as is not improbable, they will furnish the data for dating the beginning of the actual uplift of the Coast Range.

The fringing gravels are those which occur in the river canyons, along both sides of the rivers, as described by Darwin. They are evidently younger than the canyons in which they lie, whereas the mantling gravels are probably to a large extent formed of the material eroded from the canyons and consequently of similar age.

The fringing gravels are well developed along the Rio Elqui, the Huasco, and the upper Copiapó. They are typical river deposits, derived to a great extent from side canyons and often consisting of nothing more than the alluvial fan of a tributary. They do not appear to represent anything more than the transient aggradation of the river's course and subsequent partial erosion, in consequence of climatic changes, under favorable conditions of high elevation. Nevertheless, these gravels are not recent. The terraces which they constitute are usually high above the streams, beyond the reach of the highest floods, and the rivers run in rock gorges in many long stretches. The character of the gravels and the depth to which the rivers have cut since they were deposited indicate a lapse of time coordinate with that which can elsewhere be correlated with the epochs since the retreat of the older glaciation from the Pacific ranges of the United States and British Columbia.

The Rio Huasco presents a peculiarly interesting opportunity to study the mantling and fringing gravels. At Vallenar it exposes the deepest section in the former. East of the longitudinal valley it is fringed with characteristic occurrences of the latter; and above Laguna Grande, on its head waters, at an altitude that lies between 13,000 and 15,000 feet (4,000 and 4,500 meters) there are high cliffs of a gravel formation, which by its great thickness and very coarse character challenges investigation. It presents the appearance shown in Plate XLIX B, as one looks up from the outlet of Laguna Grande. The lake itself is formed by the blocking of the valley by a large slide from the cliffs. The environment of the deposit could not be observed from below. The best guess as to its correlation and origin which the available data permit is that it is a remnant of the mantling gravels carried up in the elevation of the block east of the fault that runs through the valley of Laguna Grande and past the peaks of Las Cantaritas and La Iglesia.

As regards the age of the gravels, it will be apparent from what precedes that there is reason to assign the oldest beds of the mantling gravels to the early Pliocene or earlier and the fringing gravels to the Pleistocene. If we include with the latter the recent and actual alluvial fans, the record is continuous down to the present. We thus introduce, however, the episode of river erosion by which the streams have re-excavated their channels in the gravel formations. It is well to do so, since the earlier history probably comprised similar changes in the activity of the rivers, which at times aggraded and at other times eroded their beds.

The purpose of this chapter is accomplished if it has succeeded in suggesting the complexity of the record that lies concealed in the gravel deposits of central Chile. They appear to cover all late Tertiary, Pleistocene, and Present time. They have accumulated under all the different conditions of climate which have passed over the region during the later geologic ages. The oldest beds, although younger than the middle Tertiary faulting, date from the beginning of the Cordilleran uplift. The latest gravels were washed down in the last storm. The intimate study of the formations will eventually decipher a sequence of events even more complex than that of the glaciation of northern Europe and North America, for diastrophism is associated with climatic change as a cause of variation in the nature of the deposits.

Since the gravel deposits include those of Pleistocene age, the observer will look for evidences of glaciation and will find traces of them. But they are far from common and it is desirable to describe in some detail those which we happened to observe.

EVIDENCES OF GLACIATION

Central Chile is not a region in which one would expect to find evidences of glaciation on any large scale. Of the conditions that favor the accumulation of névé and glacial ice—humidity, high latitude, and high altitude—only the last named is present, and it is obvious that the great altitudes of the Cordillera were requisite to produce glaciers, in view of the aridity of the atmosphere and the relatively low latitude of 30° more or less. It is therefore in the heights of the Andes that we should look.

This deduction bears also upon the age of the uplift of the range in relation to the glaciation. The Cordillera must have had nearly, if not quite, its present elevation when glaciers developed. Either the uplift had attained its present condition before the Pleistocene or if the Andes were materially lower than now at the beginning of that period, the glaciation belongs to the later Pleistocene.

Certain evidences of glaciation were found near Potrerillos, in latitude 26° 30′, at an elevation of 11,000 feet (3,300 meters). The railroad which ascends from the camp to the mine winds about a spur of the mountain at about a mile and a half (2 km.) from the former, and runs along a steep slope into a ravine. The exposure is toward the southwest, and in this southern latitude corresponds to the cold northwest exposure of the northern hemisphere. Here, if anywhere, snow would linger and accumulate.

In excavating the grade the superficial talus was removed and a firm surface of gravel was uncovered. It was fortunately not disturbed and in May 1923 showed all the details of grooving and striation which are illustrated in Plates L and LI. They appear to be the markings characteristic of the sole of a glacier.

The parallel grooves in the gravel and the striations on the pebbles slope down the ravine in the direction which would have been followed by a mass of ice that filled the ravine and ground against its side. The head of the ravine has not the cirque-like form that would suggest glacial plucking, but is sufficiently inclosed by mountain slopes that rise to 13,000 feet (4,000 meters) or more in altitude to afford a shaded basin in which the névé could have gathered.

The alternative explanation that the gravels had been caught in a fault and striated by friction on the fault plane was excluded by the character of the gravel formation itself and by the impossibility of reconstructing an overlying rock-mass that could have done the work.

The evidence appears to show conclusively that there was a Potrerillos glacierette, which had mass enough to consolidate and striate its bed, but did not linger long enough to sculpture its valley to any perceptible degree. It was not over a mile and a half (2 km.) long above the exposure and probably did not extend far down the very steep gorge below; but small though it was, it has left an indubitable record of glacial conditions in this latitude and at this altitude.

The age of the glacierette appeared a matter of much interest. In the bed was a quartz boulder of a deep red color, which when dug out was found to be creamy white. The red coloration was due to oxidation, which had affected the soled surface left by the glacier and had penetrated about half an inch into the cobble. Since the color was red, not yellow, there had been but little hydration, and the effect was chiefly that of the dry air under the talus. There were no granite boulders with which to compare, but the oxidation appeared to represent an effect comparable with that of the decay of granite boulders in the drift of the United States and thus suggests that the Potrerillos glacierette was an early Pleistocene incident.

A comparison with Patagonian glaciation also suggests that the cold episode in this northern latitude probably corresponded with the earlier of the two glaciations that have there been recognized, rather than with the later; for the large glaciers that gathered in the Andes in latitude 41° south have left very distinct moraines, and the older ones lie many kilometers further down the valleys. The earlier glaciation was therefore the more severe and would be the one that would leave traces, if any were left, in the drier, warmer zones.

In one other instance we ran across distinct evidences of glaciation, but not in place. In the Quebrada del Hielo (an appropriate name) Dr. Felsch and I found a small group of boulders of limestone lying as erratics upon a Tertiary volcanic tuff in the flat floor of the valley. (Plate LII B.) They were distinctly out of place. Nothing in the underlying rocks resembled them. They were rounded, surfaced, and striated, and, being from 5 to 6 feet (1.5 to 2 meters) in diameter, were such masses as to be beyond the carrying power of the small stream, unless in time of cloudburst or floating ice. They may have been transported by the former agency, which is by no means rare in these arid ranges, but the striations and planed surfaces can not be attributed to anything except glacial grinding.

The point where these boulders lie is west of a range which reaches altitudes of 15,000 to 16,500 feet (4,500 to 5,000 meters), being dominated by Cerro Azufre, a volcanic peak which rises to 16,760 feet (5,080 meters) above sea. The latitude is 27° 10′, and therefore slightly more favorable than that of Potrerillos. It would thus appear that the boulders are evidence of glaciation in the heights of this portion of the Cordillera, at least to the extent of a glacierette or two.

These facts had already established glaciation as one of the conditions of which I took account when I began the study of the Plio-Pleistocene section at Coquimbo. It nevertheless was with surprise and doubt that I observed the large boulders which occur in the marine section there and which seem to indicate that the coast also was so refrigerated that ice formed locally in a deep ravine in such quantity as to be competent to float them. The facts are stated in the description of the Coquimbo formation.

GEOLOGY ON COQUIMBO BAY

GENERAL STATEMENT

Coquimbo Bay occupies a structural depression and is floored with Pliocene and Pleistocene sediments which also form terraces around its shores. It thus epitomizes the later history of the Chilean coast. During the later Tertiary, possibly as early as the Miocene, its basement of Paleozoic granite was faulted, a ridge was elevated along its western margin, and a wide area east of the uplift was depressed. The depression reached its lowest level during the Pleistocene, probably during a mid-Pleistocene, interglacial stage, and the entire district has since been raised, including the granite ridge on the west. The story may be read in the structure of the rocks, the physiography of the hills, the fluviatile and marine terraces, the ice-transported boulders, the fossils and the marine life now inhabiting the bay. It is a consistent story, which can be sketched in outline from the observations of Charles Darwin and his successors, but which still offers a rich opportunity for investigation to the student who may have time to work out its details and the training required in various branches of geology and paleontology.

The accompanying chart (Plate LV) shows that Coquimbo Bay is the southern part of a larger embayment called La Bahia de la Serena, and that south of it is a small cove aptly named La Herradura, or the Horseshoe. Coquimbo Bay and La Herradura were formerly united when the sea stood along the elevated beach-lines, and they owe their actual basins to the currents that swept around the granite island north of La Herradura. Non-deposition and submarine scour combined to prevent them from being filled to the level of the deposits that accumulated in the lee of the island and that now form the terrace which lies between them and connects the former island with the mainland. The circular form of La Herradura is a very remarkable example of current action. Coquimbo Bay owes its elongated shape to the trend of the faulting in which it originated, and is modified in outline also by the ancient delta of the Rio Elqui.

An extensive terrace fringes the base of the surrounding heights of the Coast range and slopes toward the bays, to which the steeper descent steps down by benches that vary greatly in width according to the conditions of erosion by the changing currents as the land rose from its deepest submergence. Where the currents were adequately strong they prevented or limited deposition. Beneath quieter waters fine sediment gathered on the flat bottom. There has been but little subaerial erosion since the sea-bottom was elevated, and it remains almost unchanged, bearing witness to the recent occupation of the larger embayment by the sea, even as the marine shells do.

The strata of which the terraces are composed consist of sand and silt, with a large proportion of shells, and some of them are cemented to hard limestone. Although perfectly conformable in dip, they belong to several different periods, from Pliocene to Present, and are associated with older formations. We may distinguish the following sequence of events: *Late Paleozoic,* intrusion of granite (older rocks not seen in this vicinity); *Mesozoic* and probably *Eocene Tertiary,* uplift and erosion to the extent of laying bare the granite, faulting possibly connected with the uplift; *Miocene*?, deposition of limestone against the exposed face of the granite on the fault scarp (age not positively determined, possibly Pliocene); *Pliocene,* marked displacement on the fault east of Coquimbo Point, depression of the block underlying Coquimbo Bay, and deposition of the sands and calcareous formation of the terraces, continuing without recognized break into the Pleistocene; *Early Glacial,* distribution of large boulders, probably by floating ice; *Later Pleistocene,* continuation of the subsidence and deposition of calcareous sands to the maximum extension of the bay; *Recent,* retreat of the sea in consequence of elevation of the entire district, producing a distinct disconformity marked by gravel beds and accumulations of shells of species now living in the bay; *Present,* continued uplift without faulting.

The earlier events of this record may be passed over without discussion, since they are not peculiar to the locality and their recognition does not depend upon any observations pertinent to the description of Coquimbo Bay. The granite elsewhere occurs beneath the Triassic of the Chilean coast and is therefore assigned by Felsch to the Paleozoic. The erosion of overlying strata, including any that may have been laid down on it in this vicinity, is complete. The first sedimentary rock which is seen in contact with the granite is a limestone that has yielded one specimen of *Ostrea ingens* Zittel and that may be of Miocene age. We may begin our description with that occurrence.

In April 1923, the excavation at the northern end of the railroad yard, which is located at the eastern base of the granite promontory on the extension of the main street of Coquimbo, exposed blocks of limestone in contact with the granite. Some of them were in place and consisted at the contact of calcareous sandstone a few centimeters thick, followed by gray limestone of a much denser character than any seen in the terrace deposits. The actual thickness seen amounted to about 1 meter. The calcareous deposit penetrated the crevices of the steep slope and had evidently been deposited against it.

A well-preserved specimen, since identified by Mr. Eric Jordan as *Ostrea ingens* Zittel, was given me by the official in charge of the yard as having been taken from the limestone. The evidence of Miocene or middle Pliocene age which it affords is in keeping with the character of the rock as contrasted with the Pliocene of the terrace formation.

A fresh excavation, made while I was there and for the purpose of installing a bumper at the end of the track, exposed an irregular displacement of the limestone, which extended down into the granite. It was such a break as would occur in rocks at the surface, not under any load, at the outcrop of a fault. The fact that it went down into the granite and inclined toward the hill precluded the alternative of a slide.

The displacement thus indicated is on the line of one of the upthrust faults traced southward to Coquimbo and corresponds in its indications with the inferences confidently drawn from the more general facts of the physiography of the region. The scarp against which the limestone was deposited had been formed by faulting at some earlier date. The fault, therefore, antedated the Miocene or middle Pliocene epoch of deposition, but continued to be active at least into the Pliocene.

THE TERRACES

The terraces of Coquimbo were examined by Darwin in 1835 in the course of a trip from Valparaiso to Huasco. He rode from point to point along the coast and neighboring valleys, which he describes in his Journal with his characteristic attention to significant details. Regarding the terraces he wrote: [1]

"I spent some days in examining the step-formed terraces of shingle, first noticed by Captain B. Hall and believed by Mr. Lyell to have been formed by the sea, during the gradual rising of the land. This certainly is the true explanation, for I found numerous shells of existing species on these terraces. Five narrow, gently sloping, fringe-like terraces rise one behind the other and where best developed are formed of shingle; they front the bay and sweep up both sides of the valley. At Guasco (Huasco), north of Coquimbo, the phenomenon is displayed on a much grander scale, so as to strike with surprise even some of the inhabitants. The terraces are there much broader, and may be called plains; in some parts there are six of them, but generally only five; they run up the valley for thirty-seven miles from the coast. These step-formed terraces or fringes closely resemble those in the valley of S. Cruz and, except in being on a smaller scale, those greater ones along the whole coast-line of Patagonia. They have undoubtedly been formed by the denuding power of the sea, during long periods of rest in the gradual elevation of the continent."

In Darwin's day the capacity of rivers to transport débris was underestimated, the influence of climatic changes in causing them to erode what they had once built up was not understood, and the analogy of the extraordinary fluviatile terraces of South America with shingle beds forming in the fiords of southern Chile was striking. He was therefore led to set aside the evidence of river action in the valleys and to ascribe all of the terrace deposits of the Andes, even those which now lie at great elevations, to marine denudation and deposition. The undoubted marine terraces of Coquimbo confirmed him in this generalization, although he himself observed the mingling of marine and fluviatile deposits at the mouth of the Rio Elqui, where it enters Coquimbo Bay. The river terraces are discussed elsewhere in this volume. Darwin's description of the marine terraces is not only of great interest as the record of his observations, but is valuable in that it supplies many details of which the writer either could not or did not take note. It is therefore quoted in full: [2]

"COQUIMBO

"A narrow fringe-like plain, gently inclined towards the sea, here extends for eleven miles along the coast, with arms stretching up between the coast-mountains, and likewise up the valley of Coquimbo: at its southern extremity it is directly connected with the plain of Limari, out of which

[1] Charles Darwin, *Journal of Researches into the Natural History and Geology of the Countries Visited During the Voyage of H. M. S. Beagle Around the World,* second edition, D. Appleton & Co., 1891, p. 343.

[2] Charles Darwin, *Geological Observations on South America,* first edition, London, Smith, Elder & Co., 1846, pp. 36-41.

hills abruptly rise like islets, and other hills project like headlands on a coast. The surface of the fringe-like plain appears level, but differs insensibly in height, and greatly in composition, in different parts.

"At the mouth of the valley of Coquimbo, the surface consists wholly of gravel, and stands from 300 to 350 feet above the level of the sea, being about 100 feet higher than in other parts. In these other and lower parts, the superficial beds consist of calcareous matter, and rest on ancient tertiary deposits hereafter to be described. The uppermost calcareous layer is cream-coloured, compact, smooth-fractured, sub-stalactiform, and contains some sand, earthy matter, and recent shells. It lies on, and sends wedge-like veins into,[1] a much more friable, calcareous, tuff-like variety; and both rest on a mass about twenty feet in thickness, formed of fragments of recent shells, with a few whole ones, and with small pebbles firmly cemented together. This latter rock is called by the inhabitants *losa,* and is used for building: in many parts it is divided into strata, which dip at an angle of ten degrees seaward, and appear as if they had originally been heaped in successive layers (as may be seen on coral-reefs) on a steep beach. This stone is remarkable from being in parts entirely formed of empty, pellucid capsules or cells of calcareous matter, of the size of small seeds: a series of specimens unequivocally showed that all these capsules once contained minute rounded fragments of shells which have since been gradually dissolved by water percolating through the mass.[2]

"The shells embedded in the calcareous beds forming the surface of this fringe-like plain, at the height of from 200 to 250 feet above the sea, consist of,

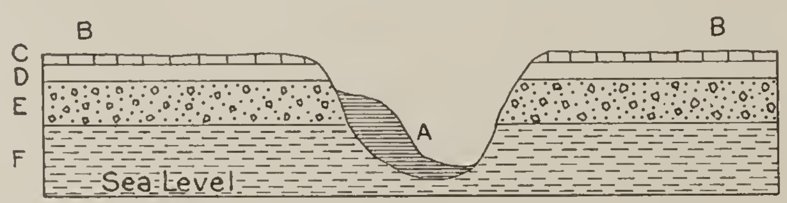
1. Venus opaca.
2. Mulinia byronensis.
3. Pecten purpuratus.
4. Mesodesma donaciforme.
5. Turritella cingulata.
6. Monoceros costatum.
7. Concholepas peruviana.
8. Trochus (common Valparaisa species).
9. Calyptræa Byronensis.

"Although these species are all recent, and are all found in the neighbouring sea, yet I was particularly struck with the difference in the proportional numbers of the several species, and of those now cast up on the present beach. I found only one specimen of the Concholepas, and the Pecten was very rare, though both these shells are now the commonest kinds, with the exception, perhaps, of the *Calyptræa radians,* of which I did not find one in the calcareous beds. I will not pretend to determine how far this difference in the proportional numbers depends on the age of the deposit, and how far on the difference in nature between the present sandy beaches and the calcareous bottom, on which the embedded shells must have lived.

"On the bare surface of the calcareous plain, or in a thin covering of sand, there were lying at a height from 200 to 252 feet, many recent shells, which had a much fresher appearance than the embedded ones: fragments of the Concholepas, and of the common Mytilus, still retaining a tinge

NO. 8.—SECTION OF PLAIN OF COQUIMBO.

Surface of plain, 252 feet above sea.



FIG, 6—Section of Plain of Coquimbo (Darwin).

Level of sea.

A—Stratified sand, with recent shells in same proportions as on the beach, half filling up a ravine.
B—Surface of plain with scattered shells in nearly same proportions as on the beach.
C—Upper calcareous bed, } with recent shells, but not in same proportions as on the beach.
D—Lower calcareous sandy bed (Losa), }
E—Upper ferrugino-sandy old tertiary stratum, } with all, or nearly all, extinct shells.
F—Lower old tertiary stratum, }

[1] In many respects this upper hard, and the underlying more friable varieties, resemble the great superficial beds at King George's Sound in Australia, which I have described in my Geological Observations on Volcanic Islands, p. 144. There could be little doubt that the upper layers there have been hardened by the action of rain on the friable calcareous matter, and that the whole mass has originated in the decay of minutely comminuted sea-shells and corals.

[2] I have incidentally described this rock in a note, p. 145, of the above work on Volcanic Islands.

of its colour, were numerous, and altogether there was manifestly a closer approach in proportional numbers to those now lying on the beach. In a mass of stratified, slightly agglutinated sand, which in some places covers up the lower half of the seaward escarpment of the plain, the included shells appeared to be in exactly the same proportional numbers with those on the beach. On one side of a steep-sided ravine, cutting through the plain behind Herradura Bay, I observed a narrow strip of stratified sand, containing similar shells in similar proportional numbers: a section of the ravine is represented in the following diagram, which serves also to show the general composition of the plain. I mention this case of the ravine chiefly because without the evidence of the marine shells in the sand, any one would have supposed that it had been hollowed out by simple alluvial action.

"The escarpment of the fringe-like plain, which stretches for eleven miles along the coast, is in some parts fronted by two or three narrow, step-formed terraces, one of which at Herradura Bay expands into a small plain. Its surface was there formed of gravel, cemented together by calcareous matter; and out of it I extracted the following recent shells, which are in a more perfect condition than those from the upper plain:

1. Calyptræa radians.
2. Turritella cingulata.
3. Oliva peruviana.
4. Murex labiosus, var.
5. Nassa (identical with a living species).
6. Solen dombeiana.
7. Pecten purpuratus.
8. Venus chilensis.
9. Amphidesma rugulosum. The small irregular wrinkles of the posterior part of this shell are rather stronger than in the recent specimens of this species from Coquimbo. (G. B. Sowerby.)
10. Balanus (identical with living species).

"On the syenitic ridge, which forms the southern boundary of Herradura Bay and Plain, I found the Choncholepas and *Turritella cingulata* (mostly in fragments) at the height of 242 feet

No. 9.—EAST AND WEST SECTION THROUGH THE TERRACES AT COQUIMBO, WHERE THEY DEBOUCH FROM THE VALLEY, AND FRONT THE SEA.

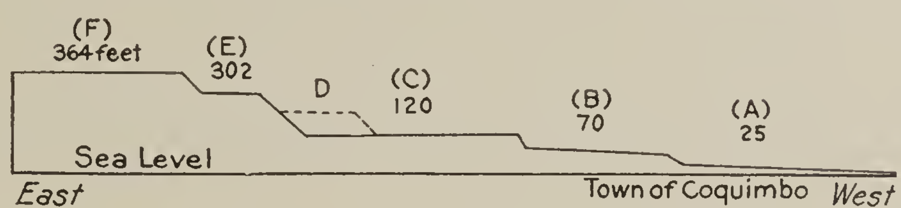


FIG. 7—Section through terraces at Coquimbo.
Vertical scale $\frac{1}{10}$ of inch to 100 feet: horizontal scale much contracted.

above the sea. I could not have told that these shells had not formerly been brought up by man, if I had not found one very small mass of them cemented together in a friable calcareous tuff. I mention this fact more particularly, because I carefully looked, in many apparently favourable spots, at lesser heights on the side of this ridge, and could not find even the smallest fragment of a shell. This is only one instance out of many, proving that the absence of sea-shells on the surface, though in many respects inexplicable, is an argument of very little weight in opposition to other evidence on the recent elevation of the land. The highest point in this neighbourhood at which I found upraised shells of existing species, was on an inland calcareous plain, at the height of 252 feet above the sea.

"It would appear from Mr. Caldcleugh's researches [1] that a rise has taken place here within the last century and a half; and as no sudden change of level has been observed during the not very severe earthquakes, which have occasionally occurred here, the rising has probably been slow, like that now, or quite lately, in progress at Chiloe and at Valparaiso: there are three well-known rocks, called the Pelicans, which in 1710, according to Feuillée, were *à fleur d'eau,* but now are said to stand twelve feet above low water-mark; the spring-tides rise here only five feet. There is another rock, now nine feet above high water-mark, which in the time of Frezier and of Feuillée rose only five or six feet out of water. Mr. Caldcleugh, I may add, also shows (and I received similar accounts) that there has been a considerable decrease in the soundings during the last twelve years in the Bays of Coquimbo, Concepcion, Valparaiso, and Guasco; but as in these cases it is nearly impossible to distinguish between the accumulation of sediment and the upheavement of the bottom, I have not entered into any details.

"*Valley of Coquimbo*—The narrow coast-plain sends, as before stated, an arm, or more correctly a fringe on both sides, but chiefly on the southern side, several miles up the valley. These fringes

[1] Proceedings of the Geological Society, Vol. II, p. 446.

are worn into steps or terraces, which present a most remarkable appearance, and have been compared (though not very correctly) by Capt. Basil Hall, to the parallel roads of Glen Roy in Scotland: their origin has been ably discussed by Mr. Lyell.[1] The first section which I will give, is not drawn across the valley, but in an east and west line at its mouth, where the step-formed terraces debouch and present their very gently inclined surfaces towards the Pacific.

"The bottom plain (A) is about a mile in width, and rises quite insensibly from the beach to a height of twenty-five feet at the foot of the next plain: it is sandy and abundantly strewed with shells.

"Plain or terrace (B) is of small extent, and is almost concealed by the houses of the town, as is likewise the escarpment of terrace (C). On both sides of a ravine, two miles south of the town, there are two little terraces, one above the other, evidently corresponding with B and C; and on them marine remains of the species already enumerated were plentiful. Terrace (E) is very narrow, but quite distinct and level; a little southward of the town there were traces of a terrace (D) intermediate between (E) and (C). Terrace (F) is part of the fringe-like plain, which stretches for the eleven miles along the coast; it is here composed of shingle and is 100 feet higher than where composed of calcareous matter. This greater height is obviously due to the quantity of shingle, which at some former period has been brought down the great valley of Coquimbo.

"Considering the many shells strewed over the terraces (A) (B) and (C), and a few miles southward on the calcareous plain, which is continuously united with the upper step-like plain (F), there can not, I apprehend, be any doubt, that these six terraces have been formed by the action of the sea; and that their five escarpments mark so many periods of comparative rest in the elevatory move-

No. 10.—NORTH AND SOUTH SECTION ACROSS THE VALLEY OF COQUIMBO

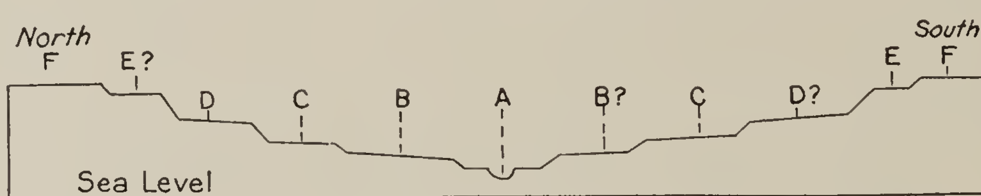


FIG. 8—North-south section across valley of Coquimbo (Darwin).

Vertical scale $\frac{1}{10}$ of inch to 100 feet; horizontal scale much contracted; terraces marked with (?) do not occur on that side of the valley, and are introduced only to make the diagram more intelligible. A river and bottom-plain of valley; C, E and F, on the south side of valley, are respectively, 197, 377, and 420 feet above the level of the sea.

ment, during which the sea wore into the land. The elevation between these periods may have been sudden and on *an average* not more than seventy-two feet each time, or it may have been gradual and insensibly slow. From the shells on the three lower terraces, and on the upper one, and I may add on the three gravel-capped terraces at Conchalee, being all littoral and sub-littoral species, and from the analogical facts given at Valparaiso, and lastly from the evidence of a slow rising lately or still in progress here, it appears to me far more probable, that the movement has been slow. The existence of these successive escarpments, or old cliff-lines, is in another respect highly instructive, for they show periods of comparative rest in the elevatory movement, and of denudation, which would never even have been suspected from a close examination of many miles of coast southward of Coquimbo.

"We come now to the terraces on the opposite sides of the east and west valley of Coquimbo: the following section is taken in a north and south line across the valley at a point about three miles from the sea. The valley measured from the edges of the escarpments of the upper plain (F) (F) is about a mile in width; but from the bases of the bounding mountains it is from three to four miles wide. The terraces marked with an interrogative do not exist on that side of the valley, but are introduced merely to render the diagram more intelligible.

"A A The bottom of the valley, believed to be 100 feet above the sea: it is continuously united with the lowest plain (A) of the former section.

"(B) This terrace higher up the valley expands considerably; seaward it is soon lost, its escarpment being united with that of (C): it is not developed at all on the south side of the valley.

