Geology and Ground-Water Resources of the Pica Area Tarapaca Province, Chile

GEOLOGICAL SURVEY BULLETIN 1189

Prepared in cooperation with the Government of Chile and the United States Agency for International Development

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By ROBERT J. DINGMAN *and* CARLOS GALLI O.

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GEOLOGY AND GROUND-WATER RESOURCES OF THE PICA AREA, TARAPACA PROVINCE, CHILE

By Robert J. Dingman and Carlos Galli O.[1]

ABSTRACT

The area of this report is represented by a 30-minute quadrangle covering a part of the western slope of the Andes Mountain Range and the eastern border of the Pampa del Tamarugal. The oasis of Pica, one of the most productive fruit-producing areas in northern Chile, has had more than 400 years of ground-water development. The objective of this investigation was to determine the possibilities of supplementing the ground-water supply of this area.

The sedimentary and volcanic rocks in the area include the Longacho, Chacarilla, Cerro Empexa, and Altos de Pica Formations and the Quaternary deposits. The rocks range in age from early Jurassic to Recent.

The Longacho Formation of Jurassic age consists of fossiliferous marine shale, in which the ammonite *Arietites* is a diagnostic fossil, intercalated with gray well-stratified mudstone, fine-grained sandstone and limestone. The exposed section of this formation is approximately 150 m (meters) thick; however, the base of the formation is covered, and the upper surface is eroded.

The Chacarilla Formation of Jurassic age is of marine and continental origin and is composed of well-stratified reddish-gray and greenish-gray shale, mudstone, sandstone, and lava. The base of the formation is not exposed, and the top of the formation has been strongly eroded so that the total thickness is unknown; however, the measured thickness in the type locality is 1,127 m. The formation contains a few marine fossils, fragments of fossil plants, and tracks of several species of dinosaurs.

The Cerro Empexa Formation of Cretaceous age overlies the Chacarilla Formation with angular unconformity. The upper and lower of the three members of the Cerro Empexa are lithologically very similar and are composed of reddish-gray conglomerate and breccia, the fragments of which are almost entirely of volcanic origin. A few flows of gray trachyte are intercalated with the sedimentary rocks. The upper and the lower member were deposited under subaerial conditions of high topographic relief and during a period of intense volcanic activity. The intermediate member is formed of well-stratified grayish-red fine-grained sandstone and mudstone and contains a discontinuous bed of gypsum in some areas. The thickness of the formation is 600 m as measured from the base to the eroded upper surface.

The Altos de Pica Formation of Late Tertiary and Pleistocene age is of continental origin and rests with marked angular unconformity on the older formations of the area. The formation includes three sedimentary members consisting of piedmont detritus and eolian deposits and two volcanic members

[1] Geologist, Instituto de Investigaciones Geológicas de Chile.

composed of rhyolitic welded tuffs. The cumulative thickness of the five members as measured in their type localities is 735 m; however, the thickness of the formation increases downdip toward the west.

The stratified rocks underlying the Altos de Pica Formation are intruded by plutonic rocks and dikes including granodiorites, granites, tonalites, diorites, gabbro, sodic microgranites, dacites, and andesites. The ages and relations of the intrusions have been only partially determined; however, the largest intrusive masses are believed to be of Late Jurassic age.

The Quaternary sediments that have greatest extent are those of the alluvial fans and the windblown sands which are now contributing to the filling of the Pampa del Tamarugal.

Angular unconformities indicate two orogenic epochs, the first occurring at the end of the Jurassic Period and the second, which was the more intense, during the Cretaceous. Intense folding and thrust faulting were produced during both epochs by strong horizontal compressional forces. The major faults and fold axes of the area trend northward.

The only formation in the area capable of yielding moderate to large quantities of ground water is the Altos de Pica Formation. Most of the 140 lps (liters per second) now discharged from this formation to the surface is obtained from springs, galleries, and one flowing well. The movement of ground water downdip through the formation is blocked by a fault along the east side of Sierra del Longacho; this fault diverts the westward-moving water to the south. In the vicinity of Pica the ground water moves upward through fractures in the Altos de Pica Formation as the sedimentary members of the formation are cemented by silica and have relatively low overall permeability. The localization of ground water in these fractures greatly reduces the possibility of obtaining wells with good yields. The history of well drilling in the area shows that only one good well has been obtained in approximately forty attempts.

INTRODUCTION

LOCATION

The Pica area is in the Departmento de Iquique in the Province of Tarapacá, the northernmost province of Chile, between the eastern edge of the great desert of the Pampa del Tamarugal and the Cordillera of the Andes (fig. 1). The area of the 30-minute quadrangle which was mapped geologically extends from lat 20°15′ S to 20°45′ S and from long 69°00′ W to 69°30′ W (pl. 1). The oasis of Pica is almost in the geographical center of the quadrangle. This village has been a center of agriculture for hundreds of years and at present produces citrus and tropical fruits for most of northern Chile. The village owes its existence to four artesian springs that discharge a total of 53 lps of very good quality water.

PURPOSE AND SCOPE OF THE INVESTIGATION

This project was the first of a series of systematic investigations of the geology and ground-water resources of Chile sponsored jointly by the Corporación de Fomento de la Producción (CORFO) and the International Cooperation Administration (ICA). The results of

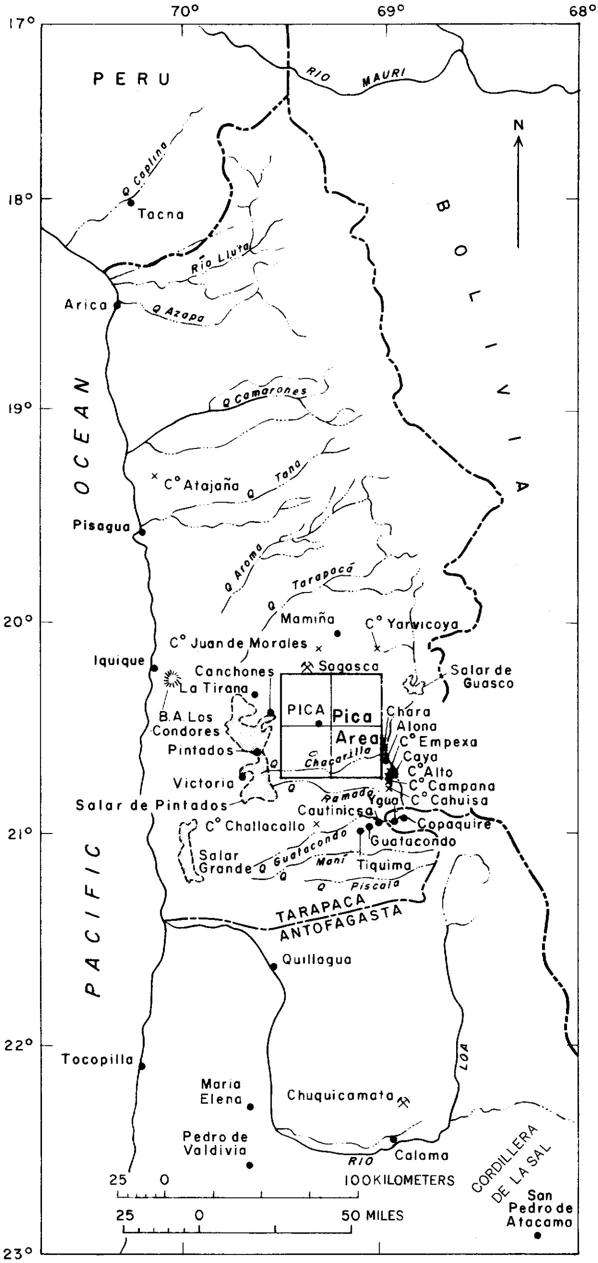

FIGURE 1.—Tarapacá Province and adjoining areas.

this investigation have been published in Spanish by the Instituto de Investigaciones Geológicas de Chile (IIG) as a part of their geologic map series (Galli and Dingman, 1962). The work involved close cooperation between the Ground Water Section of CORFO and the U.S. Geological Survey, which was working in Chile under the auspices of ICA of the U.S. Department of State. The investigation was initiated in July 1955, and the fieldwork was terminated by December 1956. During this period the work was carried on by a group of from one to four geologists.

The Pica area was selected for this first study because of the long-continued interest in developing ground water for irrigation in the vicinity of Pica. This interest has resulted in the drilling of approximately 35 deep wells in the area in the past 40 years. A large amount of money has been spent with very little in the way of encouraging results. The purpose of the present investigation was either to direct the ground-water exploration into more promising localities in the area or to determine that the area was unpromising so that the exploration could be terminated.

Inasmuch as this was the first project planned by CORFO to include both a study of the geology and a survey of the ground-water resources, it was planned so as to be a type or pattern project for future investigations. For all the Chilean personnel, this was their first contact with ground-water geology; therefore, an important phase of the project was their training in basic principles of ground-water investigation.

METHODS USED IN THE INVESTIGATION

The geology was mapped on 15° oblique aerial photographs that had a scale of approximately 1:35,000. These photographs were taken during 1955 to serve as a base for the compilation of the topographic maps of northern Chile, which are being made by collaboration between the Interamerican Geodetic Survey and the Instituto Geográfico Militar (IGM). The preliminary map of the IGM, map 2060 "Pica", at a scale of 1:250,000, was used for reconnaissance work and general orientation in the field.

The geology was transferred from the photographs to the base maps by means of a vertical sketchmaster. Topographic base maps at a scale of 1:50,000 were compiled especially for this investigation on the basis of the first-order triangulation net of the IGM. The geologic map included with this report is a compilation of the four 1:50,000 quadrangle maps (Pica, Alca, Matilla, and Chacarilla) published by the IIG (Galli and Dingman, 1962).

The colors of rocks referred to in this report are based on a comparison of the rocks with the "Rock-Color Chart" prepared by the Rock-Color Chart Committee (2d ed., 1951).

The 136 wells in the Pica Oasis and in the surrounding chacras (small farms) were inventoried, and the altitude of the land surface at each well was obtained by leveling. The water-table map (pl. 2) was based upon the data obtained in this inventory. A water-level recorder was established in a domestic well, and records of several months' variation in water level were obtained. Records of old drilled wells were obtained from the Dirección de Riego and from the Obras Sanitarias of the Ministerio de Obras Públicas (MOP). These wells were then located in the field. However, in a few cases the drifting sands of the desert had obliterated all traces of the wells, and thus it was impossible to locate them. The dug and the drilled wells of Pica were inventoried according to the standard methods of the Ground Water Branch of the U.S. Geological Survey; the drilled wells are given in table 9 and the dug wells are given by Galli and Dingman (1962). All the springs in the area were inventoried (table 10), and the discharge of most springs was measured either by using a current meter or by using a rectangular weir. Samples from the wells drilled by the Dirección de Riego de Tarapacá in the past years were studied, and well logs made from those samples.

Maximum and minimum air temperatures were taken daily in the drilling camp of CORFO during the fall and winter months of 1956.

PERSONNEL AND ACKNOWLEDGMENTS

Octavio Castillo and Alfonso Freile assisted in the geologic mapping, in the well inventory, and in other field and laboratory work.

In an investigation of this type, the diversity of fields involved requires the collaboration of many technicians. Among those who assisted was Beatriz Levi de Valenzuela who made the determinations of approximately 120 rock specimens and the description and classification of the majority of the thin sections that are included in this report. José Corvalán and Ernesto Pérez identified the fossils that were collected; Hernán Cusicanqui supervised the chemical analyses of the water and rock samples; Sonia Mehech and Adela Aquilar helped in describing the petrographic thin sections; Edgar Koeneman, of the ICA, generally supervised the well-drilling program of CORFO and solved many of the technical problems that originated during the drilling of the wells; and Enrique Froehlich, of the agricultural experiment station "Canchones" of CORFO, contributed much of the data concerning the climate, soils, and agriculture of the Pampa del Tamarugal.

Governmental offices, principally those of the Dirección Provincial de Riego de Tarapacá of the Ministerio de Obras Públicas and the

Empresa Nacional del Petróleo (ENAP), collaborated in many ways in the solution of the problems of logistics and also in the solution of the technical problems which arose during the investigation. They generously contributed equipment and also information concerning, for example, well logs, surface geology reconnaissance, fossil localities, and stratigraphic correlations.

The geologists Mordojovic, Cecioni, García, and Marino—of ENAP—have been conducting geologic exploration for petroleum in the area covered by this report and in adjacent areas since 1956. They have contributed many oral and written communications (1957; 1958) based on their field observations.

To the above mentioned personnel and to all others who have in many ways aided in the realization of this publication, we express our most sincere gratitude.

PREVIOUS INVESTIGATIONS

Brüggen (1918) published a geologic sketch map of the area north of Mamiña and east of Mamiña to the international boundary. The map shows the general distribution of the consolidated sediments of the Liparítica Formation, which are not differentiated by age, and the distribution of the sand and alluvial fill of the Quaternary. The work of Brüggen is relatively accurate, and the map and report served as a valuable guide to the authors in the beginning phases of the investigation. Brüggen (1946, 1950) made a number of other observations related to the geology and ground-water resources of the area.

Bowman (1909, 1916, 1924) visited the area and made a brief study of its geography. Taylor (1947) made a reconnaissance investigation of the water resources of the Pica area as part of an overall study of the ground-water possibilities of the Province of Tarapacá.

The Dirección Provincial de Riego (Department of Irrigation) de Tarapacá has for many years conducted a program of ground-water exploration by means of large-diameter drilled wells (as deep as 486 m) in the Pica area. The stratigraphic and hydrologic data obtained from these wells have permitted a thorough understanding of the subsurface stratigraphy of a part of the area.

Unpublished articles on various subjects are available.[2]

[2] Unpublished articles:

Biese, W., 1954a, Informe sobre el yacimiento de caliza "Santa Rosa Oriente," Iquique: Santiago, Chile, Corporación de Fomento de la Producción.

——— 1954b, Ampliación del informe del 27 de Febrero de 1954 sobre el yacimiento de caliza "Santa Rosa Oriente," Iquique: Santiago, Chile, Corporación de Fomento de la Producción.

——— 1954c, El Jurásico de Iquique: Santiago, Chile, Corporación de Fomento de la Producción.

——— 1955, Informe preliminar sobre el Jurásico de Iquique: Santiago, Chile, Corporación de Fomento de la Producción.

Parker, R., and others, 1957, Geology of the Quebrada Cerillos Area, Atacama Province, Chile: Santiago, Chile, Instituto de Investigaciones Geológicas.

GEOGRAPHY

SURFACE RELIEF AND DRAINAGE

The land surface of the Pica area is for the most part high, and altitudes range from 4,500 m in the northeastern part of the area to 1,000 m in the southwestern part. This great difference in altitude is related to the peculiar geographic situation which occurs where the slopes of the Andes merge into the Pampa del Tamarugal.

The area known as the Altos de Pica is a high plateau inclined toward the west and slightly toward the south. The crest of the plateau is nearly horizontal, has an average altitude of 4,000 m, and extends between the high mountains of Yarvicoya (Columtucsa) (5,180 m) to the north and the group of mountains known as Empexa (Chacarilla) (4,500 m) to the south. The crest of the plateau is a surface-water divide which has a moderate gradient toward the east and a relatively low gradient toward the west.

At approximately long. 69°15′ W. the gradient toward the west becomes less steep as the Altos de Pica terminates in a depression known as Pampa Pica (Pampa Brüggen); this depression extends from the Quebrada Seca in the north to Puquio de Núñez in the south and is 6 to 8 km wide. A range of hills, of which Cerro Longacho is the highest (alt 1,627 m), forms the western boundary of Pampa Pica.

The area to the west of Cerro Longacho is included in the Pampa del Tamarugal which within the area of the Pica quadrangle is locally known as Pampa Esmeralda. In the southern part of the quadrangle, the Pampa del Tamarugal includes the northeastern part of the alluvial fan of the Quebrada Chacarilla. The gentle westward slope of the Pampa is broken only by the low ranges of hills among the alluvial fans and windblown sands west of Cerro Longacho in Pampa Esmeralda.

The surface drainage of the Pica area consists of a system of dry valleys and canyons (quebradas) forming a parallel pattern toward the west and southwest. This system transports runoff from the rare periods of precipitation in the Andes to the Pampa del Tamarugal. The only permanent stream in the area is that of the Quebrada Chacarilla. This stream disappears on reaching the alluvial cone at the mouth of the quebrada.

The deeper quebradas of the area, listed from north to south, are Tambillo, which is a part of the drainage system of the Quebradas Sagasca, Ancha, Seca, and Saguachinca, which are quebradas that average 200 m in depth and discharge into Pampa Pica; the Quebrada Quisma, which south of Pica is known as the Quebrada Chintaguay; the Quebrada Puquio de Núñez and Chacarilla. Near Cerro Longacho the Quebradas Sagasca and Ancha join and cross the range of hills north of Matilla to reach Pampa Esmeralda.

Quisma is the second largest quebrada in the Pica area, if one judges by the size of area drained, and it has a correspondingly large alluvial fan. The Quebrado Puquio de Núñez is smaller and joins with another unnamed quebrada before discharging close to the oasis of Puquio de Núñez.

Chacarilla is the largest quebrada in the area and is the only one that crosses the Altos de Pica; its stream partially drains the depression that lies to the east of the Altos de Pica. The quebrada is formed by the joining of the two Quebradas Chara and Caya. Chacarilla has several other important tributaries, including Infiernillo from the north and Empexa from the south. The Quebradas Higueritas and Los Tambos originate to the west of the range of hills of Empexa and are a part of the drainage system of the Quebrada La Ramada. Near Alona the Quebrada Chararilla has a depth of 900 m. The relatively narrow upper valley widens rapidly where the course of the quebrada emerges from the area of harder and more resistent Mesozoic rocks and enters the softer and more easily eroded Tertiary-Pleistocene rocks. The alluvial cone of this quebrada is one of the largest in the Pampa del Tamarugal.

CLIMATE

TEMPERATURE

Data concerning the temperatures were obtained from the observations made at the CORFO drilling camp from May to July 1956; at the drilling camp Esmeralda during some months of 1955, 1956, and 1957; and at well 5 of the Dirección de Riego during seven months of 1955.

The maximum and the minimum temperatures from the various localities are shown in figure 2. According to the data of figure 2, the temperatures are moderate and constitute in this respect a climate that is favorable for the growth of citrus fruits.

HUMIDITY

The only available data on humidity were collected at the drilling camp of Esmeralda by the technicians of the Departamento de Riego. The absolute humidity is very low, but, as a result of the large diurnal temperature variations, the relative humidity oscillates from a minimum of approximately 10 percent during the hottest part of the day to 100 percent during many of the nights. Figure 3 includes the thermograph for the period from February 28, 1956, to March 5, 1956. An inverse relationship between temperature and relative humidity

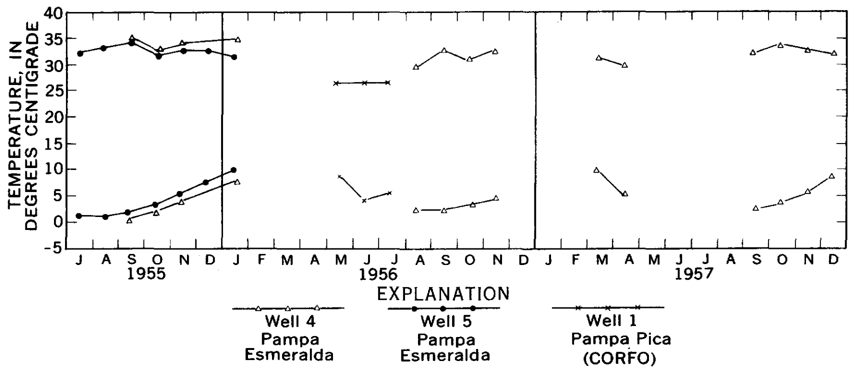

FIGURE 2.—Mean monthly maximum and minimum temperatures in the Pica area.

is clearly demonstrated in this figure. As the temperature increases during the day, the relative humidity decreases.

PRECIPITATION

The period of maximum rainfall is from December to March and corresponds to what is known as the "Bolivian Winter." The precipitation is derived from the margins of the humid air masses which move over the South American Continent from the Atlantic Ocean. These are the same air masses that contribute heavy precipitation to the Amazon basin and to the drainage basin of the Río de la Plata.

According to Almeyda (1949, p. 39, fig. 8), the 10, 25, 50, and 100 mm (millimeters) per year isohyets of precipitation pass through the Pica area. The 10 mm isohyet passes approximately through the center of the region. West of this isohyet the region virtually has no rainfall and, according to Bowman (1924, p. 56), is the part of the earth that has the least amount of precipitation. The observations which the authors of this publication made of the natural vegetation, drainage pattern, and geomorphology tend to support the conclusions of Almeyda Arroyo as illustrated on his rainfall map. On the Altos de Pica vegetation consisting of grasses and low shrubs indicates the intensity of the precipitation; the vegetation begins as a sparse cover at approximately 2,600 m and becomes more abundant as altitude increases.