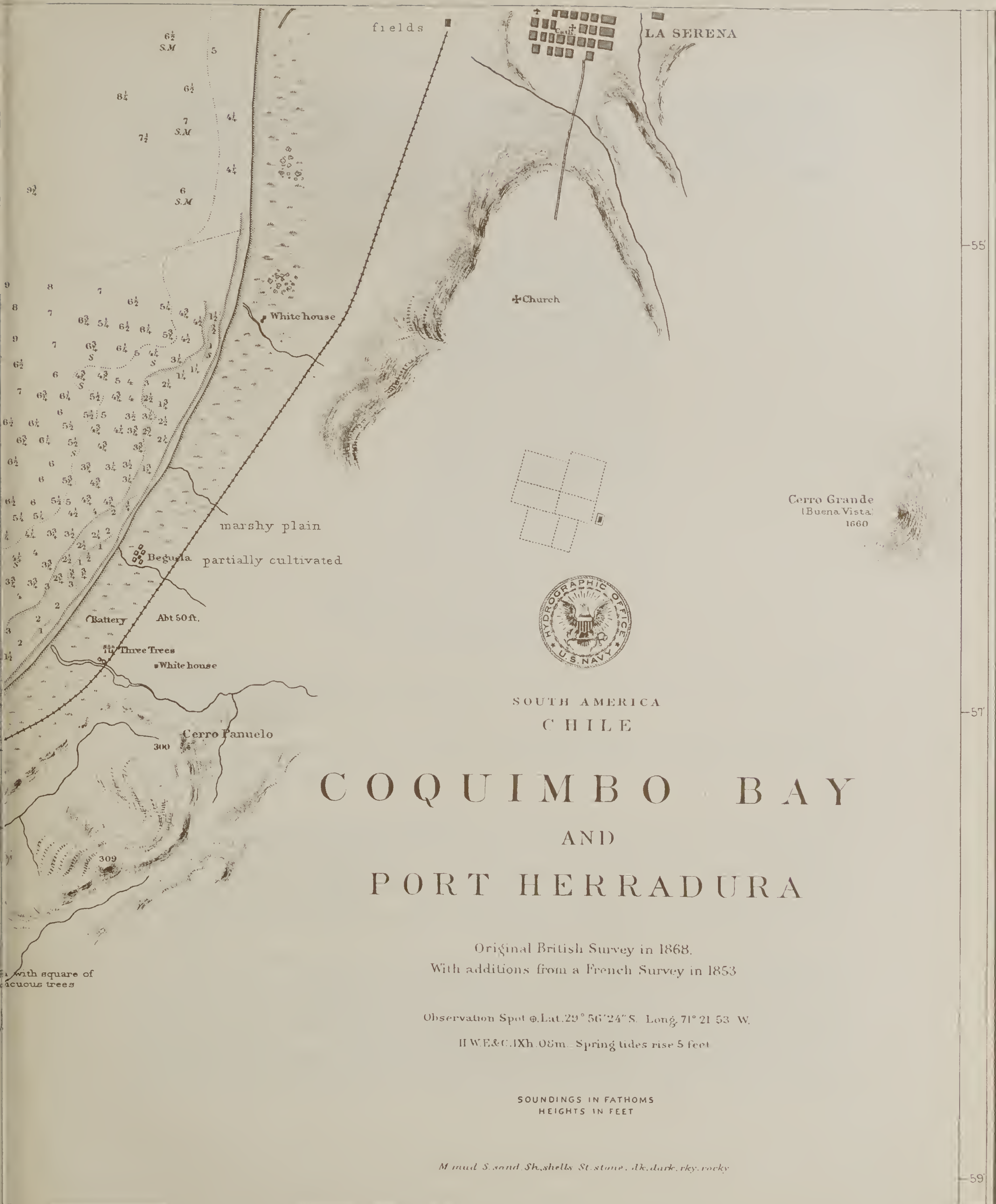
"(C) This terrace like the last, is considerably expanded higher up the valley. These two terraces apparently correspond with B and C of the former section.

"(D) is not well developed in the line of this section; but seaward it expands into a plain: it is not present on the south side of the valley; but it is met with, as stated under the former section, a little south of the town."

[1] Principles of Geology (1st edit.), Vol. III, p. 131.


CHURCH SPIRE IN LINE WIT LEADS EAST OF THE FOUL G
Outer Pajaros
PAJAROS ROCKS
Pajaros Niños
Pilcachos Rks
Tortuga Pt
Pelicanos Pt
Pelicanos Rk
LIGHT OBSCURED SOUTH OF THIS LINE
Light flashing white every 2 seconds flash 0.2 sec. eclipse 1.8 sec. 90 ft. vis. 10 m.
INNER PASSAGE
Salient Pt
Châlet (Conspic)
Obs. Point
COQUIMBO BAY
Conspic Clump
Signal Hill Semaphore
Station
Coal Pier
COQUIMBO
Landing Place (Red & wh Lts)
Coal Shed
Wreck of Dover Castle
COQUIMBO PENINSULA
Hospital.
Church Spire
Tinaja Pt
Race Course and Drill Ground
Tower
Radio Sta.
Railroad
Flagstaff Hill Semaphore
Playa Blanca
Hospital
Cerro Dominante
Abattoir
Reservoir
Gas Works
Bridge
Miedo Pt.
Cerro Alegre
Smelting Works
Church Spire
GUAYACAN
Chilean Cemetery
Herradura Pt.
THIS LINE
Knowsley Rk
PORT HERRADURA
English Cemetery
Railroad to Panucillo
Arroyo Guilebron
partially cultivated
Mill
Whale Rk.
Miramar
Wells (good water)
Herradura (in ruins)

CHART OF C



Part of Hydrographic Office, U. S. N. Chart No. 1326.

QUIMBO BAY

The writer's observations on the terraces were confined to the immediate vicinity of Coquimbo and the bluffs along the Arroyo Gulebran, a ravine which enters the bay from the east, opposite to the town. He concentrated on the stratigraphy of the marine terrace deposits and the evidences of beach-lines on Coquimbo point. Detailed descriptions of specific localities follow. (Plate LV.)

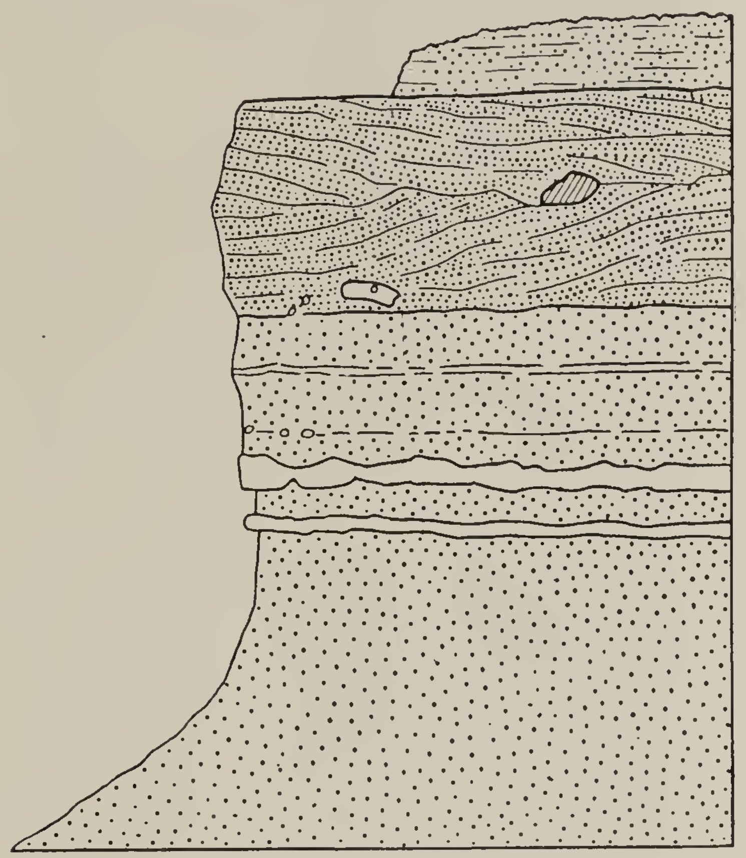


FIG. 9—Section of bluff at mouth of Quebrada Gulebron, Coquimbo.

	Meters
Top, fine, gray-brown, sandy soil	1
Sand, crossbedded, with boulder	} 2.50
Sand, with many fresh, perfect shells, and fragments	
Sand, pebbles and boulder	
Disconformity.	
Gray sand, weathering yellow, with four irregular but practically level layers of cemented shells; shells dissolved, many casts	1.80
Ferruginous gray sand, weathering yellow	2.00
	7.30

Bottom not exposed, just above tidal marsh.

My notes read: "The basal sand contains weak iron concretions, but no fossils; it is not evidently stratified; is wet and covered with an efflorescence.

The shell layers are irregular, exhibit many hollows, and are in part cemented to hard limestone. The shells are broken; the number of fragments is large and many retain the sculpture, but there are also many casts from which the shells have been dissolved.

The gravel and cobbles lie upon an eroded surface, washed by the waves of a retreating sea and covered with its detritus.

Before entering the bay the Arroyo Gulebron is crossed by the railroad, and above that point meanders in a broad meadow. The meadow is bounded by bluffs of stratified sands and limestone layers, rising successively higher to the levels of the terraces as they recede toward the hills. It is evident that the Gulebron has corraded its channel in the strata and that the bluffs expose sections of the sediments that were once laid down continuously from side to side of the present valley. It is not equally certain that the terrace fronts around the bay represent eroded scarps of subaerial origin. They may have been shaped by currents during or subsequent to deposition, and they may have received later deposits on their surfaces. The first inspection of the plan of the terraces, particularly of Herradura Cove, suggested that these latter conditions had probably existed, and supporting evidence was found in the stratigraphy. The study was not, however, exhaustive, and it is possible that the seemingly simple terrace deposits include other disconformities in addition to those which I found.

Immediately east of the crossing of the Gulebran by the railroad is a bluff 26 feet (8 meters) high. Its base is of yellow sand; there is a capping of harder sands with limestone layers, and the top consists of sands with gravel and cobbles. The detailed section, which is sketched in figure 9 from field notes, is shown on page 107.

The conclusion stated in the last paragraph followed from the examination of the section in detail. It was not anticipated, but was suggested by the very evident difference in the shells above and below the contact. Those above retained their color as freshly as any washed on the beach a few weeks before. Those below had long been subjected to the action of filtering waters, which had both dissolved and cemented them. The cobbles also were foreign to the lower sediments and indicated a change.

Seeking to extend the observations, I went north and east along the slope skirting a meander of the Arroyo Gulebron. There were no exposures for a distance of some 2,000 feet (600 meters); nothing but loose sand and brush; then a slight reentrant angle which ended in a vertical chimney gave a section 65 feet (20 meters) high. The detailed section was:

	Meters
Level of outer edge of terrace; terrace slopes north 1° 10′ toward the bay.	
Sand with fresh shells, large Pectens	7
Gravel at the contact.	
Limestone	1.5
Sand with Pectens	11.5
	20.0

Raised edge of meadow.

The lower sands in this exposure were strongly cross-stratified. They were wind-drifted sands, blown against the eroded face of the cliff, which they obscured, except at the projecting limestone ledge. The little chimney in the sands had been washed out in some recent rain and the stormwaters had carried down the large *Pectens*, which were scattered on the surface or buried on edge.

It seems not improbable that an occurrence of this kind was observed by Darwin, who described and sketched it as the recent result of deposition by the retreating sea, which had cut out the ravine by the force of the waves and currents, according to the hypothesis entertained in his day.

Eastward from the last observation, for a space of 1,650 feet (500 meters), the surface slopes consisted of wind-blown sands, obscuring all the marine deposits, but beyond that point there were precipitous bluffs. At one of these the section, on page 109, 190 feet (57 meters) high, was measured.

Coquimbo. Arroyo Culebron. General view looking north toward bluffs of Pliocene sediments.

A. Coquimbo. Quebrada Gulebron. Marine Pliocene at base of cliffs.

B. Coquimbo. Quebrada Gulebron. Secondary limestone capping upper terrace; described by Darwin as "losa."

A. Coquimbo. Quebrada Gulebron. Upper terrace near Estancia San Martin, showing upper horizon of erratics in marine strata; the lower horizon is just below the bottom of the view.

B. Coquimbo. Quebrada Gulebron. Cliffs on south side showing large erratic in marine strata in center of view.

A. Coquimbo. Pliocene, marine strata with embedded erratic; the tripod is one meter long; looking south at cliffs south of the Quebrada Gulebron.

B. Coquimbo. Near view of same large erratic in Pliocene strata south of Quebrada Gulebron.

A. Coquimbo. Quebrada Gulebron. Rock gorge from which erratics were presumably derived.

B. Coquimbo. Quebrada Gulebron. South bank in which erratics occur embedded; very large erratic in foreground; about 23 feet long by 12 feet high (7 meters by 4 meters).

A. Coquimbo. Looking south past the curve of La Herradura cove. Large boulder buried in marine Pliocene on the terrace 100 feet above sea, 1.5 miles west of the Quebrada Gulebron.

B. Coquimbo. Marine strata with embedded boulder; locality in the railroad cut east of La Herradura cove.

The sands in the above section were all marine, as is shown by the abundant fossils which they contain. The limestones were also marine deposits. They too contain

SECTION OF MARINE PLIOCENE IN BLUFF NORTH OF THE ARROYO GULEBRON, HALF A MILE EAST OF THE RAILROAD

[Fossils were collected from the strata marked with roman numerals and are described in the report by Eric Jordan under the same numbers.]

	Meters
Front of lower, high level terrace:	
Sand, fine, brown, and earthy	2.0
Calcareous sand and pebbles	0.5
Sand	3.5
Cemented shell bed, coquina with pebbles	0.5
Sand	3.0
Coquina, III, included with I and II	2.0
Sand	3.0
Coquina with pebbles	4.0
Sand	6.0
Coquina in two benches	3.0
Sand	2.5
Coquina	1.0
Pebble layer	0.2
Coquina	0.4
Sand	0.8
Coquina	0.2
Sand	0.3
Coquina, II	2.5
Sand, I	1.0
Slope of loose sand	20.0
Level of meadow.	——
Thickness	56.4

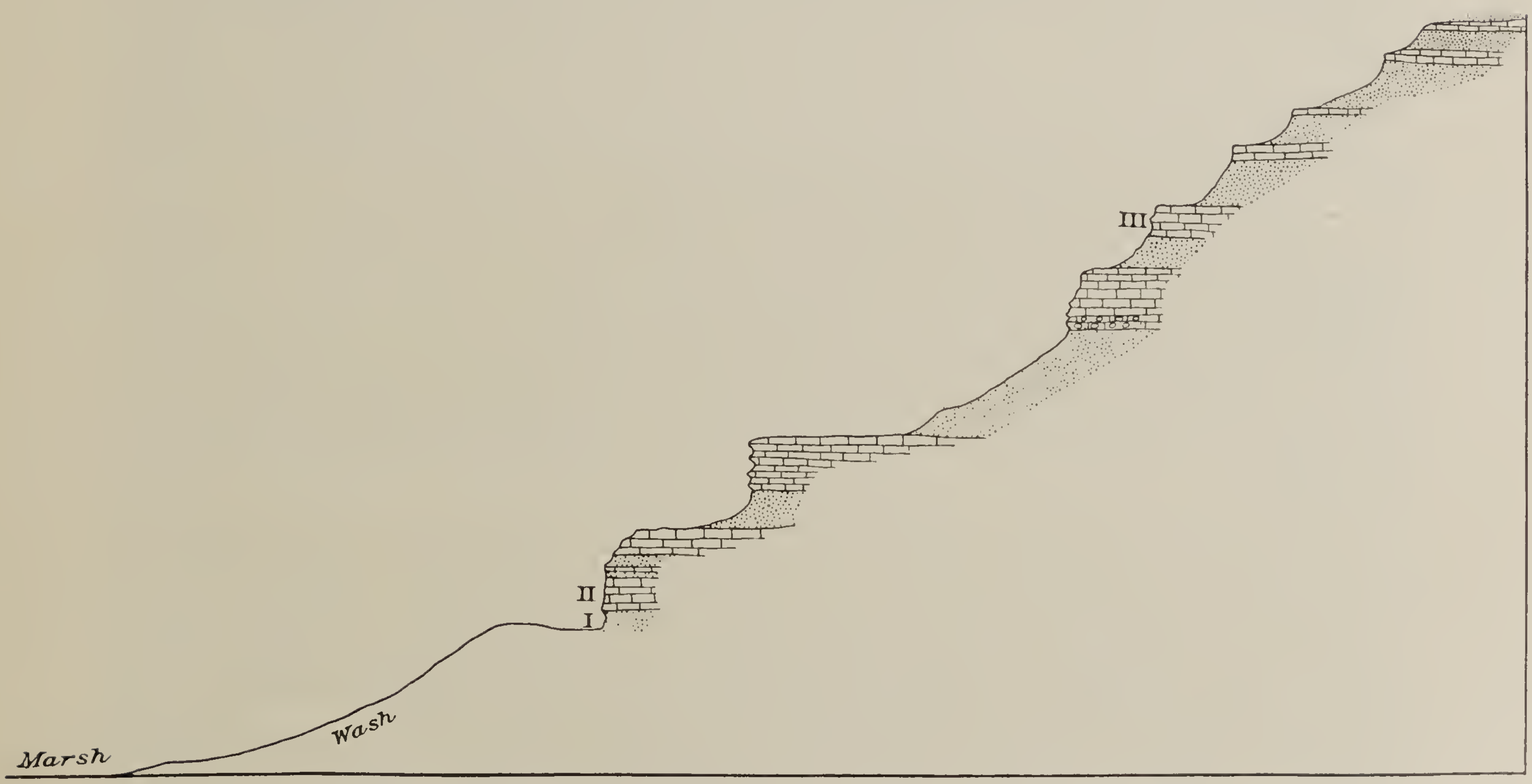


FIG. 10—Pliocene-Pleistocene(?) section, Quebrada Gulebron, Coquimbo.

numerous fossils; they are distinctly stratified with the sands; and they do not exhibit the textures or inclusions which are found in the subaerially concentrated lime formation that caps the uppermost terrace. The section thus seems to record a continuous subsidence of the block on which the sediments were laid down, rather than any alternation of rise and fall of land or sea. The conditions that determined the formation of coquina or the deposition of less calcareous sands escape our analysis, but may probably have resulted from minor rhythms of climatic changes and of the living conditions in the bay, in which winds and ocean currents played their part. (Plate LVI.)

A careful field inspection failed to show any difference in the fossils contained in the different horizons of this section. Jordan did not recognize any distinction between the few forms obtained from the horizon III and those collected from the two lower strata at the very bottom of the section. The whole fauna appeared to correspond with the Cape Fairweather Pliocene. It is not impossible, however, that more careful collecting by an experienced paleontologist may indicate changes corresponding to a passage from middle to later Pliocene or even to Pleistocene. My collections were by no means exhaustive and the material secured was not satisfactory. The collecting is difficult, the coquina being very hard, the sands very soft and friable, and the shells generally large. The fossils do not break out of the coquina, and they do not hold together in the sands. A mass of sand which was inclosed in plaster of Paris at the place where it was excavated had dried out and crumbled to loose débris before it reached the laboratory. In view of the classic interest attaching to the locality and the opportunity which it affords to fix the dates of beginning and ending of the subsidence, a thorough investigation is desirable, with intensive study on the spot.

The absence of Recent shells from the uppermost strata of this section marks it as less complete than the one observed at the bluff near the railroad and suggests that the retreat of the sea had been accomplished earlier at this point.

The meadows of the Arroyo Gulebron terminate a short mile south of the bay, where the stream comes out of a rocky canyon. (Plate LIX.) The outcrops of old igneous rock are capped on both sides by the highest terrace of marine sediments, corresponding to the one designated (F) by Darwin, that is, to the terrace which is continuous with the highest levels of the adjacent valleys in the coastal mountains. It is upon this terrace that the "losa" or secondary limestone is strongly developed.

It is striking evidence of the keenness of Darwin's observation and analysis that he recognized the secondary character of the massive limestone stratum which is extensively developed on the upper terrace and goes by the Spanish term "losa" or "*caliche*." It varies from 3 to 6 feet (1 to 2 meters) in thickness, contains many marine shells, probably of Pleistocene or Recent age, and is firmly cemented. The essential condition of its development is the rise and evaporation of ground-water charged with lime, and as this is variable, the occurrence of the superficial formation is correspondingly irregular. It is very strongly developed just south of the Quebrada Gulebron and the Estancia San Martin, and forms great slabs where it is undermined on the edge of the bluff. (Plate LVII B.) The principal interest attaching to this formation is the age of its fauna. It represents the farthest advance of the sea, and consequently the turningpoint at which subsidence gave place to elevation. It will be seen by reference to Jordan's report on the collections which I was able to make that the differences between the Pliocene and Pleistocene faunas in this region are not readily detected, except by exhaustive and thorough study, for which this reconnaissance offered no opportunity. If, as seems probable on the evidence of the great erratics embedded in the shell deposits at a lower level, the terrace formation includes the early Pleistocene as well as the Pliocene, then we have the subsidence extending into the latter epoch and must date the elevation from a time succeeding the earliest glaciation.

The evidence of the erratics which occur in the shell deposits south of the Quebrada Gulebron, and particularly on the slopes north of the Estancia San Martín, presents a problem which requires further investigation. One is puzzled to know how boulders of such size as are found in the evenly stratified shell beds could have been transported and dropped where they lie. They are also widely distributed over the floor of the ancient bay and along the coast of the island that now forms Coquimbo Point. Some agency which was active on the shores and in the bay itself was competent to carry boulders 8 or 10 feet (2 or 3 meters) in diameter to distances of a mile or more from their source in the canyon of the Gulebron or on the slopes of the old island.

The facts of occurrence in the terraces above the Gulebron meadows are as follows: No boulders of any notable size were seen on the northern side of the Quebrada. On the southern side there is a precipitous cliff with a cascade of the intermittent stream which flows from the Estancia San Martín. The strata of this section are more firmly cemented than they are on the north, and thus have the appearance of greater age, but they are continuous and the induration is a local accident. About 60 feet (20 meters) below the top of the cliff is a layer which contains a number of large rocks completely surrounded by the deposits of shells. The rocks rest on strata composed of shells, are covered by shells, and in some cases even have barnacles adhering to them. They are thus integral elements of the deposit. A second horizon marked by boulders of smaller sizes occurs about 30 feet (10 meters) higher.

The size of the embedded rocks is that of boulders which would be among the largest moved by a torrential stream on a steep grade. That agency of transportation is, however, excluded by the fact that they were deposited in marine waters, where nothing stronger than a shore current could have existed. It might be suggested that they represented the outwash of a torrent formed by a cloudburst or similar accident, but they are not associated with the deposits of mud which in that case should accompany the boulders, and their distance from the rock slope, which is about a mile, is such that the force of a torrential current would have been exhausted before they could have reached their present position. The boulders under discussion are shown in Plates LVIII-LX.

The stratification of the shell-beds, the embedding of the boulders, and their size are clearly distinguishable. It will also be noted that they are sharply angular and exhibit no signs of stream abrasion.

The erratics are all of one kind of rock, a dark, fine-grained igneous rock, probably a diabase, which outcrops in place in the canyon of the Quebrada Gulebron from a half mile to a mile from the points at which they now lie. Their occurrence at one horizon, embedded in marine shells, appears to limit the agency of their transportation to marine currents, and it would be consistent with the general direction of currents such as probably existed in the ancient day that the rocks should occur where they do, on the south side of the Quebrada, since the principal sweep of the winds and waves was from the north. It is, however, clearly beyond the power of any marine current to transport rocks of this size unless they were floated.

Two agencies of flotation may be imagined. One would consist of rafts of tree trunks carrying the rocks in their roots, the other is ice. There remains absolutely no evidence of either, and we are left to conjecture on the basis of probabilities.

The suggestion that the rocks may have been carried by floating tree trunks is put to rather a severe test by their size. It would require a large trunk, or a raft of them, to support a boulder 6 feet (2 meters) across, and some of these exceed that dimension. On the climatic side it appears improbable that the coasts of the Desert of Atacama have supported trees of sufficient size to do the work, and there is no evidence of the existence of such forest growth. If it occurred it was probably restricted to trees in the canyon, like the red-wood groves on the coast of California.

On the other hand, the occurrence of ice in the form of heavy floes could occur in latitude 30° on the shores of the Pacific Ocean only during a glacial epoch, and even then only under exceptional local conditions. It would be unreasonable to postulate any general development of such ice masses. Their local occurrence, however, seems not improbable and would explain the facts presented by the boulders without demanding unreasonable assumptions.

It is of course a fact that the glacial epochs are represented by some sort of record, either in the terrace deposits of Coquimbo Bay or in the sculpture of their surfaces. The extremely recent character of the shell deposits on the bluff at the mouth of the Quebrada Gulebron indicates that the land stood at least 30 feet (10 meters) lower within the present biologic episode of time. It is not beyond the recognized effects of uplift to assume that it may have been raised 300 feet (100 meters) since the middle Pleistocene, and the accumulation of 65 feet (20 meters) of shell deposits is within the effects of deposition of a small part of the period. These are the changes which have taken place since the deposition of the large erratics in the terrace formation, and the estimate would carry us back to the early Pleistocene.

Evidences of glaciation in the Andes are described elsewhere in this report. They indicate that the early Pleistocene was a time of the maximum expansion of glaciation in the Cordillera and was marked by glaciers in localities which now stand 10,000 feet (3,000 meters) or more above sea in this or warmer latitudes. It also appears that there was a later, less extensive glaciation, at least farther south. The ice never approached the sea and we can not attribute any direct effect to glaciation along the coast, but it is probable that the climate was severe, at least in winter, even at sea-level.

Recognizing these conditions, I would suggest the following hypothesis to account for the transportation of the erratics: The Quebrada Gulebron, though not so deep as at present, was a rock-walled ravine which lay in the shadow of the hills where it skirts the first range above the terraces in descending from the valley in the Coast range. The winter climate was sufficiently cold and precipitation sufficiently heavy to produce banks of snow and ice in sheltered places, and during exceptional successive seasons the summers were too short and chill to melt them. The winds blew the snow from the terrace levels and drifted it into the ravine, and thus there accumulated in the narrows of the Quebrada Gulebron a miniature glacierette. During seasons of high floods masses of ice from the ravine were floated out over the bay, carrying with them the erratics which now present the anomalous evidence of cold climate. This occurred at two levels, possibly in conjunction with the two glaciations. The hypothesis must be extended to cover the effects of ice on Coquimbo Point, which are yet to be described, and to account for the large boulders that lie on the terrace east of La Herradura. These imply that the climate must have been so severe that some coast ice formed in sufficient masses to afford local transportation. The episode, however, was singular, for the erratics deposited on the terrace seem to be limited to a single horizon. They do not appear to be repeated. It would seem, therefore, that we have to deal with a phenomenon which was the result of unusual conditions and was abnormal, even for the glacial epoch. The reader is asked to bear this hypothetical suggestion in mind in reading the further description of the boulders distributed over the surfaces of the terraces and on Coquimbo Point.

At sea-level surrounding its eastern extremity La Herradura presents the smooth beach of a confined water-body, and from the water a long slope rises to the foot of a terrace in which there is an excavation for the railroad that connected with the smelter on the northern side of the cove. On top of the terrace, east of the railroad and 145 feet (44 meters) above sea, are several large erratics. They lie on the surface, which consists of the horizontally bedded Pliocene shell deposits, but around each of them is a slight excavation which is probably due to wind action, and it is possible that they may have been undercut by the wind and may thus have sunk a little deeper into the shells. They are distinctly erratic or out of place in their present setting, and they are not to be assigned to the Pliocene with which they are associated. They are therefore without date, but by inference may be correlated with the boulders actually embedded in the strata south of the Quebrada Gulebron. The latter lie at a higher level and are covered by 20 meters of additional strata. If these boulders on the plain ever were so covered they have been denuded by currents of the retreating sea. It is also possible that the deposits out in the bay were lacking on account of strong currents which kept the bottom scoured. In any case, the presence of large rocks such as that shown in Plate LXI demand some transporting agent, such as ice, which would drop them where they now lie.

It is obvious that a comparison of marine bench-marks on Coquimbo Point with those which have been described by Darwin as characteristic of the eastern shore would afford opportunity for correlating the movements of the two sides of the bay during the Pleistocene uplift. It is therefore of interest to note that the elevated shell deposits are found on Coquimbo Point immediately above the town, and that there are beach lines on the granite slopes which are marked by rows of large boulders that have been carried some distance from the dikes of intrusive rock in which they originated.

The limestone on Coquimbo Point appears to be identical with that on the eastern side of the bay. It is horizontally stratified, consists of interbedded sands and hard limestone, and contains similar shells. The uppermost level is 245 feet (72 meters) above sea, as determined by aneroid. The determination does not suffice for an exact comparison with levels on the eastern side of the bay, since the measurement is not exact and the precise stratum represented in either locality could not be identified in the other. It is, nevertheless, highly probable that there is not much difference of elevation, and consequently there has been no marked tilting or dislocation during the uplift of the region around the bay. The shell deposits above the town are shown in Plate LXII. This observation bears upon the activity on the faults, since the fault which runs through the railroad yard lies between the opposite shores of the bay.

The town of Coquimbo lies crowded on the bare granite ledges of Coquimbo Point to a height of about 165 feet (50 meters) above the water and scattered houses occur at higher elevations. At 230 to 250 feet (70 to 75 meters) there is a marked bench above which there are gentler slopes and limited areas of nearly level ground. The limestone deposits described in the last paragraph occur at this elevation and occupy a reentrant angle south of a dominant pinnacle of black rock. Northward along the granite are strewn large black boulders, which are gathered at and just below the line of the bench. The pinnacle itself is composed of similar boulders that still rest in the soil formed by the subaerial decomposition of the dike. The soil is lacking on the slope along which the other boulders have been carried, and they lie on the bare granite (Plate LXIII).

The bench line is distinct in some profiles of the point, but is lacking in others. A somewhat careful survey indicated that its development depended on conditions of exposure to the waves and upon the source of material with which to form it. It follows a contour so far as it can be traced. Thus it represents to all appearances an elevated beach line, which has been washed away where it was sandy, but remains where the cobbles and boulders were spread. It is a weakly marked line, yet appears to be unequivocal in its evidence of the former level of the sea against the islet that is now the point. The shell-bearing strata confirm the observation of the profiles, although they lie a few meters lower, as might be expected of sediments laid down off a rocky shore. It thus appears to be the fact that Coquimbo Point was submerged to a level some 245 feet (75 meters) lower than that at which it now stands.

The date of the submergence is indicated by the boulders. They compare in size with those seen up the Quebrada Gulebron and on the terraces above La Herradura. Too large to have been carried by waves along the inner shore of the islet, they also require some peculiar mode of flotation to account for their distribution. As has already been suggested, the action of shore-ice during a brief episode of unusually severe climate in the earliest glacial epoch seems to afford the most probable explanation.

The physical evidence which would lead to the conclusion that the maximum submergence of Coquimbo Bay had been reached during the early Pleistocene, but at a distinct interval after the earliest glaciation, meets with some contradiction, or at least lack of confirmation, in the biologic evidence; for if the stratified marine sediments represent continuous deposition, we should expect that the warmer conditions of the Pleistocene habitat would be distinguishable from the colder waters of the glacial epoch and possibly from the later Pleistocene by faunal differences. So far as we have the evidence this is not the case.

From his examination of the fossils which I was able to secure from several localities Jordan concluded that:

> "This fauna could not have lived under conditions any more severe than the present climate of Coquimbo. The conditions were probably a little warmer than at present, for not one of the living forms is typical of southern Chile and most of the species belong more truly in Peru than in the latitude of Coquimbo. The climatic change between the deposition of these beds and that of the glacial boulders must have been great, much greater than that between the Lower and Upper San Pedro beds of California and perhaps about equal to that of a change from the climate of middle Lower California to that of British Columbia."

We may accept Jordan's conclusion as definite and final for the material which he had available for examination, but I, who collected it, do not regard that material as adequate and consider that the question is still open whether there may not be a cold-water fauna in certain strata which would represent the colder phases of the Pleistocene. To my observation, the shells above the horizon of the erratics in the southern side of the Quebrada Gulebron were practically identical with those below it, and we know that the earlier and later climates were certainly warm climates; but I did not secure a collection from the horizon of the boulders themselves, and the few fossils I did obtain from locality III, near the top of the bluff north of Gulebron, were not distinctly identified when the collection was unpacked. Neither could I be sure that they represented a horizon above the boulders, even if they had been recognized, because the boulder zone was not found in that section and levels were not carried across to its position on the south side. It is therefore possible that some more careful observer and collector may yet discover a fauna indicative of colder waters, either at and restricted to the boulder horizon or even occupying the strata to some height above that zone. If so, it would be obvious that the fauna of the milder climate retreated and returned, as that of a colder latitude advanced and retreated, while the Andes assumed a glacial cap and the shores were fringed with ice, or both took on semi-tropical aspects.

With reference to diastrophism, the evidence is more conclusive. The fault in the railroad yard traverses limestone that has yielded a typical Miocene fossil, *Ostrea ingens* Zittel. Movements therefore occurred during or after the Miocene and, since the Paleozoic granite had been raised to near sea-level before that epoch, the faulting probably began much earlier. But the apparent uniformity of level of the Pliocene beds east and west of the fault indicates that it had ceased to be active at least before the upper strata were laid down, that is, during the Pliocene. Subsidence continued, however, in the area of Coquimbo Bay, including the granite west of the fault, at least to the end of the Pliocene and probably well into the Pleistocene. This area then began to share in the uplift that has affected the whole Cordillera since Pliocene time. The evidence of that process of elevation is found in the physiography and is discussed elsewhere.

REPORT ON FOSSILS FROM COQUIMBO

By Eric Jordan

INTRODUCTION

Following is a brief report on the fossils from the vicinity of Coquimbo. I have given two lists, one of the species collected from each locality, the other a full list of all of the forms recognized from the two formations represented. I have also given a brief discussion of the probable climatic relations of the faunas. The lists are not quite complete, but I believe that little of the remaining material is sufficiently well preserved to be identified with certainty. Two species believed to be new will be described later.

Whether, on the basis of this collection, much can be added to the knowledge of the Coquimbo formation is doubtful. However, I do not know the extent of Moericke's paper. Most of the extinct species represented in the collection were described by Philippi,[1] or by older writers. Whether or not Moericke [2] discusses the climatic relations of the Coquimbo formation, I also do not know.

Species Recognized from Each Locality

Quebrada Gulebron; bank on northeastern side near the mouth; [3] Pleistocene:
- Pecten purpuratus Lamarck.
- Marcia rufa Lamarck.

Quebrada Gulebron I and II; base of the visible Pliocene section:
- Ostrea patagonica d'Orbigny.
- Mytilus chorus Molina
- Venus sp.
- Panopea coquimboensis d'Orb.
- Acanthina calcar-longum Martyn.
- Chorus labialis Hupé.
  - lævis Philippi.
  - blainvillei d'Orbigny.

Railroad cut, 0.75 Mile East of Guayacan. (Upper strata of terrace which has been scoured by marine currents, that probably removed a considerable thickness down to a hard surface in the Pliocene section.—B. W.)
- Glycimeris ovata Broderip
- Pecten purpuratus Lamarck
- Marcia rufa Lamarck
- Chione spurca Sowerby
- Chione cf. polydora Philippi
- Venus sp.
- Psammobia sp.
- Semele solida Gray
- Panopea guayacanensis Philippi
- Panopea sp.
- Arcularia cf. complanatus Powis
- Oliva peruviana Lamarck
- Trophon cassidiformis Blainville
- Tritonalia crassilabrum Gray
- Acanthina doliaris Philippi
- Turritella cingulata Sowerby
- Cerithiopsis sp.
- Bittium sp.
- Trochita trochiformis Gmelin
- Crepidula sp.
- Balanus sp.
- Balanus sp.

Terrace between Coquimbo and Guayacan. Limestone in bottom of old channel. (Same as above.—B. W.)
- Turritella cingulata Sowerby
- Balanus sp.

Railroad Yard on Coquimbo Point. (Disturbed limestone; probably materially older.—B. W.)
- Ostrea ingens Zittel

[1] *Tertiären und Quatären Versteinerungen Chiles,* Leipzig, 1887.

[2] W. Moericke, *Versteinerungen der Tertiäformation von Chile,* Jahrbuch fur Min., Geologie, und Pal., Beilage Band 10, 1895-96, S. 548-612.

[3] Superficial sediments forming the top of the bluff above an unconformity. B. W.

SPECIES RECOGNIZED FROM THE PLIOCENE AND PLEISTOCENE OF COQUIMBO

[E indicates species not known to be living]

PLEISTOCENE		Mouth of Quebrada Gulebron Pecten purpuratus Lamarck Marcia rufa Lamarck
PLIOCENE	COQUIMBO FORMATION	Quebrada Gulebron I and II; Railroad cut 0.75 mile East of Guayacan; Terrace between Coquimbo and Guayacan; Railroad yard on Coquimbo Point. Glycimeris ovata Broderip Ostrea patagonica d'Orbigny (E) Ostrea ingens Zittel (E) Pecten purpuratus Lamarck Mytilus chorus Molina Marcia rufa Lamarck Chione spurca Sowerby Chione cf. polydora Philippi (E) Venus sp. Venus sp. Psammobia sp. Semele solida Gray Panopea coquimboensis d'Orbigny (E) Panopea guayacanensis Philippi (E) Panopea sp. Arcularis complanatus Powis Oliva peruviana Lamarck Trophon cassidiformis Blainville Tritonalia crassilabrum Gray Acanthina calcar-longum Martyn Acanthina doliaris Philippi (E) Chorus labialis Hupé (E) Chorus lævis Philippi (E) Chorus blainvillei d'Orbigny (E) Turritella cingulata Sowerby Cerithropsis sp. Bittium sp. Trochita trochiformis Gmelin Crepidula sp. Balanus sp. Balanus sp.

DISCUSSION

PLEISTOCENE

The shells from the mouth of Quebrada Gulebron are undoubtedly of Pleistocene age; the preservation indicates very recent deposits. As there were only two species in the lot, it is impossible to determine the climatic relations of the fauna. Both are now living at Coquimbo, but it may be of interest to note that both range north into the tropics, Coquimbo being practically the southern limit of their range.

PLIOCENE

The above list includes 31 forms from the various localities around Coquimbo. Owing to the rather poor condition of some of the material, in contrast to the excellent preservation of other of it, full identification with any degree of certainty was in many cases impossible. Out of the list, 22 have been specifically determined. Perhaps with further work one or two more might be added.[1] Of these 22 recognized species, 9, or nearly one-half, are not known to be living at present. One genus, *Panopea*, has no recent representatives on the Pacific coast of America south of California. A number of the species are present in the Pliocene Cape Fairweather [2] series of Patagonia, and a few

[1] The *Bittium* and *Cerithiopsis* are undoubtedly new; they may or may not be extinct.

[2] Ortmann, Princeton Expedition to Patagonia, vol. IV, Paleontology, part II, 1901.

A. Coquimbo. Marine sediments on granite promontory west of bay, just above town, looking south.

B. Coquimbo. Marine sediments, just above town; near view, looking into artificial cave.

A. Coquimbo. Black point above town: a mass of boulders in place in the decayed surface of the diabase dike.

B. Coquimbo. Wave-cut bench marking high level of sea on granite islet, which is now western side of bay; boulders of black diabase, moved along beach.

occur in the Miocene of Patagonia. The Coquimbo formation has been described as Pliocene,[1] and apparently considered as belonging to one horizon throughout. The big oyster is distinctly a Miocene type, even in the Southern Hemisphere, and, although it, too, is common in the Cape Fairweather formation, I believe, on the basis of this collection, that if the beds at Coquimbo are all of the same horizon, they are of the middle Pliocene or older. However, with the relatively small amount of material at hand it is impossible to make a definite determination. Probably Moericke was able to locate the series more accurately.

As to the climatic conditions under which this assemblage lived, no definite statement can be made in degrees of temperature or latitude, for the list is not long enough, and our knowledge of the recent distribution of the species not sufficiently full. Nevertheless, some facts are evident as follows: (1) This fauna could not have lived under conditions any more severe than the present climate of Coquimbo; (2) the conditions were probably a little warmer than the present, for not one of the living forms is typical of southern Chile and most of the species belong more truly in Peru than in the latitude of Coquimbo; (3) the climatic change between the deposition of these beds and that of the glacial boulders must have been great—much greater than that between the Lower and Upper San Pedro beds of California, and perhaps about equal to that of a change from the climate of middle Lower California to that of British Columbia.

SUMMARY

It seems to me probable that these beds do not represent the top of the Pliocene, and that between them and the period of floating ice there was a hiatus, perhaps considerable, represented only by some obscure disconformity with no discordance in bedding. During this lost period the climate changed from subtropical to distinctly cold temperate. The fauna of the cold periods may well have been meager, or not represented at all in the section at Gulebron. At the close of the one or two glacial periods there was, then, return to climatic conditions at least as warm as the present, under which conditions the *Pecten* beds at the mouth of the Quebrada were deposited.

[1] Presumably by W. Moericke in G. Steinnmann, *Neues Jahrbuch für Mineralogie, Geologie, und Paleontologie,* Beilige Band X, 1896.

SAN FELIX AND SAN AMBROSIO[1]

GENERAL DESCRIPTION AND GEOLOGY[2]

San Felix and San Ambrosio are volcanic islands in the South Pacific ocean, San Felix being situated in latitude 26° 15′ south and longitude 80° 7′ west of Greenwich and San Ambrosio lying about 16 km. to the east-southeast. They are about 500 miles (800 km.) west of Chañaral, on the coast of Chile, and the same distance due north of the group of Juan Fernandez and Mas-a-fuera. The South Pacific charts show several known rocks or islets and some whose existence is recorded as doubtful, which, with the above-named islands, form an archipelago strewn on a narrow submarine ridge that extends along the meridian of 80° west from about 36° south to 26° south, the ridge being defined by the 1,000 fathom (2,000 meter) contour line. Knowing that all these islands and islets are the peaks of volcanoes, we may suspect that there are more of them than we can see; but this must remain an unverified guess until detailed soundings can be made. The depth of the ocean in this region, which lies west of the Richards Deep, varies from 2,000 to 2,500 fathoms (4,000 to 5,000 meters). The islands, therefore, represent the summits of volcanoes probably sixteen to eighteen thousand feet or more in height—that is to say, they compare with the great volcanoes of the Andes, which are situated on the other side of the deep.

San Felix and San Ambrosio are the remains of two large, distinct craters. A third crater is (possibly) indicated by Peterborough Cathedral, a precipitous islet about one mile northwest of San Felix. The rocks that rise above the sea are, however, little more than small remnants of the original group, and there is free play for the imagination in extending the curves of the crater walls beneath the unbroken expanse of sea in their vicinity.

Having sailed in May 1923 from Chañaral, the nearest port in Chile, I approached San Ambrosio from the east practically end on. It is an imposing rock, rising on its southern side 850 feet (254 meters) in a sheer precipice from the surf and sloping down northward to cliffs that are in general 350 feet (100 meters) high along the northern shore. The width of the island is but 2,600 feet (800 meters) and it is only 2 miles (3 km.) long. The chart gives its highest elevation as 1,500 feet (450 meters). There is little in its somewhat oval form to suggest the curve of a crater, but the obvious slope of the upper surface from south to north, and of the bedded lavas of which it is formed, indicates that there was a crater south of the existing fragment of the rim. On nearer approach, in circumnavigating the island, a very large number of distinct lava-flows are recognizable and many vertical dikes cutting through the flows can be made out. The volcanic structure is obvious.

[1] Bailey Willis and H. S. Washington, *San Felix and San Ambrosio, their Geology and Petrology,* Bull. G. S. A., Vol. 35, pp. 365-384, 1924.

[2] By Bailey Willis.

It is possible to land on San Ambrosio at one point, Covadonga Cove, which is nothing more than a niche in the cliffs, with just room for a moderate-sized rowboat. There, in good weather, skillful seamen may effect a landing, and from that point the cliffs have been climbed. The summit plateau is frequently covered with mist, condensed from the air currents that ascend along the southern cliffs, and is therefore covered with vegetation, consisting, according to reports, of low, spreading shrubs (*Thaumoseris* n. g. *lacerata* Ph.).[1]

I did not myself land on San Ambrosio and am indebted to Captain Stuart D. Campbell for a specimen of the lava taken from the foot of the cliffs at Covadonga Cove.

The island of San Felix, unlike San Ambrosio, is a low platform, forming a crescent and ending in two rounded hills. At the northwest extremity the so-called Cerro Amarillo is 600 feet (183 meters) high and of a deep yellow color, due to the decomposition of the basic tuff of which it is composed. At the other, the southeastern extremity, is a similar hill of the same material, 435 feet (132 meters) high, which is known as Islota Gonzales. It is separated from the main island by a breach, where the breakers roll over the scarcely submerged rocks. The intervening platform, which stretches between Cerro Amarillo and Islota Gonzales, has an altitude of 200 to 250 feet (60 to 70 meters) in the cliffs along the southern, inner, side of the crescent and of 50 to 65 feet (15 to 20 meters) along the northern coast. The total length of the curving island and islet between the extremities is about 3 miles (5 km.), and that of the island of San Felix is but 2 miles (3 km.). The width of San Felix varies from 1,600 to 3,300 feet (500 to 1,000 meters).

In approaching San Felix from San Ambrosio—that is, from the southeast—one is struck by the difference in form between the rounded hills at the extremities and the flat table between them. The difference in color is also notable, the hills being bright yellow, whereas the table is jet black. On closer examination it is apparent that the yellow tuff is the older and the black lava is the younger of the two.

It seems worth while here to introduce the story of a change of opinion that was forced on me by the actual relations of the rocks as contrasted with those which seemed to be apparent, in the view from a distance. I approached San Felix with certain preconceptions connected with the earthquake of November 10, 1922, and suggested by the accounts of the island given me by Captain Campbell, who had visited it in October 1922, and again in February 1923. In the latter visit the aftershocks of the great earthquake were frequent and severe during the four days the Captain spent in the vicinity of the island and on it. He was overcome by volcanic gases on ascending to the platform with the intention of climbing Cerro Amarillo, and he had become convinced that the volcano was an active center in which the earthquake had originated. His account was very circumstantial and so fitted in with general facts of volcanic phenomena that I expected to find evidences of recent eruption.

[1] Report of an exploration of the islands of San Felix and San Ambrosio by the frigate *Covadonga,* Don Ramon Vidal Gormaz, captain, 1875.

In approaching the island, we sailed around the southern side with a leeway of about a mile from the two extremities of the crescent, and we could clearly see the surf dashing high on the cliffs of the black platform. Captain Campbell had told me that he and his sailors had seen a dull red glow on the summit of Cerro Amarillo, when anchored some eight or ten miles distant. I therefore examined the peak for evidences of eruption. The top was cup-shaped and within it lay a mass of black lava from which small streams had run down the cliffs to the sea. No one who examined it from that distance could reasonably doubt that it was a very recent, though small, local eruption. It might even still be hot.

On the following day, with several officers of the naval vessel which the Chilean Government had courteously put at my service for the trip, I climbed Cerro Amarillo, keeping well to windward of possible gas emanations. My chagrin may be imagined when I found small bushes growing on the supposed hot lava, and was forced by a study of its relations to recognize it as a splash from the old crater which had been thrown up on the yellow tuff and had run back into the crater at the time of the eruption of the black table lava.

It had been reported in perfect good faith that San Felix was shaken by the earthquake, and that its eastern end was broken off and had sunk beneath the sea, and that it was the center of violent convulsions. It shows cracks attributable to the earthquake, but the rest of the statement is as much the work of imagination as was the recent eruption of which I thought that I saw evidences. The island is volcanic and it is probably not many centuries since the eruption of the black lava. Volcanic gases were still issuing from a crevice in the southern rim in May 1923, and they were reported by Captain Campbell and by the sailors who accompanied him in February as having been sufficient in volume to overcome him.

The bird life of the island, which many visitors have described as exceedingly abundant, had either been destroyed or driven away. I counted twenty-five live birds and fifty dead ones on the entire island, where formerly there must have been many thousands. It is probable that most of those that were killed were eaten by other birds and by insects, and that their light bones and feathers were blown from the unprotected rocks into the sea. The large colony of lobsters which lived on the reefs around the island and which formed an attraction that drew fishermen like Captain Campbell to it had been destroyed, leaving but few survivors. A Spanish diver, Mauricio Pardesano, who was with Captain Campbell on his two fishing expeditions and who also accompanied me, stated that the sea-floor was covered with the carapaces of dead lobsters. Captain Campbell and Pardesano independently stated that during their visit in February the ocean water was tepid, distinctly warm. They said that it was warmer immediately succeeding each one of the repeated earthquake shocks, and Pardesano found it much warmer on the bottom than at the surface.

These facts all point to considerable emanations of gas at the time of the great earthquake and during the succeeding months. In May, as already stated, some gas was still issuing from a crevice along the southern cliffs of the island, as was shown

A. San Ambrosio. Near view of southwest cliff, showing bedded lavas and vertical dikes.

B. San Ambrosio. From the west in silhouette against the morning sun.

A. Isla San Felix. Looking east over anchorage to basalt pinnacles known as the Catedral de Peterborough.

B. San Ambrosio. From the southeast.

A. Isla San Felix. Cerro Amarillo, the hill of yellow tuff, as seen from black lava flow looking north; height of Cerro 660 feet (200 meters).

B. Isla San Felix. Western base of Cerro Amarillo, sloping into crater showing structure of tuff.

A. Isla San Felix. Cave at junction of younger black lava flow with older tuff of Cerro Amarillo.

B. Isla San Felix. Looking south from Cerro Amarillo over recent black lava flow; Isla San Ambrosio in distance; Isla Gonzales on right.

A. Isla San Felix. View of island, looking south from ship at anchor. On right is Cerro Amarillo, 660 feet h
a large cave. Only feasible landing

B. Isla San Felix. Looking southeast from Cerro Amarillo over lava plateau of recent basalt flows.
Isla San

g; toward left stretches plateau of recent basalt flows; at contact of basalt with tuff hill the waves have eroded
s on wave-cut shelf at right of cave.

crescent, which terminates in island at right, surrounds about two-fifths of crater. In distance is seen the
\nbrosio.

by the sulphurous smell and puffs of blue vapor observed by me and by the Chilean officers. In this sense and to this extent we may consider San Felix an active volcano.

The date of the latest eruption, that of the black lava, is a matter of considerable interest, but we are forced to set it prior to the discovery of the island, in 1574, because there seems to have been no change in the general configuration of the group since Juan Fernandez first discovered it. Were this fact not unquestionable, one would not suppose the black lava to be 350 years old or more. Its surface still shows the distinct forms of pahoehoe, the glistening surfaces and the ropy eddies of recently cooled slag. One is not surprised that there is no soil, for the winds blow everything but coarse sand from the rocks, but as one walks over the irregular surface of the old flow it is very difficult to believe that it is actually as old as it must be. When, however, I ascended to the cliffs of the southern side and looked from them over the site of the old crater from which the lava must have flowed, it was less difficult to realize its antiquity. At least three-fifths of the crater wall is gone and the ocean rolls over its foundations. The southern crater wall must have existed and have stood at a height greater than that of the remaining remnant or the lava would not have poured out where it did. Whether the missing part was blown up, or melted down, or faulted off, one may guess according to one's inclinations; there is no evidence one way or the other.

Not only is the crater wall of greater San Felix lost beneath the ocean, but an even larger part of the old crater of San Ambrosio is gone and the Cathedral of Peterborough is a central remnant, a volcanic neck of a third lost crater.[1]

The Cathedral of Peterborough is a very striking rock, a group of columns rising about 175 feet (50 meters) above the sea, pierced through by the waves and surrounded by reefs that seem to represent other columns that have fallen. It is practically inaccessible, but its dense, black, jointed, columnar masses leave little doubt that it is a basaltic, volcanic neck.

I spent two half-days on San Felix and recognized three distinct types of rock of as many different periods of eruption. The youngest is the black lava which forms the platform of the island. It very distinctly overlies and is splashed up on the yellow tuff, both at Cerro Amarillo and at Islota Gonzales. The contact is easily observed at the landing place, where a cavern has been worked out of the rock. In the adjacent cliffs one may count fifteen or more distinct layers (flows), all of the same dense, black, vesicular lava, which is so uniform in appearance from end to end of the island that I was convinced that it was all of one and the same eruption. I was, therefore, satisfied to collect specimens from one locality only, namely, from the upper 10 or 15 feet (3 or 4½ meters) of the black cliff immediately above the landing, and I would suppose that any differences in the chemical composition, such as have been found in the specimens, may be explained as differences in the somewhat considerable volume of the magma.

[1] It seems to be possible, judging from the soundings given on the chart and from its columnar structure, that Peterborough is a parasitic cone of San Felix or more probably the end of a massive flow from this crater.—H. S. W.

The next older lava is the yellow tuff which forms the Cerro Amarillo and the peak of Islota Gonzales. In Cerro Amarillo the structure is that of concentric layers, which strongly suggest those that are seen on a smaller scale in the cone that forms around a small orifice in larger craters. The layers are steeply inclined and concentric to the cone, on the north side all around from east to west; on the southern side they are less complete. I do not feel sure, however, that these are original structures. The rock is greatly decomposed and the bedded structure might be due to chemical reaction and increase of volume. The latter suggestion is strengthened by the fact that they are very thin, but a few inches to a foot in thickness, and there seems to have been no crater from which the tuffs could have been extruded to form an individual cone. If, as seems most probable, the yellow tuff of Islota Gonzales is identical with that of Cerro Amarillo, they were both erupted from the intervening crater, and the conical structure of Cerro Amarillo would be secondary rather than original.

The third type of rock on San Felix is a light gray trachyte, which exhibits a very thinly laminated structure and strikingly suggests a schist. It occurs in fragments up to a foot in diameter in the yellow tuff of Cerro Amarillo and was obviously torn off from some deeper mass and brought up with the tuff. The schistose structure is so striking that I did not suspect the volcanic nature of the rock and framed some entertaining hypotheses of a continental platform or submarine fault.

The trip to San Felix was undertaken in connection with the great earthquake that shook northern Chile on the tenth of November, 1922. The immediate incentive was found in the reports of Captain Campbell, who on his return from the islands in February wrote me regarding his experiences. The basic facts were as he saw them, so far as I was able to judge, even though his fancy suggested inferences that proved to be exaggerated. It seems evident that the earthquake shook not only Chile, but also the other side of the great deep, 500 miles (800 km.) off the coast. It also broke cables at a depth of 1,200 fathoms (600 meters) in the intervening depression, and it shook down buildings in mining towns 100 miles (160 km.) east of the coast; that is to say, the width of the zone of recognized activity is 600 miles (1,000 km.). From south to north the earthquake was distinctly felt through twenty degrees of latitude, from Concepción to Iquique, approximately 1,400 miles (2,250 km.). In other words, it was so extensive that it could not be attributed to any local center of activity, such as a volcano, but may rather be classed as a regional phenomenon expressed in the elastic vibration of an enormous mass of rock underlying the great deep off the Chilean coast.

PETROLOGY OF SAN FELIX[1]

General Statement

The specimens entrusted to me by Professor Willis for study represent the three kinds of rock that were observed by him to occur on San Felix. It would appear, from the few chemical analyses that I have made, that the trachytes are rather uniform in general composition, whereas the later flows of basalt that make up the midway plateau differ somewhat more widely in their characters; so that further collections from different points on the island, especially from the latest splash of lava that has been described by Willis, and from the upper and the lower flows, would be very desirable. The analysis of a specimen of lava from San Ambrosio that was given to Professor Willis by Captain Campbell is described separately at the close of this paper.

Trachyte

There are two varieties of the trachyte that occur as blocks in the yellow tuff of Cerro Amarillo; one is very schistose and typically holocrystalline, the other is massive and decidedly vitreous. The two types appear to differ slightly in chemical composition, but less so in their mineral characters.

The variety of trachyte that seems, from the description by Willis and from the specimens collected by him,[2] to be the more abundant is medium gray, densely compact, aphanitic and aphyric; none of the specimens is vesicular. The rock is markedly, but variably, schistose. Some of the specimens split readily into thin, fairly smooth plates, whereas in others this character is less pronounced, but is still evident. The schistosity of most of the specimens is so prominent that both of the authors were led, on a first inspection, to think that the rock was a metamorphic schist.

In thin section the rock shows a somewhat peculiar trachytic texture, which resembles that of the trachyte of Mas-a-fuera described by Quensel,[3] that of Puu Anahulu on the Island of Hawaii,[4] and of the trachyte of Lahaina on Maui.[5] The texture seems to be rather usual in the trachytes of the Intro-Pacific volcanic islands. Ill-defined laths of alkali feldspar make up most of the rock. For the most part these are arranged irregularly, but here and there flow texture is evident. A considerable number of the feldspar laths are somewhat shorter and thicker; these are uniformly dull and cloudy, as if from kaolinization, although the very small amount of water shown in the analysis is opposed to this explanation. But they are of different chemical composition from the longer, thinner, clearer and more numerous laths, whose optical characters indicate that they are more sodic. Many very small prismoids of colorless pyroxene, which is presumably acmite, almost without diopside, judging

[1] By H. S. Washington.

[2] There are four specimens of this variety and one of the other.

[3] P. D. Quensel, *Die Geologie der Fernandezinseln,* Bull. Geol. Inst. Upsala, xxx, vol. 11, 1912, p. 283.

[4] Whitman Cross, *An Occurrence of Trachyte on the Island of Hawaii,* Jour. Geol., vol. 12, 1904, p. 510; and *Lavas of Hawaii and their Relations,* U. S. Geol. Surv. Prof. Paper 88, 1915, p. 35. H. S. Washington, *Petrology of the Hawaiian Islands: II, Hualalai and Mauna Loa,* Am. Jour. Sci., vol. 6, 1923, p. 106.