Although no records of precipitation have been made for the area, there are a number of stations reporting precipitation within a radius of 100 km (kilometers) from Pica. The data from these stations may be considered representative of the amount of precipitation within the mapped area. The data show that precipitation increases with altitude. The stations between sea level and 1,000 m have virtually no rainfall. Iquique (49 years of record) has an average annual rainfall of only 1.9 mm per year and a maximum recorded an-

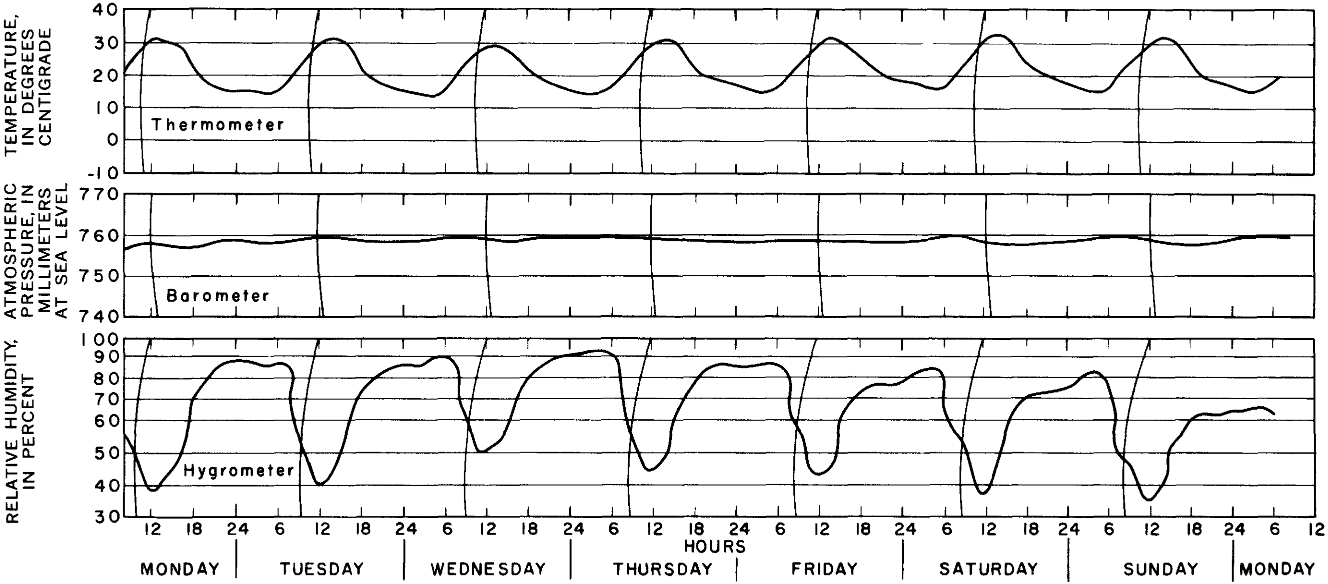

FIGURE 3.—Temperature, atmospheric pressure, and relative humidity at well 4, Pampa Esmeralda (MOP), during the week February 28–March 5, 1956.

nual rainfall of 20 mm in 1940. Canchones, at an altitude of 961 m, reported only one rainfall (less than 2 mm) during the 22 years of record. Pica, at an altitude of 1,300 m, has occasional light showers. Although no precipitation records are available, information obtained from the local residents indicates that the average annual rainfall may be on the order of 10–20 mm.

At 3,000 m, according to the data illustrated in figure 4, the average annual precipitation has increased enough to reach 100 mm per year, and at 4,000 m it is over 200 mm per year. Extrapolation of the curve of maximum precipitation shows that the maximum precipitation could reach approximately 500 mm at an altitude of 4,000 m.

EVAPORATION

Measurements of the rate of evaporation were made in the drilling camp of Esmeralda by means of a Wenzel evaporimeter during the months of August to November 1956; March, April, September, October, November, and December 1957. The data thus obtained were made available to the authors by the Dirección de Riego and are summarized in table 1. An absolute maximum evaporation of 14.2 mm was recorded one day during November 1957, and a minimum evaporation of 2 mm was recorded during August 1956.

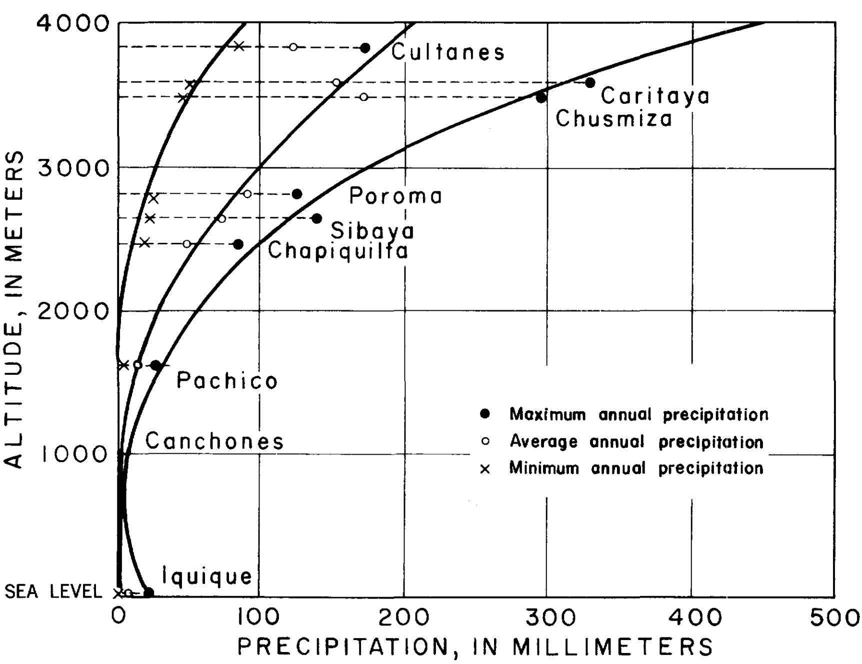

FIGURE 4.—Relation between altitude and precipitation at representative stations in the Pica area.

Observations of evaporation have been made at Canchones for several years; during this period the daily maximum reported was 34 mm, and the minimum, 11.2 mm. These values are higher than those obtained by Compañía Anglo-Lautaro at Pedro de Valdivia, Province of Antofagasta (located approximately at lat 22°30′ S., long 69°45′ W. in the nitrate area of the Pampa del Tamarugal) in evaporating pools 200 m by 220 m. In these pools the minimum daily evaporation was 1 mm and the maximum 12 mm; the average was 6 mm. The variation in data from the three stations is large and is probably due to the differences in techniques used. In general, the data demonstrate the intensity of evaporation in a desert climate.

TABLE 1.—*Average daily evaporation in Pampa Esmeralda (as reported by MOP)*

Month	*Average daily evaporation (mm)*	*Month*	*Average daily evaporation (mm)*
1956		*1957*	
August	6.3	April	4.9
September	6.9	September	8.1
October	6.9	October	8.2
November	6.6	November	9.2
1957		December	5.8
March	5.2		

CULTURE

POPULATION

The extreme aridity of the mapped area has resulted in a concentration of population near the few sources of water. The only villages in the area are Matilla and Pica. Pica has a population of approximately 1,800 inhabitants.

Matilla is 4 km southwest of Pica and has a population of about 100 inhabitants. A few years ago this village was considerably larger. However, the water supply was reduced by the drying up of a spring in the Quebrada Chintaguay, and the reduced water supply caused a corresponding reduction of the cultivated area and population.

Other inhabited areas in 1957 were Jucuma, Alca, La Calera, Chacarilla, Puquio de Núñez, and the camp at well 5 in Pampa Esmeralda. The total population of the area is approximately 2,000 persons.

AGRICULTURE

The principal economic activity of Pica and Matilla is agriculture. The cultivated area of Pica is approximately 90 hectares of which 45 are planted with orange trees, 30 with lemon trees, 10 with mango trees, and 5 with guava trees.

Approximately 0.5 lps per hectare is used for irrigation of fruit trees. This figure is surprisingly low in view of the high permeability of the soils and the arid climate of the area. The efficiency in water use may be due to a soil high in humus developed in the Pica area during the thousands of years in which this area was covered by heavy vegetation. The antiquity of the springs is indicated by the layers of peatlike material which exists to a depth of 10–15 m.

In Puquio de Núñez the principal crops are oranges and, to a lesser extent, lemons, guavas, and grapefruit. At the time this report was being written, work was being conducted to extend the galleries to increase the available water and to enlarge the number of hectares under cultivation.

At La Calera, vegetables are raised on 2 hectares. In the Quebrada Chintaguay, there is a small cultivated area which has a few mango trees located near a flowing well. In Chacarilla crops of pears, chili peppers, and corn are raised on less than 1 hectare. The 1 hectare of irrigated land in Jucuma produces pears, apples, quinces, chili peppers, and alfalfa.

The agricultural production of the area has changed for various reasons. Puelma (1855, p. 670) stated that in Pica the crops consisted of grapes, figs. pomegranate, guavas, guamos, and some green vegetables. The reduction of the water available in Matilla [3] caused a reduction of vegetation; although in 1924 there were 39,700 fruit trees, by 1944 there were only 3,320.

Small numbers of horses, donkeys, and mules are raised for local use, and a few head of sheep, goats, llamas, and swine are raised for local consumption.

TRANSPORTATION

Pica and Matilla are served by three bus lines, which have routes to the nitrate mines, to the railroad stations, and to Iquique. Within the area, burros are the principal means of transportation both for the populace and for cargo. There is a trail from Pica to Bolivia over which light trucks or 4-wheel-drive vehicles may pass. Most of the travel to Bolivia is on foot over various trails.

The roads are generally in bad condition. The best road runs from Matilla to Pintados, which is on the Pan-American Highway. The road from Matilla to Canchones and La Tirana, which connects with the Pan-American Highway to Iquique (130 km), is in general unimproved and in many localities follows an old wagon trail. The remaining roads are primitive trails made by animals or animal-drawn vehicles. An unimproved landing strip at Pica is used by small planes of the military air base near Iquique; these small planes can land on the loose sand of the desert.

[3] Ojeda, S., 1945, Regadío de Matilla: Santiago, Chile, Ministerio de Obras Públicas, v. 441, p. 8.

GEOLOGY

STRATIGRAPHY

MESOZOIC ROCKS

Sedimentary rocks of marine and continental origin crop out within the mapped area and range in age from Jurassic to Quaternary; they are divided into five formations. The formations are, from oldest to youngest, the Longacho, Chacarilla, Cerro Empexa, Altos de Pica Formations, and the Quaternary deposits (table 2 and fig. 5).

The Longacho Formation of Early Jurassic (Lias) age is composed of shale, mudstone, fine-grained sandstone, and limestone. The formation is exposed in several small areas north of Pica where it is overlain unconformably by the Altos de Pica Formation as illustrated in the geologic sections of plate 1.

The Chacarilla formation of Late Jurassic age is well exposed in the southeastern part of the Pica area. The formation is composed of sandstone and shale of continental and near-shore origin.

The Cerro Empexa Formation of Cretaceous age overlies the Chacarilla Formation with angular unconformity. The Cerro Empexa is for the most part composed of clastic material of volcanic origin and is divided into three members.

The Altos de Pica Formation of Late Tertiary and Pleistocene age overlies the Mesozoic sediments with an angular unconformity of as much as 90°. This angular unconformity marks the strongest period of orogeny that has affected the area. The Altos de Pica Formation has the widest areal distribution of any of the formations and is also the most promising hydrologically. The Quaternary is represented by a thick and irregular accumulation of alluvial and eolian material, found principally in the western part of the Pica area.

LONGACHO FORMATION

The Longacho Formation of Early Jurassic age is named for exposures in the Cerro Longacho area. These rocks were first reported by Brüggen (1918, p. 9) and later by Felsch (1920, p. 470). The formation includes beds of gray fossiliferous marine shale, limestone, mudstone, and fine-grained sandstone. The structure is an open asymmetrical anticline intruded in some localities by igneous rocks.

The formation crops out over an area of approximately 3 sq km (square kilometers) which includes Cerro Longacho. Because the formation is poorly exposed, the total thickness could not be accurately measured. The exposed thickness of the formation, however, is estimated to be from 120 to 150 m. It is not possible to determine the relationship between this formation and the other formations of the area except with the overlying Altos de Pica Formation. The Longacho

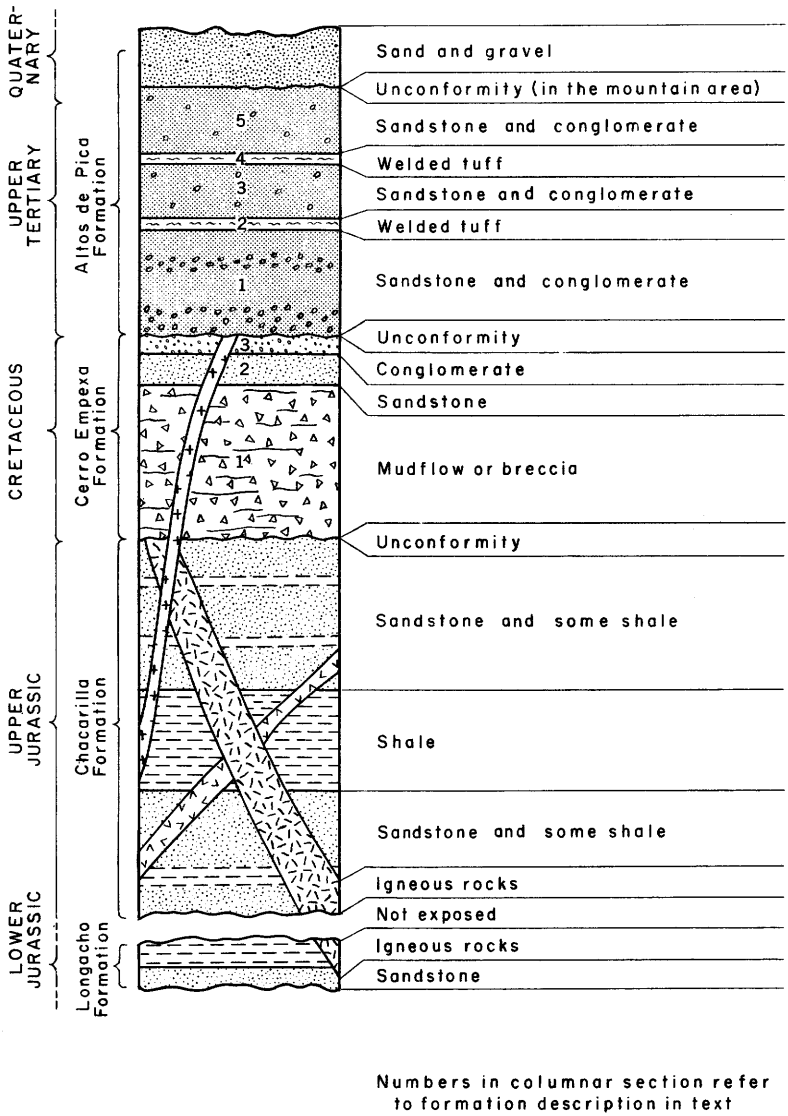

FIGURE 5.—Stratigraphic column and relation of igneous rocks.

Formation is exposed as inliers of Jurassic rock surrounded by deposits of Tertiary and Quaternary age which overlie the Longacho with angular unconformity.

The most abundant rock types are silicified mudstone, limestone, and shale. In most localities, the rocks are light colored and range from yellowish brown to gray and green. In a few localities they are stained red by limonite. The shale has a conspicuous fissility and

TABLE 2.—*Geologic formations in the Pica area*

Era	Period	Epoch	Age	Formations	Intrusive rocks penetrating the formations	Rocks and field relations	Sedimentary environment	Fossils	Thickness, in meters	Water-bearing properties
Cenozoic	Quaternary			Altos de Pica		Sand Limestone Mudrock Fanglomerate Chlorides and sulfates	Continental		Variable	In Chacarilla Quebrada, water bearing but probably of low permeability. In other areas, Quaternary sediments fair source of water where saturated.
	Tertiary	Late Tertiary				—Unconformity— (in the mountain area) Gravel Sand Conglomerate Tuff Welded tuff Sandstone Fanglomerate	Continental		[1] 735	Contains water in sedimentary members but permeability reduced by cementation. Igneous members contain small quantities of water in fractures.
Mesozoic	Cretaceous			Cerro Empexa	Amphibolitic diorite porphyry Andesite	—Unconformity— Trachyte Siltstone Sandstone Gypsum Conglomerate Breccia	Continental		[1] 600	Very poor.
	Jurassic	Malm		Chacarilla	Granite Granite porphyry Granodiorite Sodic Microgranite Diorite Andesite Amphibolite	—Unconformity— Siltstone Sandstone Shale Orthoquartzite Conglomerate Trachyte	Marine and Continental	*Posidonomya* sp., *Exogyra* sp., plant fragments, ammonite, dinosaur tracks	[1] 1,127	Very poor.
		Liassic	Lotharingian Sinemurian	Longacho	Rhyolite Dacite Andesite Diorite Gabbro Granite porphyry	———?——— Shale Siltstone Sandstone Limestone Tuff	Marine	*Arietites* spp., *Nucula*? sp., *Oxytoma* sp.	[2] 120–150	Very poor.

[1] Thickness at type locality.
[2] Estimated minimum thickness.

parts in laminae about 1 mm thick. In localities where the shale is highly silicified, the tendency is for the rock to fracture in a conchoidal pattern, leaving sharp-edged fragments.

Fine-grained sandstone is also distributed throughout the formation. The matrix of the sandstone is composed of clay and calcite cemented with a microgranular calcite; the sand grains are predominantly quartz.

In places, layers of tuff are intercalated. The tuff is silicified to the extent that it is difficult to differentiate in the field between the pyroclastic rock and the mudstone.

A line of small hills north of Cerro Longacho includes outcrops of limestone, jasper, and fine-grained diorite. These hills are just to the west of the extension of the fault which forms the eastern boundary of the Sierra del Longacho. The microcrystalline limestone is brownish gray and contains fragments of sponge spicules. In some localities near the diorite intrusion the limestone has been silicified to jasper by contact metamorphism.

South of Cerro Longacho the original stratification is obscured by hydrothermal alteration which has caused chloritization and silicification of the sediments. Where the sediments have been most altered, secondary foliation has been imparted, and the color is a yellowish orange with bluish-green zones. The greenish color is due to chlorite which in some beds appears as small flecks more intense in color than the pastel background. The altered rocks are friable where they have been exposed to weathering. Dark-gray silicified concretions ranging in size from a few centimeters to 1 m have been observed in these beds.

The fine stratification, the absence of ripple marks and crossbedding, the predominance of mudstone and fine-grained sandstone, as well as the faunal assemblage, suggest marine deposition at moderate depths. A few beds of medium-grained sandstone and the presence of bivalve fossils suggest that at least parts of the formation were deposited in the sublittoral zone.

The Longacho Formation is intruded by dikes of andesite, dacite, diorite, granite porphyry, and gabbro; these dikes have altered adjacent host rocks by contact metamorphism. Coarse-grained light-gray quartzite was observed north of Cerro Longacho in contact with the andesite intrusive.

The following section, which was measured in a small quebrada northeast of Cerro Longacho, includes only a part of the total thickness of the formation, but in this locality the rocks are believed to be representative of the formation.

Section of the Longacho Formation 500 m northeast of Cerro Longacho

Altos de Pica Formation (member 2).
Angular unconformity.

Longacho Formation:	Meters
Shale, gray, and light-gray fine-grained sandstone, with some reddish-gray beds colored by iron oxide; very regular stratification, the beds having a minimum thickness of 1 mm and a maximum of 8 cm; a few thin interbeds of tuff	7
Sandstone, light-gray (weathered pinkish gray), very hard	1
Shale and mudstone, light-gray; in part highly silicified	4
Sandstone, gray (weathered reddish gray), very hard	1
Shale and mudstone, light-gray, with intercalated gray fine-grained very hard sandstone in beds 50 cm thick; near base, a few interbeds of greenish-gray tuff, laminated in parts	54
Sandstone, reddish-gray; laminated; in beds 50 cm thick	15
Mudstone, sandstone, and tuff, variegated, thin-bedded	5
Sandstone, gray, fine-grained	1
Mudstone, light-gray, thin-bedded	5
Exposed thickness of Longacho Formation	93

Base covered.

The age of the formation as determined by three species of *Arietites* is earliest Jurassic (Lotharingian and Sinemurian). Both Brüggen (1918, p. 6) and Felsch (1920, p. 470) assigned a Jurassic age to the rocks of this formation but did not attempt to place them as to epoch or age.

The fossils which were collected in three scattered localities are all of Jurassic age. Corvalán has identified the following fossils:

Pelecypoda

Oxytoma sp. Five incomplete specimens that have well-preserved characteristics of the subgenus *Pteria* (=*Avicula*); four of these specimens belong to the same species, but the fifth, which is the mold of a right valve, may represent another species.

Nucula ? sp. One poorly preserved mold.

Cephalopoda

Arietites sp. 1. One well-preserved specimen and eight mold fragments.

Arietites sp. 2. Eight mold fragments.

Arietites sp. 3. One mold fragment.

The sediments of the Longacho Formation represent the easternmost outcrop of marine Mesozoic sediments in this locality; however, there are extensive outcrops of marine and continental Mesozoic sediments in the Quebrada Chacarilla to the south and in the Quebrada Tarapacá to the north.

CHACARILLA FORMATION

GENERAL ASPECTS

The Chacarilla Formation, of Late Jurassic age, is named for typical exposures near the small cultivated area of Chacarilla, in the quebrada of the same name. The sediments are well exposed in this locality, and the type section was measured 1.5 km to the southwest of Chacarilla.

The Chacarilla Formation consists of a thick section of well-stratified consolidated sediments including mudstone, shale, sandstone, orthoquartzite,* and a few trachyte flows. The color of the sediments ranges from reddish gray to greenish gray. The lower part of the formation is predominantly of shallow-water marine origin, and the upper part, of near-shore continental origin. The rocks are strongly folded.

These rocks were first described by Felsch (1917) and later by Decat.[4] In 1957, García remeasured Felsch's section in the Quebrada Guatacondo, noting many additional stratigraphic, structural, and paleontological details. The formation is exposed in an area from the Quebrada Chacarilla and Alona toward the south. To the east the Chacarilla Formation is bordered by the Cerro Empexa Formation, and to the west, by the Altos de Pica Formation. In the outcrop area the formation is very well exposed but in a few localities it is covered by conglomerates and tuffs of Tertiary-Pleistocene age. The thickness at the type locality is approximately 1,100 m; however, this is not the total thickness of the formation. According to García, 3,650 m of the formation are exposed in the Quebrada Guatacondo.

The base of the formation is not exposed within the Pica quadrangle. Felsch (1917) reported that rocks equivalent to the Chacarilla Formation in the Quebrada Guatacondo are in disconformable contact with underlying bituminous black shales and quartzitic sandstones, containing poorly preserved ammonites of Early Jurassic age. García and the authors reached the same conclusions.

The Chacarilla Formation is overlain in some areas by the Cerro Empexa Formation. The contact is marked by an angular unconformity where exposed near Chacarilla and in the Higueritas syncline. In other localities the Altos de Pica Formation overlies the Chacarilla Formation with an angular unconformity of as much as 90° (fig. 6).

Parallel or erosional disconformities typical of continental sedimentation exist within the formation; however, in general, beds are well stratified. The upper part of the formation was deposited in

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*Quartz sandstones that have a siliceous cement and therefore fracture across the grains (Pettijohn, 1957, p. 295).

[4] Decat, J., 1931, Informe sobre el reconocimiento geológico de la provincia de Tarapacá teniendo en vista la posibilidad de encontrar petróleo y agua: Santigao, Chile, Directción de Obras Públicas, v. 441.

FIGURE 6.—Angular unconformity between the Chacarilla and the Altos de Pica Formation. Exposed wall of the Quebrada Chacarilla is approximately 700 m high.

fresh water or under lagoonal conditions, and the lower part of the formation is predominantly of shallow-water marine origin.