[5] Whitman Cross, *Lavas of Hawaii and their Relations,* U. S. Geol. Surv. Prof. Paper 88, 1915, p. 26.

from the chemical analysis, and minute grains of magnetite are scattered through the rock. A scanty, colorless, isotropic or feebly birefringent base is probably the nephelite that is shown in the norm.

An analysis of a moderately schistose specimen is given in No. 1 of the accompanying table. It is that of a dominantly sodic trachyte, such as is associated with highly sodic, nephelite-bearing rocks in many well-known comagmatic regions. The high alkalies and the high ratio of ferric oxide to ferrous, the latter characteristic of holocrystalline as opposed to hyaline lavas, are the most notable features, and the rather high zirconia is a minor feature of some interest. The norm (table III, No. 1) shows a small amount of diopsidic acmite and of nephelite. The average feldspar is a decidedly sodic orthoclase. It is probable, as has been remarked, that the stout cloudy feldspars are of potassic orthoclase, whereas the more numerous clear, thin, and longer tables are of a more sodic anorthoclase than the average.

The great similarity between this trachyte and those of other Intro-Pacific islands is shown by the analyses of such lavas that are cited in Table I for comparison. They will be discussed later.

HYALO-TRACHYTE

One of the specimens of trachyte from Cerro Amarillo is of a type rather different from that just described. This rock is much darker gray, and it shows many minute glistening faces of feldspar in a dense, very dark gray, aphanitic groundmass, which has the subresinous luster characteristic of many vitreous lavas. There is only a very slight tendency to schistosity in this specimen; the fracture is generally even, but parallel to one plane the fracture surface is slightly wavy, made up of narrow, parallel, low, rounded ridges, like a slightly crumpled schist.

The thin-section shows some small phenocrysts of orthoclase, as sharply defined, well-shaped, thick tables, many of which are twined according to the Carlsbad law. These appear to be of orthoclase that contains little or no soda, which was the first mineral to crystallize. There are present also rather more numerous, less well-bounded, thinner and longer tables of a more sodic feldspar. These feldspars lie, with marked flow texture, in a base of light-brown glass, which itself shows flow texture in streaks of slightly darker material. Very few, minute crystals of olivine are present, which for the most part are seen clearly only under high powers. Grains of magnetite are very rare and no pyroxene is present.

The chemical composition of this trachyte (No. 2, Table I) differs from that of the schistose type chiefly in the lower silica and soda, the higher ferrous oxide, and the slightly higher magnesia and lime, although these differences change the position of the rock in the quantitative classification only in the subrang. Phosphorus pentoxide is rather high, a feature that seems to be characteristic of many of the lavas of the Intro-Pacific volcanoes. The norm (Table III) shows the presence of a little nephelite but no pyroxene. There appear to occur in the Pacific fewer analogues of this type of trachyte than of the other.

Table I—*Analyses of trachytes*

	1	2	3	4	5	6
SiO_2	62.54	58.22	63.43	62.02	61.90	58.84
Al_2O_3	18.33	18.31	18.64	18.71	18.37	20.30
Fe_2O_3	2.11	2.63	2.78	4.30	2.46	2.74
FeO	0.82	1.91	1.02	0.10	0.66	0.64
MgO	0.33	0.97	1.38	0.40	0.46	0.60
CaO	0.92	1.52	1.68	0.86	0.58	1.66
Na_2O	8.02	6.14	6.77	6.90	7.95	7.48
K_2O	5.70	5.78	3.82	4.93	5.36	5.72
H_2O+	0.15	1.47	0.24	0.80	1.52	0.68
H_2O-	0.05	0.86		0.31	0.61	0.31
CO_2	none	none	n. d.	none	n. d.	n. d.
TiO_2	1.24	0.92	0.28	0.31	0.20	0.72
ZrO_2	0.12	n d.	n. d.	0.06	n. d.	n. d.
P_2O_5	0.13	0.90	0.18	0.24	0.01	0.13
Cl	n. d.	n. d.	0.04	none	n. d.	n. d.
S	0.03	n. d.	0.01	0.02	n. d.	n. d.
Cr_2O_3	none	n. d.	n. d.	none	trace	0.02
MnO	0.15	0.16	0.09	0.15	0.26	0.12
BaO	none	n. d.	n. d.	0.02	n. d.	0.07
	100.64	99.79	100.36	100.13	100.34	100.03

1. Schistose trachyte, blocks in tuff, Cerro Amarillo, San Felix. H. S. Washington, analyst.
2. Hyalo-trachyte, blocks in tuff, Cerro Amarillo, San Felix. H. S. Washington, analyst.
3. Trachyte, Mas-a-fuera, Juan Fernandez Islands. Sahlbom, analyst. P. Quensel, Bulletin of the Geological Institute of Upsala, volume 11, 1912, page 283.
4. Trachyte, Puu Anahulu, Hualalai, Hawaii. Washington, analyst. H. S. Washington, American Journal of Science, volume 6, 1923, page 108.
5. Nephelite trachyte, Mauratapu, Huahine, Society Islands. Morley, analyst. Iddings and Morley, Proceedings of the National Academy of Sciences, volume 4, 1918, page 114.
6. Phonolite, Vaitia, Taiarapu, Society Islands. Morley, analyst. Iddings and Morley, op. cit., page 114.

Nephelite Basanite

The "basalts" of the low middle portion of San Felix appear megascopically to be quite uniform, but the specimens collected by Willis show, chemically, considerable variation. They are all dense, black, mostly aphanitic and almost aphyric lavas. Most of the specimens are of typical pahoehoe, fresh and with the characteristic corded surfaces and finely uniform vesiculation of this form of lava. These have rather sparse, very small phenocrysts of dark-green olivine scattered through a dense, aphanitic, slightly brownish-black groundmass, which has a subresinous luster. One specimen comes from what appears to be a flow of aa lava; at least the vesiculation is of the kind with few irregularly shaped and rather large vesicles. This is very dark gray, not the jet black of the pahoehoe specimens, and contains some small phenocrysts of yellow olivine in a dense aphanitic groundmass that has a dull stony luster without any resinous quality.

The thin-sections of all these basalts are very unsatisfactory for study, because, even if very thin, they are so black, dense and opaque that very little of their texture or mode is visible. Both types show some small (up to 1 mm.), well-formed phenocrysts of fresh olivine, which is entirely free from inclusions. There are no phenocrysts of feldspar, pyroxene or other minerals. The groundmass in the pahoehoe specimens is black and almost perfectly opaque, the thin edges alone showing slight indications of the presence of extremely minute feldspar needles and small prismoids of pyroxene embedded in a brown dusty glass. These are seen rather better in the specimen of aa, which is slightly more crystalline than the pahoehoe, but the feldspar needles are too minute for satisfactory identification of the kind of plagioclase. No trace of flow texture is visible in any of the thin-sections.

TABLE II—*Analyses of nephelite basanite and basalt*

	1	2	3	4	5	6	7
SiO_2	46.22	43.20	43.47	43.37	46.43	44.74	43.76
Al_2O_3	12.29	8.51	17.30	8.48	10.91	16.74	11.58
Fe_2O_3	2.14	3.49	6.87	2.91	3.15	3.70	4.39
FeO	7.91	7.84	7.09	11.00	10.26	8.53	7.57
MgO	7.55	12.04	8.60	25.93	11.08	4.80	12.97
CaO	8.94	10.21	6.09	5.03	10.09	9.88	9.64
Na_2O	4.04	5.07	2.53	1.33	3.16	4.42	3.03
K_2O	3.33	0.69	0.74	0.58	0.54	1.14	1.84
H_2O +	0.08	0.78 }	3.46	{ 0.19	0.66	1.12	0.47
H_2O −	0.04	0.71 }		{	0.15	0.33	......
TiO_2	5.86	6.78	2.68	1.03	2.59	3.68	3.41
ZrO_2	0.02	n. d.	n. d.	n. d.	none	n. d.	n. d.
P_2O_5	1.12	0.58	0.27	0.19	0.67	0.70	0.45
Cl	n. d.	n. d.	0.18	0.08	n. d.	n. d.	n. d.
S	0.02	n. d.	0.12	trace	0.07	n. d.	n. d.
Cr_2O_3	0.05	n. d.	n. d.	n. d.	none	trace	n. d.
MnO	0.17	0.15	0.07	9.13	0.09	0.19	n. d.
BaO	none	......	n. d.	n. d.	none	n. d.	n. d.
	99.78	100.05	99.60	100.25	99.85	99.97	99.72

1. Nephelite basanite (pahoehoe), San Felix. Washington, analyst.
2. Nephelite basanite (aa), San Felix. Washington, analyst.
3. Nephelite basanite, Mas-a-fuera, Juan Fernandez Islands. Sahlbom, analyst. Quensel, op. cit., page 280.
4. Picrite basalt, Mas-a-fuera. Sahlbom, analyst. Quensel, op. cit., page 287.
5. Olivine basalt, lava of 1801, Hualalai, Hawaii. Washington, analyst. American Journal of Science, volume 6, page 102.
6. Nephelite basalt, Tapahi, Tahiti, Society Islands. Foote, analyst. Iddings and Morley, Proceedings of the National Academy of Sciences, volume 4, 1918, page 115.
7. (Nephelite) basalt, Matavanu Volcano, Savaii, Samoan Islands. Heussler, analyst. Klautsch, Jahrb. Preuss. Geol. L.-Anst., volume 27, 1910, page 174.

TABLE III—*Norms of San Felix rocks*

	1	2	3	4
Or	33.92	34.47	19.46	3.89
Ab	49.51	48.99	14.67	12.05
An	.....	1.95	5.84	.....
Ne	6.96	1.56	10.51	15.05
C	.....	1.22	.....	.....
Ac	4.63	.....	.....	2.77
Di	1.72	.....	24.61	36.66
Ol	.....	1.68	7.52	10.10
Mt	.....	3.71	3.02	3.71
Il	2.28	1.82	11.25	12.92
Hm	0.48	.....	.....	.....
Ap	0.34	2.02	2.69	1.34

1. Schistose trachyte, No. 1, Table I, I(II).5".1."4.
2. Hyalo-trachyte, No. 2, Table I, I(II).5.1.3(4).
3. Nephelite basanite, No. 1, Table II, III.6."2.(3)4.
4. Nephelite basanite, No. 2, Table II, IV.2.2.2".2.

Two analyses were made of these " basalts," one of a very fresh, corded pahoehoe (Table II, No. 1), the other of the specimen of aa (Table II, No. 2). Although they resemble each other in their most general features, there is considerable difference between them. The low silica and alumina and the high soda show that they are not analyses of ordinary basalts, and the norms (Table III) indicate that much nephelite would have been present had they been fully crystallized. The norms indicate also that the feldspar is, in general, oligoclase or even more alkalic, and the norm of No. 2 shows a small amount of acmite, indicating an excess of soda. The presence of such highly sodic feldspar in rocks that are so femic is somewhat unusual. The percentage of titanium dioxide is very high in both rocks, as is also that of phosphorus. The former feature appears to be general among the more femic lavas of the Pacific, while high phosphorus is common in the more feldspathic ones.

Tuff

The tuff that makes up Cerro Amarillo, and presumably Islota Gonzales also, is dense, compact and very coherent, breaking with an uneven fracture. It can be readily scratched, but not cut, with a knife-blade. Its color is a rather deep yellow-orange, about the " cinnamon " of Ridgway (15″); the luster is dull and earthy. Throughout the mass are scattered many small (from 1 mm. to 1 cm.), usually rounded fragments of a jet-black substance, with a vitreous luster, which study of the thin-section shows to be a basaltic glass. None of the specimens brought back by Willis shows the platy parting noted by him in the mass.

The thin-sections show that the tuff is composed for the most part of a bright orange-yellow, opaque or subtranslucent, indefinite substance, partly in somewhat rounded or irregular areas, with narrow veinlets of calcite between them here and there. Small crystal fragments of olivine are not very numerous; there are rare small black grains of magnetite, but no definite crystals of either feldspar or pyroxene are present. The black basaltic inclusions consist very largely of a light yellowish-brown glass, in which are scattered many sharply formed crystals and fragments of colorless olivine, which contains few very minute grains of magnetite. In the thinner parts of the glass base can be seen, somewhat vaguely, very small thin prisms of a colorless, transparent mineral, with oblique extinction, which is considered to be pyroxene. No crystals of feldspar could be definitely made out. The glass is finely vesicular, with many small rounded vesicles, some of which are filled with secondary calcite. The basalt resembles the very glassy nephelite basanites already described, except that the glass base of the fragments in the tuff is much lighter brown and far more transparent, without the abundant black dust of the flow material and with minute microphenocrysts of pyroxene rather than of feldspar in the glass base. An analysis of these fragments would be of interest. The contacts between the basaltic fragments and the yellow tuff base are sharp. The yellow tuff is probably a lithic, devitrified and somewhat decomposed tuff [1] of the glassy basalt of the fragments, which approaches the nephelite basanites in composition.

An analysis was made of a typical specimen of the yellow tuff, the results of which are given in Table IV, No. 1, with some of the very few usable analyses of basaltic tuffs that are to be found in the literature. The analysis is notable chiefly for the high alkalies, in which respect (as well as in the low alumina) it is in marked contrast with the other analyses, which are of basaltic tuffs. The high titanium dioxide and phosphorus pentoxide may also be mentioned. These three features, as we have seen, are characteristic of the analyses of the black, highly vitreous, nephelite basanites that make up the flows of San Felix. This correspondence in certain chemical features gives additional weight to the supposition, already suggested by the presence of the fragments of brown hyalo-basalt, that the yellow tuffs of San Felix are derived from nephelite basanite; they are certainly not derived from ordinary basalts, as the analyses in Table IV render evident.

TABLE IV—*Analyses of tuffs*

	1	2	3	4	5	6	7
SiO_2	36.35	39.00	47.43	34.39	37.82	43.48	45.18
Al_2O_3	8.14	15.58	17.20	13.05	13.16	9.74	10.55
Fe_2O_3	5.57	6.13	4.20	5.20	14.11	6.66	2.85
FeO	3.50	3.11	5.27	0.98	0.14	4.19	7.90
MgO	9.05	6.55	4.85	8.62	11.75	10.83	9.90
CaO	7.44	6.82	7.56	18.52	13.39	8.90	9.68
Na_2O	4.70	3.22	3.53	2.56	1.66	5.62	4.61
K_2O	3.25	0.59	1.51	0.24	1.49	3.89	2.03
H_2O+	4.01	6.03	2.42	3.72	......	......	......
H_2O-	8.35	8.18	3.12	2.22	......	......	......
CO_2	4.00	1.83	none	10.89	5.56	......	......
TiO_2	4.76	2.59	3.00	0.63	n. d.	5.70	6.38
P_2O_5	0.83	n. d.	n. d.	n. d.	0.82	0.99	0.86
MnO	n. d.	n. d.	n. d.	n. d.	0.24	......	......
	99.95	99.63	100.09	101.09	100.41	100.00	100.00

1. Yellow basanite tuff, Cerro Amarillo, San Felix Island. Washington, analyst.
2. Yellow basalt tuff, Monte Pozzolana, Linosa Island. Washington, analyst. Journal of Geology, volume 16, 1908, page 29.
3. Gray basalt tuff, Monte Levante, Linosa Island. Washington, analyst. Loc. cit.
4. Basalt tuff, Copper Island, Commander Islands, Bering Sea. Staronka, analyst. Morozewicz, Com. C. Russ., Mem. 72, 1913, page 73.
5. Basalt tuff, Punch Bowl, Oahu, Hawaiian Islands. Lyons, analyst. American Journal of Science, volume 2, 1896, page 427. Ignited before analysis; includes 0.15 SO_3, 0.05 FeS_2, 0.07 CuO.
6. Yellow tuff, San Felix, calculated free from H_2O and CO_2.
7. Mean of nephelite basanites of San Felix, calculated free from H_2O and CO_2; minor constituents neglected.

If it be assumed that the water and carbon dioxide of the tuff are in large part addition products, and that there has been relatively little loss of the original material, and the analysis is recalculated to 100 per cent on a water-free and carbon-dioxide-free basis, the figures shown in No. 6 of Table II are obtained. Comparison of these with the figures of the two analyses of San Felix nephelite basanite given in Table II

[1] L. V. Pirsson, *The microscopical characters of volcanic tuffs—a study for students*, Am. Jour. Sci., vol. 40, 1915, pp. 201-208.

shows the remarkable correspondence. In the tuff, ferric oxide is higher relatively to ferrous because of oxidation, but the mean of the chief constituents of the two nephelite basanites is remarkably like the recalculated analysis of the tuff, as will be seen on comparing Nos. 6 and 7 of Table IV.

General Conclusions

It would appear from the specimens brought back by Willis that the lavas of the San Felix volcano are, so far as known, of only two kinds—a decidedly sodic trachyte and somewhat variable nephelite basanite, which seems to be uniformly highly vitreous. There is little doubt that the yellow tuff is derived from nephelite basanite magma closely similar to that of the flows. The prominent characteristic of these two types of lava is their high content in alkalies, especially in soda, while high titanium and phosphorus appear to be other constant characters of minor, but still considerable, interest. This conclusion as to the generally highly sodic character of the San Felix lavas is subject to the limitations imposed by the absence of specimens from the lower flows and from various parts of the island. Such basaltic lavas, especially if highly vitreous, may appear megascopically to be very uniform and yet be modally and chemically very diverse. It is, therefore, possible that the earlier, lowermost flows are less sodic and more typically basaltic than the upper, which were the ones examined.

In this predominantly highly sodic character of its lavas San Felix appears to differ widely from other Pacific islands. At Mas-a-fuera, it is true, both soda trachyte and nephelite basanite, closely like those of San Felix, occur, but these are accompanied by basalt and picrite basalt, whereas at the neighboring Juan Fernandez the lavas appear to be, to judge from Quensel's descriptions, only olivine basalt, with neither trachyte nor basanite. Trachyte, also highly sodic, occurs at several other Pacific volcanic islands, as do also nephelite basanite and similar rocks high in soda; but at all of them the predominant lavas are more or less normal basalts or andesites; so that the general magmatic character is basaltic—that is to say, sodi-calcic, somewhat modified by distinctly sodic facies. But this is not the place for a general discussion of the Intro-Pacific lavas, and reference may be made to papers by Lacroix,[1] Marshall,[2] and Iddings.[3]

One further point may be briefly spoken of. From the field observations made by Willis, especially the inclusion of the trachyte blocks in the yellow tuff and the relations of the tuff and the basanite flows, it would appear that the trachytic lavas at San Felix were earlier, in the sense that lavas of trachyte had been poured out and consolidated before those of basanite, which they must underlie.

At Mas-a-fuera Quensel noted that the trachyte occupies the higher parts of the island, while the basalt and basanite flows lie below them on the lower parts. He argues from this that " there had taken place in the volcanic throat a differentiation

[1] Lacroix, *Les roches alcalines de Tahiti,* Bull. Soc. Géol. France, vol. 10, 1910, p. 120.
[2] Marshall, *The Geology of Tahiti,* Trans. New Zealand Inst., vol. 47, 1915, p. 361.
[3] Iddings, *The Petrology of the South Pacific Islands and its Significance,* Proc. Nat. Acad. Sci., vol. 2, 1916, p. 413.

according to specific gravity." It is somewhat difficult to follow the reasoning of Quensel, because, if the (supposedly) liquid trachytic magma formed a layer above that of the heavier basaltic magma in the volcanic throat, one might reasonably expect the trachytic flows to have been the first to have been extruded, and so to have formed the lower parts of the volcano, whereas the lower-lying basaltic magmas would have followed these and hence have formed the upper parts of the volcano. Without fairly detailed field observations as to whether the various types of lava issued from lateral vents at different elevations or overflowed the crater edges, it is impossible to discuss such occurrences with intelligence, and in the absence of such observations any generalizations based on such supposed " sequences " appear to us to be premature. In any case, the sequence at San Felix appears to be contrary to what Quensel imagines it to have been at Mas-a-fuera.

It should be said, furthermore, that in these and all such cases we have under our observation only the extreme uppermost tip, an almost infinitesimal part, of a colossal volcano, comparable with the giants of the Andean line, and of which we know, and can know, little or nothing of its lower lavas. It behooves us, therefore, to be cautious in our generalizations, or, still better, to abstain from them until more data are available.

BASALT OF SAN AMBROSIO

After the preceding pages had been put into type for the article in the Bulletin of the Geologic Society, the specimen of basalt collected by Captain Campbell on San Ambrosio came to hand, and thin-sections and a chemical analysis of it were made. It turned out to be an olivine-free basalt, containing a little orthoclase and nephelite, similar chemically to the specimen of pahoehoe from San Felix, the analysis of which is given in No. 1 of Table II.

The rock is very dark gray, almost black, very dense and fine grained, and entirely without vesicles. It is probably from the interior of a thick aa flow. No phenocrysts of any kind are present. Thin-sections show that it is made up largely of a peculiar augite in very small equant anhedra or thin prisms. The color of the augite is somewhat variable, mostly gray with a slightly purplish tone, partly yellowish or light brownish through incipient alteration. Small, thin plates and laths of multiply twinned plagioclase, mostly about Ab_2An_1 to Ab_1An_1, are rather abundant, and there are less well-shaped and generally thicker plates of what appears to be sodic orthoclase; these are mostly untwinned. Small grains of magnetite are present, but are not numerous. No olivine grains are to be seen. There is a small amount of clear colorless basis interstitial in patches; some of this is feebly birefringent and some isotropic. It is probably the nephelite indicated by the norm as present or, in part, glass. The microtexture is typically basaltic, and there is no indication of flow.

A chemical analysis gave the results shown below. This and the corresponding norm greatly resemble the analysis and norm of the pahoehoe of San Felix, which has been called nephelite basanite because of its content in olivine and the notable amount of nephelite in the norm. Limburgitic basalt would probably be a more appropriate name for this than the one used above. Because of the small amount of nephelite present and the absence of olivine the San Ambrosio lava may best be called tephritic basalt.

SiO_2	45.41
Al_2O_3	14.58
Fe_2O_3	3.22
FeO	8.74
MgO	4.98
CaO	9.83
Na_2O	3.53
K_2O	2.39
$H_2O +$	0.82
$H_2O -$	0.27
TiO_2	5.30
P_2O_5	1.00
MnO	n. d.
	100.07

Norm	
Orthoclase	14.46
Albite	19.39
Anorthite	16.96
Nephelite	5.40
Diopside	20.51
Olivine	5.24
Magnetite	4.64
Ilmenite	10.03
Apatite	2.35

Tephritic basalt, (III).5″.″3.4. San Ambrosio Island, South Pacific. Washington, analyst.

In the analysis of the San Ambrosio basalt may be noted the rather high alkalies, especially potash, and the high titanium and phosphorus oxides. Both of these last two peculiarities appear to be characteristic of the more femic lavas (basalt, basanite, etc.) of the Intro-Pacific volcanoes. In the San Ambrosio rock the abundant titanium is mostly in the augite, as is shown by its peculiar color and the small amount of "ore." The resemblance of this analysis to that of the San Felix pahoehoe indicates the intimate relation of the two volcanic islands.

APPENDIX I

REPORT ON SEISMOGRAMS OF THE EARTHQUAKE OF NOVEMBER 10, 1922

By J. B. Macelwane, S. J., and Perry Byerly

THE EPICENTER OF THE EARTHQUAKE AS DETERMINED BY SEISMOGRAPHIC DATA

It may seem superfluous to discuss the seismographic records of the Chilean earthquake of November 10, 1922, in view of the two studies already published by Sieberg and Gutenberg and by the latter alone.[1] However, the authors feel that the more extensive material available to them and their entirely independent analysis of the records and calculation of the epicenter are a sufficient contribution to require publication in this volume if the study of the earthquake is to be complete.

This instrumental part of the report was undertaken at the request of Professor Willis after he had completed his study of the phenomena in the field but before any of his conclusions were available. Most of the labor of preparing it has devolved upon the junior author. The senior author has been able to do little more than suggest and criticise throughout the progress of the work.

For the purpose of the location of the epicenter of the earthquake of November 10, 1922, Professor Bailey Willis has collected from a great number of seismographic stations throughout the world original seismograms of this earthquake, or copies of them. In addition to these there were available reports from certain other stations. These stations are listed in tables on page 139, and in the last column of each table the nature of the data is given: O representing original seismogram; C, copy; and R, report only. A considerable number of additional records were loaned but these were not suitable for the exact determination of times.

When the study was first undertaken it was suggested by Professor Willis that, since the field observations pointed to more than one center of violent intensity, the analysis of the seismograms might also point to this same multiplicity of epicenters. Gutenberg[2] has concluded from the study of the records that perhaps three shocks were registered, of which the second originated at a point west of the first. But impulses which arrive after the beginning of the earthquake and which may be due to later shocks at the source are difficult to identify exactly as to time of arrival since they are confused by the motion due to the earlier shock.

However, the possibility was considered that two shocks from separate foci might have occurred at times so close together that waves from one source would be the first to arrive at stations in one direction while waves from the other source would arrive first at stations in another direction.

[1] A. Sieberg und B. Gutenberg, *Das Erdbeben in der chilenischen Provinz Atacama am 10 November 1922*, Ver. der Reichsanstalt für Erdbebenforschung in Jena, Heft 3, 1924; also B. Gutenberg, *Bearbeitung der instrumentellen Aufzeichnungen des Atacamabebens am 10 November, 1922*, Nachtrag zu Heft 3.

[2] Gutenberg, *loc. cit.*

In this study there was a lack of seismograms from stations close to the center of disturbance and the location of the epicenter was thus dependent on observations at distant stations. In such a case, the imperfections of the travel time curves for these distances together with the possibility that at some stations one of the early first preliminary waves of Mohorovičić [1] may have been registered, or perhaps the beginning of P_n may have failed to register, cause a considerable discrepancy to enter into the computed epicentral distances of the stations. Thus for this earthquake the epicentral distances as computed from the S-P intervals at the various stations fail to reach to a common intersection. The tables given by Gutenburg in Sieberg's "Erdbebenkunde" were used in the investigation.

In the first trials an effort was made to reduce these discrepancies by assuming two epicenters, one near Iquique with a time of occurrence of $0 = 4 - 32 - 42$, and the other near Coquimbo and a time of occurrence about 20 seconds earlier. But this did not offer a satisfactory solution. Nor were other efforts to explain discrepancies of computed distances by multiple epicenters successful.

Finally a group of 26 stations at epicentral distances of less than 100° were chosen since for such distances our travel time tables are less in error. Where possible these stations were selected for the sharpness of the first arrival and the excellence of the time service, but in certain regions all the stations available were used.

The times of the arrival of P at these stations were taken and the probability method of Geiger [2] was applied to compute a most probable position of the epicenter. After two adjustments this resulted in placing the epicenter at $\phi_0 = 29°00' \pm 14'$ $\lambda_0 = 69°59' \pm 19'$; and the time of occurrence at $t_0 = 4h\ 32m\ 33s \pm 2s$ U. T. November 11, 1922.

From the co-ordinates of the various stations and those of the epicenter, the epicentral distance of each station was computed. This distance was then used with Gutenberg's tables and the expected arrival times of P and S were computed.

In table 2 are given for the 26 stations used in locating the epicenter the observed arrival times of P and S together with the differences of the observed and computed values. In table 3 the same data are given for other stations.

It must be remembered that the epicenter of an earthquake as indicated by the records of seismographs points to the region of the beginning of disturbance and does not at all define the extent of the source.[3]

[1] A. Mohorovičić, *Rad Jugoslavenske Akademije, 1922.*
[2] L. Geiger, *Herdbestimmung bei Erdbeben aus den Ankunftszeiten,* Göttingen, 1910.
[3] H. F. Reid, *Starting Points of Earthquake Vibrations,* Bull. Seis. Soc. America, vol. 8, pp. 79-82, 1918.