There is little variation in the type and color of the sediments included in the formation. The beds are reddish gray and greenish gray and range from claystone to medium-grained sandstone. Only one conglomerate bed of small areal extent was found in the formation.

One of the most common rocks of the formation is reddish-gray fine-grained sandstone. Microscopically this rock is cemented by hematite, which in some parts is concentrated in irregular forms. The sand grains are generally subangular and consist of quartz that shows undulatory extinction.

The orthoquartzite occurs in many outcrops. Microscopically the cement is seen to consist of recrystallized quartz grains and sericite. Hematite is abundant, but the percentage in the rock is variable.

Calcareous beds of dark-gray carbonaceous shale have been mistaken for coal deposits by the local populace. The dark-gray color of these beds results from the included organic material.

The one conglomerate bed in the formation is 3 m thick and consists of a coarse-grained sandy matrix cemented with calcium carbonate. The boulders are of heterogeneous origin and are well rounded. Some of the boulders are composed of quartz showing undulatory extinction; others are composed of quartz porphyry that has a microgranular groundmass and quartz phenocrysts, alkalic feldspars, chert, limestones with algal(?) impressions, sericitic quartzite, and well-rounded epidote.

Several trachyte flows, averaging approximately 20 m in thickness, are intercalated with the sediments and are exposed 3 km east of Chacarilla chacra. The composition and the texture of the rock vary little throughout the lava flows. Macroscopically the rock is dark greenish gray; it is porphyritic in texture and has feldspar phenocrysts. In thin sections the groundmass is seen to consist mainly of orthoclase that has magnetite microcrystals. The most abundant phenocrysts are orthoclase as large as 2 mm in diameter and plagioclase, 8 mm in diameter; magnetite phenocrysts, 2 mm in diameter are present in small proportion. Sericite, chlorite, and calcite are alteration products.

The base of the Chacarilla Formation as exposed west of Ygua in Guatacondo Quebrada consists of rocks that are not similar to the typical beds of the Chacarilla Formation. In this locality the rocks consist of hundreds of meters of well-stratified silicified sandstone that is weathered uniformly gray. Near the base of this sandstone is a 20-meter-thick bed of mudstone that contains molds of plants. The occurrence of fossils in this locality was first reported by García; later, the authors collected a number of specimens and submitted them to Dr. Humberto Fuenzalida of the University of Chile for identification. However, no age determination could be made because the specimens lacked distinguished features.

The following stratigraphic section was measured in the type locality.

Section of the Chacarilla Formation measured from its upper contact with the Cerro Empexa Formation at the point where the contact crosses the Quebrada Chacarilla southward toward the interior of the Quebrada del Carbón

	Corrected thickness (meters)
Cerro Empexa Formation.	
Angular unconformity.	
Chacarilla Formation:	
Sandstone, dark-gray (weathered reddish brown), fine-grained, well-sorted; some layers laminated; more easily eroded than the overlying breccia of the Cerro Empexa Formation; at base, grades downward into reddish-gray siltstone and friable shale that weather to angular fragments	19
Sandstone, reddish-gray, very fine grained, well-sorted, hard, well-cemented; in beds 0.4–0.5 m thick	98
Orthoquartzite, light-gray (weathered reddish gray), fine-grained, massive, very resistant to erosion	24
Sandstone, reddish-gray, fine-grained, weathered, with intercalated shale lenses	21
Sandstone, reddish-gray, fine-grained, with intercalated beds 0.2–0.5 m thick of shale of the same color; bedding planes have current lineations; a few beds show crossbedding. Hard, well-cemented beds of sandstone and shale are intercalated with friable beds	300

Chacarilla Formation—Continued	*Corrected thickness (meters)*
Shale, greenish-gray, friable, with intercalated hard beds of reddish-gray sandstone. Color of the shale may be due to alteration as a change from greenish-gray to reddish-gray has been observed along the strike of beds. Some poorly preserved plant remains found	96
Shale, greenish-gray, friable, with intercalated hard sandstone beds 1–2 m thick and beds 0.1 m thick of dark-gray shale containing carbonaceous material and calcite. An andesitic dike, striking N. 65° W. and dipping 60° N., intrudes these beds	128
Shale, dark-gray (contains carbonaceous material and calcite), weathered, with intercalated reddish-gray, hard, massive sandstone	79
Sandstone (80 percent), reddish-gray, hard, massive, with intercalated beds 4 m thick of dark-gray shale (20 percent). Shale is laminated (0.5 mm); has carbonaceous material and calcite; contains *Posidonomya* sp	99
Granite porphyry, light-gray (weathered light yellowish brown); shows altered zones in brown veins; occurs as sill, striking N 30° E., dipping 76° W.; has uneven and rounded contact with the sedimentary rocks	--
Sandstone, greenish-gray, one bed of orthoquartzite 1 m thick	40
Covered area overlain with strong angular unconformity by conglomerate of member 1 of the Altos de Pica Formation	125
Mudstone, reddish-gray, with intercalated sandstone, orthoquartzite, dark-gray shale, and light-gray shale	48
Mudstone, reddish-gray; intruded by a dike of amphibolitic diorite porphyry and by a 7 m dike of dark-greenish-gray actinolitic, porphyritic rock having phenocrysts as large as 20 mm	22
Orthoquartzite, fine-grained, with intercalated greenish-gray shale	28
Sandstone and pelitic sedimentary rocks; tightly folded near stock	?
Exposed thickness of Chacharilla Formation	1,127

Intrusive contact.

Metamorphic rocks were observed only in contact zones within a few meters of major intrusive bodies. In a few localities the sedimentary rocks are broken, and their stratification is destroyed in the contact aureole. The mudstones affected by contact metamorphism are lighter than normal and have no stratification; the orthoquartzites are lithologically unaltered but are broken into subangular fragments; in general, the rocks in the zone of contact metamorphism show silicification, epidotization and pyritization.

In many areas, structures of sedimentary rocks may be observed. The fine-grained sandstones contain oscillation ripple marks that have an average wave length of 30 mm and an amplitude of 3 mm. Current lineation marks are also present. Deltaic crossbedding, typical of deposits in slow-moving water, is much more common in the upper part of the section than are the ripple marks. The orientation of the crossbedding, in general, indicates that the sediments were deposited in water that was flowing westward. This direction of sedimentation, coupled with the intercalation of marine beds, indicates that the Late Jurassic sea was immediately west of the area and that the shoreline moved back and forth over the area several times while the sediments of the Chacarilla Formation were being deposited.

AGE AND CORRELATIONS

Paleontological evidence that would indicate the age of the Chacarilla Formation is almost lacking in the studied area; however, all the available data indicate a Jurassic and probable Late Jurassic age for the formation. Felsch (1917, p. 322) described the southward extension of the rocks of the Chacarilla Formation where they are exposed in the Quebrada Guatacondo. Without fossil evidence, Felsch (Decat, 1931, p. 9) attributed the rocks of the formation to the, "* * * Jurassic and in part, perhaps, to the Cretaceous." The Chacarilla Formation in this area overlies conformably or perhaps disconformably bituminous sediments containing Early Jurassic ammonites.

The fragments of plant fossils which occur in several localities in the Quebrada Chacarilla are in such a poor state of preservation that they are of no value for age determination.

The impression of an ammonite was found by the ENAP geologists in the last dry waterfall in the Quebrada Empexa before its junction with the Quebrada Chacarilla. This impression was located in a highly silicified mudstone bed in the contact zone of a granite porphyry intrusion. According to Cecioni (oral commun., 1958), the ammonite belongs to a Late Jurassic species. The fossil is poorly preserved and shows little ornamentation.

Impressions of valves, interior molds, and shell fragments of very small bivalves were collected from the dark-gray carbonaceous shales of the Quebrada del Carbón. These fossils correspond to *Posidonomya*, a dysodont pelecypod that ranges in age from Paleozoic to Jurassic. Species of *Posidonomya* have been used successfully in many areas as the basis for division of the Jurassic Period. The fossil remains are deformed, and generally only the impression of the shell remains. The fossils are not sufficiently preserved to permit a specific identification which might indicate their age. It is possible to observe affinities with Chilean Jurassic *Posidonomya* species, as well as with Argentine and European species (*Posidonomya alpina* Grass, *P. buchii*, and *P. ornata* Quenstedt). Although the specimens studied show variations in the form of the shell, they all have the same ornamentation and therefor are considered to belong to the same species. The ornamentation consists of rounded concentric striae which are notably wider than the intervening depressions. In all the specimens the shell is very small, not exceeding 3 mm in length and 2 mm in height. These dimensions are considered to be diagnostic.

The specimens are similar to the group of *Posidonomya alpina* Grass (Weaver, 1931, p. 216) from lowermost Bajocian (zone of *Leioceras opalinum*) of the central Neuquen (Argentina). The resemblance is apparent in the somewhat elongated suboval form of some specimens as well as in the ornamentation. The valves of the specimens from the Chacarilla Formation are much more equilateral, however, and are approximately one-fourth as large as *P. alpina*, *P. buchii*, and *P. ornata* Quenstedt. The last two species were described by Philippi (1899, p. 41) from a locality near Caracoles, Antofagasta Province, Chile.

The specimens from the Chacarilla Formation are most similar to those of *P. ornata* Quenstedt, which, according to Weaver, is included in the group of *P. alpina* Grass. Groeber (1918) reported that *P. alpina* was found in Argentina in sediments from lower Bajocian to Callovian.

The specimens of *Posidonomya* from the Chacarilla Formation definitely are of Jurassic age, but there are few characteristics on which to base a more restricted age. These specimens are related to those species collected in Chile and Argentina from sediments of Middle Jurassic or early Late Jurassic age.

Dinosaur tracks were discovered during the course of the geologic mapping of the Chacarilla quadrangle. This is the first reported occurrence of dinosaur tracks in Chile. The tracks were found in five different localities, all on the slopes of the Quebrada Chacarilla or its tributaries. The best assembly of tracks is exposed on steeply dipping beds of fine-grained sandstone on the south wall of the quebrada in three localities between 4 to 5 km upstream from the Chacarilla Oasis. In this area, literally hundreds of tracks are exposed. Unfortunately, the best exposure is approximately 500 m above the valley floor and can be reached only by a trained mountain climber. Other tracks are exposed in the Quebrada del Carbón, 50–100 m above the first dry waterfall and in a small tributary quebrada on the south side of the Quebrada Chacarilla, approximately 1 km east of the eastern border of the Chacarilla quadrangle.

An intensive search was made in at attempt to discover fossil remains, particularly teeth; the teeth are reported to be resistant to decomposition in the swampy or deltaic environment which probably existed at the time the trackways were formed. Several days of search failed to disclose any remains.

All the exposed trackways occur in beds of sandstone which dip between 40° and 60°. Many photographs were taken of these tracks although it was very difficult to obtain photographs vertical to the surface of the bed because of the inclination of the strata. Photographs of various types of tracks are included in figures 7–11. A complete series of photographs was sent to Dr. Joseph T. Gregory Curator of the Department of Vertebrate Paleontology of the Peabody Museum of Natural History, Yale University. Dr. Gregory made the following comments based on an inspection of the photographs (written commun., September 1958):

The two trackways shown in your photographs numbered 1 through 11 [figs. 10, 11A, and 11B] appear to belong to a large three-toed dinosaur. A majority of these tracks seem to have sharp, narrow claw marks such as would be made by a carnivorous theropod such as *Allosaurus* or *Tyrannosaurus*. Photograph number two [fig. 11A] indicates rather short and broadly rounded toes. This appears on the whole to be the best preserved track of the lot. Is it possible that this was on a firmer sediment than the others and that the narrowness of the toe marks shown in the other photographs [fig. 11B] is the result of slumping of the sediment partly filling the track after the animal had gone by? I would tend to associate a track of the type shown in photograph two with an ornithischian dinosaur such as *Iguanodon* rather than a theropod. If it is part of the same trackway, it must have been made by the same animal which obviously cannot be both a theropod and ornithopod.

The interesting series of tracks shown in your photographs 12, 13, 16, and 17 [fig. 8A and 8B] appear to be those of large quadrupedal form. I can detect very little of the morphology of the foot in these tracks except that it seems to

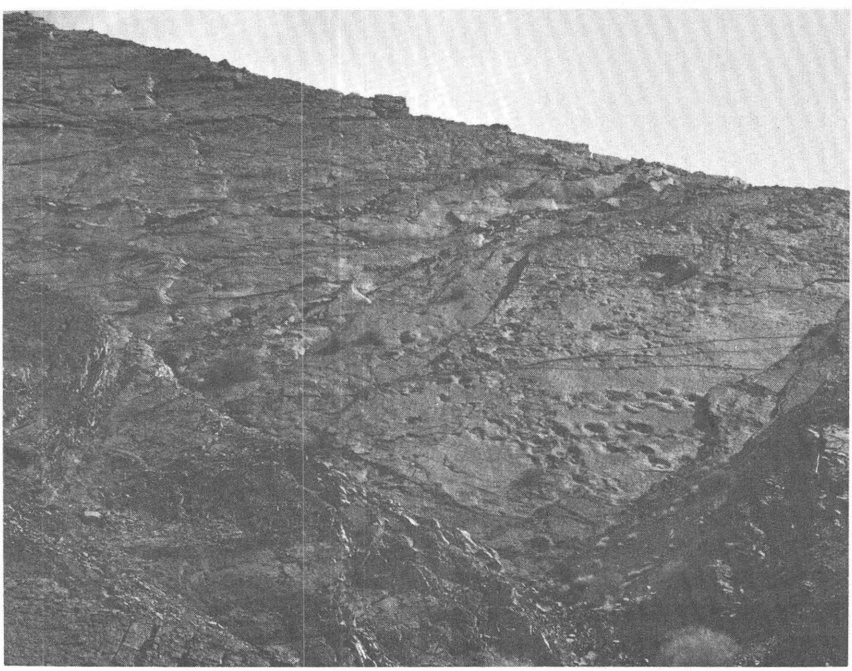
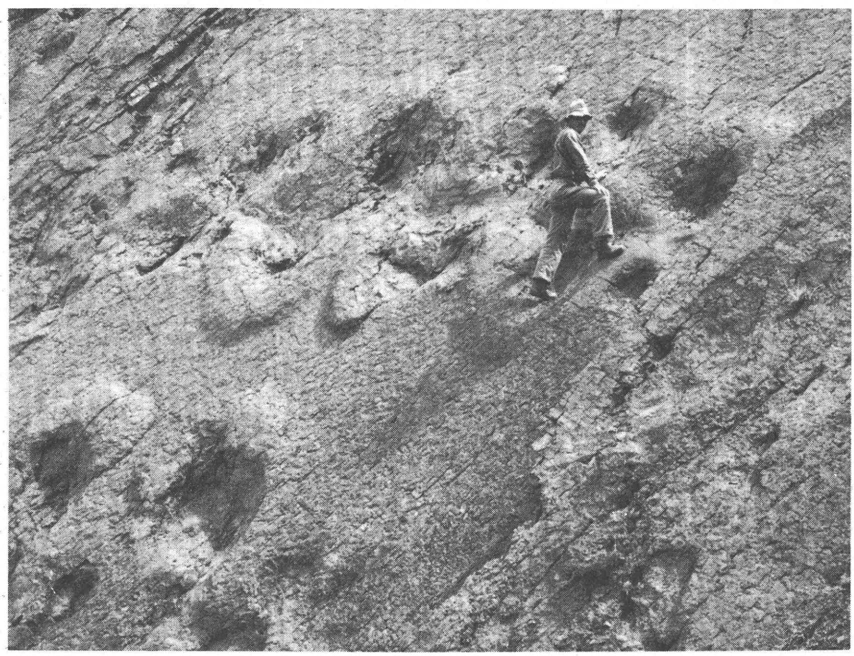


FIGURE 7.—Assembly of dinosaur trackways in the Chacarilla Formation, Quebrada Chacarilla.

A



B

FIGURE 8.—Detail of larger tracks shown in figure 7. Individual tracks are 90 cm in diameter. Mud ridges are 10–15 cm above dipslope of rock.

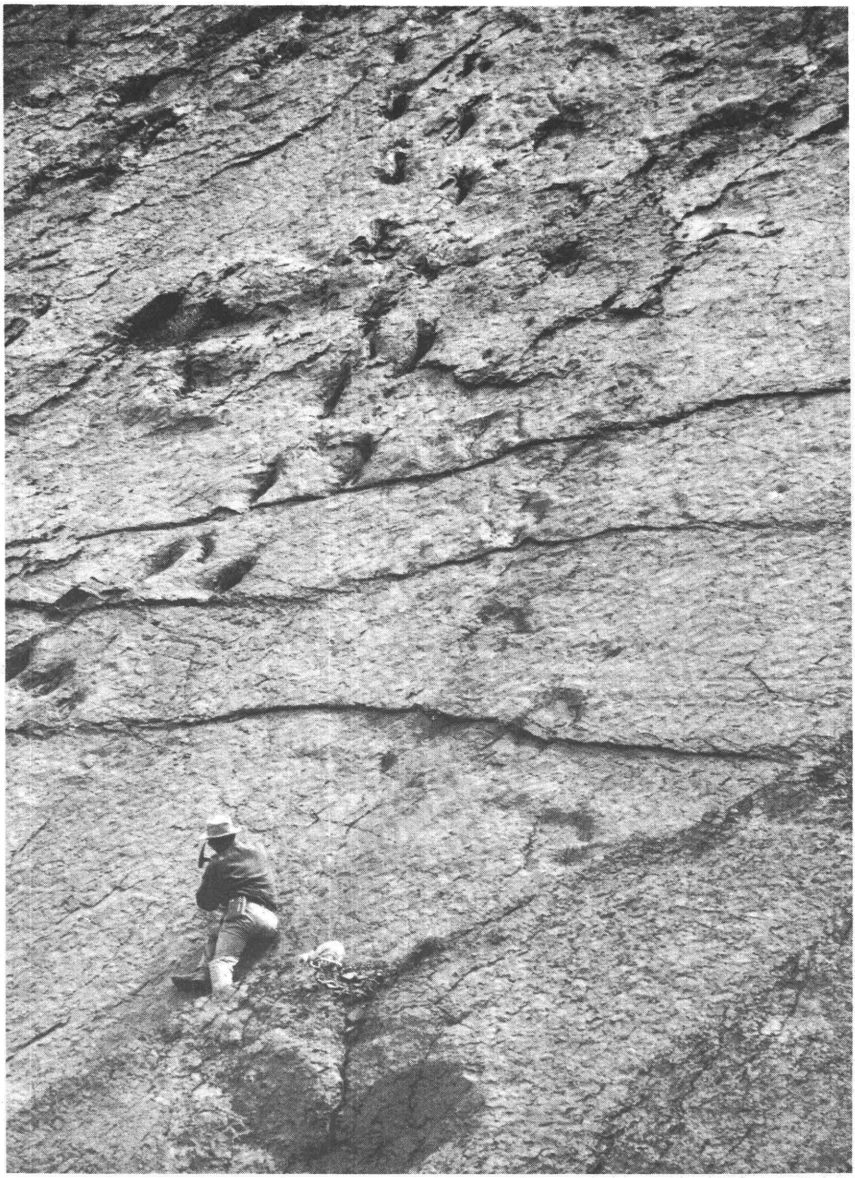


FIGURE 9.—Closeup of curved trackway shown in upper part of figure 7.

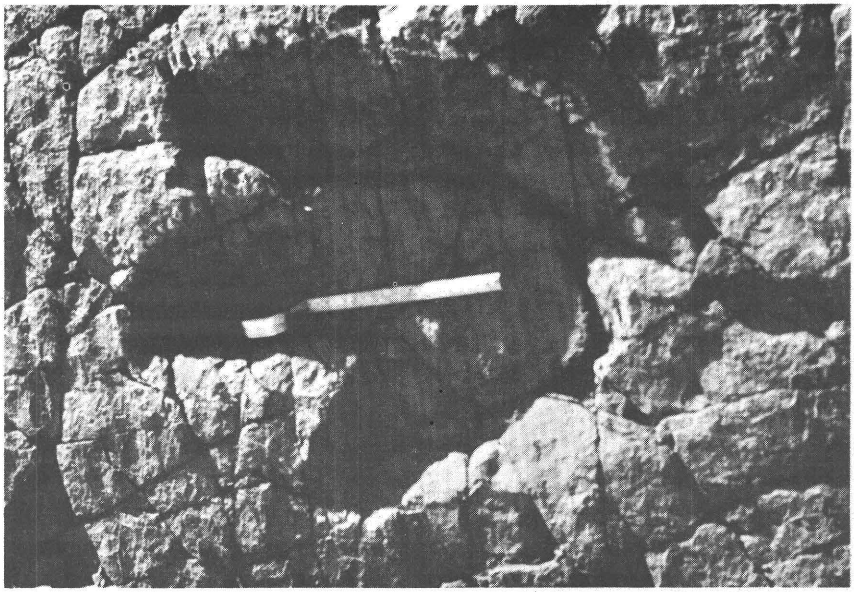
FIGURE 10.—Dinosaur trackways at second locality in Quebrada Chacarilla. Scale is 2 m long.

have made a rather round dishlike impression. Such tracks could easily be made by one of the large sauropod dinosaurs and the very large size of those footprints suggest this group also.