Arrival Times of P and S

Station	Δ°	P	O-C	S	O-C	Data	Station	Δ°	P	O-C	S	O-C	Data
		m s	*s*	*m s*	*s*				*m s*	*s*	*m s*	*s*	
Santiago	4.5	33 35	— 8	34 24		O	Vera Cruz ...	54.4	42 02	— 4	49 39	—01	R & C
Villa Ortuzar .	11.3	35 21	+ 3	36 36	+10	R	Tacubaya	56.0	42 16	—03	49 50?	—13	R & C
La Paz	12.6	35 40	+ 5			R	Cambridge	71.0	43 42	—08	52 46	—26	O
Rio de Janeiro.	24.8	38 00	— 5	42 27	+ 4	O	Joahnnesburg .	84.0	45 00	— 3?	55 33?	— 1	O
Washington ..	68.2	43 33	+ 1	52 30	— 4	C	Spokane	87.7	44 47	—37	55 12	—61	O
Georgetown ...	68.2	43 37	+ 5			R	Coimbra	89.7	45 14	—21	56 25	— 7	O
St. Louis	70.2	43 45	+ 2	52 55	— 3	O	Marseilles	99.9	46 30	+ 3	57 27	?—31	R & O
Ithaca	71.7	43 53	— 1			C	Oxford	100.6	46 25	— 6			C
Ann Arbor	72.4	44 04	+ 8	53 16	— 8	O	West Bromwich	100.7	46 23	—08			C
Chicago	72.6	44 01	+ 3	53 09	—19	C	Paris	101.0	46 34	+01			C
Good Hope ...	73.1	44 20	+19	53 42	+ 8	C	Edinburgh ...	102.0	46 33	—04			O
Northfield	73.2	44 07	+ 6	53 31	— 3	O	Uccle	103.1	46 34	—08			C
Ottawa	74.6	44 11	+ 1	53 43	— 8	C	Zurich	103.8	46 48?	+03			O
Lick	82.1	44 57	+ 5	53 03	—11	O	Rocca di Papa.	103.9	46 45	—01			O
Berkeley	82.8	44 54	— 2	55 21	0	O	Strasbourg	103.9	46 48	+02			C
Lisbon	88.3	45 24	— 4	56 32	+13	O	DeBilt	104.2	46 41	—06			C
San Fernando.	88.7	45 28	— 2	56 36	+13	C	Pompeii	104.6	46 19?	—30			O
Malaga	90.0	45 31	— 6			O	Frankfort	105.1	46 49	—02			O
Victoria	90.9	45 40	— 2	56 21?	—22	O	Nordlinger	105.7	46 53	—02			O
Toledo	92.1	45 49	0	56 41	—13	C	Munich	106.0	46 50	—05			O
Apia	93.3	45 57	+ 2	57 02	— 3	O	Hamburg	107.4	46 54?	+20			C
Algiers	94.9	46 03	0	57 07	—10	O	Vienna	108.9	47 08	0			O
Cartuja	95.5	45 46	—20			C	Batavia	144.7	52 10?	(P′)—12			C
Tortosa	95.5	45 58	— 7	(57 17)	(—3)	C	Bombay	144.7	49?47	— 5			O
Barcelona	96.8	46 09	— 3			C	Tokyo	154.1	52 33?	(P′)—08			C
Honolulu	98.6	46 39	+18	57 23	—24	C	Osaka	157.7	52 52	(P′)4			R & C
Balboa	39.1	40 27	+11			O	Manila	162.4	52 49	(P′)—4			C
Vieques	47.4	41 02?	—16			C	Hong Kong ...	172.3	52 50	(P′)—7			C

APPENDIX II

DISTRIBUTION OF INTENSITIES

By DR. LUIS SIERRA VERA

Note. Dr. Luis Sierra of Copiapó, a devoted student inspired by Comte Montessus de Ballore, undertook the labor of analyzing the responses to the questionnaires, which were sent out to secure information regarding the personal experiences and observations of the inhabitants in the shaken region. The three hundred answers have been summarized in an earlier part of this volume (pages 42 to 45), but no attempt was there made to evaluate the intensities at different points. To this task Dr. Sierra brought special experience and knowledge of his countrymen. His digest of the data and his estimates of intensity, expressed in terms of the Rossi-Forel scale, are given in the following tables. The localities are arranged in order of latitudes, from north to south. B. W.

DISTRIBUTION OF INTENSITIES

Place	Name	Hour	Furniture overturned	Direction	Sounds observed	Ground	House	Damage	Intensity
Salado (latitude 26° 22'; longitude 69° 45'; elevation 5500' (1660 ms.); site, on shallow river gravels)	Carlos Jorquera D.	11^h55^m	Sideboard, cabinets, etc.	Toward west	Like a fast locomotive.	Alluvium	Wood with corrugated iron roof		
Chañaral (latitude 26° 22'; longitude 71° 43'; elevation, sea-level; site, marine beach deposits)	Rafael Basaure C.	Before midnight	Nothing fell	......	Like cart	Slag heap	Wood with galvanized iron.	No damage by terremoto; washed away by earthquake wave.	
	Guillermo Zepeda	11^h50^m	None	......	Like surf on beach.	Solid	Wood with roof of corrugated iron.	By terremoto, no; maremoto destroyed it.	
	Jose, Neniguer P.	......	......	......	......	......	......	By the maremoto.	
	Maria Toro de Zevallos.	......	None	......	Like heavy cart...	Beach sand	Wood with corrugated iron.	Only by maremoto which swept away the building.	
	Oswald Fernie	About 12	Nothing fell	......	....Do.	Sand	Wood frame with zinc.	Not by the terremoto; maremoto destroyed everything.	
Potrerillos (latitude 26° 27'; longitude 69° 30'; elevation 10400' (3100 ms.); site, old fringing gravels)	Luis, S. Rojas A.	About 12^h m	Nothing fell	......	Like a roaring....	Solid	Adobes, wood, and zinc.	Insignificant	Eighth degree.
	Hermojenes, Pizarro ...	11 50	....Do.	......	......	Limey beds	Corrugated iron ..	None	Seventh degree.
	Enrique, Vicuna M. ..	11 55	Pictures, etc.	......	Like that of heavy truck.	Solid	Adobes and wood frame.	Slight	Eighth degree.
	Manuel Ossandón	11 50	Nothing	......	Roar underground.	Alluvium	Adobes	Only cracks	Do.
	Jose F. Figueroa	11 55	Nothing fell	......	Like thunder	Solid	Canvas	None	Seventh degree.
	Valentin Pena	11 50	Nothing	......	Roar underground.	Wash	Adobe	Slight	Eighth degree.
	Jorje Vallejos Gallo.....	11 50	....Do.	......	Like thunder	Solid	Adobe and wood..	Slight	Do.
Caldera (latitude 27° 03'; longitude 70° 53'; elevation, sea-level; site, rocky coast; thin shore deposits)	Francisco Liñandarija ..	11^h50^m	Nothing fell	......	Like explosions ...	Solid	Wood	None	Seventh degree.
	Enrique Escobar R.	11 45	....Do.	......	......	....Do.	With cane and roof of zinc.	None	Do.
	Jorje Lado Bercera.....	11 50	None	......	Great noise	......	Cane with mud and zinc.	None	Do.
	Bernardo Tornini	11 50	Nothing fell	......	Like thunder	Rocky	....Do.	None	Do.
	Guillermo W. Lara.....	11 55	None	......	Like that made by steamboat working.	Silt	Wood, cane, and mud.	None	Do.
	Ana S. de Bacz.........	11 48	Nothing fell	......	Like thunder	Solid rock	Wood with roof of zinc.	None	Do.
	Jose Rubio	11 53	....Do.	......	Like report of artillery.	Clayey	Tapiales and adobes.	Appreciable	Eighth degree.
	Santiago H. Faull......	11 45	....Do.	......	Like thunder	Solid	Adobes, cane, and wood.	Slight	Do.
Puquios (latitude 27° 11'; longitude 69° 55'; elevation 4085' (1238 ms.); site, shallow gravels in canyon)	Arturo A. Cabrera	11^h55^m	Nothing fell	......	Like a roar.......	Alluvium	Wood frame, adobe and wood.	Appreciable	Eighth degree.
	Jacinto Herrera A.	11 55	Tables, wardrobes, etc.	Toward north	......	....Do.	Wood frame	....Do.	Do.
	A. Mahuecin Robledo ..	11 55	Tables, cabinets, etc.	....Do.	......	....Do.	Adobes and wood.	Considerable	Ninth degree.

DISTRIBUTION OF INTENSITIES—*Continued*

Place	Name	Hour	Furniture overturned	Direction	Sounds observed	Ground	House	Damage	Intensity
Copiapó (latitude 27° 22′; longitude 70° 22′; elevation 1220′ (370 ms.); site, swamp muck, sands and gravels)	Carlos A. Gonzales	$11^h 55^m$	Sideboard and small table.	Northeast	Strong noise preceding.	Alluvium	Framework with Guayaquil cane.	Uninhabitable	Tenth degree.
	Francisco E. Yuraszeck G.	Just before midnight	Nothing	......	Nothing	....Do.	Pine wood	Partial destruction.	Ninth degree.
	Ramon Albornoz	11 48	Everything	North to south	Unappreciable	....Do.	Tapiales, adobes, wood, and Guayaquil cane.	Destroyed	Tenth degree.
	Luis A. Romo Ch.	11 55	Various furniture.	Toward west	Strong	Firm	Wood with Guayaquil cane.	Heavy damage	Ninth degree.
	Federico Melendez M.	......	Nothing	......	Like thunder	....Do.	Wood frame	Small	Do.
	Juan de D. Picon	11 50	A bureau	......	......	Alluvium	Tapiales and adobes.	Moderate damage	Do.
	Alfredo R. Ansieta	11 50	Various furniture.	Toward east	Like a heavy cart.	....Do.	Walls and wood frame.	Heavy damage	Do.
	Manuel F. Munizaga	11 50	Cabinets and statuary.	From south to north.	Like a heavy cart.	....Do.	Adobes and adobes with wood.	....Do.	Do.
	Manuel Corona F.	11 50	Some	Toward south and west.	Like thunder	....Do.	Wood with Guayaquil cane.	Moderate	Do.
	Ernesto Berg. Floto	11 50	Wardrobe and iron safe.	Toward south	......	......	Tapiales, adobes, and wood frame.	Heavy damage	Do.
	Ernesto Pareda L.	11 55	One table	......	......	Very alluvial	Tapiales, adobes, and wood frame.	....Do.	Do.
	Manuel Castillo Z.	11 50	Wardrobes and cabinets.	To the southeast.	Noise	......	Frame with brush.	Uninhabitable	Tenth degree.
	Jorje Laferriere	11 50	Some	Toward north	Subterranean	Alluvial	Adobes and tapiales.	....Do.	Do.
	Crisologo Cispedes	11 45	Much	Varying	Like a distant cart.	Sedimentary	Wood frame with Guayquil cane.	Heavy damage	Ninth degree.
	Jorje Barquin V.	11 45	Some	Toward north	Strong	Alluvium	Walls and wood frame.	Roofs destroyed and base of walls.	Do.
	Domingo Riveros T.	Just before 12	Destroyed	......	Like thunder	....Do.	Tapiales and adobes.	Total destruction.	Tenth degree.
	Ramon Rosas A.	......	Nothing	......	......	......	Tapiales	Heavy damage	Ninth degree.
	Luis Gmo. Brand	11 46	......	......	Like heavy cart	Firm	Wood frame	Appreciable	Eighth degree.
	Jose Escauriaza	......	Cabinets and shelves.	Toward southeast.	....Do.	Alluvium	Wood frame	....Do.	Do.
	Ladislao Agullo	11 50	Part of clothes press.	Toward north	Thunder and detonations.	....Do.	....Do.	Heavy damage	Ninth degree.
	Margarita, v. de Pellegrini.	......	All the furniture.	Northwest	Like thunder	....Do.	....Do.	Appreciable	Eighth degree.
	Alberto Vallejos C.	11 50	Wardrobes	West	Like surf	Firm ground	....Do.	Moderate	Do.
	Roberto Meeks V.	......	Many fell, others not.	......	......	Soft	....Do.	Considerable	Ninth degree.
	Felix Piuciro O.	11 50	Everything fell	Toward south and to north.	Like that of auto.	Wash	Wood frame, boards, and some adobe.	....Do.	Do.
	Horacio Arce B.	11 55	A cabinet	Northeast and southwest.	Preceded by loud noise.	Alluvium	Wood frame with zinc roof.	Appreciable	Eighth degree.
	Julio A. Bravo	11 50	......	......	Like thunder	....Do.	Wood frame, boards, and mud.	....Do.	Do.
	Vicente Rogers C.	11 48	Some, such as bookcases.	Forward	......	....Do.	Wood frame	....Do.	Do.
	Aristides G. Garcia	11 47	Did not fall, but moved toward west.	From east to west.	......	Near hill	Adobes, wood, and corrugated iron.	Moderate	Do.
	Fabriciano Morales	11 55	A cabinet	Toward southwest.	......	......	Wood frame	Insignificant	Do.
	Oscar Letelier	11 55	Wardrobes and shelves.	Toward west	Like discharge of artillery.	Sediment	Adobes, cane, and wood.	Moderate	Do.
	Lidia Richards	11 55	Nothing fell	......	......	......	Mud	Insignificant	Do.

DISTRIBUTION OF INTENSITIES—*Continued*

Place	Name	Hour	Furniture overturned	Direction	Sounds observed	Ground	House	Damage	Intensity
Copiapó—Cont'd. (latitude 27° 22'; longitude 70° 22'; elevation 1220' (370 ms.); site, swamp muck, sands and gravels)	Pedro Villagran A.	11^h50^m	Cabinets, small tables, wardrobes, etc.	In all directions	Like heavy cart	Alluvium	Adobes and corrugated iron.	Appreciable	Eighth degree.
	Samuel Jenkins	11 50	Wardrobes	Toward east	Like thunder	....Do.	Wood and cane	Slight	Do.
	Francisco Finus	11 55	Cupboards and tables.	To the east	None perceived	......	Adobes and wood frame.	Appreciable	Do.
	Anjel E. Guerra O.	11 53	Wardrobes and cabinets.	....Do.	......	Wash	Tapiales and cane.	Considerable	Ninth degree.
	Guillermo Barth C.	11 45	Wardrobes and cabinets.	Toward south	......	Alluvium	Adobes and wood.	Appreciable	Eighth degree.
	Ricardo A. Vallejos	11 55	Bureaus and wardrobes.	From east to west.	Muffled and prolonged.	....Do.	Wood frame	....Do.	Do.
	J. Amadio Beluzan	11 55	Heavy wardrobes	To east	Very violent	......	Cane and mud	Moderate	Do.
	Amalia Julio, vda. de Amor.	About 12	Many articles of furniture.	From east to west.	Like thunder	On solid hill	Adobes and cane.	Considerable	Ninth degree.
	Manuel Meneses R.	11 50	One round table with three legs.	To northwest	....Do.	Alluvium	Adobes with wood.	Moderate	Eighth degree.
Tierra Amarilla (latitude 27° 29'; longitude 70° 18'; elevation 1620' (490 ms.); site, on river gravels)	Lorenzo Jofre Flores	11^h55^m	Wardrobes and others.	Toward north	Like thunder	Alluvium	Cane with wood and mud.	Considerable	Ninth degree.
	Jose Felix Zamorano	11 54	Shelves, etc.	South to north	....Do.	....Do.	Wood, brush and roof of zinc.	Appreciable	Eighth degree.
	Juan 2° Echeverria	11 55	A wardrobe	Toward east	....Do.	Firm	Wood frame	Moderate	Do.
	Pedro Cerda	11 45	Some fell	......	....Do.	Alluvium	Wood frame with cane.	....Do.	Do.
	Carmelo Destefani	11 45	Buffets, tables, etc.	Various	Varied	Firm	Wood with cane	....Do.	Do.
	Eduardo Thaden	11 55	Wardrobes, cabinets, etc.	Toward south	Like a very heavy cart.	Alluvium	Cane and mud	Appreciable	Do.
	Martin Vitali	11 45	Tables, chairs, etc.	Various	Like thunder	Rock and alluvium.	Cane, mud, and wood.	Considerable	Ninth degree.
Carrizal Bajo (latitude 28° 04'; longitude 71° 12'; elevation, sea-level; site, rocky coast)	Pedro Cuello	11^h50^m	Tables, wardrobe, etc.	Toward south	Like thunder	Firm rock	Wood, mud, and corrugated iron.	Slight	Eighth degree.
	Vincente Arredondo	......	Bookcases with books.	......	Like heavy cart	Firm	Wood	None	Seventh degree.
	Fernando A. Zadivich	11 56	......	......	......	Solid rock	Wood and corrugated iron.	......	......
	Carlos A. 2° Echegaray	11 56	Nothing fell	......	Like thunder	Rocky	Wood	None	Seventh degree.
	Juan A. Contreras	......	......	......	......	Solid rock	Wood	None	Do.
	Tomas C. Tello	11 55	None	......	Like roar	Solid	Wood with mud	None in building.	Do.
Huasco (latitude 28° 27'; longitude 71° 17'; elevation, sea-level; site, rocky coast)	Luis Hurtado V.	11^h55^m	All the furniture	Toward south	......	......	Adobes with wood and zinc.	Considerable	Ninth degree.
	J. Manuel Villanueva	11 50	Nothing fell	......	Like thunder	Alluvium	Tiles and adobes with zinc roof.	Uninhabitable	Tenth degree.
	Clodomiro Marticorona	11 55	Nothing	......	Like a very heavy cart.	Solid	Wood frame and zinc.	Slight	Eighth degree.
	Pedro Cruz	11 50	Some boxes	Toward east	......	Solid	Wood and zinc	None	Seventh degree
	Antonio Montero	11 55	Wardrobes, cabinets, tables, etc.	Toward west	Like a heavy cart.	Solid	Wood frame and zinc.	Considerable	Ninth degree.
	Francisco Quinones	11 55	......	......	Like thunder	Solid	....Do.	Slight	Eighth degree.
	Pedro 2° Ruiz	11 50	Wardrobes, sideboards, tables, etc.	Some toward north; others toward west.	......	Alluvium	Wood frame with adobes and mud.	Uninhabitable	Tenth degree.
Freirina (latitude 28° 30'; longitude 71° 06'; elevation 270' (81 ms.); site, on gravel and fault)	L. Vega A.	......	Nothing fell	......	Like detonations	Solid	Brush and mud	Insignificant	Eighth degree.
	Braulio Blanco Torres	......	Cabinets, etc.	Toward west	Like a moving train.	Gravel	Wood frame and corrugated iron.	Moderate	Do.
	Felix M. Amengual	11^h58^m	Nothing fell	......	Like detonations	Solid	Tapiales and adobes.	Considerable	Ninth degree.
	Luis A. Roman	11 54	Cabinets, tables, etc.	......	Like thunder	....Do.	Adobes, wood, and zinc.	Moderate	Eighth degree.

DISTRIBUTION OF INTENSITIES—*Continued*

Place	Name	Hour	Furniture overturned	Direction	Sounds observed	Ground	House	Damage	Intensity
Vallenar (latitude 28° 35′; longitude 70° 48′; elevation 600′ (180 ms.); site, river mud and gravel)	Silvano Vargas, M.	11h40m	Wardrobe, sideboard and shelves.	Toward east	Like detonations..	Alluvium	Adobe with woven brush.	Uninhabitable	Tenth degree.
	Eduardo Wolf	11 45	Contents of shelves.	......	Subterranean	Of gravel	Wood frame with small adobes.	Moderate	Eighth degree.
	Ivan Franulic	11 50	Mostly pictures ..	......	......	Alluvium	Adobe with boards and corrugated iron.	Heavy damage ..	Ninth degree.
In the bed of the Rio Huasco and on the lower part of a tributary alluvial fan.	Alejandro Flores	11 55	Tables, boxes, stands, etc.	......	Like a train in motion.	....Do.	Tapiales, adobe, and zinc roof.	Very great	Do.
	Zacarias Rocas, G.	11 55	Various articles of furniture.	......	Like underground thunder.	....Do.	Adobe, wood, and corrugated iron.	Considerable	Do.
	Custodio Cruz	......	Everything fell ..	Toward west	......	Coarse stream wash.	Tapiales and adobe.	Uninhabitable	Tenth degree.
	Arsenio Tapia, O.	After 12	Pictures and racks.	Fell down	Like thunder	Alluvium	Adobe and wood..	....Do.	Do.
	Manuel Varela, D.	11 50	Wardrobe	Toward east	....Do.	....Do.	Tapiales, wood, and mud.	Uninhabitable	Do.
	Ceferino Tornero	......	All furniture	From north to south.	Like surf of sea.	Firm	Adobes, wood, and zinc.	Moderate	Eighth degree.
	Francisco Cantuarias ..	11 57	......	......	......	Alluvium	Tapiales, adobe, and wood.	Considerable	Ninth degree
	Pascual Soler	11 50	Everything buried.	......	......	....Do.	Tapiales and adobes.	Heavy damage ...	Do.
	Ricardo Adriazola	11 54	Wardrobes and washstands.	Various	Like formidable thunder.	Coarse stream wash.	Walls adobe and wood frame.	Considerable	Do.
	Hernando Osandon	11 54	The furniture did not fall.	......	Like heavy truck.	Made ground	Wood frame with galvanized iron.	Small	Eighth degree.
	Guillermo Gray, L.	12 00	Wardrobes, stands, etc.	Various	Like heavy cart..	Alluvium	Tapiales, adobes. and wood.	Very appreciable.	Ninth degree.
	Luis de Block	11 55	Almost everything.	From south to north.	Like that made by a big automobile.	Bed of old river..	Adobe walls and zinc roof.	Walls shook much; roof did not.	Do.
	Leoncio Bardian	11 46	Furniture was crushed.	......	Like thunder	Alluvium	Adobe wall, wood frame, and wood	Uninhabitable	Tenth degree.
	Delfina P. v. de Femenias.	11 55	Much was demolished.	......	......	......	Adobes and wood frame, roof of boards and zinc.	....Do.	Do.
	Erminia C. de Diaz....	......	All the furniture..	......	......	Alluvium	Wood, zinc, corrugated iron, and tapiales.	....Do.	Do.
	Elba J. Pinto..........	......	....Do.	......	......	......	Tapiales, with thatched roof.	....Do.	Do.
	Augustin Barraza	11 55	Sideboard	......	Like thunder	......	Wood frame, adobes.	Only in walls.....	Eighth degree.
	Ester Flores de Mery..	......	Nothing fell over.	......	......	Alluvium	Tapiales and adobes with zinc roof.	Uninhabitable	Tenth degree.
	Pantaleon Barraza	......	....Do.	......	......	Sandy	Adobe and wood..	Considerable	Ninth degree.
	Francisco Diaz	11 55	Everything fell ...	Toward south	......	Alluvium	Tapiales and wood.	Uninhabitable	Tenth degree.
	Hector Mieres, A.	11 49	Tables, chairs, etc.	......	Like noise of trucks.	Firm	Adobes, wood frame, and zinc.	....Do.	Do.
	Jose M. Caballero......	......	Wardrobes, pictures, etc.	To the front.......	......	......	Adobe walls, adobes, and wood.	Moderate	Do.
	Rosa Juleta, J..........	......	Furniture did not fall.	......	......	......	Adobes, wood frame, and wood.	Appreciable	Do.
	Transito v. de Ordenes.	11 50	Everything fell ...	......	......	......	Mud walls and adobes.	Uninhabitable	Do.
	Abdon Naini	11 55	....Do.	Various	......	Sandy	Adobes and mud walls.	....Do.	Do.
	Abraham Q. Rodriguez.	Before midnight	....Do.	Toward east	Like a suberranean landslide.	Alluvium	Adobes	Considerable	Ninth degree.

DISTRIBUTION OF INTENSITIES—*Continued*

Place	Name	Hour	Furniture overturned	Direction	Sounds observed	Ground	House	Damage	Intensity
Vallenar—Cont'd. (latitude 28° 35'; longitude 70° 48'; elevation 600' (180 ms.); site, river mud and gravel)	Hernando Mancilla	Before midnight	......	......	Like heavy cart...	Alluvium	Tapiales and adobes.	Uninhabitable	Tenth degree.
	Carlos Aguilar	11h50m	Bookshelves, bureaus, etc.	Toward east	....Do.	Earth	Tapiales, adobes, and zinc.	....Do.	Do.
	Luis A. Hidalgo........	11 55	Everything fell ..	Toward north	Like a rapidly moving cart.	Alluvium	Tapiales and thatch.	....Do.	Do.
	Max Nolff	11 50	......	......	......	....Do.	Tapiales with zinc roof.	....Do.	Do.
In the bed of the Rio Huasco and on the lower part of a tributary alluvial fan.	Juan A. Pereira.........	11 50	Much fell	Toward south	Like thunder	......	Adobes and wood frame.	Moderate	Eighth degree.
	Guillermo Gallo	11 50	Wardrobes, bookshelves, etc.	From north to south.	Like noise of train.	Sedimentary	Adobes and wood..	Considerable	Ninth degree.
	Victor Aróchas	11 40	All the furniture.	......	......	Alluvium	Wood frame and adobes.	....Do.	Do.
	Hector Miranda	......	Nothing fell from movement.	......	......	......	Tapiales and adobes.	....Do.	Do.
	Pablo A. Morales.......	11 55	Everything fell ...	Various	Like loaded truck.	......	Adobes, wood frame, and zinc.	Uninhabitable	Tenth degree.
	Maximo Reygadas	12 00	Nothing fell	......	Like thunder	Alluvium	Adobes, tapiales and corrugated iron.	Considerable	Ninth degree
	Ventura Galan	11 45	Everything fell ...	Toward southwest.	......	......	Tapiales, adobes, wood, and corrugated iron.	Uninhabitable	Tenth degree.
La Serena (latitude 29° 55'; longitude 71° 15'; elevation 70' (21 ms.); site, on terrace of gravel and Pliocene limestone and sands)	Gustavo Lagos	11h50m	Nothing fell	......	......	Solid, rocky	Adobe and wood..	Insignificant	Eighth degree.
	Jose M. Zarate.........	11 47	A mirror	Toward south	Like a rock slide..	Rocky	Adobes with zinc roof.	Moderate	Do.
	Blanca D. de Lazo....	11 50	Nothing	......	Like thunder	Firm	Adobes with wooden roof.	Nothing	Seventh degree.
	Josias Richards C.	11 50	A goblet from the table.	......	Like that of a vehicle.	Firm	Adobes and wood frame.	Moderate	Eighth degree.
	Pedro Godoi L.	12 15	Some pictures.....	Toward south.....	Like thunder......	Firm	Wood frame, adobes, and zinc roof.	Appreciable	Do.
	Maria E. Araya	12 10	Some small tables.	......	Appeared like an automobile.	Solid	Adobes and wood..	....Do.	Do.
	Oscar Miranda G.	11 55	Mostly tables	Toward north ...	......	Solid	Tapiales, wood, and corrugated iron.	None	Seventh degree.
	Antolin Anguita B.	12 00	Objects from shelves.	From east to west.	......	Firm	Adobes and zinc...	Moderate	Eighth degree.
	Federico Kuhlmann	11 55	Pedestal with a vase.	Toward west	Like passage of heavy truck.	Firm	Tapiales, wood frame and galvanized iron.	Appreciable	Do.
	Eulojio Robles R.	11 50	Nothing fell	......	......	Solid	Wood and zinc....	Insignificant	Do.
	Alfredo Claussens	11 52	....Do.	......	......	......	......	......	......
	Luis F. Alfaro V.	11 55	Some furniture ...	......	Like thunder	......	Tapiales, adobes and wood.	Insignificant	Eighth degree.
	Maria L. Pinto.........	11 56	No furniture fell.	......	......	Solid	Adobes with zinc..	None	Seventh degree.
	Luis R. Barraza	11 47	......	......	Like a rock-slide..	Rocky	Adobes, wood, and zinc.	Slight	Eighth degree.
	Oscar Cabezas B.	11 55	Nothing fell	......	......	Solid	Adobes	Insignificant	Do.
	Emilio de la Torre.....	11 50	....Do.	......	Like sound of sea.	Solid	Adobes and wood.	Moderate	Do.
	Hugo Bravo R.	11 55	All the furniture.	From south to north.	Like thunder	Alluvium	Adobes and wood.	Heavy damage ...	Ninth degree.
	Julio Mantero	11 55	Nothing fell	......	......	Firm	Adobes, wood frame, and zinc.	Insignificant	Eighth degree.
	Rosa Cortez A.	11 55	....Do.	......	Subterranean noises.	Solid	Wood frame and adobes.	None	Seventh degree.
	Bernardo Cortiz D.	11 50	Tables, pictures, etc.	Toward south	Like a heavy cart.	Firm	Adobes, wood, and zinc.	Slight ....Do.	Eighth degree.
	Eduardo Olivares C. ...	11 57	Wardrobes, sideboards, tables, etc.	From east to west.	Like that of carts.	Solid	Light material ...		Do.

APPENDIX III

GEOLOGY OF ATACAMA

OUTLINE OF THE ESSENTIAL FACTS OF THE GEOLOGIC PLAN AND STRUCTURE OF THE PROVINCE

By JOHANNES FELSCH
Geologist, Bureau of Mines and Geology, Chile

(Translation)

GEOLOGY OF ATACAMA

The disastrous earthquake of November 10, 1922, by which the cities of Copiapó, Vallenar, and Chañaral were partially destroyed, and in consequence of which the entire population of the province of Atacama has suffered greatly, has led to a study of the geologic causes of the severe and frequent shocks experienced in that region.