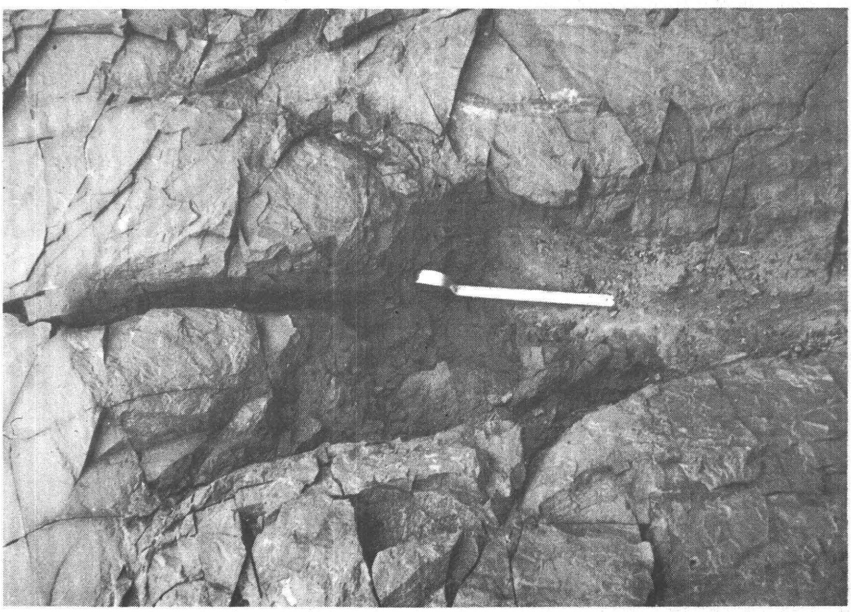
I am greatly puzzled by the rather elongate footprints which appear to have perhaps three toes at the anterior end as shown in your photographs 14 and 15 [figs. 9 and 7]. The latter shows them in proximity to the more rounded sauropod type of trackway which I have just commented on. It is conceivable from the shape of the foot that they might be some quadrupedal ornithischian dinosaur, perhaps a *Stegosaur*, although the size seems very large for that group. The shape of the foot and the arrangement of the trackway is quite unlike what would be expected in one of the ornithopods * * *

Although these identifications are extremely uncertain, I can say that there is nothing about this assemblage which would be inconsistent with either late Jurassic or early Cretaceous age. Even were it possible to make far more definite identifications of the forms it would be scarcely feasible to distinguish formations of these ages on the basis of trackways alone. Dinosaur faunas of the late Jurassic and early Cretaceous are quite similar in composition.

According to Muñoz Cristi (oral commun., 1958), Tavera in 1941 studied various fossils for the Instituto de Fomento Minero de Tarapacá. These fossils were collected from outcrops in the Quebradas Piscala and Maní in the southern part of Tarapacá Province. The sediments in this area are of the Chacarilla Formation, according to García (oral commun., 1958), who has studied the area but has not



A



B

FIGURE 11.—Detail of individual tracks from trail shown in figure 10. Twenty centimeters of scale is extended.

been able to locate fossils. The fossils are ammonites and were identified by Tavera as the following Late Jurassic species:

Perisphinctes andium Steinmann (one specimen)
P. roubianus Fontannes (fragments)
P. sp. (impression)

The angular unconformity which separates the overlying Cerro Empexa Formation from the Chacarilla Formation is a result of the cycle of orogeny which occurred at or near the end of the Jurassic Period (Ruiz and others, 1960). This angular unconformity has been observed in many other localities in Tarapacá Province (Cecioni and García, 1960). Sediments younger than Late Jurassic age have not been observed below the unconformity. These stratigraphic relations support the dating derived from the paleontological data. In view of the correlations, the lithology, and the fossils, the authors consider the evidence sufficient to assign the Chacarilla Formation to the Jurassic System and probably to the Upper Jurassic Series.

CERRO EMPEXA FORMATION

The Cerro Empexa Formation, of Cretaceous age, is named after Cerro Empexa (4,063 m), which is south of the Quebrada Chacarilla; this mountain is composed of rocks of this unit. The formation is exposed in four small areas in the southeastern part of the Pica quadrangle and also in one locality in the northeast part of the quadrangle. The best section is exposed in the Higueritas syncline, 13 km east of Chacarilla, where the type section was measured.

The formation consists of a thick sequence of sedimentary rocks and lava flows which is divided into three members. The lower and upper members consist of poorly stratified reddish-gray breccia and conglomerate and gray to grayish-violet trachyte flows. The middle member includes beds of grayish-red fine-grained sandstone and one irregular bed of gypsum intercalated in the other sediments. The formation was deposited in a terrestrial environment.

The rocks of the Jucuma area are weathered, discolored by iron oxides, and very closely fractured so that the original texture and structure of the sediments is obscured; however, their general aspect suggests that they may pertain to member 2 of the Cerro Empexa Formation.

The Cerro Empexa Formation, which overlies the Chacarilla Formation with strong angular unconformity, underwent a long period of erosion prior to the deposition of the Altos de Pica Formation. The nearly undisturbed Altos de Pica Formation overlies it with angular unconformity of as much as 90 degrees. The thickness of the Cerro Empexa in the type locality is approximately 600 m; however, this is not the total thickness as a part of the formation has been removed by erosion.

The Cerro Empexa Formation is intruded by a few thin dikes in widely separated localities. Contact metamorphic changes were observed only in very narrow zones surrounding the intrusive bodies. The intrusive rocks include amphibolitic diorite porphyry and a neck of propylitized andesite.

MEMBER 1

The basal member consists of material of igneous origin redeposited in a terrestrial environment. The sediments are breccias and conglomerates which have an arenaceous matrix composed primarily of fragments of volcanic rocks. The matrix also includes twinned plagioclase; porphyritic rocks; a few crystals of augite; and buff, reddish-brown, and black shards of volcanic glass. The cavities in the matrix are partially filled with chlorite. The phenoclasts are of all sizes and are of volcanic origin; they resulted from the reworking of contemporaneous volcanic flows. In some localities the conglomerates contain angular fragments of the underlying Chacarilla Formation. Some of the sediments appear to be fanglomerates. The angular form of the phenoclasts indicates a very short history of transportation. In some localities, torrential sorting is conspicuous. In Tiquima (Quebrada Guatacondo), the Cerro Empexa Formation includes well-rounded phenoclasts of plutonic rocks.

Near Alona, member 1 consists almost entirely of dark-grayish-green to dark-violet lava flows. These volcanics include porphyritic sodic trachytes, which have a groundmass containing abundant magnetite and augite; the larger phenocrysts, approximately 5 mm in diameter, are clay, which is probably an alteration product of albite and oligoclase, and the smaller phenocrysts, approximately 0.5 mm in diameter, are augite. These volcanic rocks are massive and in many localities brecciated. The fragments in the breccia have a slightly different color than the groundmass but are of the same composition. Stratification is poorly defined and in some sectors, not recognizable.

Member 1 is the most widely distributed member of the Cerro Empexa Formation. It crops out near Alona, near Chacarilla spring, and also in the Higueritas syncline.

Member 1 overlies the Chacarilla Formation with angular unconformity. The upper contact of the member with member 2 is concordant. The lithology of member 1 indicates an extreme change from the tranquil sedimentary environment in which the Chacarilla Formation was deposited. The material from which the sediments of member 1 were derived consisted of lavas and pyroclastic materials which were rapidly eroded and redeposited without much transportation; there was essentially no contribution from rocks outside the area or from the underlying formations.

The section of member 1 in the type locality is as follows:

Sections of the Cerro Empexa Formation on the northern side of the Higueritas syncline, 13 km southeast of Chacarilla spring

Cerro Empexa Formation (member 2).	
Conformable contact.	
Cerro Empexa Formation (member 1):	*Meters*
Conglomerate, reddish-gray, fine, as large as 16 mm, with intercalated beds of tuff, arenaceous tuffites, and pelitic beds. The small phenoclasts are not conspicuous in the arenaceous tuffitic matrix	20
Breccia, reddish-gray; medium, as large as 64 mm. Trachyte phenoclasts are angular to subrounded; notably larger in some strata; have colors which differ only slightly from that of matrix. Some fragments are cut by fractures. Well-cemented matrix consists predominantly of sandy material of volcanic origin	280
Breccia, reddish-gray, thickly bedded, coarse. Phenoclasts are angular to subrounded, unsorted; range in size from gravel to blocks; originate from rocks of the underlying formation and from contemporaneous effusives; diminish in size toward upper part of layer and show increased proportion of rocks of volcanic origin. Sandstone matrix is reddish-gray; cemented; poorly sorted; has predominant coarse sand fraction; includes very light gray fragments of kaolinized feldspar. Stratification is coarse	150
Exposed thickness of the Cerro Empexa Formation (member 1)	450
Angular unconformity.	
Chacarilla Formation.	

MEMBER 2

The second member is exposed in the type locality where it is concordant with the upper and lower members of the formation; it also occurs near Jucuma in the northwest part of the Pica quadrangle. This member is lithologically very different from the other members of the formation and is similar to the mudstones and reddish-gray sandstones of the Chacarilla Formation. The rocks of member 2 include grayish-red friable mudstone which has a ferruginous clay matrix and contains phenoclasts of quartz and plagioclase. Fine-grained friable grayish-red sandstone is intercalated with the mudstone. In the type locality the entire thickness of the member (102 m) is composed of thin regular beds. Seventy meters above the base of the member there is a lenticular bed of gypsum approximately 2 m thick.

The section of member 2 in the type locality is as follows:

Section of member 2 of the Cerro Empexa Formation in the type locality

Cerro Empexa Formation (member 3).	
Cerro Empexa Formation (member 2):	*Meters*
Mudstone and sandstone. Sandstone is grayish-red, fine-grained, decomposed, friable; in uniform beds 0.2–0.3 m thick	30
Gypsum; lenticular; also fills fractures in the adjacent beds	2
Mudstone and sandstone, similar to the beds overlying the gypsum	70
Total thickness of the Cerro Empexa Formation (member 2)	102
Cerro Empexa Formation (member 1).	

MEMBER 3

Member 3 concordantly overlies member 2. The only known exposures of this member are within the Higueritas syncline. The total thickness of the member is unknown as the upper part has been eroded. The member consists of porphyritic trachyte beds intercalated with volcanic breccia. The trachyte has a fine-grained groundmass; the phenocrysts consist of orthoclase crystals as large as 2 mm in size and abundant albite crystals as large as 1 mm in size. The quartz crystals comprise less than 5 percent of the phenocrysts and occur in crystals as large as 0.6 mm. Secondary calcite occurs in large aggregates. The coarsely layered and highly decomposed trachyte is gray and violet, but on the surface it is weathered pink. The section of member 3 in the type locality is as follows:

Section of member 3 of the Cerro Empexa Formation as measured in the type locality

Top eroded.	
Cerro Empexa Formation (member 3):	*Meters*
Trachyte, gray and violet (weathered pink), in general highly decomposed, with intercalated coarsely layered breccia	40
Cerro Empexa Formation (member 2).	

AGE AND CORRELATIONS

The age of the Cerro Empexa Formation is considered to be Cretaceous. No fossils have been found in this formation; however, the correlations proposed by the ENAP geologists and the absolute age determination of a sample of the rock that intrudes the formation would place the Cerro Empexa in the Early to Middle Cretaceous. The Juan de Morales quadrangle (15-minute), which joins the western half of the northern border of the Pica quadrangle, was mapped by Galli (1964, Geol., Juan de Morales quad., Tarapacá Prov., Chile: Unpub. M.S. thesis, Utah Univ.). In the Juan de Morales quadrangle the pluton that forms Cerro Duplijsa intrudes rocks of the Cerro Empexa Formation. The age of the intrusive rocks was calculated by the Geochronology Laboratory of the U.S. Geological Survey to be 95±10 millions years as determined by the lead-alpha radiometric method (Ruiz and others, 1961, table 1, p. 1556).

García (oral commun., 1958) believed that the orogeny that folded the rocks underlying the Cerro Empexa Formation may correspond to the Nevadian cycle of the Late Jurassic. The geologists of ENAP correlate the Cerro Empexa Formation with the Atajaña and Blanco Formations (Neocomian), which are exposed in the Coastal Range, 5 km south of Cerro Atajaña, situated to the west of Pampa Tana. This correlation is based on the position of the Atajaña, Blanco, and Cerro Empexa Formations above the angular unconformity that truncates the formations of Jurassic age; the similarity in lithology between member 2 of the Cerro Empexa Formation and the Atajaña Formation; and the absence of large intrusive bodies in the three formations. The Atajaña Formation which includes reddish-gray sandstones and conglomerates, is conformably overlain by the light-yellow standstone and fossiliferous marine limestone of the Blanco Formation of Early Cretaceous age. The ENAP geologists also extend their correlation to the Caleta Coloso Formation, exposed 20 km south of the city of Antofagasta.

CENOZOIC ROCKS

ALTOS DE PICA FORMATION

The Altos de Pica Formation of late Tertiary and Pleistocene age was formed from detrital material derived from the denudation of the ancestral Andes. Within the detrital material are intercalated pyroclastic sequences which suggested the names given to the formation, such as Traquítica (Bertrand, 1885); Liparítica and Riolítica (Brüggen, 1918). The last two formation names are still in general usage. Inasmuch as the pyroclastic rocks comprise less than 10 percent of the formation in the Pica area, it is misleading to assign a volcanic rock name to the entire sequence, and, for this reason, the authors consider it advisable to replace these names with a geographic name taken from the type locality.

The dual origin of the formation was discussed in an earlier report (Galli, 1957, p. 14), and the name Altos de Pica Formation was proposed to conform with the stratigraphic code, which states that a local geographic feature should be used in naming a formation. The Altos de Pica Plateau (4,500 m) is the most prominent physiographic feature of the region because it is high and because its morphology contrasts with that of the nearby mountains. The plateau is formed entirely on the Altos de Pica Formation. For these reasons, it was considered appropriate to use the name Altos de Pica to designate these rocks of Tertiary and Pleistocene age.

The formation forms the major part of the surface of the Pica quadrangle. With the exception of the area of Chacarilla, all the high part of the quadrangle is underlain by the Altos de Pica Formation. The outcrops extend south of the quadrangle and increase in number north and east. Throughout most of the outcrop area, the exposures are interrupted only by the quebradas exposing outcrops of older folded rocks, but in some of the outcrop area the formation is covered by Quaternary detrital deposits.

The Altos de Pica Formation is in unconformable contact with underlying Mesozoic formations or with older formations. Numerous parallel disconformities exist between the members of the formation and within the members of the formation.

The Altos de Pica Formation is separated by the authors into five members. Members 1, 3, and 5 are of sedimentary origin, and members 2 and 4 are intercalated units consisting principally of welded tuffs (table 3). The pyroclastic rhyolite was considered to be lava in previous reports. It is, however, ignimbritic and was formed by incandescent avalanches or "nuées ardentes".

The sedimentary members are piedmont deposits containing—particularly members 3 and 5—intercalated beds of eolian origin. The fanglomerates of the lower part of member 1 are composed primarily of material derived from the rapid erosion of the folded rocks that underlie the member. The lithology of member 3 which overlies the welded tuffs of member 2 is uniform. Member 3 includes yellow crossbedded sandstone and torrential conglomerate; these rock types indicate an alternation between eolian and fluvial conditions during the time of their deposition. The lithology of member 5 varies greatly; in the vicinity of El Algarrobal it consists predominantly of eolian sediments; farther to the north near the northern limit of the

TABLE 3.—*Stratigraphic section of the Altos de Pica Formation*

Member	Thickness (meters)	Lithology
5	200	Sand, dark-gray to grayish-green, medium- to fine-grained, poorly consolidated, crossbedded (predominantly eolian); contains ventifacts, has upper surface covered by rounded pebbles and cobbles from many sources.
4	23	Rhyolitic tuff, varicolored, pink, yellowish-gray or white, porous; has phenoclasts of pumice and crystalline material. Corresponds to a lateral facies of the volcanic ash overlying the welded tuff in other areas.
3	173	Sandstone, yellowish-gray, medium- to coarse-grained uniform, crossbedded; contains concretions, ventifacts; intercalated with conglomerates that show torrential bedding.
2	17	Rhyolitic welded tuffs, varicolored, pink, yellowish- to dark-gray; in general, coherent. Welded tuffs are underlain by tuffs that are not welded.
1	322	Conglomerate, yellowish-buff; containing phenoclasts from many sources; intercalated with sandstones, medium- to coarse-grained, of the same color; and tuffs and tuffites. Sequence typical of torrential sedimentation.
		Angular unconformity

Pica quadrangle and also near La Calera, the lithology is very similar to that of member 3. In most outcrops member 5 is overlain by a thin mantle of water-worn pebbles and boulders that have a thick coating of well-developed desert varnish.

The Altos de Pica Formation is of terrestrial origin and is not known to contain fossils. The gentle westward dip of the formation is broken by two monoclines and a few faults of little significance. The type localities of the various members are as follows: member 1, the south wall of the Quebrada Chacarilla, 7 km downstream from the chacra; member 2, at Salto Chico in the Quebrada Chintaguay; members 3 and 5, the southern slope of the Quebrada Chacarilla, near El Algarrobal; and member 4, at Salto Grande in the Quebrada Quisma.

The total thickness of the formation obtained by summing up the thicknesses of the five members as measured in their type sections is approximately 735 m. This is apparently not the maximum thickness of the formation. Brüggen (1950, p. 123) reported that 1,000–1,500 m of this formation are exposed in the Quebradas Tarapacá and Aroma. In general, the sedimentary members increase in thickness toward the west, and the pyroclastic members increase in thickness toward their points of origin in the east.

MEMBER 1

The distribution of member 1 is not uniform. The conglomerates first filled the lowest parts of the old land surface and, for this reason, are not observed in Cerro Longacho or in the upper course of the Quebrada Chacarilla areas which were topographically high at the time of the deposition of the member. The member is particularly well exposed in the lower course of the Quebrada Chacarilla and Salto Chico in the Quebrada Chintaguay. Detailed sections were measured in these localities.

The member overlies the older, folded rocks with great angular unconformity, in places as much as 90°. The relation of member 1 with the overlying member 2 is concordant, and no appreciable hiatus is considered to exist between them in spite of the fact that cut and fill features are observed at the contact. The cut and fill features are considered to originate in the normal process of alternate erosion and deposition typical of sedimentation in a piedmont environment. The same cut and fill features are observed within member 1. The stratification of member 1 is well defined, but the beds are lenticular as a result of hydrodynamic sedimentation on a steep gradient. In the lower 100 m of the member, the sedimentary rocks resemble mudflow deposits.

Pyroclastic strata are intercalated within member 1. Some of these strata are of large horizontal extent. Close to Chacarilla chacra a bed of rhyolitic ash, several meters thick, is exposed near the base of the member. In some places, pyroclastic lenses are interbedded with the darker sediments and are conspicuous because of their lighter color. The rhyolitic composition of the pyroclastic rocks is typical of all five members of Altos de Pica Formation.

The member increases in thickness toward the west, and its maximum thickness is probably not exposed because the strata dip under the sediments of the Pampa del Tamarugal. In the Quebrada Chacarilla the member pinches out to the east at a maximum altitude of 3,250 m. The absence of the member at high altitudes indicates that during the time of its deposition erosion was predominant in these localities and that the material removed was transported and deposited in the piedmont plain that was developing toward the west.

The following stratigraphic section was measured in the type locality.

Type section of member 1 of the Altos de Pica Formation

Altos de Pica Formation (member 2).	
Altos de Pica Formation (member 1):	*Meters*
Conglomerate, yellowish-buff, torrential, with intercalated yellowish-buff sandstone. Phenoclasts are poorly sorted, angular to well-rounded, and come from many sources. Some epidotized; some are composed of rocks unknown in the quadrangle. Matrix (minor in proportion to the phenoclasts) is poorly cemented, poorly sorted, and predominantly sand-sized. Sandstone is medium to coarse grained; uniform; crossbedded; has fragments of mica, orthoclase and plagioclase, and includes subangular rock fragments; at various levels has ellipsoidal concretions, as large as 5 cm in diameter, showing six or seven concentric layers composed of the same material as the sandstone. Cut and fill features are common	160
Tuffaceous sand, pale-yellow	10
Conglomerate, similar to the upper bed	20
Rhyolitic tuff, arenaceous, very light gray; has abundant mica fragments, and scattered subangular phenoclasts	1
Conglomerate, similar to those previously described	28
Rhyolitic tuff, similar to the preceding	3
Conglomerate, similar to the other conglomerate beds but less well stratified; contains a large proportion of angular to subangular fragments	100
Exposed thickness of the Altos de Pica Formation (member 1)	322
Angular unconformity.	
Chacarilla Formation.	

At Salto Chico (little falls) in the Quebrada Chintaguay the authors remeasured the section described by Brüggen (1918, p. 22), that is, the upper part of member 1. The lower part of the Altos de Pica Formation in the same area was penetrated in well C. The samples from well C were studied by Felsch in 1917, and his descriptions were published by Brüggen (1918, p. 23). Felsch classified the samples from a depth of 133 to 140 m as "liparita de estructura vidriosa" (rhyolite with glassy structure) and the samples from 216 to 245 m as "liparita dura" (hard rhyolite). These samples have been lost and with them the opportunity to determine whether they were actually lavas or welded tuffs. These two layers have not been observed in outcrops of member 1 in the Pica area. In spite of the absence of petrographic information in the lithologic description, Felsch's report suggests the possibility that in the subsurface, at least near Salto Chico, there may be welded tuffs that are older than those of members 2 and 4, but similar in that they originated from nuées ardentes. The rhyolitic tuffites of the member as exposed in the Quebrada Chacarilla may represent redeposition of ashy phases of such welded tuffs.

The following stratigraphic section was measured at Salto Chico in the Quebrada Chintaguay:

Section of member 1 of the Altos de Pica Formation measured at Salto Chico in the Quebrada Chintaguay

Altos de Pica Formation (member 2).	
Altos de Pica Formation (member 1):	*Meters*
Sandstone, yellowish-gray; secondary limonite in some zones; in basal part, coarser-grained and more poorly stratified	17
Sandstone, gray, poorly sorted; contains pink ash and fragments of volcanic rocks	2
Tuff, light-gray, fine-grained, poorly consolidated; contains phenoclasts of sedimentary rocks	1
Conglomerate, yellowish-buff; torrential bedding; contains subangular to subrounded phenoclasts of various origins, as large as 20 cm; has well-cemented matrix; is interstratified with lenticular gray sandstone	23
Tuffite, light-gray; contains thin lenses of silt 2–3 mm thick	1
Tuffite, light-grayish-buff, sandy; has a few rounded fragments of older volcanic rocks; very finely stratified in laminae of 5 mm	1
Sandstone, grayish-buff, fine- to coarse-grained; contains grains of sanidine, albite and volcanic ash. Some parts are massive; other parts contain intercalations of ash 5 cm thick that contain fragments of pumice	6
Conglomerate, yellowish-buff; torrential bedding. Phenoclasts vary in size and lithology. The smaller phenoclasts are more rounded; some phenoclasts show eolian abrasion. Matrix is sandy, yellowish-buff, poorly cemented, and contains limonitic layers a few centimeters thick	3
Sandstone, yellowish-gray, medium-grained, poorly cemented; contains opaque quartz grains and euhedral fragments of mica and feldspar; crossbedded in part; beds 2–12 cm thick; contains ellipsoidal concretions, as large as 5 cm, showing six or seven concentric layers composed of the same material as the sandstone; contains beds of light-reddish-orange ash a few centimeters thick, lenses of pumice fragments as much as 30 cm in length, and a few lenses of silt	10
Exposed thickness of the Altos de Pica Formation (member 1)	64
Covered slope.	