The earthquake of November 10 caused a great movement of the sea all along the coast from latitude 31° south to latitude 21°. This great disturbance of the sea, extending more than a thousand kilometers from north to south, in itself proves that the vibrations of the earth's crust were very strong in the sea-bottom as well as on the land. The town of San Antonio, situated in the valley of the Copiapó River, at a distance of a hundred kilometers from the coast, was almost completely destroyed. It thus appears that the earthquake was of great extent from east to west as well as from north to south, and it is obvious that the shock was caused by tectonic movements that affected the western coast of the continent.

A fault of important magnitude had been observed at a point 2 km. west of Vallenar and another at a distance of 9 km. east of Copiapó, in the course of a geologic reconnaissance executed by the author for the purpose of finding water-supply for the railroad. These faults have a course of N. 15° E. Nearly all the faults encountered in the course of this reconnaissance in the western slope of the Cordillera in the province of Atacama have a similar direction. Furthermore, the greater part of the numerous metalliferous veins in the province have a similar strike and the fractures in which the vein-matter was deposited were originally caused by tectonic pressure.

The first visit (after the earthquake) to the cities of Vallenar and Copiapó in January, 1923, showed plainly that the houses facing on north-south streets had suffered much more than those on east-west streets.

An incident that occurred in the house of Don Felipe Matta in Copiapó during the earthquake clearly demonstrated that the shocks of the earthquake were oriented in a direction perpendicular to the above-mentioned points, that is to say, that the shocks had a causal relation to the faults. At the time of the earthquake there stood in the house of Señor Matta a sideboard with a polished top. It was placed against a wall which ran N. 30° E., and on it was a heavy bronze fruit-dish standing on three feet. In consequence of the shocks the fruit-dish danced from southeast to northwest and fell from the western edge of the sideboard to the ground, after having recorded its march across the varnished top quite clearly by the scratches made by its feet. The scratches show that the fruit dish moved from S. 66° E. to N. 66° W., that is to say, perpendicular with reference to a line running N. 24° E.

With these facts in mind, I began my study of the region between Caldera and Copiapó.

In the coast, about 25 km. southwest of Caldera, opposite a large island, I encountered a reverse fault which is readily visible and has a course of N. 35° E. It was traced throughout a length of 40 km. The block to the west of the fault is overthrust about 18 meters upon the block to the east. Both masses are covered with sandstone, probably of Pliocene age, and the displacement of this stratum facilitates the recognition of the uplift on the fault. The fault being so young, it is well marked in the morphology of the surface. The Morro of Copiapó which bounds the plain of the Quaternary terrace between Monte Amargo and Caldera on the west, owes its existence chiefly to this fault.

The fault may also be observed where it is indicated by disturbances of the Pliocene beds in the southern part of the Bahia Inglesa, 15 km. southeast of Caldera. Small springs occur along the line of the fault in Chorrillo, opposite the large island, in the southern border of the Bahia Inglesa and in the Aguada de Leon, 15 km. northeast of Caldera. The Aguada de Leon gives off a little hydrogen sulphide.

Fifteen kilometers west of Monte Amargo, the valley of the Copiapó is narrowed by an outcrop of gneiss that projects above the Quaternary terrace. The altitude of the latter at this point is 108 meters. Between the narrows of Monte Amargo the floor of the valley is formed by beds of shells and sands of Pliocene age partly covered by Quaternary deposits. In the narrows the bottom of the valley has an altitude of 65 meters. The Pliocene with *Ostrea maxima* occurs at an altitude of 108 meters, on top of the gneiss, and the same Pliocene stratum occurs at a level of 80 meters only 120 meters east of the narrows. Thus it is evident that the narrow has resulted from the elevation of the gneiss, as is proved by the position of the stratum with *Ostrea maxima* on the east of the fault and on the west of it.

To the north and to the south of Monte Amargo the marine shell beds of Pliocene age constitute terraces that have an altitude of 240 meters; 5 km. west of Monte Amargo the Pliocene terraces terminate along a line that has a general north-south course. The calcareous beds are almost horizontal. In the narrows, which are mentioned in the preceding paragraph, the Pliocene beds dip gently toward the east in such a manner that they disappear under the Quaternary deposits that constitute the banks of the river to within 5 km. of Monte Amargo. It thus appears that the Pliocene terraces to the north and south of Monte Amargo are cut off along their western edge by a fault which has a throw of 103 meters.

Thus it is demonstrated that the coastal zone between Caldera and Monte Amargo is traversed by three faults which run approximately parallel with a N. 35° E. course. The first of these faults extends from the Chorrillo through the Bahia Inglesa and Caldera to the Aguada de Leon and occasions an elevation of the western block by 18 meters over the eastern block. The second fault occurs at the narrows and has raised the western block about 28 meters above the eastern. The third fault has caused the western block to drop 103 meters below the eastern.

These modern faults have, in fact, a course that is perpendicular to that indicated by the fruit-dish in the house of Señor Felipe Matta in Copiapó in consequence of the movements in the shock of November 10, 1922.

My preliminary studies had already led me to this conclusion toward the middle of March 1923, when there came to Copiapó Professor Bailey Willis, of Stanford University, in California. He was charged with the duty of making a study of the earthquake of November 10, 1922, and the undersigned received instructions from the Director of Mines and Geology to assist Professor Willis in that investigation. During the months of May and June we conducted a reconnaissance of the Rio Copiapó from Monte Amargo to the head of the Rio Manfias, of the Quebrada de Paipote as far as its head in the western slope of the Cordillera, and also in the valley of the Rio Huasco from its head in Laguna Grande to its outlet to the sea (also the valley of the Elqui from Rivadavia to La Serena).

In the course of these excursions the undersigned directed his observations especially to the identification of the stratigraphic horizons of this part of Atacama. Professor Willis took special note of the structural geology. The accompanying map presents the results of our reconnaissance.

Inasmuch as the undersigned has more specially studied the stratigraphy, the following report is devoted particularly to a description of the rock formations that make up the geologic column of the province.

The province of Atacama may be divided into three zones, which are distinguished by their morphology as well as by the strata of which they are composed:

(1) The coastal zone constitutes a belt along the coast, having in the latitude of the valley of Copiapó a width of 54 km. It narrows little by little toward the north, but widens toward the south. It consists geologically of metamorphic rocks of Paleozoic age, upon which rest unconformably sediments of the upper Tertiary, which are found, however, only in a few places. This coastal zone is a mountain range which parallels the coast and reaches altitudes of 800 meters.

(2) As a second zone, we may designate the western slopes of the Cordillera Real as far west as the eastern border of the coastal zone. It is composed in large part of marine sediments of Mesozoic age, which are frequently intruded by basic igneous rocks and tuffs of similar composition. Furthermore, at the close of the Mesozoic and the beginning of the Tertiary there were intrusions and extrusions of the acid igneous rocks of the Andes in the foothills of the Cordillera.

(3) The third zone lies in the summit plateaus of the Cordillera Real and is made up of lavas and tuffs, the products of modern volcanic eruptions.

The metamorphic rocks of Paleozoic age that constitute the mass of the coastal zone also constitute the basement rocks beneath the Mesozoic sediments in the foothills of the Cordillera. This Paleozoic basement may be found here and there in the slopes of the Cordillera Real at the bottom of deeply eroded valleys. Outcrops of the Paleozoic basement are especially common along the tectonic fault-lines.

The basement rocks of Paleozoic age comprise the following: (1) Gneiss. (2) Mica schists, slates, and quartzites. (3) Granites and plagioclase granites, that often form large massive intrusions in the metamorphic schists. Thus, 2 km. south of the port of Chañaral there is an extensive outcrop of an intrusion with a cover of black slates. Apophyses of the granite penetrate the slates. (4) Intrusions of black diabase that are highly metamorphosed, and which occur in the Paleozoic basement, probably also belong to the Paleozoic. On the other hand, the obscure dikes of porphyry that frequently cut the masses of gneiss and Paleozoic granite represent plutonic rocks of Mesozoic age. They are especially frequent in the Paleozoic granite that is exposed in the Quebrada of the Rio Salado between Chañaral and Carmen.

MESOZOIC HORIZONS

The Mesozoic strata lie unconformably upon the basement rocks of the Paleozoic. Forty-three kilometers east of Pueblo Hundido in the Quebrada del Rio Salado the Paleozoic gneisses are overlain by the gray limestones of Neocomian age. Generally, however, there is a layer of basal conglomerate or of conglomeratic sandstone between the limestones and the Paleozoic gneiss. These basal conglomerates testify to the activity of the waves of the Neocomian sea before the limestones were deposited. Three kilometers east of Paipote in the valley of Copiapó the gneisses and mica schists are covered by beds of labradorite porphyry, and these in turn are overlain by the limestones of the Neocomian. At the point known as Las Juntas, which is at the confluence of the Rio Jorquera and the Rio Manfias, the Paleozoic gneisses are covered by a quartz porphyry over which extend conglomeratic sandstones with chunks of petrified trees and frequent plant remains. The latter indicate that the conglomerates belong to the Rhetic. The thickness of the continental sediments is 60 meters more or less. Upon these in turn lie calcareous sandstones followed by gray limestones with many fossils. *Vola alata* (Bush) is especially common. The fossils demonstrate the lower Jurassic or Liassic age of the calcareous sandstones and gray limestones. In the Quebrada de Iglesia, on the eastern bank of the Rio Manfias, the Liassic strata are overlain by red sandy limestones that are of middle Jurassic or Dogger age, according to the brachiopods and corals which they contain.

These reddish gray limestones carrying the same Middle Jurassic fossils are succeeded in the Quebrada de Paipote by reddish marls. Six kilometers upstream from the Hacienda la Puerta, in the Quebrada de Paipote, the grayish red limestones of the Middle Jurassic form an anticline that rises in the floor of the Quebrada. On both limbs these limestones of the Dogger are overlaid by bedded lavas of labradorite porphyry having a thickness of 70 to 100 meters and over the porphyry there come reddish gray marls. In the Quebrada de Jorquera also there are eruptions of labradorite porphyry overlying the Dogger. In general, eruptions of labradorite porphyry accompany the sediments of the Middle Jurassic.

Pyroxene porphyries and breccias are found 1,200 meters downstream from the Hacienda la Puerta, in the Quebrada de Paipote, overlying the red marls. Furthermore, at Chimbero, 20 km. north of the Quebrada de Paipote, there occur eruptions of pyroxene porphyry melaphyre in association with black limestones and black calcareous slates, which, according to the fossils that they contain, belong to the horizon of the Tithon of the upper Jurassic. It may be said that eruptions of melaphyre are almost always associated with the sediments of the upper Jurassic.

To the Neocomian we may assign the eruptives and dikes of diabase that occur in association with greenish gray and reddish sandstones. The latter are overlaid by gray limestones with fossils characteristic of the Neocomian.

Fossiliferous sediments of later age than the Neocomian limestones have not been found by me in the Cordillera of the province of Atacama.

POST-NEOCOMIAN INTRUSIONS

Intrusions of quartz diorite, of diorite without quartz, and flows and dikes of amphibolite andesite and pyroxene andesite have, without doubt, occurred subsequent to the deposition of the Neocomian limestones. In Chimbero, 100 km. north of Copiapó and in the Chañarcillo, 60 km. south of Copiapó, the Neocomian limestones in contact with intrusions of diorite are metamorphosed into aphanitic marbles with garnets. In other places, as, for example, in the valley of the Rio Huasco between Toro and Caracol, the intrusions of diorite have produced contact metamorphism with Jurassic horizons.

The eruptions of andesite are in general more recent than the intrusions of diorite. One frequently encounters dikes of andesite that cross the mass of diorite. The acid eruptions of trachyte and liparite are the most recent in the region of the foothills of the Cordillera Real. In the upper stretches of the Quebrada de Paipote, at the place called El Obispo, there occurs an eruption of trachytic breccia immediately above an overthrust fault by which the red marls of the Middle Jurassic are thrust over a large flow of amphibolite andesite.

It thus appears that at this point the eruptions of trachyte are more modern than the andesite. The outflows of liparite and trachyte are especially closely connected with the tectonic lines in the western slope of the Cordillera. In the upper part of the western slope of the Cordillera the eruptions of liparite constitute large lava-flows which are frequently accompanied by white masses of liparite tuff. The liparite flows in this region cover the deposits of gravel that fill the Tertiary valleys. Lavas or tuffs of more recent age than the liparite flows do not occur in the western slope of the Cordillera in the province of Atacama.

The high Cordillera was not visited by me during this trip. It is probable that the terraces in the vicinity of Monte Amargo, that contain beds of limestones with lamellibranchs which were described in the introduction to this report, are but little younger than the eruptions of liparite.

It is appropriate to state that the excursions were made very rapidly and that it was not possible to take sufficient time to ascertain by looking for fossils the age of all of the horizons seen. Especially in the valley of the Rio Huasco it is possible that there may be mistakes in the distribution or age of the formations shown in the geologic map. Nevertheless, the general geologic character of the more important tectonic lines was definitely ascertained. Thus, for instance, in the case of the overthrust which occurs 9 km. east of Copiapó, the Paleozoic gneisses are found to rest upon Neocomian limestones. The overthrusts in the Quebrada de Paipote were recognized upon evidence of equally satisfactory character.

Thus, as a result of these reconnaissance studies, it is recognized for the first time that the province of Atacama is characterized by a geological structure consisting of overthrust sheets between which the faults strike N. 25° to 35° E. There is much to be done to complete these studies in the future, and there will then be opportunity to correct such mistakes as may have resulted from the reconnaissance nature of the work which is the basis of this report.

APPENDIX IV

GEOLOGIC NOTES

BY BAILEY WILLIS

COPIAPÓ VALLEY BELOW COPIAPÓ

Place—Monte Amargo and vicinity, a railway station in the valley of the Copiapó River.

Position—Longitude 70° 41′ to 47°, latitude 27° 21′ to 22° S.

Observations—At a point 4 km. east of Monte Amargo a tributary of the Copiapó has cut a channel about 10 meters deep in beds of sand, peat and diatomaceous earth. The strata are intimately and irregularly interstratified. The peat is a sponge of loose roots with some carbonized layers. It is very light and not compacted. The bed rock is not exposed.

Monte Amargo station, elevation 137 meters above sea; a well sunk for water encountered peat. The nearby banks of the river show peat under 10 meters of sand. (See Plate L.)

The hill called Monte Amargo is on the northern side of the valley and consists of granite with diabase intrusions (spec.). The following observations were made on the joints in the diabase: Strike N. 42 E. magn.; dip 55 SE.; strike N. 67 W., dip 80 S.; strike N. 18 E., dip 48 W.

At a point about 5 km. west of Monte Amargo the heights of the river terraces on the north bank were measured with hand level. Taking the flood plain as datum they were: Lower terrace 8 meters, capped with calcareous tufa or caliche; upper terrace 70 meters. Gypsum is quarried from the lower terrace between this point and Monte Amargo.

The course of the Rio Copiapó to and beyond Monte Amargo to the sea is straight west. It flows through a canyon (angostura), however, in the outer Coast Range. Thus the character of the valley, which is recently filled at Monte Amargo and is incised below that point indicates recent uplift.

Place—Toledo and vicinity, a railway station situated at the junction of the Ferrocarril Longitudinal with the Copiapó-Caldera line, where the longitudinal valley joins the transverse valley of the Copiapó River, at the northwest base of the Cerro Bramador, or Singing Mountain; elevation 291 meters.

Position—Longitude 70° 27′ west, latitude 27° 19′ south.

Observations—Faulting was suspected in this vicinity because the longitudinal valley was regarded as of tectonic origin, but no fault was identified. On the contrary, on ascending to a rock terrace on the west side of the longitudinal, 90 meters above the valley floor and about 3 km. west of Toledo, it was found to represent an earlier (Pliocene?) valley floor, which could be recognized in shoulders and passes on the slopes of the longitudinal valley from southeast to southwest and also along those of the Copiapó from northwest to northeast. Its slope, as observed with hand-level, was noticeable and toward the west, the coastal block to which it belongs having been tilted in that direction. The continuity of this floor precludes the possibility of faulting along the axis of the longitudinal valley, at least since the river has cut its level.

Because of the fractured condition of the rock the existence was suspected of a transverse fault of pre-Pliocene or Pliocene age, trending about N. 60° W. across the rock bench from which the above observations were made and passing southwest of Cerro Bramador into the Copiapó basin, southwest of the city. Its presence was not demonstrated however. (See Plate XXXIV A.)

Observations on joints in basal complex in rock terrace on west side of longitudinal valley, 90 meters above the plain: Strike north 62° west magnetic, dip 64° north; strike north 25° east, dip vertical; strike north 85° east, dip 85° south. Descending from terrace to the plain, joints observed in aplite dike, very clearly defined: Strike north 11° east, magnetic, dip 80° west and strike north 60° west, dip 85° north. The former of these two is displaced on the latter about 2 cm. north on the west side.

QUEBRADA DE PAIPOTE

FROM PUQUIOS NORTHEAST TO EL BOLO

Being a description of a geologic section reconnoitered in the Quebrada de Paipote between Puquios, a station at the end of a branch railroad, longitude 69° 53′, latitude 27° 10′, elevation 1,238 meters above sea by railroad, and a place called El Bolo, at the mouth of the Quebrada del Hielo, longitude 69° 37′, latitude 27° 07′, elevation 2,110 meters by barometer.

The rocks seen in this section belong chiefly to the Mesozoic, comprising sediments of the ages from Rhetic to Neocomian, together with associated eruptive flows and intrusives. They are grouped and identified by Felsch as follows:

Neocomian: Reddish standstones, shales, and thin-bedded gray limestones, with diabase,
Upper Jurassic: Dark limestones and calcareous shales, associated with porphyritic breccias and instrusive melaphyres.
Middle Jurassic: Reddish gray limestones interbedded with red and green shales and sandstones, accompanied by massive flows of labradorite porphry.
Lower Jurassic: Heavy, gray limestones and calcareous sandstones.

The western end of the section is in the Lower and Middle Jurassic, the middle is largely in the Neocomian, and the eastern part is again Jurassic. Thus there is a suggestion of synclinal structure, but there are no extensive eastward dips. All the strata dip more or less steeply westward, except for local folds, and are thrust up on a number of faults. The structure is too complex to be untangled during a ride such as we had to make and the following notes indicate only the more conspicuous details. Rhetic conglomerates, sandstones, and coal beds were examined in the Quebrada de Carbon, tributary to the Paipote about 15 kilometers east of Puquios.

Distance east of Puquios. Km.

ROCKS AND THEIR RELATIONS

0 Dark purple and green porphyries (melaphyres?) are intruded into gray (Upper Jurassic?) limestones, which had previously been folded. The relations are exposed at Puquios and also 1 km. farther east at the waterhole, at the mouth of the gorge that leads up to Carrera Pinto.

1 Limestone (Upper Jurassic?) forms cliffs on the southern side of the canyon and is traversed by a thrust. (See panoramic view, plate XXXVII A.)

1.8 The limestone rests on labradorite porphyry. Younger intrusives cut the sediments.

2.2 Steeply dipping red sandstones (Neocomian?) with black pebbles are here separated from overlying green sandstones by a zone of disturbed strata corresponding to a thrust. Both series are cut by intrusives.

3.8 At this point limestone is discordantly overlain by labradorite porphyry, which is overthrust upon it. The limestone dips 45° to 50° west.

5.1 Quartzite under sandstone.

6.2 Red sandstone (Neocomian?) conformably underlies sandstone of last note, indicating that it is not Palæozoic quartzite, as was suspected, but is a local metamorphic.

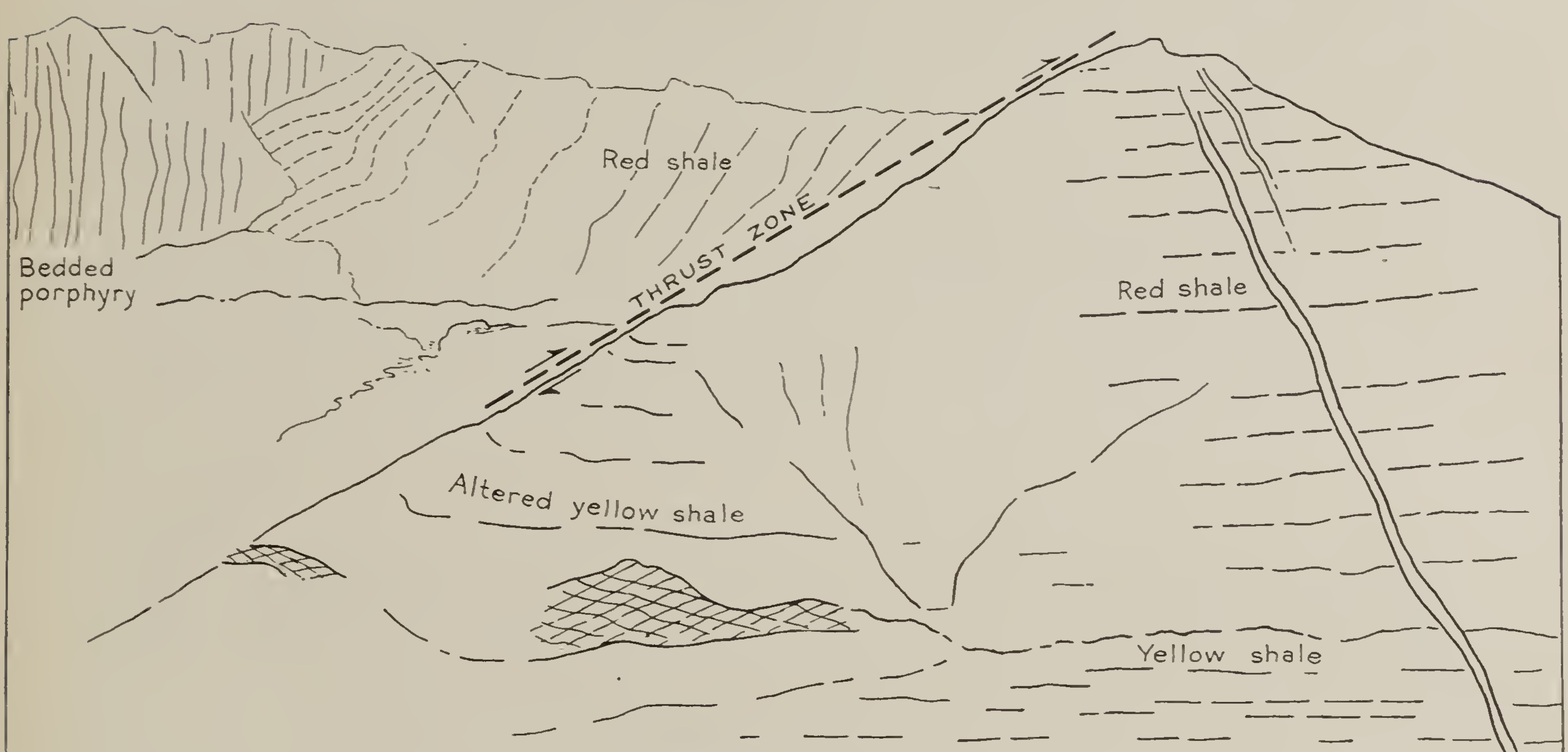


FIG. 11—Field sketch of thrust, Quebrada Paipote.

Km.

10.7 Red sandstone and conglomerate with black pebbles, seen also at 2.2 km. east, here dips 45° west at the canyon level, but rises to vertical dip higher up, against a small thrust. Acid dikes lie in the plane of the thrust, striking north 44° east magnetic and dipping 70° northwest.

13.7 From the last observation on, the cliffs of the canyon consist chiefly of altered porphyritic breccias (Upper Jurassic, Felsch?). At this point red sandstone is overthrust on violet-colored breccia. Strike north 15° west, dip 50° west.

14.8 The breccias appear to form the greater part of the southern wall of the canyon for the last kilometer. The northern wall exhibits a zone of thrusting in the red sandstones and breccias. At this point strata of unlike character form the opposed limbs of a faulted structure demonstrating a thrust of more than 300 meters. (See fig. 11.)

15.9 Junction of a canyon from the north, the Quebrada de San Andres, with the Paipote. The rocks are red sandstones, extensively intruded by dikes and greatly leached; altered Neocomian? Dip 80° to 85° west.

16.6 The south side of the canyon shows red shale (Middle Jurassic?) forced up to a vertical attitude and associated with younger intrusives, but overlying massive labradorite porphyry in apparent conformity (lowest Middle Jurassic?). The labradorite porphyry forms the massive walls of La Puerta, extending about 3 km. eastward up the Paipote. (See Plate XXXVII B.)

20 Hacienda de La Puerta, located at a spring zone in the Quebrada de Paipote. A group of old adobe houses tucked into the massive porphyry cliffs.

21 At this point the labradorite porphyry is interbedded with red sandstones and shales, dipping about 25° east, but upturned to past the vertical in the canyon walls. (See fig. 11.)

Distance east of Puquios. Km.	
24	Here red shale, highly calcareous, conformably underlies the labradorite porphyry, which is a breccia and occurs as a stratified series of flows interbedded with the shale. The breccia may have been submarine.
24.9	Red shale conformably overlying porphyry. The shale is fossiliferous and of Middle Jurassic, Dogger; age according to field determination by Felsch.
25.5	Conglomerate bed, 5 feet thick, containing pebbles of porphyry, with calcareous sandstone in red and green shales.
26 to 27.4	In this distance the labradorite porphyry forms an anticlinal arch within which the green and red shales are somewhat complexly folded and faulted. It is apparent that the porphyry was competent to lift enough of the load to give the shales within the arch freer displacement than they would have had otherwise. (See fig. 12.)
28.5	Since the last observation we have passed over a shallow syncline in the labradorite porphyry. At this point the dip is 20° toward the northwest.
29.9 to 31.4	In this stretch we have crossed a low anticline in the red shales and labradorite porphyry (Middle Jurassic, Felsch).
33.7	Since last observation the course is northeast from a fork of the quebrada, along a shallow syncline. At this point, El Bolo, is the mouth of the Quebrada del Hielo, which issues from a narrow gorge in white to yellow rhyolite or trachyte (Felsch). The latter is a Tertiary(?) intrusive along a fault plane, which marks the boundary between the Middle Jurassic terranes and Tertiary lavas.
35	East side of trachyte dike; green tuffs and flows of andesite dip 30° away from it and then flatten out to extend eastward in nearly horizontal position. These are Tertiary by their acid character and undisturbed attitudes.
36	In the Quebrada del Hielo. Limestone erratics, 3 feet in diameter, lie on the surface at one point. They exhibit glacial striæ, deeply grooved and crossing each other on rounded surfaces, showing that they were transported either by floating ice or by cloudburst from an altitude at which there was a glacier. The Quebrada del Hielo heads in the Cerro Tronquitos, about 20 km. east by south from El Bolo at an altitude of 4,000 to 4,500 meters. This evidence of glaciation thus falls in line with that seen at Potrerillos, q. v. The limestone blocks contain large oysters which suggest Upper Jurassic forms (Felsch). Some of the boulders consist of a peculiar limestone conglomerate with yellow sandstone and shale fragments in a red sandstone matrix. (See Plate LIII B.)

FIG. 12—Field sketch of anticline, Quebrada Paipote.

From the Quebrada del Hielo we returned to La Puerta and the next day to Puquios, reviewing our observations en route. At the Quebrada de Carbon, which enters the Paipote just west of the forks of the Paipote and San Andres, we turned south into the Quebrada de Carbon and followed it up about 2.5 km. to the exposures of coal beds in the Rhetic.

The Rhetic strata are composed of coarse conglomerate and sandstone, of which the part that is here exposed measures about 120 meters in thickness and carries three coal beds. The strike is south 45 east and the dip 50° northeast. The formation continues downward to a great thickness. It is cut by dikes. The coal beds are 3, 5, and 12 feet thick. The thickest is divided by two strata of sandstone into three benches of coal. All the beds are greatly compressed and sheared and are valueless.

For observations in the Quebrada de Paipote west of Puquios see notes of the ride from Puquios to Chulo, which follow.

QUEBRADA DE PAIPOTE

FROM PUQUIOS SOUTHWEST TO CHULO

Observations between Puquios and Chulo riding from Puquios down the Quebrada de Paipote to the railroad junction on the main line at Chulo. For extension of the section eastward see notes of the ride from Puquios to El Bolo, page 160.

Distance from Puquios.

ROCKS AND THEIR RELATIONS

At Puquios the rocks are Mesozoic eruptives intruded into folded upper Jurassic limestones which were subsequently overthrust. (See Plate XXXVII A.)