MEMBER 2

Member 2 of the Altos de Pica Formation consists of ashy rhyolitic tuff overlying rhyolitic welded tuff. It crops out over a wide area where the younger members of the Altos de Pica Formation have been removed by erosion. In large sectors of the Chacarilla area, it has been removed by erosion as have the other members of the Altos de Pica Formation.

Member 2 is conformable with the underlying and overlying members of the formation; however, where the member directly overlies rocks older than member 1, it is observed to be in angular unconformity.

The extensive deposits of this member were considered to be lava flows by earlier authors (Brüggen, 1918, p. 13; 1950, p. 269; Felsch, 1920, p. 471; Decat [5]). It is highly probable that beds of similar origin in the western slopes of the Domeyko Range attracted the attention of Sundt (1909, p. 118) and caused him to write the following phrases (translated from Spanish):

"We are here in front of the same enigma, that has been presented many times: a trachyte rock that by its petrographic character seems to have come to the place that it now occupies in a liquid state, meanwhile because of the situation in which it is found it appears that it must have fallen as an ash."

These suggestive words were written some years before the general acceptance of the petrologic hypothesis of the welded tuff. Most of these rocks would now be classified as welded tuffs (Iddings, 1909, p. 331) or ignimbrites (Marshall, 1935, p. 323). Enlows (1955, p. 1239) stated, "Welded tuffs are thought to be due to eruptions of superheated gasses, heavily charged with incandescent ash and volcanic sand which have been termed 'nuées ardentes', or glowing clouds, by Lacroix (1904, p. 203). This material is not rained down as from an ash shower but descends the mountain side like a hot avalanche. So much solid is suspended in the cloud that it becomes too dense to surmount obstacles and behaves rather like a liquid."

The type section of member 2 was measured at Salto Chico in the Quebrada Chintaguay. In this locality, the sequence is 17 m thick and appears to have been formed by two eruptions; the resulting strata are separated by a breccia approximately 30 cm thick. The upper stratum contains the petrographic features that have been described and considered to be typical of welded tuffs (Enlows, 1955, p. 1243) The petrographic features of member 2 are described in table 4.

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[5] Decat, J., 1931, Informe sobre el reconocimiento geológico de la provincia de Tarapacá teniendo en vista la posibilidad de encontrar petróleo y agua: Santiago, Chile, Dirección de Obras Públicas, v. 441, p. 4.

TABLE 4.—*Petrographic table of member*

Unit	Hardness	Color	Groundmass	
			Percentage	Differentiation
a	Very hard	Reddish gray	63	Yes
b	Very hard	Pale red	60	Yes
c	Very hard	Dark gray	70	No
d	Medium	Reddish brown	80	No
e	Slightly consolidated	Orangish red	80	No
f	Slightly consolidated	Very light orange	95	No

Although the upper, ashy phase is not exposed at Salto Chico, it is present in other localities. This phase consists of grayish-white or light-gray, friable, porous, rhyolitic tuff of low specific gravity; the tuff contains particles of pumice, conspicuous fragments of quartz, sanidine, biotite, and irregular xenoliths of poorly stratified volcanic rocks. The weathered surface is pinkish gray. Eutaxitic texture has not been observed. The thickness of this ashy phase is variable, a maximum of 7 m being observed at El Algarrobal. In outcrops where the rhyolitic phase is present and the ashy phase is thin or absent, the ashy phase originally present was probably removed by erosion. The relationship of this ashy phase to the ignimbritic unit is evident, because in all localities it may be observed to grade downward into the coherent welded tuffs having markedly eutaxitic texture.

At Salto Grande in the Quebrada Quisma, the aspect of the tuff changes completely at 1.5 m below the erosion surface. Above this depth, 70–80 percent of the tuff consists of a hypohyaline groundmass of microliths of feldspar, quartz, and vitreous pigment. Axiolitic structure is common. The groundmass is crossed by veins of quartz and chalcedony. The phenoclasts are principally euhedral quartz, as large as 1.5 mm; albite; biotite, as long as 6 mm; and glassy, reddish-brown, rhyolite which has phenocrysts of quartz, sanidine, and plagioclase. The rock is soft and megascopically has the appearance of an ashy tuff. Microscopically, however, it is very similar to unit b, a welded tuff, of the type section. The ashy tuff beds grade downward into typical thoroughly welded tuffs, which crop out for a few tens of meters along the quebrada in a gently folded anticlinal structure.

At Salto Chico of the Quebrada Chintaguay, the upper beds are of a different original structure. The top of unit a in this outcrop is strongly eroded. Its contact with the underlying unit b is conformable and can be easily observed from a distance. Unit b is massive and uniform and contains many collapsed or partialy collapsed gas bubble

2 of the Altos de Pica Formation

Phenoclasts		Elongation of fragments	Glass		Remarks
Embayment	Plagioclase		Index of refraction	Color	
Yes	Sodic Oligoclase	Yes	1.501	Transmitted light, light chestnut. Reflected light, light chestnut.	Eutaxitic texture.
Yes	Sodic Oligoclase	Yes	1.515	Same as unit a	Eutaxitic texture.
Yes	Sodic Oligoclase	Yes	1.495	Same as unit a	Pronounced eutaxitic texture.
No	Sodic Oligoclase	No	1.491	Transmitted light, light chestnut. Reflected light, reddish brown.	Eutaxitic texture.
Yes	Sodic Oligoclase	No	1.498	Same as unit a	
No	Sodic Oligoclase	No	1.490	Same as unit a	

holes elongated parallel to the plane of the base of the unit and also to the eutaxitic texture. These vesicles have a maximum length of 80 cm; however, the majority range from 10 to 20 cm. The basal portion of unit b is formed by a breccia approximately 30 cm thick as described in the stratigraphic section. This type breccia was reported by Enlows to be typical of a welded tuff, and it may have originated as a result of the dragging effects of the incandescent avalanche over the older surface, which here was a very recently deposited welded tuff (unit c). These two units are considered to be essentially contemporaneous, and there may have been an interval of only a few hours or even minutes between their deposition. To explain a similar phenomenon in the Rhyolite Canyon Formation in Arizona, Enlows (1955) suggested that the second eruption may have followed the first so rapidly that there was no time for the fine material to settle, and so it was swept away by the second nuée ardente. This would explain the absence of an upper ashy phase overlying the older welded tuff of unit c.

Below the basal breccia of unit b occurs a succession of atypical ignimbrites. The sequence is inverse to that which is considered to be normal. The upper part (unit c) of this sequence consists of a very dark-gray welded tuff whose color may be due to disseminated magnetite in the vitreous groundmass, magnetite that is too fine to be identified microscopically. The eutaxitic texture is not as evident as in unit b but is recognizable in thin section. This rock rings when struck with a hammer and fractures easily. Downward unit c grades into the welded tuff of unit d which in turn grades downward into the unconsolidated tuff of units e and f. The basal tuffaceous units can be explained in two ways. They could have been formed by a small nuée ardente which did not contain sufficient heat to produce welding. The resulting ash bed could then have been covered by typical welded tuffs, and the heat that flowed downward by conduction into the ash could have caused consolidation and welding of the upper part of the unconsolidated tuff. The other possibility is, as Enlows (1955, p. 1242) suggested, that such unconsolidated basal layers may result from the chilling of the base of the deposits of the nuée ardente.

The lithologic sequence outlined above was observed with local modifications throughout the quadrangle. Although the lower unit is not always the same, the member can be considered as the product of two or possibly three successive deposits of nuées ardentes. The place of origin of the welded tuffs is unknown, but the authors consider that they possibly emanated as explosive eruptions from north-south fissures underlying the upper part of the Altos de Pica Plateau. The eruptions of nuées ardentes would have settled back over the fissure and thus would have concealed it from observation. Great areas in northern Chile covered by welded tuffs would indicate the possible existence of a series of such fissure vents along the crest of the Andes.

The breccia at the base of unit b may correlate with the rhyolitic breccias which occur in the small hills north of Pampa Esmeralda. Microscopically the breccias at Esmeralda show banding characterized by zones of typical welded tuff in which calcitic cement is abundant. The phenoclasts consist of small fragments of quartz, sanidine, and albite. Eutaxitic texture is poorly developed. The phenoclasts comprise approximately 30 percent of the rock.

The following stratigraphic section of member 2 was measured at the type locality.

Type section of member 2 of the Altos de Pica Formation

	Corrected thickness (meters)
Altos de Pica Formation (member 3).	
Altos de Pica Formation (member 2):	
Unit a:	
Rhyolitic welded tuff, porphyritic; eutaxitic; has alternating layers approximately 10 cm thick. In less indurated layers, tuff is grayish orange pink; has cineritic groundmass; has fragments consisting of quartz, sanidine, plagioclase and biotite, the fragments of plagioclase being as large as 2 mm, and those of biotite, 1 mm. In more indurated layers, tuff is reddish-gray; horny lustered; has partially devitrified agglutinated vitreous groundmass (63 percent of the rock) containing flattened fragments of glass differentiated to spherulites as large as 10 mm and margarites of reddish-brown glass; has fragmental or euhedral phenoclasts (37 percent of the rock), approximately 3 mm in size, composed of quartz (45 percent), sanidine (39 percent), sodic oligoclase (14 percent), and biotite (2 percent), some phenoclasts show embayment	3

	Corrected thickness (meters)
Altos de Pica Formation (member 2)—Continued	
Unit b:	
Rhyolitic welded tuff, grayish-orange-pink to light-red, massive, poorly stratified; petrographically identical to the more indurated layers of the overlying unit; characterized by concordant parallel bands of bubble holes, which are as much as 80 cm long, but which generally range from 10 to 20 cm. Some of these bubble holes are lined with druses of crystalline quartz. Base of unit consists of 0.3 m of brecciated welded tuff lithologically similar to the above rhyolitic welded tuff, but less indurated; contains subangular fragments of reddish-gray and dark-gray welded tuff; is crossed by veins of amorphous silica	6
Unit c:	
Rhyolitic welded tuff, dark-gray, very hard, porphyritic, eutaxitic; has vitreous luster. Groundmass (70 percent of the rock) composed of undifferentiated glass shards in axiolitic form; index of refraction $n=1.495$ (73 percent SiO_2 according to the scale developed by W. O. George in 1924); shows eutaxitic texture and molding of shards around the phenoclasts. Phenoclasts (30 percent of the rock) show embayment and include tabular crystals of sanidine as large as 1 mm, quartz crystals as large as 2 mm, sodic oligoclase (very scarce) as large as 1.5 mm, elongated crystal flakes of biotite, and grains of magnetite. The upper contact is abrupt and the lower is gradational. Quartz druses, as large as 20 cm, occur in the upper part, filling vesicles	3
Unit d:	
Rhyolitic welded tuff, reddish-brown, consolidated, porphyritic, eutaxitic texture, with parallel elongated fragments of black glass as much as 1 cm in length. Groundmass (80 percent of the rock) composed of glass with axiolitic structure, and pumice. Index of refraction of glass $n=1.491$ (75 percent of SiO_2). Phenoclasts are of quartz as large as 2 mm, twined sodic oligoclase as large as 1 mm, sanidine as large as 2 mm, and biotite as large as 1 mm. Scarce angular xenoliths. The contact with underlying unit is gradational	2
Unit e:	
Rhyolitic tuff, orangish-pink, slightly consolidated, porphyritic, low specific gravity, porous. Groundmass (80 percent of the rock) composed of glass with axiolitic structure and pumice. Index of refraction of glass $n=1.498$ (72 percent of SiO_2). Without fluid texture. Shards are molded around a few of the phenoclasts. The phenoclasts are of sanidine (30 percent) as large as 2 mm; quartz (30 percent) rounded and embayed, as large as 3 mm; twined sodic oligoclase (40 percent) as large as 2 mm; scarce biotite fragments as large as 5 mm. Abundant xenoliths of pumice and rhyolite are oriented parallel to base of unit. The contact with underlying unit is gradational	1

749-447 O—65——4

	Corrected thickness (meters)
Altos de Pica Formation (member 2)—Continued	
Unit f:	
Rhyolitic tuff, very light orange, porphyritic, poorly consolidated, thin bedded, porous; low specific gravity; not eutaxitic; stained with limonite. Groundmass (95 percent of the rock) is composed of undifferentiated glass shards in axiolitic form; index of refraction $n=1.50$ (72 percent SiO_2); does not show molding of shards around the phenoclasts. Phenoclasts (5 percent of the rock) are of twinned translucent sodic oligoclase as large as 1 mm, quartz as large as 4 mm, sanidine as large as 1 mm and laths of biotite as large as 5 mm	2
Total thickness of the Altos de Pica Formation (member 2)	17
Altos de Pica Formation (member 1).	

MEMBER 3

The distribution of the outcrops of member 3 is similar to that previously described for member 1. Member 3 is absent in the highest slopes of the eastern part of the quadrangle. In general, it crops out at approximately 3,000 m and increases in thickness downslope and toward the west. West of Cerro Longacho in the Pampa del Tamarugal, the member is covered by younger sediments.

In all the localities where member 3 has been observed, it overlies the welded tuffs of member 2 and may be overlain by either member 4 or 5; this depends on whether or not the tuffs of member 4 exists in the locality. Internal stratification, as in member 1, includes many minor disconformities, such as scour and fill features.

The rocks of member 3 are in general reddish yellow. They record alternating periods of eolian and fluvial deposition. At Salto Grande in the Quebrada Quisma, sand dune sediments are well exposed between thick fluvial conglomerates. The eolian sediments are reddish yellow and show well-defined wedge-shaped crossbedding. The texture is uniform, and numerous ventifacts showing varnish and eolian abrasion are identical to those on the present desert floor.

The fluvial sediments are more common toward the top of the member. Concretions are concentrated in the scour channels that exist within the member. The sediments of the member are commonly cemented with calcareous and siliceous cement.

The member has a thickness of 173 meters as measured in the type section at El Algarrobal. At Salto Grande in the Quebrada Quisma, the member is 170 meters thick.

The following stratigraphic section of member 3 was measured in the type locality.

Type section of member 3 of the Altos de Pica Formation

Altos de Pica Formation (member 5).	
(Member 4 was not deposited in this locality).	
Altos de Pica Formation (member 3):	*Meters*
Conglomerate, reddish-yellow; torrential; has subangular to subrounded boulders as large as 40 cm and lenticular deposits which show cut and fill features. Intercalated sandstone is yellowish-gray silty; medium- to coarse-grained; uniform texture; has ventifacts, eolian crossbedding, and in some places a laminar texture; contains concretions, 2–3 cm in diameter, the same color as the bed, cemented with calcium carbonate	40
Sandstone, reddish-yellow; similar to the overlying strata; has angular fragments of gravel size and thin beds of very light gray silty tuffite; contains one bed of conglomerate 50 cm thick	43
Conglomerate, reddish-yellow; similar to the overlying unit; occurs in lenses showing torrential deposition intercalated with yellow sandstone	25
Sandstone, reddish-yellow; similar to the preceeding unit; very uniform in texture and lithology throughout unit; grades downward into the upper ashy phase of member 2, which in this locality has been redeposited in poorly stratified beds containing incorporated ventifacts	65
Total thickness of the Altos de Pica Formation (member 3)	173
Altos de Pica Formation (member 2).	

MEMBER 4

The deposits of member 4 cover all the area of the Altos de Pica from the northern border of the quadrangle southward to the Quebrada Chacarilla. This member has one of the most extensive outcrop areas of any unit within the quadrange. According to the maps of Bolivia (Ahlfeld, 1946) and Chile (IIG, 1960), toward the east and the north this member is exposed for many kilometers. The member thins toward the west to a featheredge at an altitude of approximately 2,000 m.

Felsch (1920, p. 472) reported the thickness of the member to be 450 m near Alona and to the north; the same author measured 500 and 600 m, which is the maximum thickness observed for member 4. Near Alona the authors estimated a thickness of 250 m.

Member 4 is concordant with both the underlying and the overlying members. In some localities minor cut and fill features are observed along the contacts, as well as within the member.

The phases of the member are well differentiated and have in general the same texture and lithology as member 2 (table 5).

TABLE 5.—*Petrographic table of member*

Unit	Hardness	Color	Groundmass	
			Percentage	Differentiation
a	Poorly consolidated	Very light orange	75	In part
b	Medium hard	Light orangish red	65	In part
c	Medium hard	Light reddish gray	45	No
d	Medium hard	Dark gray	70	No
e	Very hard	Light chestnut gray	85	Yes

Section of the lateral ashy phase of member 4 of the Altos de Pica Formation

	Meters
Altos de Pica Formation (member 5).	
Altos de Pica Formation (member 4):	
Rhyolitic tuff, grayish-orange-pink (weathered pink), porphyritic, porous; low specific gravity; incipient eutaxitic texture. Groundmass (70 percent of the rock) is isotropic; consists of glass shards; index of refraction $n=1.942$ (75 percent SiO_2). Phenoclasts (30 percent of the rock) show some embayment and include rounded fragments of quartz as large as 2 cm in diameter, elongated biotite as much as 2 cm long, sodic oligoclase fragments as large as 1 mm, sanidine fragments as large as 2 mm, magnetite grains as large as 3 mm, and very small amounts of amphibole. Lower contact is gradational	20
Rhyolitic ash, light-gray, porphyritic, poorly consolidated, porous; low specific gravity; not eutaxitic; appears to be finely laminated, the laminae being 1 cm or less; contains fragments of pumice lapilli (2–3 cm) size	3
Total thickness of the Altos de Pica Formation (member 4)	23
Altos de Pica Formation (member 3).	

In the higher parts of the Altos de Pica Plateau, the piedmont sedimentary deposits do not separate the pyroclastic members of the Altos de Pica Formation. There the contact between the two pyroclastic members is impossible to locate as the rocks are lithologically identical. Member 2 almost certainly underlies member 4; however, even if it were exposed, it could not be separated from member 4. Only in the Quebradas Chacarilla and Tambillo has the erosion reached the older rocks and exposed the contact between the pyroclastic members at the point where the intercalated member 3 wedges to a featheredge.

Samples were taken from an exposure in the Quebrada Quisma at an altitude of 3,800 m. A petrographic comparison of these samples

4 of the Altos de Pica Formation

Phenoclasts		Elongation of fragments	Glass		Remarks
Embayment	Plagioclase		Index of refraction	Color	
Yes	Sodic oligoclase	No	1.507	Transmitted light, light chestnut.	
Yes	Intermediate oligoclase.	Very scarce.	1.507	Transmitted light, light chestnut.	Poorly developed eutaxitic texture.
Yes	Intermediate oligoclase.	Very scarce.	1.495	Colorless	Eutaxitic texture.
Yes	Intermediate oligoclase.	Scarce	1.507	Colorless	Eutaxitic texture.
Yes	Sodic oligoclase	No	1.515	Transmitted and reflected light, light chestnut.	Eutaxitic texture.

demonstrates that vertical gradation occurs within the units of this member as shown in table 5.

The generalized section of the ignimbritic deposits of the Altos de Pica Formation in this locality is as follows:

Section of member 4 of the Altos de Pica Formation in the Quebrada Quisma

Altos de Pica Formation (member 4):

Unit a:

Rhyolitic tuff of the upper, ashy phase, very light orange, unconsolidated, porphyritic; slightly eutaxitic; low specific gravity. Groundmass (75 percent of total) is composed of poorly differentiated glass shards in the form of axiolites. Phenoclasts consist of quartz as large as 2.5 mm, sanidine as large as 2 mm, sodic oligoclase, biotite, and magnetite.

Unit b:

Rhyolitic welded tuff, light-orangish-pink; poorly consolidated; groundmass (65 percent).

Unit c:

Rhyolitic welded tuff, light-pinkish-gray, porphyritic, poorly consolidated; eutaxitic. Groundmass (45 percent of rock) composed of undifferentiated glass (axiolites). Phenoclasts include intermediate oligoclase fragments as large as 2.5 mm, quartz fragments as large as 1.5 mm, biotite, amphibole, magnetite, and zircon.

Unit d:

Rhyolitic welded tuff, dark-gray, porphyritic, poorly consolidated; well-defined eutaxitic texture. Groundmass (70 percent of total) composed of glass (axiolites). Phenoclasts include intermediate oligoclase fragments as large as 2.5 mm, quartz fragments as large as 2 mm, sanidine fragments as large as 1.5 mm, biotite, magnetite, and a few fragments of amphibole and zircon.

Altos de Pica Formation (member 4)—Continued *Meters*

Unit e:

Rhyolitic welded tuff, light-grayish-brown, porphyritic, hard; marked eutaxitic texture near phenoclasts. Groundmass (85 percent of total) composed of glass (which mostly occurs in the form of spherulites), partly devitrified. Phenoclasts include sodic oligoclase fragments as large as 6 mm, quartz fragments as large as 4 mm, sanidine fragments as large as 3 mm, biotite and magnetite.

Approximate thickness of the Altos de Pica Formation (member 4) 25

Base covered.

MEMBER 5

Member 5 of the Altos de Pica Formation has the largest surface distribution of any of the formations within the Pica area. Eolian and fluvial sediments record the conclusion of a cycle of erosion and the deposition of sediments derived from the adjacent mountains. The member has been only slightly eroded, but in some localities it is buried by Quaternary sediments of various types. The sediments of this member thin eastward to a featheredge at an altitude of approximately 3,000 m. The member thickens downdip to the west and plunges under the sediments of the Pampa del Tamarugal.

The lower contact of the member is conformable with member 3 or, if it is present, with member 4. Cut and fill surfaces recording minor disconformities occur within the member and are most common where the sediments are torrential.

The lithology of this member has more lateral variation than that of any other member of the Altos de Pica Formation. In the type locality at El Algarrobal, the member is dark gray. It is predominantly eolian in origin, is poorly consolidated, and is uniform in texture and lithology throughout the section. As exposed in the Quebradas Seca and Quisma and also in La Calera, the member consists of a light-yellowish-brown sandstone and a few gravel beds. The sandstone beds contain concretions and are crossbedded. A conglomerate of fluvial origin occurs near the base of the formation; in places, it fills the minor channels that were cut in the top of the tuff beds of member 4.

In many localities, beds of pyroclastic origin are intercalated with the sedimentary strata of fluvial and eolian origin. The basal unit of the member in the Quebrada Infiernillo is a very light gray friable rhyolitic ash which has many redeposited fragments of lapilli size. East of Pica, volcanic ash forming one of the upper beds of the member is notable in many outcrops because of its white color. The thickness of the member is variable. The member is not found on the Altos de Pica Plateau at an altitude higher than approximately 3,000 m nor on Sierra Longacho.