Km.

1.4 Riding south 15° west magnetic we here cross a fault on an anticlinal axis striking south 35° west magnetic. The south limb is thrust up over the northern, bringing red shale against labradorite porphyry.

2.9 From this point the view down the quebrada is nearly along the strike, crossing a gentle syncline to the adjacent anticline. Both banks of the valley are of green shale, probably Lias.

3.6 The valley enters the line of a thrust on the axis, which is marked by a vein of yellow limonite that can be seen passing out on the southern side several kilometers ahead. Labradorite porphyry occurs south of the thrust. The quebrada is eroded in the northward dipping limb of the anticline, the dip varying from 30° on the southeast side to 10° on the northwest.

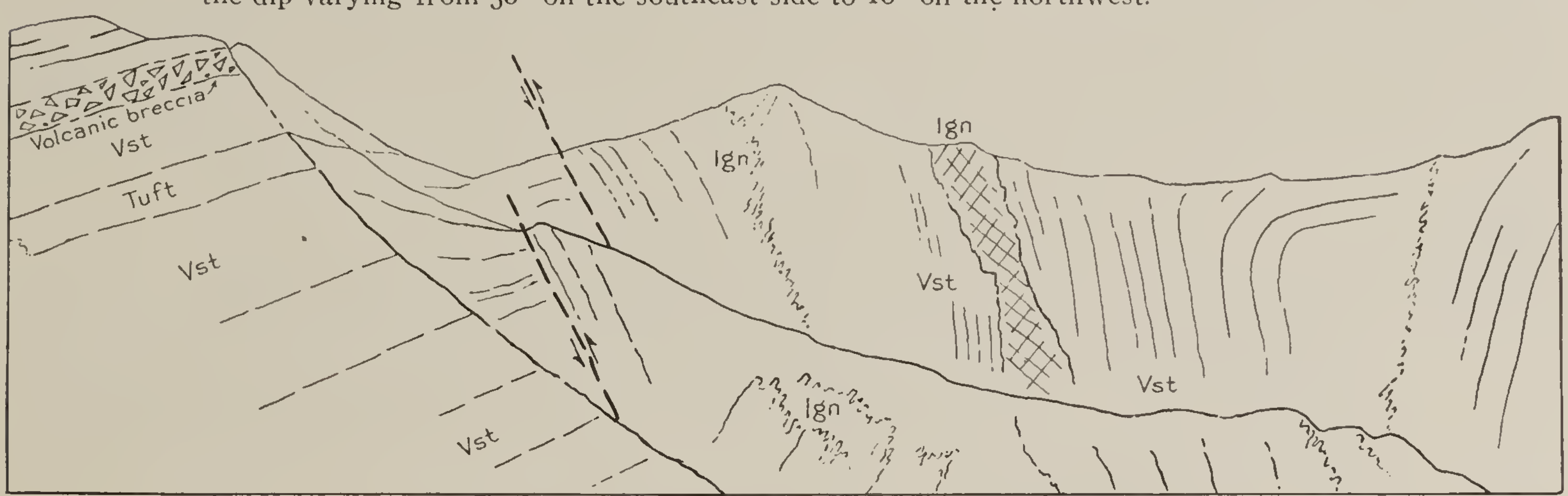


FIG. 13—Field sketch of thrust, Quebrada Paipote.

Km.

8.8 The rocks at this point are thin-bedded volcanic breccias with soft lava flows, eroded in conical forms. They belong to a coarse breccia zone that lies above the labradorite porphyry.

9.8 Kilometer 27 on the railroad. The axial fault noted above can be seen in the canyon wall about 2 km. distant. The dips indicate a broken anticline. All higher hills show a gentle dip to the southeast. Strata north of the fault also dip 20° southeast, toward the fault.

Estacion Venado. Approaching this station Cerro Venado bears south 10° west and exhibits the Jurassic strata of the Dogger and Lias horizons dipping gently southeast.

17.8 Railroad kilometer 19, whence the quebrada trends southwest.

19.1 Turned north 67° west magnetic across the Quebrada to examine the rocks in the gullies on the northern side. A thrust plane passes through this point of observation bearing north 12° east and south 14° west magnetic in opposite directions and dipping 70° west. (See fig. 13.)

19.6 Cliffs of fawn-colored acid breccia dipping 80° north.

20.8 Railroad kilometer 16. The structure is synclinal.

22.8 Railroad kilometer 14. The strata are sharply turned upward on the west limb.

29.8 Railroad kilometer 7. Looking southeast to a high point in the range, Cerro Garin, we see a crest of labradorite porphyry forming cliffs over a softer green formation, all dipping southeast. To the north of Cerro Garin the sediments and igneous breccias lie nearly flat, but maintain the southeastward dip. (See fig. 14.)

FIG. 14—Field sketch of Cerro Garin.

30.8 Railroad kilometer 6. At this point is the contact of greenish sedimentary strata overlying thick-bedded brown porphyry breccias, all dipping 15° southeast. The bedded porphyry extends past Chulo and forms the walls of the Quebrada all the way to Paipote, some 15 km. They are Mesozoic and probably all Jurassic.

UPPER COPIAPÓ VALLEY

PAIPOTE TO PORTO DE CANTARITO

Being a description of geologic notes made in riding up the upper Copiapó Valley from Paipote to La Junta, thence via the Port° de La Iglesia to the headwaters of the Rio Manfias, and to the Port° de Cantarito.

Paipote, latitude 27° 25′ south; longitude 70° 12′ west; elevation 439 meters, R. R.
La Junta, latitude 28° 02′ south; longitude 70° west; elevation 1,365 meters, map.
La Iglesia, latitude 28° 13′ south; longitude 69° 55′ west.
Port° de Cantarito, latitude 28° 36′ south; longitude 69° 53′ west; elevation 4,106 meters.

The rocks encountered in the upper Copiapó Valley comprise both sedimentary and igneous classes and range in age from the Paleozoic to the Neocomian. Granites occur at both ends of the section and are regarded as the oldest of the rocks. The Jurassic and Cretaceous terranes represent the horizons which are exposed by the Quebrada de Paipote in their extension along the strike southwestward. The major structural facts are similar in the Quebrada de Paipote and the upper Copiapó Valley, but there are material local differences, as would be expected in a section of sediments alternating with lava flows, sheets and dikes, and traversed by numerous faults.

Distance from Paipote southward.

ROCKS AND THEIR RELATIONS

Paipote is at the junction of the Quebrada de Paipote with the upper Copiapó Valley, which immediately widens into the basin of Copiapó. The surrounding rocks are granite and diabase of the Paleozoic series of the coast ranges.

At Paipote there is a high promontory of rock immediately northwest of the Casa Florida, a ranchhouse. The rock is Paleozoic diabase, which is conspicuously jointed and exhibits three distinct joint systems, namely:

(1) Strike north 82° west; dip 58° south.
(2) Strike north 8° west; dip 75° west.
(3) Strike northeast; approximately, dip 55° southeast; irregular.

Km.
1.5 The west bank of the Copiapó exposes a quartzite assigned to the Paleozoic. It is intruded by diorite which east of the river also occurs in thick flows interbedded with black limestone. The limestone and porphyry series extends east to Chulo (see notes on the Quebrada de Paipote), dips southeast and comprises Jurassic terranes. The sequence is well exposed in the Quebrada de Melendez, which enters the upper Copiapó Valley from the east 4 km. south of Paipote.

4 Quebrada de Melendez. In the mouth of the Quebrada, about a kilometer east of the railroad, the exposed rock is an altered eruptive of the Paleozoic facies. The cliffs expose a fault contact on which the Paleozoic is overthrust upon the Mesozoic in obvious superposition. The relations are well exposed in the northern spur of Cerro Ladrillos looking northeast, and also toward the southwest in Cerro Ojancos. The contact zone is intruded by later igneous rocks and is mineralized. Farther up the Quebrada de Melendez is fossiliferous blue limestone which weathers yellow. The strata dip gently to the southeast and constitute the lower part of a thick series which presumably includes both Jurassic and lower Cretaceous horizons. (See fig. 15.)

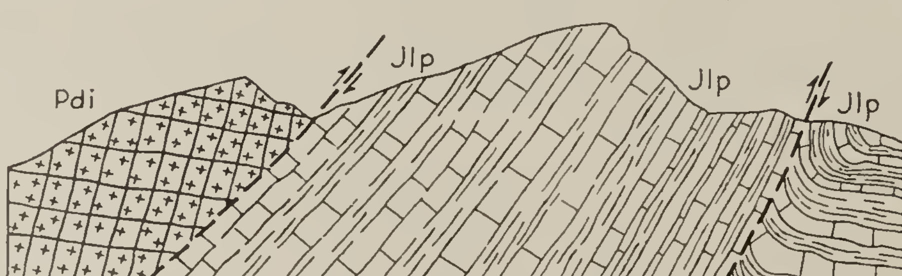
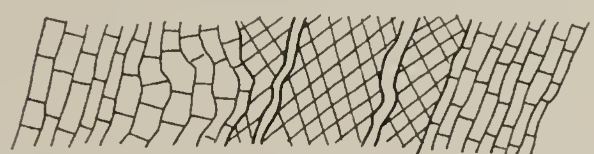


FIG. 15—Field sketch of thrust in Cerro Ladrillos.

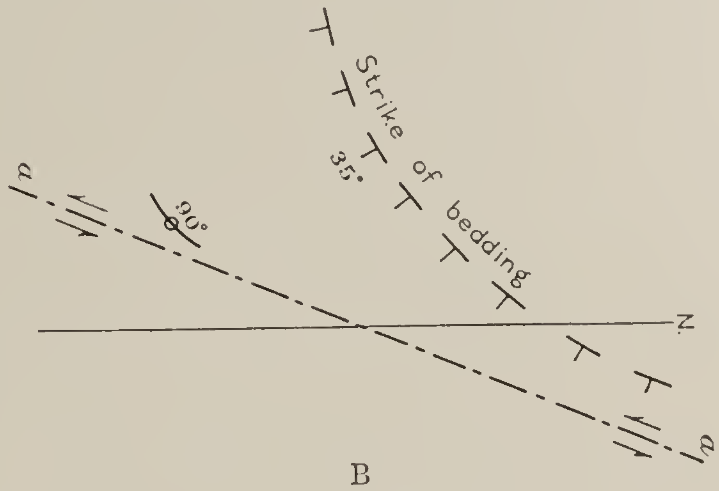
Totoralillo. From the Quebrada de Melendez to Totoralillo the valley is eroded at a small acute angle to the strike of the Jurassic and Cretaceous limestones and volcanic flows, which dip southeastward on a gentle flexure. Near Totoralillo the western escarpment of the canyon, which is here narrow and bold, exhibits an overthrust, striking north 15° east magnetic and dipping 45° to 60°

west. The yellow limestone series (Cretaceous) is duplicated thereby. The lower section extends southward up the valley, but passes over an anticline and dips southeast beyond Totoralillo.

Pabellon. Between Totoralillo and Pabellon the Cretaceous limestones are sharply folded and somewhat crushed. At the turn in the valley about 2 km. north of Pabellon the strata crossing the canyon expose a bedded flow or sheet of igneous rock between two thick strata of limestone. There is a good deal of crushing in the igneous rock, and the limestone on the northwest is overturned. This is regarded as a fault contact. (See figs. 16 A and B.)



A



B

Figs. 16 A and B—Field sketch of Cretaceous limestone and intrusive, section and plan; near Pabellon.

For 5 km. above Pabellon the canyon is cut in dark volcanic rocks identified by Felsch as pyroxene andesite. It is in part a volcanic breccia and is probably early Tertiary.

From Pabellon a side trip was made to the mines of Chañarcillo.

Hornito. Hornito is situated near the middle of a section of volcanic flows and breccias assigned to the early Tertiary, which extend from near Pabellon to within about 2 km. of Tres Puentes. In the immediate vicinity of Hornito these volcanic beds are contorted and faulted. The strike changes from north by east to nearly east and west, and the dip varies from vertical to 35° toward the southeast. The rocks are overthrust and the sequence is repeated. (See fig. 17.)

Fig. 17—Field sketch of thrust near Hornitos.

Tres Puentes. Two km. north of Tres Puentes the very heavily bedded eruptive is greatly sheared and exhibits minor thrusts (kodak). The joints in the eruptive have the following positions:

Joints 1, north 64° west, dip 80° southwest, every 2 to 5 feet corresponding to bedding.
Joints 2, north 52° west, dip 52° southwest.
Joints 3, south 63° west, dip 60° southeast.

About 1 km. north of Tres Puentes the early Tertiary eruptives are in contact with a dark, massive altered igneous mass containing much mica, classified by Felsch as diorite and assigned to the Mesozoic. This rock extends south from Tres Puentes to the vicinity of Loros. It exhibits a great deal of crushing and is much altered.

Loros: From Loros to San Antonio the canyon walls are of diabase assigned to the Cretaceous.

San Antonio. San Antonio is located on red sandstone and shale of the upper Jurassic, which lie folded in a shallow syncline. A strong dike of "liparite" cuts across the valley and exhibits a strongly sheared structure. It appears to have intruded a fault zone and subsequently to have been faulted. In the east wall of the canyon north of San Antonio the red sandstone strata appear to end abruptly above the eruptive breccias and suggest a thrust from the northwest. But since the lava flows and the red sandstones are interbedded it is probable that the contact is one of deposition, at which the strata abut against the end of the flow.

Quebrada Calquis. At this point calcareous sandstone and limestone strata, assigned to the upper Jura or Tithon on the evidence of fossils, are overthrust by red sandstones of the older Jura. The upper Jurassic strata extend southward to the Estancia Lautaro, and for about a kilometer beyond it. They there overlie dark-green and violet sandstone and conglomerate containing fossil wood, which is assigned to the Rhetic. The Rhetic dips about 60° and the Tithon about 30° with a strike of about south 15° west. The Rhetic conglomerate is about 100 feet thick and lies upon a great mass of dark lava flows which contain amygdules and exhibit flow structure. They appear to represent a submarine volcano.

La Junta. This point may be considered the head of the Copiapó River, since it is the junction of three streams by which it is formed. The upper course, in a straight line with the canyon below, is called the Rio Manfias, and two large tributaries, the Rio Jorquera and the Rio Pulido, come in from the east. The canyon widens at the junction, but the rivers enter from deep gorges.

The rock at the junction is a gneissoid granite which is assigned to the Paleozoic. It is completely overarched by the volcanics which underlie the conglomerate of supposed Rhetic age. It is possible, however, that the fossil wood on which the age is predicated may belong to the Jurassic and that the volcanic activity occurred in that period. This would seem more consistent with observations on the Rhetic elsewhere.

From La Junta the trail ascends the Manfias a short distance, but turns east from the inaccessible canyon and ascends between the Manfias and the Pulido to the Vegas de la Iglesia. The route lies wholly in dark volcanic lava flows, probably of the lower Jura. The anticline which exposes the Paleozoic at La Junta descends on a vertical dip eastward to a syncline from which the beds rise, dipping 20° to 30° west. The syncline is succeeded by a broad anticline which also assumes a vertical or overturned dip toward the southeast. The strata were identified as lower Jurassic by the occurrence of smooth *Pectens* and large ammonites.

Las Vegas de la Iglesia. This is a wild amphitheater lying at the western base of the precipitous Cerro de la Iglesia, a granite mass. The valley is inclosed on the west by a moraine of granite 110 meters high, which is composed of boulders derived from the Cerro de la Iglesia. The amphitheater thus corresponds with the bed of a local glacier which gathered in the shadow of the great peak. The height of the peak is given as 3,840 meters, and that of the amphitheater is probably about 2,600. (See fig. 18.)

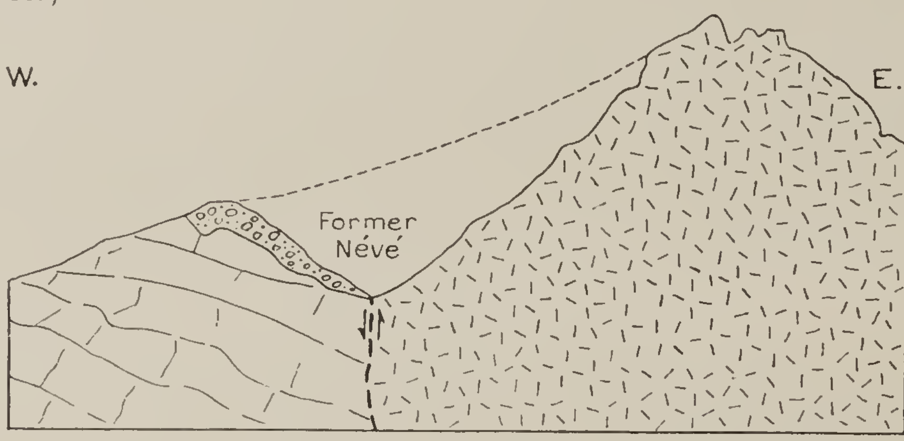


FIG. 18—Field sketch of bed and moraine of glacierette in Cerro de la Iglesia.

The moraine rests upon recent or late Tertiary volcanics, which dip east toward the granite and extend west to the Jurassic eruptives upon which they lie.

The pass of Las Vegas de la Iglesia is located on a line of thrust which traverses the granite and is occupied by Tertiary volcanics. The section may be seen looking north from a point 3 km. south of the pass. The view shows a granite knob west of the pass with Jurassic overlying the granite on its western slope and Tertiary volcanics filling the pass on the east. In this view the volcanics appear to have an anticlinal structure, indicating subsequent disturbance. The thrust lies along the line of outflow of the volcanics and cuts partly across granite north of the Vegas and between granite and Jurassic south of that point. (See fig. 19.)

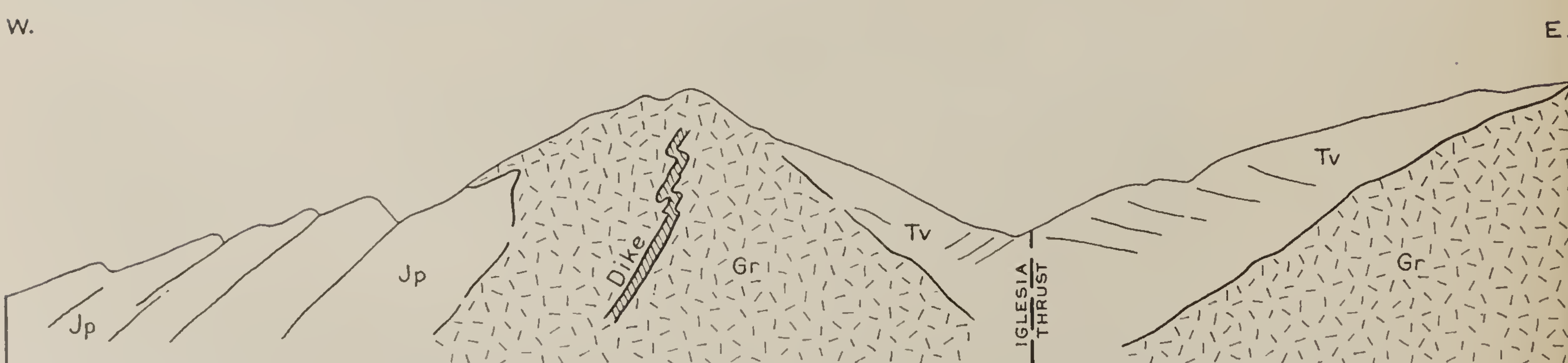


FIG. 19—Field sketch of La Iglesia thrust.

From Las Vegas de la Iglesia the trail descends into the upper canyon of the Manflas, partly over Tertiary volcanics and partly over the Jurassic which lies west of the volcanic belt. Where the trail strikes the river near latitude 28° 22′ south, 69° 59′ west, there are extensive exposures of the red and gray limestones of the middle Jurassic, with many fossils.

The headwaters of the Manfias, where the river flows northwest, run through Tertiary volcanics as far east as the Porto de Cantarito, east of which high peaks of very precipitous character and gray color resemble the Cerro de la Iglesia and like it probably represent a granite range.

From the Port° de Cantarito the route descends to the northwestern headwaters of the Rio Huasco past Lago Grande, and thence down that stream to Vallenar (see notes which follow).

VALLEY OF THE RIO HUASCO

PORTO DE CANTARITO TO HUASCO ON THE COAST

The following notes represent the observations taken in riding from the Port° de Cantarito southward down the canyon past Laguna Grande to La Pampa in a southwesterly direction and thence in a west-northwesterly course down the Rio Transito and its continuation as the Rio Huasco to the sea.

In general the section is a repetition of the rocks observed on the upper Rio Copiapó, representing chiefly the Mesozoic horizons, to a point about 5 km. east of Vallenar, where the Paleozoics of the Coast Range begin and from there on form the canyon of the lower valley.

DETAILS OF OBSERVATIONS; ROCKS AND THEIR RELATIONS

Laguna Grande is a small lake dammed by a large landslide from a coarse gravel deposit of Pleistocene or Pliocene age, which forms very remarkable cliffs on the east side of the valley. The height of the cliffs was estimated at about 400 meters, and the mass of the formation appeared most unusual. It contained very large boulders such as are characteristic of alluvial fans in regions of cloudbursts, and is probably an alluvial fan deposit, but of an age which antedated the development of the canyon and of the faulting which has accompanied the recent elevation of the Cordillera. As seen from Laguna Grande, this great gravel deposit, elevated high in the range far above any of the agencies by which it could have been formed, is one of the most striking evidences of recent displacement which we observed in the Cordillera. The elevation of Laguna Grande is given as 3,473 meters and that of the granite peak east of it as 5,237 meters. The gravel formation is probably more extensive eastward on the slopes of the peak than can be seen from the canyon below. It invited further investigation, but a winter storm prevented. (See Plate XLIX B.)

At the outlet of Laguna Grande the cemented gravel masses form a chaotic dam over which the stream falls in a cascade and which, geologically speaking, can have but a brief existence.

To the northwest of the outlet of Laguna Grande the mountains are composed of Tertiary volcanics. The stream appears to run upon a line of faulting similar to that at Las Vegas de la Iglesia.

Below Laguna Grande to the vicinity of La Pampa the prevailing rock is granite, which exhibits facies ranging from a dark green gabbro to light gray granite with pink and red varieties. The granite is cut by black dikes of melaphyre. The structure of the granite is gneissoid, the result of shearing which takes a curved attitude rising very steeply from the west with a curve convex upward. Joints which dip about 40° east are of general occurrence, and they are frequently occupied by dikes of the melaphyre. Nearly vertical dikes and others in less systematic positions also occur. The dikes are of a very uniform width and appear to have entered the granite when it was in a state of tension and to have occupied the spaces between the joint blocks.

From La Pampa westward the sheared granite extends toward El Portillo, about 5 km., where it is succeeded by the Jurassic dipping westward. The contact appeared to present a zone of shearing and probable displacement. The Jurassic extends to El Tránsito at the mouth of the Quebrada de Chanchoquin, which is a narrow canyon eroded on a distinct thrust. The rocks are assigned to the lower Jurassic and are repeated west of the thrust with an eastern dip, but are presently succeeded by gneiss of the underlying Paleozoic.

At the Quebrada de Tabaco the Paleozoic is traversed by a thrust which is indicated by the disturbance and shearing of the rocks exposed in the gorge.

Proceeding west the Paleozoic is overlain by altered sandstones and conglomerates dipping westward. The conglomerate becomes very heavy in the upper western part. The terrane may represent the "Gomero" or lower Mesozoic, possibly Rhetic.

The supposed Rhetic is succeeded by volcanics and sandstones of the Jurassic, which dip nearly vertically near the contact but flatten to a dip of 40° and extend to the junction Tránsito with the Rio del Carmen at La Junta del Carmen.

At La Junta del Carmen the nearly vertical dip is pushed eastward by a thrust which brings more gently dipping beds of the Jurassic over the Jurassic, that is there is a thrust within the Jurassic terranes. The Jurassic beds are succeeded by a mass of diorite regarded by Felsch as Cretaceous or possibly Tertiary, which extend to Maiten.

From Maiten to Marmol the rocks are bedded andesites and andesitic tuffs, which for a long distance lie in a flat position, but at Maiten they are turned up vertically and are seen to lie upon limestones of Neocomian(?) age, dipping 50° east.

At Pedro Leon Gallo the Neocomian limestone is underlain by porphyritic breccias of the upper Jurassic, which extend to the Quebrada del Jilguero on a flat-lying eastern dip. They are locally much crushed and sheared, especially in the vicinity of Pedro Leon Gallo which is on the line of one of the major thrust faults. At the Quebrada del Jilguero the cliff exhibits the effects of recent faulting and displacement in the earthquake of 1922. (See Plate XXII B.)

The Quebrada del Jilguero is cut in rock only for a short section near its mouth, while higher up its banks are of gravel and its course has been excavated across the wide terrace which borders the Rio Huasco in its course westward across the wide valley that lies between the foothills of the Andes and the Coast Range in this vicinity. The contact between the Jurassic breccias and the Paleozoic lies under this terrace and was not observed.

SECTION ON THE RIO ELQUI

Observations made in a trip by train from La Serena to Rivadavia, 70 km., and thence on foot to Monte Grande in the canyon of the Rio Claro. Returning the trip was made from Rivadavia to Vicuña by hand car and thence by train to La Serena. The observations made on the up-trip were checked on the return, and the combined results are given in the notes.

ROCKS AND THEIR RELATIONS

Altovalsol: The effects of the earthquake are seen in the slightly cracked houses of frame and adobe construction. Throughout the fields the mud walls of tapiales remain standing. The effect of the shock was evidently very moderate.

Las Rojas: Between Altovalsol and Las Rojas granite forms the hills and river bed with rapids. It is a massive light gray rock with dark intrusions. At this point there are conspicuous granite hills on the south side of the river and the same rock extends eastward. The stream has worn conspicuous pot holes.

Pelicana: The point of rocks east of the station consists of dark green even-grained diabase, apparently intruded in the granite. It is greatly jointed and probably Paleozoic.

Marquesa: Coming from Pelicana the railroad follows an open valley trending north by east. The valley is continued in that direction by the Quebrada Marquesa, while the river, coming from the southeast, emerges from a narrow gorge. The latter is cut in bedded Jurassic breccias and lava flows, which dip 35° westward toward the granite. The contact of the granite and Jurassic is a fault contact, the granite being upthrust from the west.

Almendral: From Marquesa to this point the Jurassic breccias dip westward, but here pass over an anticline and dip 20° eastward. The massive brown beds of the lava flow are accompanied by thinner strata which may be sediments.

Gualligaica: The bedded Jurassic flows appear to overlie a diorite which is probably intrusive and younger. The diorite is a large mass extending eastward.

Tambo: The diorite, which has extended to this point, is in this neighborhood in contact with bedded breccias dipping 10° eastward from it.

Vicuña: Between Tambo and Vicuña there is a broad syncline which at Vicuña is followed by a broad flat anticline. The rocks are the bedded breccias which we regard as Jurassic. From Vicuña they dip eastward and come to form dark rugged peaks which were covered with snow.

Durazno: The railroad cuts above Durazno show the greatly jointed breccias covered with river gravel on the terraces. There are many boulders of granite and even the larger ones appear to be thoroughly decayed, indicating an early Pleistocene age for the gravel deposit.

Arenal: From a point a short distance above Durazno a gneissoid granite of Paleozoic facies forms both walls of the canyon. The structure is similar to that seen on the headwaters of the Huasco above La Pampa. The granite is intruded by andesite of uncertain age, possibly Tertiary. On the east the granite is covered by dark red lava flows and breccias associated with red sandstone, which we regard as Jurassic. They extend to Rivadavia in the higher mountains, but the canyon is in granite.

Rivadavia: At Rivadavia, at the junction of the Rio Claro with the Rio Turbio, the rock is granite which is overlain by sediments containing fossils of the Lias and associated with flow breccias, all of which dip west. The Lias is represented by red calcareous sandstone, outcropping on the road south of Rivadavia and extending up the Claro Valley on the west side. The strata rise from a nearly flat west dip almost vertically against the fault, which strikes north 5° east and dips 70° west in the heights south of the river. The granite underlies the Lias, which was deposited on a very hilly surface having a relief of at least a hundred meters, so that the thrust sometimes brings Lias against granite as if deposited on it, or granite over Lias in obvious fault contact. Where remnants of the Lias occur east of the fault the strata lie as deposited upon granite, as just above Paignano. The canyon above Paignano is cut in granite at least as far as Monte Grande. At Paignano the canyon turns south on granite, and it is possible that there is a fault passing through Monte Grande, but we were unable to proceed as far as that to verify the inference. The valleys of the Rio Claro and the Rio Turbio appear to be eroded in a broad zone of complex thrusts, lying between Paignano on the east and Diaguitas on the west. It corresponds in general position and character to the fault zone encountered on the upper Rio Huasco, and possibly may be represented by the complex overthrusts found in Asientos canyon near Potrerillos, with which it corresponds in strike.