North of the Quebrada Ancha and of Pampa Esmeralda is found what Felsch (1920, p. 588) calls "the modern cone of sandstones and conglomerates of La Calera." The geomorphology of this part of the plateau, the varied origin of its sediments, and the accentuated roundness and dark original color of the igneous and sedimentary phenoclasts, confers to the area the appearance of an alluvial cone, and this part of the plateau is easily differentiated from the lower slopes of the Altos de Pica. The impression of an alluvial cone is misleading inasmuch as the topography and the sedimentation are continuous between the slopes of the Altos de Pica Plateau and the apparent cone. The structural depression east of the Sierra Longacho continued to form after the deposition of member 5, and this resulted in accentuated south-facing slopes which caused the deposits north of the depressed area to have the appearance of an alluvial cone. The dark phenoclasts of the conglomerates originated near Cerro Yarvicoya in an area different in lithology from that of the Altos de Pica Plateau.

Type section of member 5 of the Altos de Pica Formation measured on the north-facing slope of Quebrada Chacarillo at Algarrobal

	Meters
Altos de Pica Formation (member 5).	
Top exposed:	
Sand, dark-gray, medium to fine; eolian in origin; has intercalated thin beds of gypsum and a few ventifacts; near base, a friable, very light gray thin sandstone bed, cemented with calcareous cement; at surface, covered with layer of rounded boulders originating from many sources and showing well-formed desert varnish	112
Sand, dark-gray, medium to fine; contains ventifacts and has gypsum that locally occurs as cement	60
Sandstone, yellow, medium- to fine-grained, crossbedded	1
Sand, greenish-gray, medium to fine, uniform, crossbedded, has a few ventifacts; contains intercalated bed of gypsum a few centimeters thick; toward bottom, color changes to dark gray	27
Exposed thickness of the Altos de Pica Formation (member 5)	200
Altos de Pica Formation (member 3).	

AGE AND CORRELATIONS

Sufficient evidence has not been accumulated to permit a definite determination of the age of the Altos de Pica Formation. No fossils have been found and stratigraphic relations are such that the formation overlies the older beds with marked angular unconformity. The geographic isolation of the area with respect to other regions where the Tertiary and Pleistocene geology has been studied necessitates comparison over great distances with consequent tenuous correlations. According to present knowledge of Andean geology, the formation was probably deposited during late Tertiary and Pleistocene, but there is very little data on which to base a more definite age.

The ages proposed for various Tertiary and Quaternary formations in Chile and adjacent areas are shown in table 6. According to Ahlfeld (1946, p. 247), a fairly good correlation may be made between the Estratos del Río Mauri in Bolivia and the Formación Liparítica of Brüggen (Altos de Pica Formation). The Estratos del Río Mauri are subhorizontal and overlie the folded Corocoro (lower Tertiary beds) with angular unconformity and this relationship suggested to Ahlfeld a Pliocene age. This age was affirmed a few years later by Ahlfeld (1954, p. 19). At one time, Ahlfeld assigned the formation a Miocene age (Ahlfeld, 1941, table 1). The formation is approximately 500 m thick in Bolivia (Ahlfeld, 1941, p. 248) or, according to Muñoz R. (1951, p. 11), at a minimum 600 m plus 10–40 m of rhyolitic tuffs.

Most geologists in Chile have assigned the Altos de Pica Formation to the Miocene Epoch. Brüggen (1918, p. 9) was the first to suggest this epoch, and his opinion was later supported by Felsch (1920, p. 470). Earlier, Felsch (1917, p. 322) suggested a very late Tertiary or a Pleistocene age for this formation in the Quebrada Guatacondo. Later, Felsch (1933, p. 412) suggested a Pliocene age. More recently, Brüggen (1950, p. 118) expressed the following opinion: "The age of the rhyolite is determined, on one hand, by its relations with the red beds of the San Pedro Formation (Lower Tertiary) over which the rhyolites lie with pronounced angular unconformity. On the other hand, the rhyolites are older than the dislocations of the Upper Tertiary which gave origin to the great longitudinal valleys of northern Chile and therefore must be of Miocene age." In spite of the ambiguity of this determination and the lack of other correlative data, this age has been accepted (Fuenzalida in Hoffstetter and others, 1957, p. 193).

Dingman (1963) tentatively assigned the welded tuffs in the vicinity of San Pedro de Atacama to the Pliocene on the basis of potassium-argon age determinations. He stated (translated from Spanish), "Potassium-argon age determinations now in progress in the Branch of Isotope Geology of the U.S. Geological Survey seem to eliminate the possibility of the tuffs being of Pleistocene age. A minimum age of approximately 5 million years is indicated, or a late Pliocene age; however, the analytical uncertainties do not exclude a possible Miocene age. Additional work may resolve the age more closely."

The tuffs in the San Pedro area may be the equivalent of those in the Pica area.

Douglas (1914) discovered a few fragments of a mandible of a *Nesodon* in the sediments of the Mauri area (Bolivia). He reported that C. W. Andrews considered the fossil almost identical to specimens from sediments of the Santa Cruz Formation (Miocene) in Argentina. Douglas called the fossil-bearing sediments "The Mauri Volcanic Series," and in these beds he also discovered a tree trunk that, according to N. Bancroft, is a dicotyledon similar to a Lauracae. The mandible is of considerable interest because it is the only data that can be used to assign a definite age to a formation which can be correlated with some certainty to the Altos de Pica Formation.

Several other geologists have worked in the three countries bordering Chile in areas where sediments similar to those of the Altos de Pica Formation are exposed. Hausen (1939, p. 166) considered the Miocene sequence which he studied in the Cordillera de Lípez—an area which extends from Bolivia into Argentina—correlative with the Formación Liparítica of Brüggen. He extended the correlation to the rhyolitic sequence studied by Douglas in the Tacna (Peru)-Arica (Chile) area. Vilela (1953, p. 26) thought that the volcanic rocks of Argentina and Chile, referred to by Hausen, correlated with the "Old dacites and dacitic tuffs" of northern Argentina and that they were probably Miocene in age. Thus, these authors favor a Miocene age for formations correlative with the Altos de Pica. Vilela (1953, p. 16) pointed out that such an age is not conclusive inasmuch as the age of the Calchaqueña Formation, which includes the dacitic series, was not based on fossil evidence but rather on lithologic correlation and structural relations with similar formations in other areas. Frenguelli (1936, p. 477) thought that the Araucaniano (Pliocene) was correlative with the Estratos Jujeños (Steinmann, 1930). On the other hand, Ahlfeld (1956, p. 181) correlated the Estratos Jujeños with the Estratos del Río Mauri, which in turn he would correlate with the Altos de Pica Formation, (Ahlfeld, 1946, p. 248).

Jenks (1945, p. 13–15; 1948, p. 51–56) described the Chachani volcanics of the Arequipa quadrangle of southern Peru. This sequence, especially the "massive tuffs", are lithologically very similar to the pyroclastic members of the Altos de Pica Formation. The "massive tuffs" are of dacitic or rhyolitic composition and are ignimbritic in appearance. To these Jenks assigned a Middle Tertiary age. Fenner (1940, 1948) was the first to recognize that the tuffs of the Arequipa area were deposited by nuées ardentes.

Most authors previously cited agree in placing the Altos de Pica Formation and its members which may be correlated with the Estratos del Río Mauri and perhaps the sequence that covers slopes east of the Salar de Atacama (Brüggen, 1946, p. 74) in the upper Tertiary.

TABLE 6.—*Tertiary and Quaternary formations in northern Chile and adjoining areas* [1]

Period	Epoch	Bolivia (Douglas, 1914)	Bolivia (Ahlfeld, 1946)	Peru (Jenks, 1948)	Chile (Brüggen, 1950)	Argentina (Groeber, 1957)	Chile (Galli and Dingman, 1962)	Chile (Doyel and Henriguez, written commun. 1962)	Chile (Dingman, 1963)
Quaternary	Pleistocene					Riolítica Formacion [2] (Chile)	Altos de Pica Formation	Lluta Formation [2]	Unnamed formation of ash-flow deposits [2]
	Pliocene		Estratos del Rio Mauri [2]			Araucaniano Formacion			
	Miocene	Mauri Volcanic Series [2]		?	Liparítica Formacion [2] Riolítica Formacion [2]			??	

Tertiary	Oligocene		Corocoro System	Chacani Volcanics ?				Putani Formation Arica Formation	San Pedro Formation Tambores Formation
	Eocene								
	Paleocene				San Pedro Formacion				

[1] From Dingman, R. J., and Lohman, K. E., 1963, Late Pleistocene diatoms from the Arica area, Chile, Short papers in Geology and Hydrology: U. S. Geol. Survey Prof. Paper 475-C, art. 78, p. C70.

[2] Stratigraphically and lithologically equivalent to the Altos de Pica Formation.

Groeber (Hoffstetter and others, 1957, p. 195) disagreed with this age; he considered the Formación Liparítica of Brüggen to be Quaternary in age on the basis that, if the formation were Miocene in age, its structure would be independent of recent relief and would be folded like the Tertiary sediments in the San Pedro area. Harrington (1961, p. 195) considered the lavas and welded tuffs exposed in the eastern parts of Antofagasta and Atacama Provinces, Chile, to be early Pleistocene in age.

The most definite proof of a Miocene age is the identification of the mandible of the *Nesodon*, reported to be almost identical with other specimens of the same genus from the Santa Cruz Formation of the Patagonia, which are of Miocene age. Unfortunately, there is no other paleontological evidence to support this age.

The possible Pliocene age is based both on the correlation of the Altos de Pica, the Estratos del Río Mauri, the Estratos Jujeños, and the Araucaniano—which are linked together by various authors to establish a relation with the last-named formation, which is of Pliocene age and which is lithologically comparable to the Altos de Pica Formation—and on the potassium-argon age determinations of similar tuffs near San Pedro de Atacama.

In the opinion of the authors, these premises are too weak to justify the assignment of the Altos de Pica Formation to an epoch. The deposition of the Altos de Pica Formation is considered to have commenced during the late Tertiary and to have continued into the Pleistocene. Many more detailed geologic studies must be made before a more definite age can be determined.

QUATERNARY DEPOSITS

Quaternary deposits of many different types are found within the mapped area. Terrace and piedmont deposits, alluvium, saline deposits, sand sheets, and sand dunes are indicated on the geologic map. Other deposits, such a mudflows and travertines, are not indicated because of the map scale; however, in some localities these deposits are numerous.

TERRACE DEPOSITS

Alluvial terraces occur at various levels above the modern stream beds. They are distributed throughout the piedmont area and along the borders of the alluvial cones of the Quebradas Chacarilla and Sagasca. The sediments are heterogeneous, and many local variations are observed depending on the geology and the topography. Mudflow deposits make up the larger part of the terraces. In the Quebradas Saguachinca and Quisma, the terraces are above the reach of ephemeral mudflows and flood water; thus in these localities the terrace surfaces are almost completely covered by eolian sand.

Outcrops of limestone in the Chacarilla area are approximately 200 m above the floor of the Quebrada Chacarilla. The outcrops are distributed along a terrace level on the north wall of the quebrada and extend in an east-west direction for approximately 3 km. The limestone beds are approximately 20 m thick and are in subhorizontal position. In addition to the limestone, the terrace deposits include thick beds of conglomerate and friable sandstone. These deposits lie over the beds of the Chacarilla Formation with angular unconformity. The upper part of the terrace is hidden in some localities by detrital material derived from the welded tuffs of the Altos de Pica Formation. Muñoz M.[6] wrote that limestone seems to correspond to a stagnant lacustrine environment in which evaporation caused calcium carbonate to crystallize out of saturated solutions. The authors do not believe that the limestone is lacustrine in origin, and they suggest that its origin is similar to that of the travertines which are being deposited at the present time by the surface water flowing in the Quebrada Chacarilla.

The limestone is very light gray and fine-grained. Microscopically it is seen to consist of an aggregate of calcite grains approximately 0.2 mm in diameter, which are in part recrystallized. The limestone contains scarce crystals of plagioclase and quartz, fragments of magnetite, and a small amount of clayey material. The phenoclasts of the conglomerates are of varied origin and are in general subangular; the matrix is light-gray, tuffaceous, and poorly cemented.

PIEDMONT DEPOSITS

The sediments which form the Quaternary piedmont deposit are exposed in the Longacho area. Inasmuch as the material was deposited in many small alluvial fans at the mouth of small quebradas that had very limited drainage areas, the relatively fine grain reflects the limited competency of the transporting agent. The phenoclasts are derived almost entirely from the resistant rocks of the Sierra Longacho (welded tuffs, intrusive rocks, and Liassic sediments).

ALLUVIAL FAN DEPOSITS

Alluvial fans cover extensive areas especially near the mouth of the Quebradas Chacarilla, Sagasca, Quisma, and Chintaguay. The alluvial fan of the Quebrada Chacarilla covers some 350 sq km in the southwestern part of the Pica quadrangle. The fan deposit extends from the western border of the Andes to the eastern slopes of the Coastal Range some 35 km to the west. Near the apex of the

[6] Muñoz M., E., 1953, El yacimiento de mármol de Chacarilla, Iquique: Santiago, Chile, Departamento de Minas y Combustible, 1–B, Iquique No. 1, p. 4.

fan, the sediments are composed of fanglomerates and conglomerates, whereas near Pintados, close to the Coastal Range, the sediments are very clayey and saline and have very low permeability. However, some of the wells drilled in this area along the western border of the Pampa del Tamarugal have penetrated thick layers of coarse-grained sediments.

The alluvial fan of the Quebrada Sagasca is very similar to the previously mentioned cone both lithologically and morphologically. This alluvial fan covers less than 20 sq km near the northern border of the quadrangle and in many localities is overlain by active sand dunes.

The alluvial fan of the Quisma–Chintaguay drainage system is not so extensive. The sediments of this fan reach Canchones and underlie a large part of Pampa Esmeralda. On Pampa Esmeralda the deposits are almost completely covered by the modern sand sheets.

MUDFLOW DEPOSITS

Mudflow deposits are characteristic of desert and semiarid mountainous regions. Within the area of investigation the consolidated mudflows are distributed from the mountain headwaters of some of the local drainage basins to the interior of the Pampa del Tamarugal. The color of the mudflow varies according to the type of rock from which the mudflow is derived. In the Quebrada Chacarilla the deposits are derived from the erosion of the Chacarilla Formation and, therefore, are reddish brown. In the Quebrada Quisma the deposits are derived from the Tertiary-Pleistocene rocks and are yellowish tan. The phenoclasts in the cenuglomerates are of all sizes and are derived from the local rocks and especially from the porphyritic granites, trachytes, sandstones and welded tuffs. Most of the phenoclasts are angular to subangular. The mudflows are not stratified or sorted, and therefore the phenoclasts show a chaotic distribution. However, along the border of the recent deposits which overflow the terraces in the Quebrada Chacarilla, a marginal line of phenoclasts are found which are larger than those in the center of the deposit. This difference in phenoclast size may be the result of the reduced transportation capacity of the viscous mud along the border of the mudflow tongues.

TRAVERTINES

Travertine is being deposited along the course of the stream in the Quebrada Chacarilla, especially in the upper course. The travertines are banded and porous. The form and morphologic detail of plants is preserved in the holes in the travertines.

SAND DEPOSITS

Windblown sand is being actively deposited in the form of sheets or dunes principally in the Pampa Esmeralda, Pampa Pica, and Puquio de Núñez areas, and also on the lower slopes of the mountains, generally below an altitude of 2,200 m. At higher altitudes the sands are confined to localities protected from the winds. Some of the minor quebradas near Pica have not been washed out by torrential water for many years and are now almost completely filled by eolian sands.

Samples of sand were obtained from the dunes approximately 3 km north of Pica. Samples were obtained from the windward slope of the dune, from the cuspid of the dune. from the leeward slope of the dune, and from the desert floor. The mechanical analyses of these samples indicate that the sorting of the sand depends upon the location of the sand (fig. 12).

The results of the microscopic study of the heavy minerals separated from the sand are indicated in figure 13.

The histograms of the sand samples indicate that the clasts from the dunes are well sorted, whereas the material from the desert floor is poorly sorted and includes a large percentage of coarse clasts. This confirms what is apparent to an observer, that the desert floor is armored by coarse sand grains and that the dunes move across it without disturbing its surface.

The heavy mineral analyses also indicate the similarity of the dune sands to each other and their difference in percentage composition from the sand of the desert floor. The desert floor contains less hornblende and more of the heavier magnetite and hematite. This difference probably indicates that a selective separation resulting from specific gravity, as well as from grain size, causes more of the heavier minerals, as well as more of the coarser grains, to be left behind as the dunes move across the desert floor.

SALINE DEPOSITS

Near the western border of the Pica quadrangle are areas underlain by the saline deposits; these areas form the eastern border of the central salar of the Pampa del Tamarugal. The salt deposits are very light gray and contain intercalated tan clastic beds. According to analyses made by Froehlich (oral commun., 1958), the clayey and sandy soils contain salts: chlorides and sulfates combined with sodium, calcium, magnesium, and in some localities with potassium. The carbonates are very scarce.

In the vicinity of Matilla and Puquio de Núñez, partly limonitic sands and gravels are cemented by salts that may contain a high percentage of gypsum. The saline cement was probably deposited by

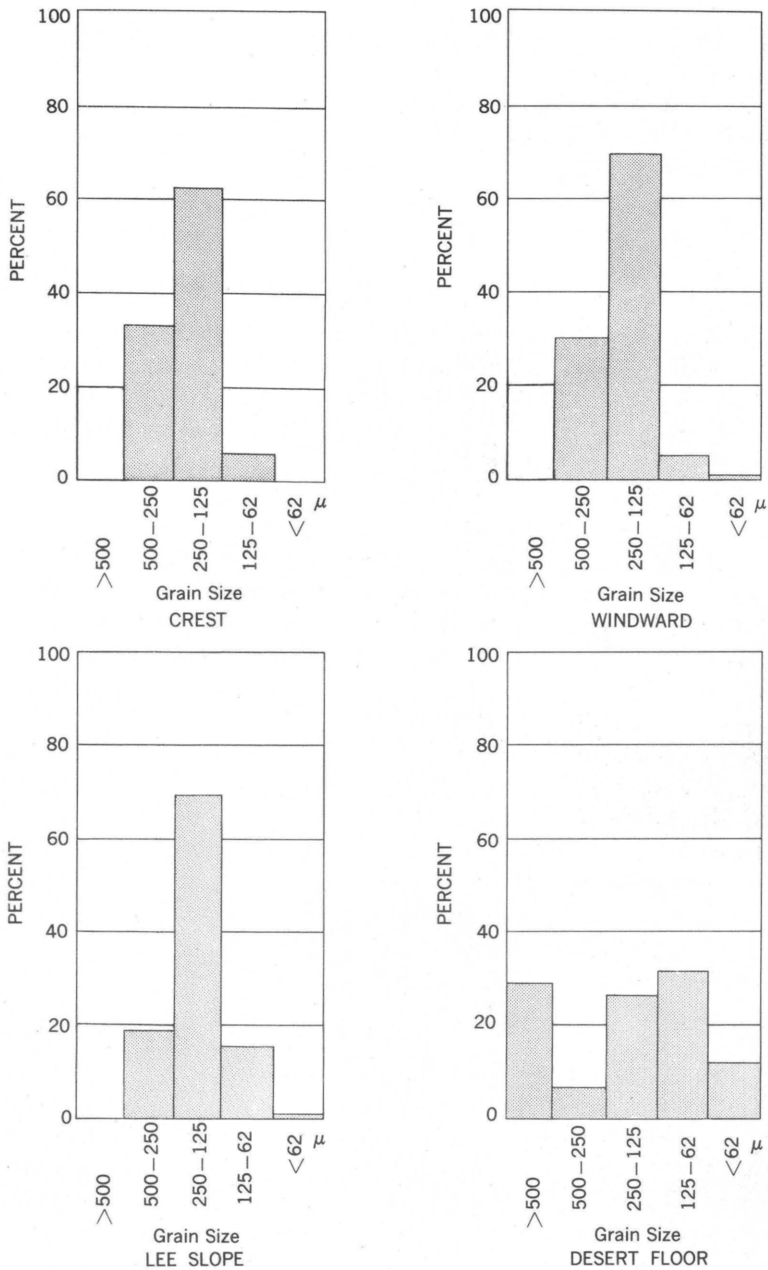

FIGURE 12.—Size histograms of selected sand samples from the dune area, Pampa Pica.

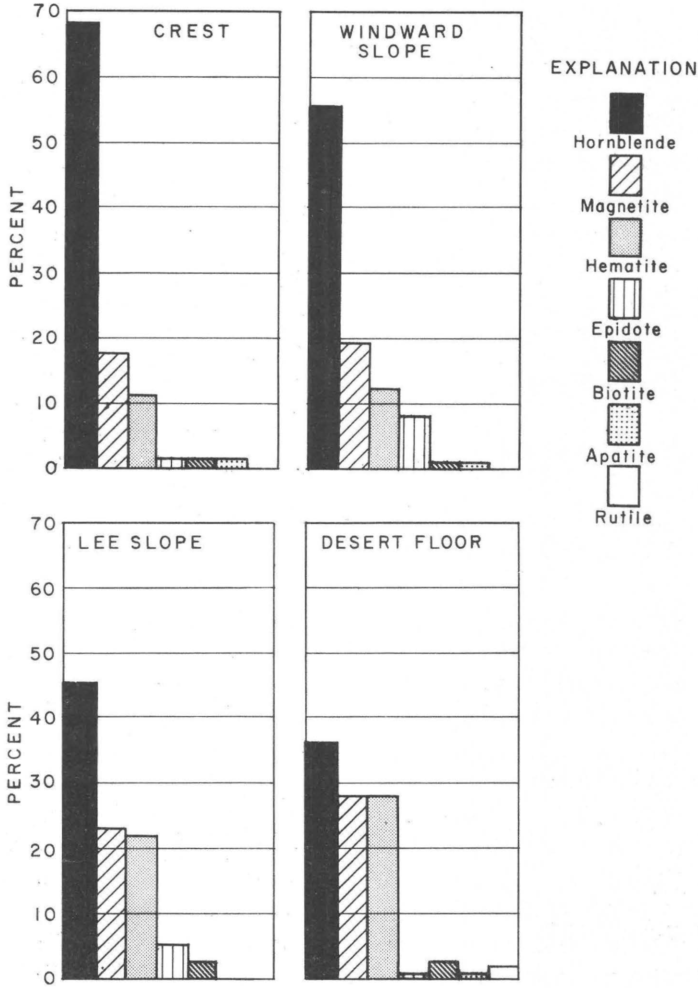

FIGURE 13.—Heavy minerals in selected samples from the dune area, Pampa Pica.

ground water near the lower limit of the phreatic zone. The sands and gravels make up light-gray areas that contrast with the yellowish-tan of the modern sands. The stratification of these deposits can be observed in the galleries of Matilla. The deposits occur along the eastern side of the Sierra Longacho, which acts as a dam or barrier against the westward flow of surface and ground water. (See section on "Ground-water resources.")

INTRUSIVE ROCKS

GENERAL ASPECTS

Intrusive rocks of many different lithological types penetrate all the formations older than the Altos de Pica. Within the quadrangle, they are exposed in the Quebrada Tambillo, in the Longacho area, to the southeast of the Quebrada Chacarilla, and as dikes in the small hills to the north of La Calera.

There are many references to these rocks in the work of Brüggen, Felsch, and others. All the rocks have received the name of Andean Diorite (Muñoz Cristi, 1950, p. 87) and are so indicated in the Geologic Sketch Map of Chile compiled by Muñoz Cristi and Flores Williams and amplified by Brüggen (1950, geologic map included with text).

Recent investigations have indicated at least three ages of intrusive activity: Cretaceous, Cretaceous-Jurassic, and Paleozoic (Ruiz and others, 1960). On the basis of the present investigations, the generic name Andean Diorite has been dropped from usage in Chile (IIG, 1960).

The scarcity of outcrops of the pre-Tertiary rocks and the large intervening areas covered by the Altos de Pica Formation have made it difficult to correlate the various intrusive rocks. For this reason, it is more convenient to describe these rocks in groups according to the formations which they penetrate rather than to describe them separately and to attempt doubtful correlations (table 7).

To the east of Jucuma in the Quebrada Tambillo, plutonic rocks of various types form the largest outcrop of intrusive rocks within the mapped area. Unfortunately, because the contact between these rocks and the Cerro Empexa Formation is concealed, the relationship cannot be established.

These plutonic rocks are completely isolated from the pre-Tertiary sedimentary formations. Their only contact is with the Altos de Pica Formation which overlies the strongly eroded surface of the intrusive. The plutonic rocks outcrop in the botton and sides of the canyonlike quebrada for 9 km from the south of Tapinga to approximately 2 km upstream from the Jucuma chacra. The oldest rock in this outcrop area is a medium-gray granodiorite. (See table 7.) The rock is hard, has clearly defined joint systems, and, in some areas, is intruded by thin quartz-plagioclase dikes and thin pegmatite dikes. In some localities the rock has had lit-par-lit injection. A few local migmatized zones exist near the contact of the intrusive and the host rock.

The second magmatic cycle of this area is represented by yellowish- and olive-gray granites. Other intrusive rocks of the same cycle include orangish-gray tonalites, greenish-gray diorities, and pinkish-gray aplite; the aplite occurs in dikes.

Southwest of Tapinga in a small hill, which is an island surrounded by rocks of the Altos de Pica Formation, are exposed light-gray tonalite porphyries.

In the sector between Tapinga and Jucuma, there are many large xenoliths of sedimentary rock included in the plutonic mass. One of these xenoliths is composed of quartzite that megascopically and microscopically appears to be identical with the orthoquartzites of the Chacarilla Formation. Another inclusion is composed of a dark-gray shale. This xenolith has an exposed surface area of 1 m by 5 m.

The intrusive bodies of the Longacho area are plugs and dikes of many different lithologic types. Cerro Longacho is formed in part of very dark gray andesite. A small rounded hill south of the principal peak is underlain by porphyritic dacite. Other igneous bodies of smaller extension are composed of granite porphyry, microdiorite, gabbro, and rhyolite.

The Chacarilla Formation is also penetrated by many igneous rocks, the most common of which is a granite porphyry. Megascopically the rocks are light greenish-gray and light orange; they are iron stained along the joint systems. The sector most thoroughly invaded by these rocks is a belt in the vicinity of the Quebrada Empexa a short distance east of the Quebrada Chacarilla. In this area the intrusive body consists of a diorite plug approximately 1 km wide crossed by many thin dikes. Near the borders the diorite is differentiated into granodiorites and micrograniites. The igneous rocks and the dikes of granite porphyries between the main igneous body and the Quebrada Chacarilla are differentiated offshoots of the main mass.

Aplitic granites are exposed near the eastern limit of the Quebrada Chacarilla.

The oldest rocks that intrude the Chacarilla Formation are dikes of hard amphibolite which are exposed 2 km south of the Chacarilla chacra and 500 m east of the locality in which the ammonite (p. 23) was found, that is, in the first waterfall in the Quebrada Empexa upstream from its junction with the Quebrada Chacarilla. These dikes, which are exposed in only a small area, are crossed by dikes of granite porphyry.

The most recent intrusives in the Chacarilla Formation are dikes of amphibolic diorite porphyry and andesite, as much as 30 m wide.

The Cerro Empexa Formation is intruded only by a few dikes of igneous rocks. The previously mentioned dikes of amphibolic diorite porphyry cross the formation in a few localities, and an andesite dike intrudes the formation near the axis of the Higueritas syncline.

TABLE 7.—*Petrographic description of intrusive rocks in the Pica area*

Rock type	Color	Texture	Composition		Remarks
			Groundmass	Phenocrysts	
Quebrada Tambillo area [Intrusive relation with sedimentary rocks other than overlying Tertiary unknown]					
Granodiorite	Medium gray.	Hypidiomorphic	Plagioclase (andesine) 50 percent; orthoclase 18 percent; quartz 13 percent; biotite 5 percent; amphibole 6 percent; chlorite 6 percent; magnetite 2 percent.	------	
Granite	Olive gray	Medium grained, equigranular.	Orthoclase 40 percent; quartz 30 percent; plagioclase 25 percent; chlorite 8 percent; amphibole 5 percent; magnetite 2 percent.	------	Crystal size ranges from 0.8 to 2.6 mm; plagioclase is highly altered.
Tonalite	Orangish gray.	Granular hypidiomorphic.	Intermediate plagioclase, amphibole, and quartz.	------	
Diorite	Greenish gray.	Medium grained, hypidiomorphic.	Intermediate plagioclase, amphibole, orthoclase, and quartz.	------	Quartz is very scarce.
Granodiorite porphyry.	Light gray	Porphyritic	Plagioclase, amphibole, magnetite.	Quartz 49 percent; plagioclase 32 percent; biotite 13 percent; orthoclase 4 percent; amphibole 1 percent; magnetite 1 percent.	Evidence of recrystallization and introduction of quartz in the groundmass.

Longacho area

[Intrudes Longacho Formation]

Andesite	Dark gray	Porphyritic	54 percent of total; hypidiomorphic, feldspar microlites, probable vitreous pigment and magnetite.	46 percent of total, andesine, augite, hypersthene, magnetite.	In hand specimen the rock has the general aspect of a basalt.
Dacite	Reddish gray.	Porphyritic	Microgranular, probably composed of quartz and feldspar.	Feldspar (euhedral), biotite, probable amphibole and scarce quartz.	Phenocrysts as large as 2 mm. Rock is deeply decomposed.

Chacarilla area

[Intrudes Chacarilla Formation]

Granite porphyry.	Light orange.	Porphyritic	Granular to trachytic; abundant quartz, biotite, orthoclase, sericite and hematite.	Scarce, maximum sized are orthoclase of 2.2 mm. Include quartz, orthoclase, and biotite.	Biotite fills fractures. Groundmass crystals average 0.04 mm.
Diorite	Greenish gray.	Granular hypidiomorphic.	Plagioclase 80 percent; amphibole 18 percent; magnetite 2 percent.	----------	
Microsyenite	Pinkish gray.	Aplitic	Orthoclase 75 percent; quartz 10 percent; plagioclase 8 percent; magnetite 7 percent.	----------	
Aplitic granite	Light gray	Aplitic	Orthoclase 39 percent; albite 26 percent; quartz 20 percent, diorite 12 percent; magnetite 2 percent.	----------	
Amphibolite	Dark green.	Basaltic porphyry.	35 percent total, chlorite, calcite, scapolite, and apatite.	65 percent of total, apatite and amphibole.	
Amphibolic diorite.	Dark greenish gray.	Porphyritic	Sericitized feldspar, augite, chlorite and magnetite. Quartz and chlorite are secondary.	Feldspar altered to sericite, hornblende, augite and magnetite.	Sericite phenocrysts as large as 2 mm; hornblende phenocrysts as large as 1 cm.

AGE AND CORRELATIONS

The age relationship between the various intrusive rocks and between the intrusive rocks and the sedimentary formations may be satisfactorily established in some areas. In other areas, such as Cerro Longacho and the Quebrada Tambillo, where the pre-Tertiary rocks are poorly exposed, the data which can be collected are insufficient to establish age relationship.

In the area of Chacarilla the intrusive rocks may be separated into three magmatic cycles, the rocks being well differentiated with respect to lithology and clearly separated in geologic time. The first cycle of intrusion is represented by dikes of amphibolite that apparently are the oldest intrusive rocks in the area. They intrude the Chacarilla Formation and are truncated by the post-Late Jurassic unconformity; therefore their age is Latest Jurassic or Early Cretaceous.

During the second cycle of intrusion, the Chacarilla Formation was invaded by the diorites and their segregations and differentiations into various holocrystalline masses and dike rocks. Of these, the granite porphyries have the widest distribution and cross cut amphibolites of the first cycle. The granites that are exposed along the upper course of the Quebrada Chacarilla are probably of this magmatic cycle, but, inasmuch as they are not in contact with any other igneous rocks, it is impossible to be certain of this relationship. The age of this second cycle is also probably Late Jurassic or Early Cretaceous inasmuch as the dikes penetrate the Chacarilla Formation and are truncated by the post-Late Jurassic cycle of erosion. The intrusion of these rocks was probably almost contemporaneous with the post-Late Jurassic orogeny. The rocks of this second cycle have the widest distribution of the igneous rocks in the Chacarilla area.

The geographic and stratigraphic isolation of the outcrops of plutonic rock in the Quebrada Tambillo does not permit their age to be established other than as pre-Altos de Pica.

The third intrusive cycle in the Chacarilla area consists of diorite porphyry and propylitized andesite which intrude both the Chacarilla and Cerro Empexa Formations. This intrusion occurred after the deposition of the Cerro Empexa Formation and before the cycle of erosion which preceded the deposition of the Altos de Pica Formation.

The intrusive rocks, which outcrop in the Longacho area and which intrude the Lower Jurassic sediments cannot be correlated with the previously discussed magmatic cycles because of lack of data and because of the geographic isolation of the exposures. Their age may only be determined as post-Early Jurassic and pre-Late Tertiary.

The strongest intrusive activity of the Pica area is of Late Jurassic or Early Cretaceous age and does not correspond with the principal orogeny (Late Cretaceous) that affected the area. This view conflicts with the conclusions drawn by other authors who considered the major period of intrusion in the area of Pica to be younger than Jurassic.

Recent investigations have clarified some of the age relationships of the intrusive rocks in northern Chile (Ruiz and others, 1960). According to Ruiz, there were at least three periods of intrusion of granitic rocks, the youngest occurring during the Late Cretaceous. Age determinations were made by the Geochronology Laboratory of the U.S. Geological Survey in Washington, D.C. One of the samples was obtained from the Quebrada Duplijsa north of Cerro Juan de Morales. The age of this microgranite porphyry was determined to be 95 ± 10 million years. The relationship between this intrusive and those of the mapped area is unknown; however, some of the intrusive activity of the Pica area was probably contemporaneous with that of the Juan de Morales area. Possibly the third cycle of intrusive activity in the Chacarilla area may correlate with the Juan de Morales intrusion.

STRUCTURAL GEOLOGY

GENERAL FEATURES

The orogeny at the end of the Cretaceous folded the Cretaceous and older rocks into a series of asymmetrical anticlines and synclines that have northward striking axes. A strong angular unconformity separates these rocks from those of the Tertiary and Quaternary which form a homocline dipping gently to the west. The homocline is cut by numerous faults that have small displacements and by a monocline that is found near its western border. The difference in the structural aspects of the Cretaceous and older rocks as compared to the Tertiary and Quaternary deposits makes convenient the discussion of the structure in two sections.

MESOZOIC ROCKS

LONGACHO FORMATION

The structure in the Longacho area is an asymmetrical dome that has Cerro Longacho, the principal peak, as the focal point. Inasmuch as this dome is only a local feature, it may have been caused by the intrusion of the andesite. Farther to the south the Longacho Formation is folded in an asymmetrical anticline that has a very open crest, the axis trends approximately north, the west limb dips 10°–20°, and the east limb dips 25°–30°.

The largest known fault in the area is that which extends just to the east of the Sierra Longacho. This ridge has gentle western slopes and steep eastern slopes and represents the upthrown side of a normal fault; the depression of Pampa Pica represents the downthrown side of the same fault. In the Pica area the dislocation along this fault may be observed from near Matilla to 2 or 3 km north of Cerro Longacho. Farther to the north, outside of the mapped area, the same fault or zone of faulting may be observed in the Quebrada Sagasca and the Cerro Juan de Morales west of Mamiña. It is possible that Cerro Puquio de Núñez and also the Cerro Challacollo, which is located south of Pica in front of the mouth of the Quebrada Guatacondo, are related to the same fault. Knowledge of the subsurface stratigraphy of Pampa Pica, as known through the wells drilled in the area, permits a calculation of the approximate displacement on the fault. The deepest well penetrates 325 m of the Altos de Pica Formation and terminates in member 2 of the same formation. To this thickness may be added approximately 300 m for member 1 which would make a total thickness of approximately 600 m of Tertiary and Pleistocene fill at this point. The Altos de Pica Formation does not crop out on Cerro Longacho but a thin veneer of member 2 is exposed on the flanks of the hill. If the height of Cerro Longacho above Pampa Pica is added to the probable thickness of the sediments as determined from the above-mentioned well, the minimum vertical displacement on the fault would be approximately 900 m.

CHACARILLA AND CERRO EMPEXA FORMATIONS

These formations are characterized by large and small folds that vary from smooth open to tight overturned structures. In general, the folds are asymmetrical. Most of the anticlines have relatively sharp crests as compared to the wider, smoother troughs of the synclines. The crests of the larger anticlines are complicated by a number of small zigzag folds.

Most of the faults are small and are near the crests of the anticlines. In the Guatacondo area the faulting is more common and includes at least one overthrust fault within the Chacarilla Formation.

The Mesozoic formations of the Chacarilla area are folded into three major synclines and three anticlines that have numerous smaller folds superimposed on the major strucures.

From west to east the first major structure is the Quebrada Empexa syncline which is exposed in the Quebrada Empexa. Most of the structure is concealed under the Altos de Pica Formation. The syncline is overturned: its axial plane trends N. 20° E.; the west limb strikes N. 50° W. and dips 60° E.; the east limb strikes N. 45° E. and is overturned to dip 83° S. The trough of the syncline is very sharp.

The overturned anticline of the Chacarilla Formation is very well exposed a short distance east of the chacra. The axial plane strikes approximately N. 20° E. to approximately N. 20° W., and the fold plunges north. The western limb is complicated by many minor folds which near the chacra form a zigzag outcrop pattern. South of the Quebrada Chacarilla the structures on the western limb of the anticline can be better observed and consist of two major folds along the western limb and three minor folds in the crest. The western limb has its steepest dips toward the east. The structure of the eastern limb is less complicated; 2 km east of the axis the beds dip 45° E. and in the trough of the Higueritas syncline 3 km east of the axis the beds are almost horizontal.

The Higueritas syncline is asymmetrical. The axial plane of the fold strikes approximately N. 30° E. to approximately N. 30° W. The fold plunges south. The trough of the syncline is wide and uncomplicated. The western limb of the syncline has very low dips; it is simple in structure, with only a small zone of minor folds exposed in the Quebrada Empexa. The eastern limb is overturned and dips abnormally east. South of the Quebrada Chacarilla in the zone of the northernmost outcrops of the Cerro Empexa Formation, the syncline is approximately symmetrical and has a wide open U-shaped trough.

The Cuesta de Lípez anticline to the east of the Higueritas syncline is asymmetrical. The axis of the anticline parallels that of the Higueritas syncline and the fold plunges north. Near the headwaters of the Quebrada Higueritas, the crest of the anticline is complicated by many tight isoclinal folds.

A syncline is found to the east of the Cuesta de Lípez anticline. The rocks in the area of the syncline are trachytes and have no recognizable bedding; therefore, their stratigraphic position cannot be determined and their structure is impossible to ascertain. No faults could be recognized in the area; therefore the syncline must be formed between the Cuesta de Lípez anticline and an anticline just inside the border of the Pica quadrangle.

CENOZOIC ROCKS

The gentle homoclinal westward dip of the Altos de Pica Formation terminates abruptly in a monoclinal fold which forms the eastern boundary of Pampa Pica. This monocline is locally folded into a small anticline at Salto Chico in the Quebrada Chintaguay where the beds of the east limb dip 4° E. and those of the west limb dip 16° W. The monoclinal structure extends from the Quebrada Seca southward to the latitude of Puquio de Núñez. The structure probably represents a hinge area along which folding occurred as a result of movement along the major fault east of the Sierra Longacho. It is also possible that the monocline formed as a result of faulting in the underlying Mesozoic rocks. The soft incompetent beds of the Altos de Pica Formation may have adjusted to the movement by folding so that increased dips resulted to the west on the downthrown side of the fault. Between the monocline and the Longacho fault is a large depression known as Pampa Pica. East of the Pica quadrangle along the west side of the Salar de Guasco depression, there seems to be another monoclinal warp in the Altos de Pica Formation. Here the layers dip steeply to the east.

The present inclination of the homocline of the Altos de Pica Formation in the eastern part of the Pica quadrangle may be the result of a slight tilting of the formation after its deposition; however, the present slope of approximately 3–6° W. is on the order of magnitude that would be expected for the original depositional slopes of these sediments.

The faults observed in the Altos de Pica Formation in general strike north, but some faults strike N. 45° E. In the Altos de Pica, block faults that have a throw of approximately 15 m may be observed. The fault scarps have been very well preserved owing to the exceptional aridity of the area; however, they are minor physiographic features.

Near El Algarrobal along the walls of the Quebrada Chacarilla, two reverse faults were observed in the Altos de Pica Formation. These two faults delineate a small graben that has had a relative downward movement of a few meters. The faulting was apparently prior to the deposition of the alluvial fill of the Quebrada Chacarilla as the faults do not displace this fill. Along the south wall of the quebrada, a bedding plane fault was observed at the base of member 2 of the Altos de Pica Formation. To the east the inclination of the fault plane increases, and it cuts the sediments at an angle of approximately 25°.

A fault, striking N. 45° E., displaces member 2 a few meters vertically in Quebrada Chintaguay a short distance east of Salto Chico.

The low range of hills north of Campamento Esmeralda are interpreted to be fault blocks partially covered by alluvium. The blocks are believed to be the result of displacement on three parallel, north-trending faults. In the southern part of the range, the faults apparently strike N. 25° E. The east side of each fault is downthrown. These same faults are the explanation for the small exposures of Jurassic rock approximately 10 km to the north.

GEOMORPHOLOGY

The area of this investigation is included in the Atacama Desert which is the most arid desert in the world. The Pacific anticyclone, the downslope drying of the easterly trade winds as they cross the Andes, and the cold Humboldt Current of the Pacific are the natural phenomena which have caused this tremendous desert in northern Chile and western Peru.

The three fundamental physiographic elements of the region are the mountain complex of the Chacarilla area which was first eroded and later partly covered by the Tertiary-Pleistocene sediments and pyroclastics; the morphologically young plateau of the Altos de Pica; and the young piedmont plain that forms the lower slopes between the Altos de Pica and the Pampa del Tamarugal.

At high altitudes in the mountain complex of the Chacarilla area, a mature topography has formed owing to the nondeposition of the Altos de Pica Formation. At somewhat lower altitudes the Altos de Pica Formation has been almost entirely removed by erosion, and a topography of early maturity has formed; the topography shows a well-formed drainage system, sharp V-shaped valleys and ridges, and a few undissected highlands capped by remnants of the Altos de Pica Formation.

In contrast, the Altos de Pica plateau is a fossil plain in the first stage of dissection. Its youthful topography, consisting of large flat areas, is cut by a few steep-walled canyons and by a maze of consequent drainage which forms complicated dendritic patterns. At the foot of the mountains huge alluvial cones are in the process of formation.

Water has been the most important agent in modeling the landscape. The short, intense rainfall typical of desert areas may occur in this part of the Atacama Desert every few years or even tens of years. Moderate to heavy rainfall of the torrential type occurs in the Andes at altitudes above 3,000 m. The waters of these torrential rains encounter a drainage net that is not adequate to accomodate the load. The flood waters descending with great force erode the fluvial deposits and the regolith that has accumulated along the sides of the canyons, and this eroded material forms mudflows of exceptional size and force. The material that is transported by these floodwaters is deposited in alluvial fans which may be as long as the fan at the mouth of the Quebrada Chacarilla which is 35 km in length. The waters from the larger floods reach the base of the Coastal Range.

The present process of erosion on the Altos de Pica Plateau is being realized over a surface formed by all the local geologic events. Slopes above an altitude of more than 4,000 m are formed by the homoclinal dip of the welded tuffs. Toward the south this plateau butts against the Mesozoic rocks of the old mountain complex. Slopes down to 3,000 m are constructed on the dip surface of the same tuffs. Slopes below 3,000 m are composed of coalescing piedmont deposits. The products of the modern erosion grade downward into the alluvial fans that are contributing to the deposits in the Pampa del Tamarugal. The surface of the undrained Pampa is local base level.

There are remnants of an older land surface which was formed by a cycle of erosion which occurred prior to the deposition of the Altos de Pica Formation. The sediments and pyroclastics of the Altos de Pica Formation cover this land surface except in the area of Chacarilla. In this area the old surface is hardly recognizable because it was dissected during the pre-Altos de Pica cycle of erosion. Apparently, the landscape prior to the deposition of the Altos de Pica Formation consisted of a tremendous east-west intermontane area between Cerro Yarvicoya and Cerro Empexa. The old land surface was of high relief as is shown by the height of these hills or mountains above the Altos de Pica Plateau and by the deep V-shaped valleys exposed in the walls of the Quebrada Chacarilla and its tributaries. This old land surface does not fit into the theory of Bowman (1909), who postulated the development of a peneplain in northern Chile and Bolivia during Late Tertiary time. The present land surface of the Altos de Pica Plateau has little or no relation to the old surface.