APPENDIX V

PETROGRAPHIC SKETCH

By HENRY S. WASHINGTON

PETROGRAPHIC SKETCH

It was the original intention that the rocks collected by Willis should be described by H. S. Washington, and the general results embodied in an appendix to this volume. This intention, however, was not carried out, and it is now proposed that the results of such a petrographic study shall form the subject of a separate paper, to be published elsewhere, in which all the specimens will be described in detail, and the results of this examination of these Chilean rocks, as in a way representing the Andean and Cordilleran Circum-Pacific igneous rocks, will be contrasted with the Intro-Pacific volcanic lavas. In the meantime, and for this purpose, a dozen chemical analyses of Willis' specimens were made in the Geophysical Laboratory of the Carnegie Institution of Washington by Miss Mary G. Keyes. As a part of the main paper, and to put them on record as a contribution to our knowledge of the Andean igneous rocks, they are presented here (Table, page 176), with very brief and sketchy descriptions of the petrography of the rocks that were analysed. Some of the specimens that were studied were not fresh, but they were analysed notwithstanding, for lack of better material. The amounts of CO_2 in these cases were not determined, the completion of the analyses being postponed to a future occasion. For this reason the summation of certain of the analyses is very low (as in Nos. 5, 10, 11, and 12), this being noted in the Table. The numbers in parentheses (B. W. 3145, etc.) are those borne by the specimens. The analyses are arranged in the order of decreasing percentage of SiO_2.

PETROGRAPHICAL DESCRIPTIONS

(*1*) *Granite, Chañaral*—Coarse grained; very light, almost white, in color. Composed mostly of alkali feldspar with much quartz, and few small shreds of dark mica. Typical granitic texture shown in thin section. Much more orthoclase than oligoclase: the former mostly untwinned, and the latter with many very fine twinning lamellæ, of about the composition Ab_6An_1. The mica is mostly muscovite, but is not well crystallized and is rare. There are very few ore grains. There is some evidence of crushing.

(*2*) *Biotite granodiorite, Copiapó*—Megascopically fine grained, light gray in color: showing small specks of black biotite in mixture of feldspar and quartz. In thin section the quartz shows no inclusions. The feldspar is fresh and not much twinned. It is mostly oligoclase, about Ab_3An_1, many grains with borders of orthoclase. The pale olive-green, not very pleochroic biotite forms irregular shreds. Some small, irregular grains of ore are apparently ilmenitic magnetite, to judge from the somewhat brownish color. The texture is granitic.

(*3*) *Hyalodacite, Agua Encantada*—Small phenocrysts of slightly yellowish white feldspar are scattered through a phaneric, almost black, fine-grained groundmass of quartz and feldspar, with black mesostasis. Thin sections show some flow texture. The feldspar phenocrysts are subhedral, many fragmentary. Most of them are of oligoclase, about Ab_3An_1; these show not well developed twinning lamellæ. A few fragmentary and anhedral, small quartz phenocrysts. There are some subhedral prismoids of very pale greenish augite, with extinction up to about 40°, with coarse cleavage. There is no biotite. The few somewhat irregular ore grains are apparently somewhat ilmenitic. The microgroundmass is dusty and pale brownish, with some flow texture around the phenocrysts. It is highly vitreous and the "dust" is irresolvable under high powers.

(4) *Biotite granodiorite, Near Copiapó*—Fine grained, phaneric, light gray. Thin sections show typical granitic texture. Very little quartz, in small anhedra. The feldspar is almost all andesine, somewhat twinned, about Ab_3An_2, some with borders of orthoclase. Very little orthoclase. Some olive-green biotite, in irregular grains and thick tables, which occasionally are poikilitic about the plagioclase. Irregular grains of somewhat brownish, ilmenitic magnetite are not very abundant.

(5) *Biotite granodiorite, Cortadera Station*—Medium grained, black biotite, with very slightly yellowish feldspar and some quartz. In thin section the texture is typically granitic. The amount of quartz is apparently less than that indicated in the norm. The abundant andesine, about Ab_1An_1, is much altered with the production of calcite. There is little orthoclase. There is considerable olive-green biotite in very ragged individuals. The not very abundant, irregular ore grains are of the pure black of magnetite, so that the TiO_2 is probably mostly in the biotite, which is darker than in the preceding specimens.

(6) *Hornblende hyalodacite, Cerro Doña Inez*—Small prisms of black hornblende, with many phenocrysts of white feldspar, but none of quartz, are scattered through a very light gray, almost white, groundmass. The thin sections show many sharp subhedral phenocrysts of andesine, somewhat twinned, about Ab_3An_2, with fewer of subhedral orthoclase. No quartz is visible. The small, euhedral prisms of olive-green hornblende are not abundant, and there is an occasional small table of green biotite. The not abundant, irregular ore grains are black, so that much of the rather large amount of TiO_2 is probably in the hornblende. The microgroundmass is pale gray and slightly "dusty" (the "dust" being irresolvable under high powers). It is very vitreous but there is no evidence of flow.

(7) *Augite andesite, Quebrada Carrizo*—The highly porphyritic lava shows very abundant phenocrysts of slightly yellowish feldspar, that are mostly squarish and equant in all sides of the specimen. These are mostly about 2 mm. in diameter. There are very few small and inconspicuous prisms of black augite. The groundmass is very fine grained and pale brownish gray, without evidence of flow texture. In thin section the rock appears to be holocrystalline. The feldspar phenocrysts in thin section are not very well defined, and show little twinning. They are mostly andesine, about Ab_3An_1. The rather abundant olive-green augite forms subhedral prismoids, which are without inclusions except for a few small ore grains near the borders. The few small (0.02 to 0.10 mm.), irregular ore grains are apparently somewhat ilmenitic. The colorless microgroundmass is apparently holocrystalline, very fine grained and made up mostly of feldspar that is evidently somewhat more albitic than the phenocrysts, with possibly a little quartz. There is no flow texture.

(8) *Diabase, Pueblo Hundido*—This shows some small, tabular phenocrysts of whitish feldspar, in a very fine-grained or aphanitic, slightly brownish-black groundmass. In thin section the feldspar phenocrysts are seen to be tabular, not well twinned,

of about the composition Ab_2An_1. They are not very fresh. The general microgroundmass shows a subophitic texture, made up of small laths of andesine, with anhedral olive-green augite that is more or less interstitial between the feldspar tables. There are a few small anhedra of quartz. The rather large and irregular grains of ore are brownish and decidedly ilmenitic, and some very small and slender prisms of apatite are present.

(*9*) *Diabase, Aguada Algarroita*—The rock is very fine grained, dense, and aphyric, except for rare and small phenocrysts of black augite. The general color is slightly brownish black, but appears dark gray under the lens. The thin sections are rather unsatisfactory. There are a few phenocrysts of colorless augite and many small prismoids of the same mineral, which must be a diopside, to judge from the norm. These, and a few small grains of olivine, are embedded in an indefinite, apparently feldspathic base. There are no definite feldspar phenocrysts, but a few very small, twinned tables of andesine are seen here and there. The not very abundant ore grains are decidedly ilmenitic. The rock, as a whole, seems to be somewhat altered.

(*10*) *Labradorite porphyry, Rio Manfias*—The specimen shows many tabular phenocrysts of glassy plagioclase (up to 1 cm. long and 0.2 cm. wide), in a dark-brownish, fine-grained groundmass. In thin section the euhedral tabular feldspar phenocrysts show well-developed twinning lamellæ. They are of about the composition Ab_1An_1, and are very fresh. There are no phenocrysts of augite to be seen in the sections. In the microgroundmass are many small (up to 0.2 cm. long) laths of feldspar, of about the composition Ab_2An_1, that are little twinned. There are a few small, indefinite anhedra of colorless pyroxene, and much dirty, dark reddish-brown and opaque mesotasis interstitial between the small feldspar laths. Small scales and specks of red transparent hematite are present. The rock is evidently not fresh, as is also shown by the large amount of CO_2 found on analysis: this existing apparently in calcite derived from diopside in the opaque mesostasis, and not visible under the microscope. Indeed, the rock is so altered that it would not have been analysed but for the fact that the specimen is representative of a type that seems to be fairly abundant in the region.

(*11*) *Orthoclase diabase* (*?*). *Cortadera Station.*—The rock is black, and shows a few very small phenocrysts of feldspar, and still fewer of yellow olivine, in a dense, finely grained groundmass. The microscopic study was very unsatisfactory. The few sharply euhedral feldspar phenocrysts are of orthoclase, which is untwinned and not very fresh. The few small phenocrystic grains of olivine are fresh. Thin sections show that the rock is made up largely of colorless or pale yellowish pyroxene in ragged prismoids, with many small subhedral microphenocrysts of plagioclase, with much interstitial, indefinite, colorless, birefringent material, of low refractive index, that may be in part the nephelite shown in the norm, and in part some of the orthoclase. There may be a little glass present, but no ore grains are visible under the microscope. On the whole, it must be confessed that the rock, both modally and chemically, is a puzzling one, and that the bestowal of an appropriate name is difficult. The name selected here must be regarded as provisional and subject to further and more detailed study.

(*12*) *Diabase* (*?*). *Quebrada Paipote*—This is a medium gray, densely fine-grained aphanitic rock, with no phenocrysts. The thin sections show that the rock is composed largely of colorless or pale yellowish subhedrally prismoidal and somewhat felted augite, with small subhedral microphenocrysts of plagioclase, that has been much decomposed with the production of calcite. There are many small (0.01 to 0.03 mm.), highly euhedral and mostly octahedral grains of ore, dark brownish in color and evidently very ilmenitic. The rock is obviously much altered.

Analyses of rocks from Atacama, Chile

(Mary G. Keyes, analyst)

	1	2	3	4	5	6	7	8	9	10	11	12
SiO_2	76.71	65.01	64.83	61.96	61.00	60.03	58.45	54.76	53.25	52.64	50.17	48.80
Al_2O_3	12.61	15.40	14.90	16.63	15.35	17.29	16.31	12.51	17.85	15.95	18.75	15.33
Fe_2O_3	0.30	1.62	1.46	2.78	1.70	1.51	2.09	4.60	0.64	6.40	2.93	2.83
FeO	0.97	2.49	2.06	2.72	3.46	2.62	2.91	7.88	2.92	1.51	4.56	4.71
MgO	0.15	1.29	1.60	2.02	2.32	2.43	3.26	2.77	5.41	1.74	5.04	5.57
CaO	0.82	4.25	3.79	6.06	4.43	5.97	5.13	5.76	10.96	7.82	3.91	7.34
Na_2O	4.42	4.68	3.80	4.29	2.98	4.11	4.80	3.85	4.38	4.63	3.42	3.33
K_2O	2.44	2.52	3.35	1.39	3.11	1.72	2.79	2.50	0.72	1.27	6.64	2.06
H_2O+	0.51	0.63	1.60	0.57	1.49	1.00	1.14	1.26	1.05	0.92	0.95	2.80
H_2O-	0.10	0.06	0.24	0.19	0.12	0.08	0.17	0.14	0.32	0.36	0.03	0.18
CO_2	...	...	...	...	p. n. d.	...	...	...	...	p. n. d.	p. n. d.	p. n. d.
TiO_2	1.25	2.12	1.63	1.57	1.67	2.74	2.46	3.02	2.72	2.56	2.65	2.92
P_2O_5	0.04	0.21	0.19	0.17	0.17	0.24	0.42	0.58	0.05	0.26	0.08	0.19
MnO	0.06	0.09	0.05	0.05	0.02	0.05	0.08	0.10	0.07	0.09	0.07	0.06
	100.38	100.37	99.50	100.40	97.82*	99.79	100.01	99.73	100.34	96.15*	99.20*	96.12*

* Low summation due to non-determination of CO_2.

Norms

	1*	2	3	4	5	6	7	8	9	10†	11	12
Q	38.46	17.40	20.70	17.64	18.96	15.00	6.96	8.52	...	6.24	...	0.54
Or	14.46	15.01	20.02	8.34	18.35	10.01	16.68	15.01	3.89	7.78	38.92	12.23
Ab	39.30	39.82	31.96	36.15	25.15	34.58	40.35	32.49	37.20	38.77	15.46	27.77
An	3.89	13.34	13.62	21.96	19.18	23.91	14.73	9.45	26.97	19.18	16.40	20.85
Ne	...	...	...	...	...	...	...	...	...	...	7.24	...
Di	...	6.05	3.46	5.62	1.54	3.03	6.05	12.80	21.44	9.50	2.41	11.58
Hy	0.40	0.40	2.40	2.50	6.65	4.70	5.40	6.40	1.70	...	...	10.06
Ol	...	...	...	...	...	...	...	...	1.57	...	9.34	...
Mt	...	2.32	2.09	3.94	2.55	0.46	2.32	6.73	0.93	...	4.18	4.18
Il	2.28	3.95	3.04	3.04	3.19	5.17	4.71	5.78	5.17	3.19	5.17	5.47
Hm	0.32	...	...	...	...	1.12	0.48	...	...	6.40	...	...
Ap	...	0.34	0.34	0.34	0.34	0.67	1.01	1.34	...	0.67	...	0.34

* Includes C 0.92. † Includes Ru 0.90, Wo 2.20.

1. (B. W. 3145). Granite, I.3(4).1(2).4. Chañaral, South side of bay, near Barquito.
2. (B. W. 3119). Granodiorite, "II.4.2.4. Copiapó, Hill near R. R. station.
3. (B. W. 3146). Hyalodacite, I(II).4.2".(3)4. Aguada Encantada, 60 kms. N by E from Potrerillos.
4. (B. W. 3134). Granodiorite, (I)II.4.3.4". 6 kms. SW of Copiapó.
5. (B. W. 3147). Granodiorite, (I)II.4.3.3" Cortadera Station, Quebrada de Asientos, Potrerillos R. R.
6. (B. W. 3137). Hyalodacite, (I)II.4".3.4. Cerro Doña Inez Volcano, 50 kms. NE of Potrerillos.
7. (B. W. 3182). Andesite, II."5.2".4. Quebrada Carrizo, 50 kms. N of Potrerillos.
8. (B. W. 3144). Diabase, II".4(5).2.4. Pueblo Hundido, Near Empalme, Km. 39, Chañaral R. R., Coast Range.
9. (B. W. 3112). Diabase, II.5.3."5. Near Aguada Algarroita, Vallenar.
10. (B. W. 3142). Labradorite porphyry, II."5.3.4". El Tolar, Rio Manfias.
11. (B. W. 3163). Orthoclase diabase (?), II.5".2".3. Cortadera Station, Quebrada de Asientos, Potrerillos R. R.
12. (B. W. 3150). Diabase (?) altered, II".5.3.4. La Puerta, Quebrada Paipote.

INDEX

A. Salaverre, Peru. A landing on northwest coast of Peru in lea of a small promontory. This is a characteristic west coast port of South America, which is poor in harbors. Steep rise of mountain is an effect of recent warping and faulting. Light-colored areas are sand dunes which are here blown up to a height of 3,000 feet.

B. Copiapo. Panoramic view from bridge, comprising sweep from northeast to southwest and showing marshy character of river bed. Wall along river bounds area that has been filled in and on which maximum destruction occurred.

A. Copiapó. The Capella de Candelaria, an adobe chapel more than 100 years old, which has survived repeated earthquakes. Its adobe walls are tied together by iron rods which go through from side to side and are fastened with key plates. The tower is a very light construction with wood frame. On right is a new church built in 1923, collapse of roof of old chapel having rendered it unfit for service.

B. Copiapo. Plaza of Juan Godoy. Houses adjoining the plaza on both sides and the church escaped serious damage to their external walls, but interior plastering was generally destroyed. Foundation material is of gravel and construction of buildings is superior to that of most houses in the city. Block of adobe houses on right was built after earthquake in 1810, at a time when necessity for good workmanship was appreciated.

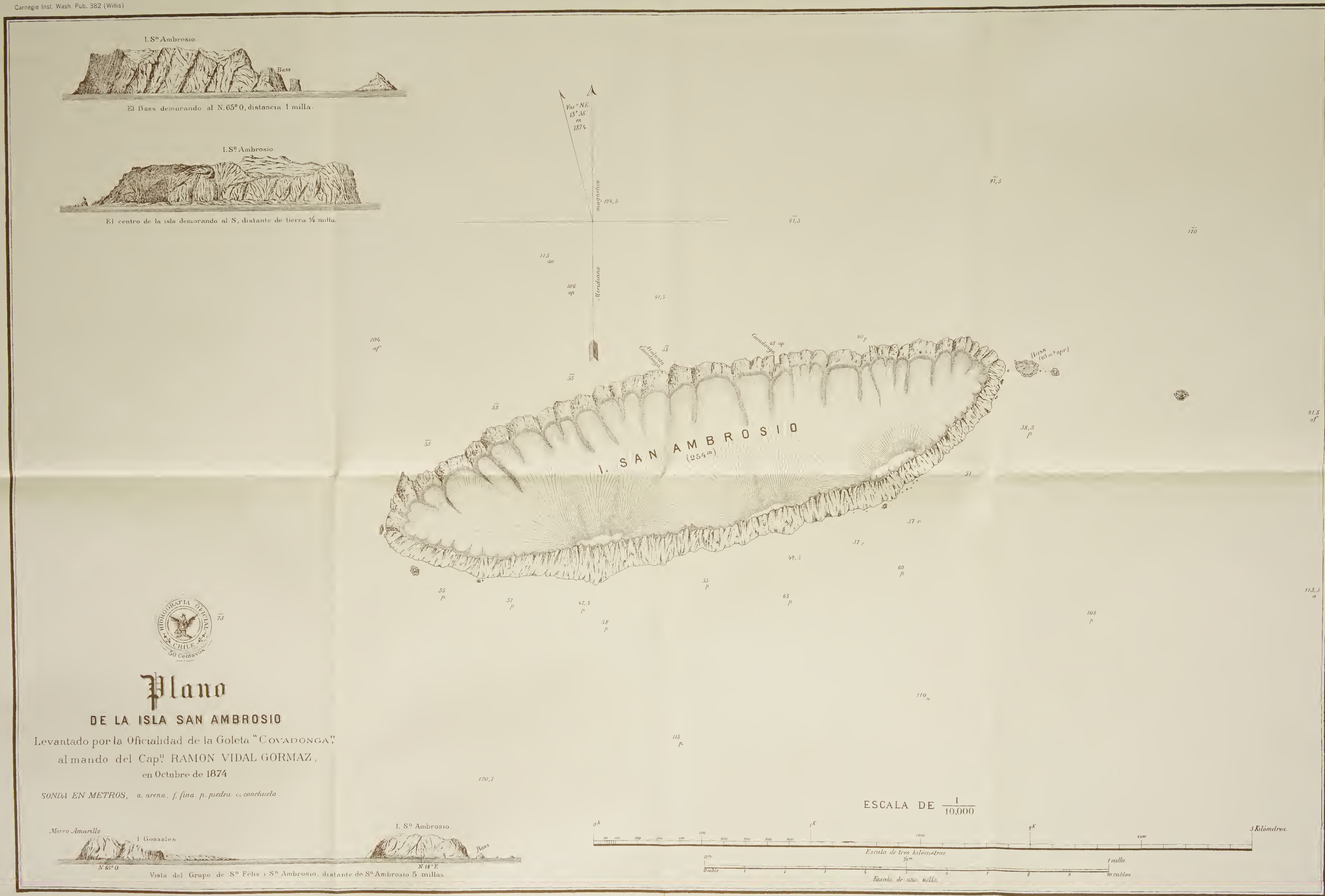
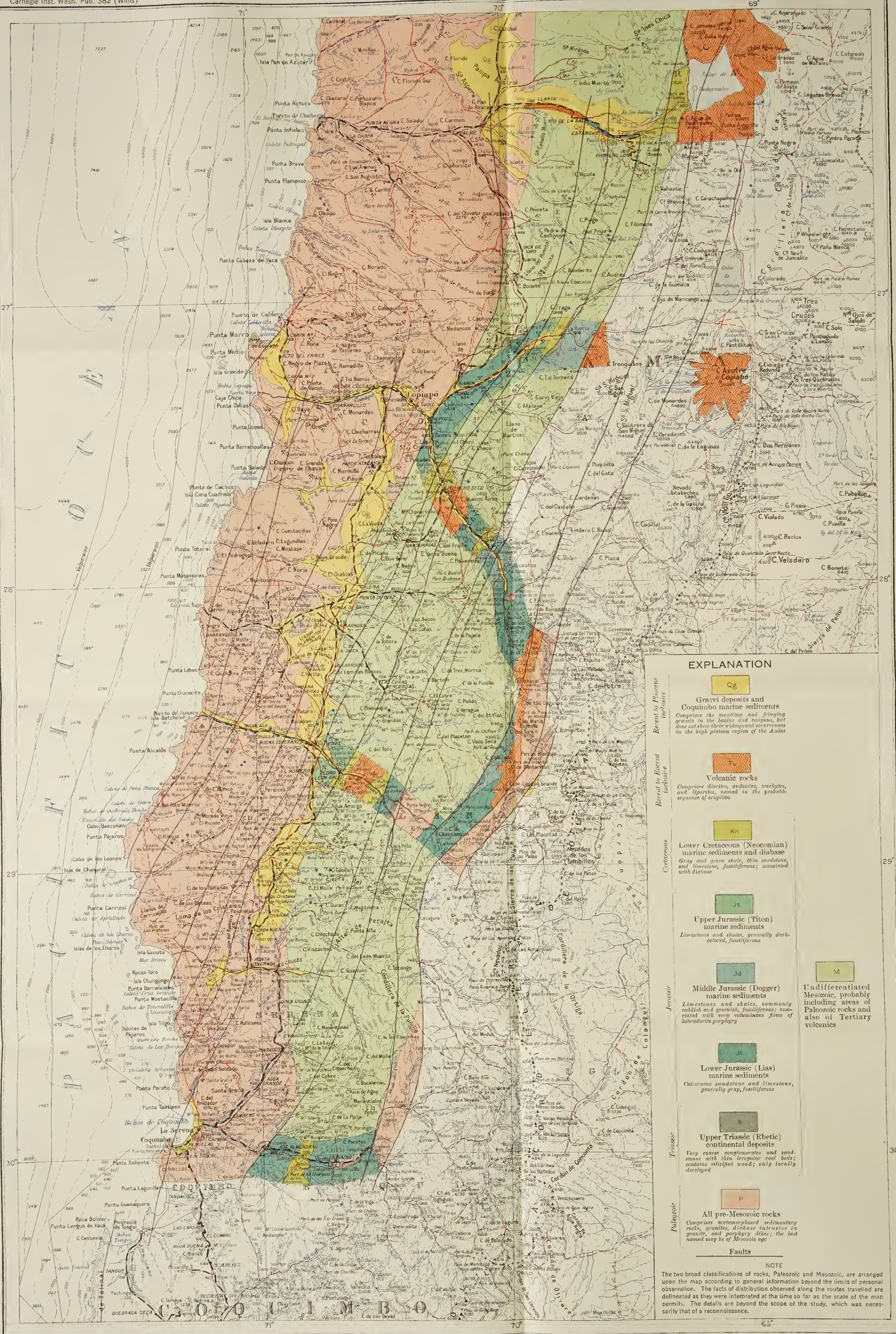


CHART OF THE ISLAND OF SAN AMBROSIO PREPARED BY THE COVADONGA EXPEDITION, CAPTAIN RAMON VIDAL GORMAZ, IN CHARGE, 1874

Facsimile of the official publication by the Minister of the Marine 1875



A. Hoen & Co. Lith.

Base from the Atacama and Coquimbo-San Juan Sheets of the Millionth Map of Hispanic America published by the American Geographical Society of New York

GEOLOGIC SKETCH MAP OF ATACAMA, CHILE

Based upon field notes of Bailey Willis and Johannes Felsch, 1923

Scale 1/1,000,000

10 0 10 20 30 40 50 English Miles

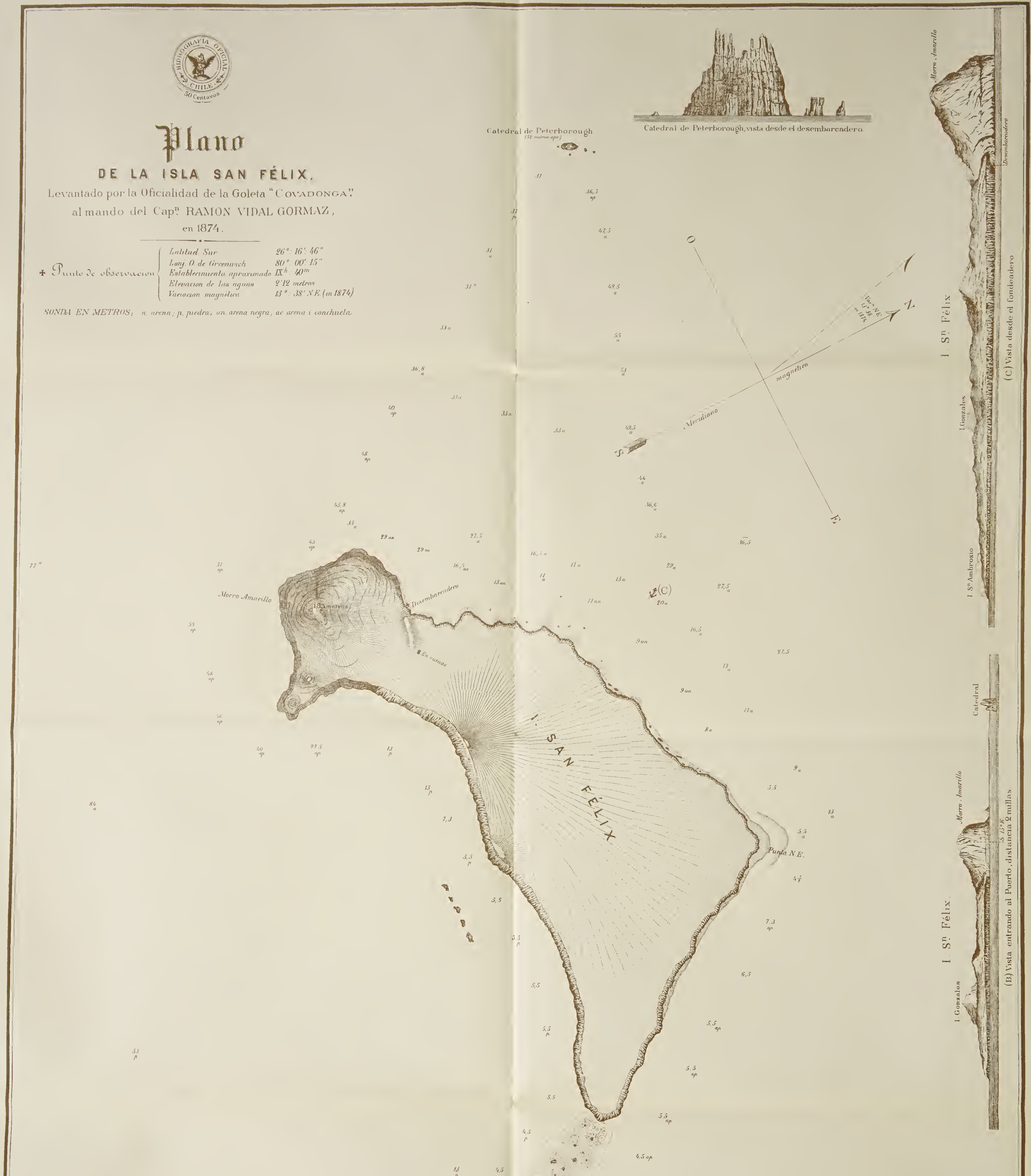
10 0 10 20 30 40 50 Kilometers

A. Vallenar. View of valley looking up Huasco river toward the foothills of the Andes; showing high terrace south of river.

B. Vallenar. Looking north; view of Huasco valley and broad plain which lies between Coast Range on left and foothills of Andes on right; showing successive terrace levels by which the slope rises in three steps to height of 660 feet (200 meters) above river.

A. Upper Copiapo valley. View from southeast to south and west. On left is Cerro Ladrillos, composed of Jurassic lavas and forming western foothills of Andes. Upper Copiapó valley extends into distance southward. High hills behind trees consist chiefly of Paleozoic granite and diabase. On right is upper portion of basin of Copiapó and locality called Paipote.

B. Vicuña. Panoramic view of Rio Elqui, comprising heights of Andes on left and city of Vicuña on right. At this point the Jurassic lavas form an anticline, there are no faults, and the city, although built in the river plain, suffered but little damage.



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