The Altos de Pica Plateau is the most conspicuous constructive land form of the present topography. The plateau is cut by a few faults and is bordered on the east and west by flexures. The topography is youthful, and erosion is controlled by steep-walled canyons. The drainage net is consequent on the tuffs that cover the older rocks. The general drainage is to the west and southwest. Subsequent drainage has formed only in a few localities along the faults that exist in the Altos de Pica Formation. The changes in stream courses as a result of faulting, may be observed clearly in the aerial photographs. The drainage has not been integrated into one net, and most of the quebradas descend independently to local base level, which is controlled by the Pampa del Tamarugal or in a few places by the Pampa Pica. The present erosion consists almost entirely of the deepening of the youthful stream channels by the hydrodynamic action of the ephemeral floods that descend with great force during the summer. Because no rainfall falls on the lower slopes of the plateau, practically no erosion takes place there except for the deepening of the canyons. The old land surface of the plateau is left intact and is unaffected by the passing of the flood waters through the canyons. The walls of the canyons are steep and in some localities vertical; the course of the stream is marked by many falls. Above 3,000 m the surfaces of the interfluvial areas are in the initial stage of erosion. They are covered by a pavement of regolith composed of rock in situ, loose blocks, sand, and gravel. Disintegration of the rocks through exfoliation and decomposition may be observed in all parts of the plateau. Some of the decomposed blocks maintain their original form but may be so thoroughly weathered that they crumble at a touch. The exfoliation and cracking of the rocks is, in part, a result of the extreme diurnal temperature variation and the strong insolation of the rock surface; moisture present during part of the year probably aids the exfoliation and cracking. The daily temperature variation of the air in winter may be more than 30°C at 1,300 m. According to Mortensen (1927), information obtained from Wetzel indicates that the temperature registered in the surface of the soil may be 11°C higher than the air temperature. Froelich (oral commun., 1958) made systematic measurements of this phenomena in Canchones, the agricultural experimental station of CORFO. He observed that on a clear summer day, when the relative humidity was 20–30 percent and the air temperatures, 30–32°C, the temperature of the bare silty sandy soil would reach 69°C. On the same day during the night hours, the temperature of the air would fall to 10–12°C, and the soil temperature would be the same temperature or a slightly lower temperature. According to these measurements, the difference in temperature on the land surface may be as much as 60°C. Expansion of freezing water in the interstices and incipient fractures of the rock is another cause of rock desintegration at high altitudes during the times when precipitation is sufficient. The wind removes the material of decomposition, abrades the rock, forms ventifacts, and erodes the differentially resistant strata of Tertiary and Pleistocene age.

Below approximately 3,000 m, the plateau is underlain by the sedimentary rocks of the Altos de Pica Formation. The physiography is similar to that previously described; however, a few physiographic differences have originated because sedimentary rocks are different in lithology. The walls of the canyons are not as steep, and a larger proportion of the plateau surface is covered by sand. At this altitude the plateau surface is covered by a pavement of rhyolitic rock fragments rounded during torrential transportation at the time of original deposition. North of the Quebrada Ancha, the surface of the plateau is about the same, but the drainage is more closely spaced. The quebradas of the secondary drainage system are deeper and in many localities are partly filled by windblown sand. The topography in this area is that of an incipient badland. No large quebradas have been formed because runoff from precipitation at higher altitudes is diverted either to the north by the Quebrada Sagasca or to the south by the Quebradas Ancha, Seca, or other quebradas.

The dominant land form in the southern part of the quadrangle is the mountain complex which evolved to a mature topography during the Late Cretaceous and Early Tertiary. The surface of the mountain complex is deeply dissected by the streams of the present cycle of erosion, but in a few of the divides, relicts of Tertiary and Pleistocene beds remain. The stream courses are superimposed in an approximately parallel drainage net that is oriented toward the southwest in the lower course of the stream. The integration of the drainage is taking place very slowly, and in certain places, the slowness to integrate is due to the great depth of the quebradas. During the first stages of the evolution of the topography, there were many changes in stream course. These changes are easily identified on the aerial photographs. The drainage pattern is not subject to structural control for the direction of the fold axes is almost due north, and the streams cross the structures at approximately right angles. The steep-walled quebradas may have depths of hundreds of meters—for example, the Quebradas Chacarilla and Higueritas. The well-defined divides between the quebradas are mostly knife edged except where small mesas are capped by remnants of the Altos de Pica Formation. The courses of the quebradas are very young, particularly the courses of the tributary quebradas which characteristically have many waterfalls owing to the resistant harder rock layers. The base level of the tributary quebradas is controlled by the level of the Quebrada Chacarilla which in turn is controlled by the Pampa del Tamarugal. Most of the present erosion in the Chacarilla area is produced by the minor quebradas which are deepening rapidly but are not depositing.

The Quebrada Chacarilla is the largest in the quadrangle. Near the Cuesta de Lípez the quebrada reaches its maximum depth of 900 m. The Mesozoic Formations are exposed in the quebrada walls in its upper course. Physiographically the quebrada is complex: in the area of Alona the stream is youthful, but further downstream the quebrada shows many characteristics of a mature stream. Genetically the quebrada was a consequent stream which followed the original inclination of the Altos de Pica Formation that once covered the area around Chacarilla, but now the stream is superimposed on the older formations. The stream has not reached a profile of equilibrium as falls are found near El Algarrobal and Alona. The walls of the quebrada are in general very steep and the lateral spurs have not been eroded; the affluent streams are youthful and in a few places have an extremely high gradient (fig. 14). Low terraces are seen downstream from the chacras but are practically nonexistent in the upper course of the quebrada. One must conclude that the stream actually existing in the quebrada is underfit if the size of the quebrada is compared to the flow of a few liters per second. The agent of erosion is not the tiny

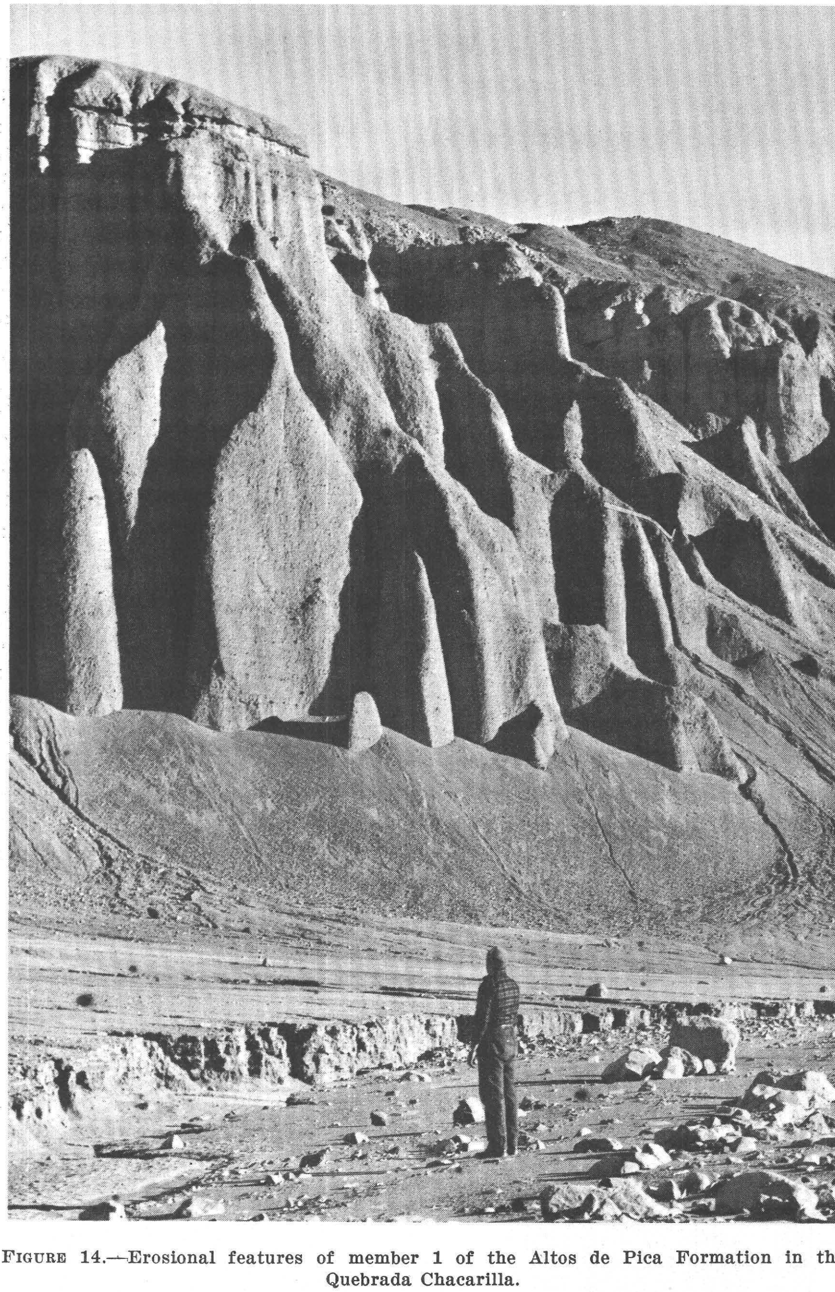

FIGURE 14.—Erosional features of member 1 of the Altos de Pica Formation in the Quebrada Chacarilla.

stream but rather the raging flood waters from the torrential rains that occur every few years. These floods have been estimated to have flows of hundreds of cubic meters per second. The same conditions exist in the other major quebradas of the area.

The detrital material originating from the erosion of the mountain complex has been and is being deposited at the base. These deposits constitute a young piedmont plain that is a typical bajada formed by many coalescing alluvial fans which are in the process of forming. These cones are only eroded where a few small, temporary channels have been cut by recent flood waters. These small channels exist for a few kilometers west of the mouths of the quebradas. The relief of the major alluvial cones is very irregular if one observes it in detail. This irregularity is due to the wandering ephemeral channels which the water has followed in transporting material from the mountains; these wandering channels are found on the surface of the cones. The blocks that are not from the most recent deposits are covered by desert varnish and may be broken, exfoliated, or decomposed by weathering, the type of weathering depending on the lithology of the rock. Nearer the interior of the Pampa del Tamarugal, the boulders are smaller, and the land surface is more regular. The drainage of the bajada is toward the west except in a few stretches of the Quebrada Seca and in the other unnamed quebrada to the west of Cerro Longacho which borders the alluvial fan of La Calera. These courses are in part subsequent where they follow fractures or formation contacts. The landscape of the piedmont results from the decline in the transporting capacity of the water in the drainage system and from the lack of precipitation. The detrital material is slowly covering the lower slopes of the high hills, such as Longacho, and also the small hills north of Esmeralda and Cerro Puquio de Núñez. Cerro Puquio de Núñez was considered to be a relict of older rocks (Brüggen, 1918, p. 33) or the base of the Tertiary (Felsch, 1920, p. 479). The authors are of the opinion that the hills are relicts of an old alluvial fill which may have been uplifted by movement along the Longacho fault.

In the upper course of the Quebrada Chacarilla, two high terraces are above the present floor of the quebrada, one at 240 m and the other at 480 m. In the middle and lower course of the Quebrada Chacarilla, a modern terrace may be observed 5–10 m above the present stream channel. In other quebradas such as Quisma, Saguachinca, and Infiernillo, two systems of high terraces may also be observed.

The effects of the mudflows on the form of the landscape show in the alluvial fans of the small quebradas in the high mountains to the lowest part of the Pampa del Tamarugal. The material of which the mudflow sediments are composed is derived from the talus slopes along the sides of the quebradas. This material is removed by mass wasting and by the waters of the torrential rains and is transported through the steeply sloping minor quebradas to their mouths.

The mudflows from the small quebradas join in the principal quebrada and flow downward to the alluvial cone of the pampa. The mudflow follows the stream channels and overruns the low terraces in some localities. Observers report that the mudflows advance with a front several meters high and that they move at a velocity of approximately 15 km per hour. The advance is slow enough that in the populated quebradas a horseman rides ahead of the advancing mass to warn the inhabitants of the approaching danger. Harrington (1946, p. 155) reported that, according to witnesses of similar phenomena in El Volcán (Argentina), the mudflows advance rhythmically making jumps of 5–10 m every few seconds. The flow reaches its maximum volume soon after the passage of the front; it then may continue for a half day or more during which time the volume and the viscosity are gradually reduced. The dried and mud-cracked sediments overlie the modern terraces of Chacarilla. The sediments are cenuglomerates which are extremely variable in grain size and sorting. The various mudflows derive their colors from the multicolored rock layers which were eroded. Thus, the mud rock deposits are strikingly banded. The mudflow terminates with a stream of relatively clear water which erodes the new deposits and cuts the small canyon through which the permanent stream will flow for the next few years until the next mudflow occurs. These sediments are finally deposited in the alluvial cone by the decline in competency of the stream to transport. The fragments of larger size are deposited near the apex of the cone, and the finer materials are deposited in the broader more nearly horizontal outer area of the cone. Some of the floods are of such volume that they reach the base of the Coastal Range with sufficient force and viscosity to transport large fragments. Near Pintados, which is located on the western border of the Pampa del Tamarugal in front of the mouth of Quebrada Chacarilla, phenoclasts as large as block size may be observed. Deep wells drilled in the pampa near the Coastal Range have penetrated thick beds of very coarse grained plastic material.

The surfaces of the dried mudflows are characteristically very hard, rough, undulating and, where the fine sediments were deposited, are broken by mud cracks. Angular phenoclasts of all sizes protrude from the deposits in which they are firmly cemented. In the small alluvial cones in the mountain areas, the course of the last mudflow may be observed by the temporary channel cut in the high gradient surface. The temporary channels are bordered by mud ridges as much as 1 meter high.

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Many landslides are found in the Quebrada Chacarilla. The most extensive of these are in the upper course of the quebrada. One of the largest landslide blocks is on the south side of the quebrada, near the axis of the Higueritas syncline. In this locality, topographic occurrence and lithologic conditions are very favorable for the occurrence of landslides. At one time the course of the stream curved farther to the south producing a very steep wall approximately 700 m high. The rocks in this quedrada are the mudstones and shales of the Chacarilla Formation which can act as a slide plane if moist. Other landslide blocks may be observed on the north side of the quebrada a short distance west of the Chacarilla chacra and south of the quebrada at El Algarrobal.

Modern eolian sand deposits cover large areas of the bajada and of the lower part of the mountain complex (fig. 15). At high altitudes the sands partly fill some of the quebradas and are deposited in any locality which is sheltered from the wind. The sand is probably the secondary deposition of material derived from the pampa where these sediments contain a large fraction of sand grains. According to Fuenzalida,[7] some of the sand may have originated from the plutonic rocks in the Coastal Range. The primary transportation agent is the occasional sand storms which fill the air with sand to approximately 1,000 m above the pampa. Two of these sand storms were observed by the authors during the course of the fieldwork. Fuenzalida has observed that the "dust devils", which are common in the pampa, carry sand to high altitudes and that later the sand is redeposited smoothly over the surface of the pampa. The authors doubt the efficiency of the "dust devils" as a major agent of transportation. The major part of the windblown sand in the area of study is derived from the areas of sedimentation to the west in the Pampa del Tamarugal, although the original source of the sand was probably the erosion and decomposition of the rocks of the mountain complex of the Pica area. In the Pica area the predominant winds are from the west and southwest. The direction of these winds determines the physiographic details such as ripple marks, abrasion of the rocks, and orientation of the dunes. On the geologic map the files of dunes may be observed to trend approximately N. 70° E.

In the Pampa del Tamarugal the winds tend to be more variable, perhaps owing to the sheltering effects of the Coastal Range. The zone of compound and barchan sand dunes north of Pica may result from the moderate winds partially intercepted by Sierra Longacho. In some localities, transverse sand ridges have been formed normal

[7] Fuenzalida, H., 1956, Informe sobre las condiciones geomorfológicas del desierto del norte de Chile: Santiago, Chile, p. 7.

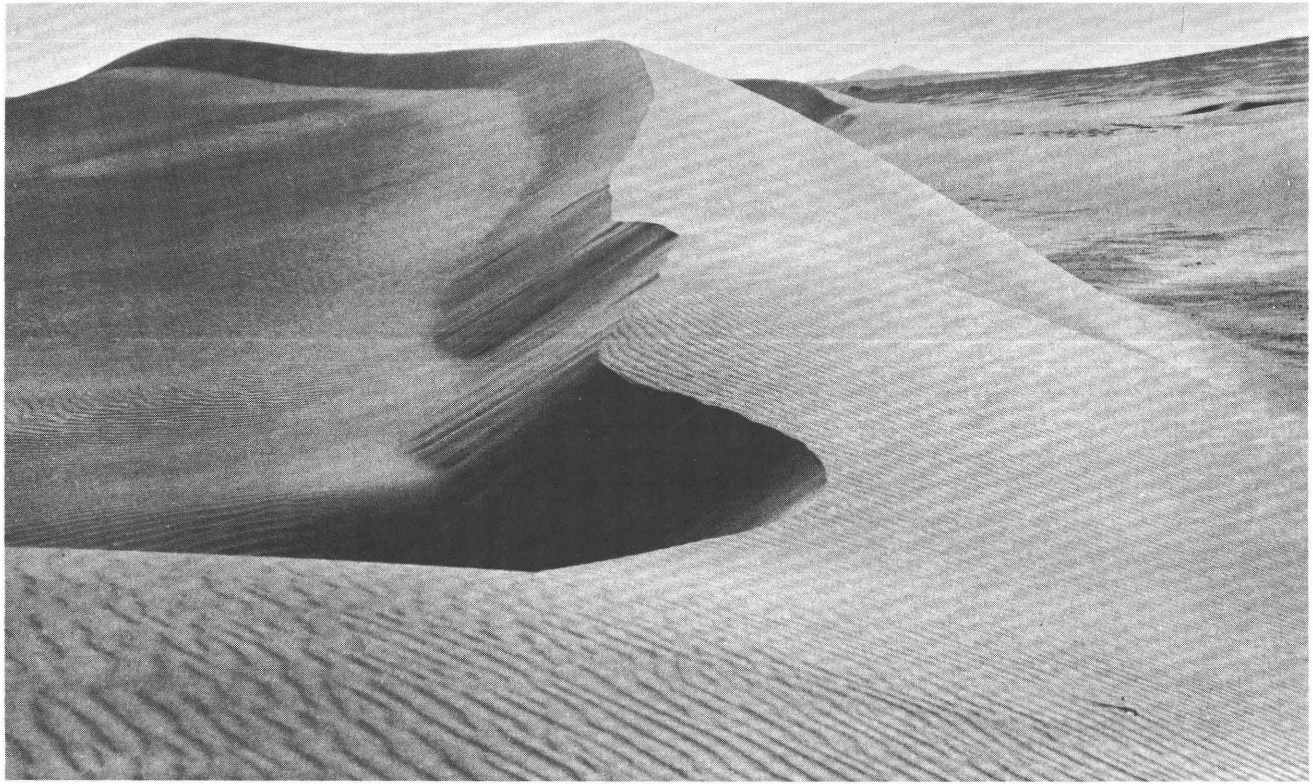

FIGURE 15.—Longitudinal sand dune located on east side of Pampa Pica. Dune shows effects of diurnal reversal of winds from westerly upslope winds of the day to easterly downslope winds during the night.

to the predominant wind direction in Pampa Pica. In the upland areas, longitudinal sand ridges have formed along the divide between the quebradas. The sand ridges are oriented approximately parallel to the predominant wind direction. In all areas which are underlain by sand sheets the surface is covered by ripple marks and highly varnished ventifacts.

GEOLOGIC HISTORY

The sequence of the events that form the geologic history of the Pica area are known with some degree of certainty; however, owing to the lack of evidence, it has been impossible to determine the geologic age of all the events. The formations of Early and Late Jurassic age were dated by paleontologic evidence, but the Cerro Empexa and the Altos de Pica Formations were assigned ages on the basis of stratigraphic position and lithologic correlations; therefore, there must remain a certain doubt as to their absolute ages.

The Longacho Formation was deposited during the Early Jurassic in a marine environment at moderate depth and contains ammonite fossils typical of this age. It was presumably during this epoch that the margin of the South American Continent emerged somewhere east of the present outcrops of the Longacho Formation.

No rocks are exposed in which were recorded the geologic events that occurred between the deposition of the Lower Jurassic rocks of the Longacho Formation and the deposition of the Upper Jurassic sediments of the Chacarilla Formation. During the deposition of the lower part of the Chacarilla Formation, the shoreline alternately transgressed and regressed, and this alternation resulted in intercalated beds of continental and shallow-water marine origin. Ultimately the shore-line regressed, and the upper part of the formation is entirely continental in origin. Fossil ammonites and bivalves are found in the marine sediments of this formation; fragments of plants and dinosaur tracks are found in the continental sediments.

After the deposition of the Chacarilla Formation, there was probably a hiatus for the rest of the Late Jurassic time. At or near the end of the Jurassic Period, the area was folded and uplifted. At the same time the sediments were intruded by igneous rocks which now form the most widely distributed intrusive body of the area. During the first part of the Cretaceous Period, the area was apparently mountainous and was deeply eroded. Over this mountainous surface, volcanoes which formed left thick deposits of trachytic lavas. These lavas were partially eroded and redeposited to form the sediments of the Cerro Empexa Formation. Although paleontologic evidence is lacking, the Cerro Empexa is assigned a Cretaceous age.

The orogeny that affected the Jurassic and Cretaceous Formations is the strongest recorded in the area. The strong compressional forces of this orogeny resulted in folding, faulting, and overthrust faulting of the formations; the result apparently was an area of high relief. The following period of erosion was long and lasted from Late Cretaceous to Miocene time.

The piedmont deposits derived from the erosion of the older formations form the heterogenous Altos de Pica Formation, which consists of alternating members of welded tuffs and clastic sediments. The welded tuffs originated as deposits of nuées ardentes during a period of intensive volcanic activity; they covered most of the mountain complex and solidified as a mantle extending into the lowlands. The Altos de Pica Formation apparently is unfossiliferous and has been tentatively assigned to the late Tertiary and Pleistocene. During and after the deposition of this formation, slow epeirogenic movements raised the zone to its present relief and formed the Pampa del Tamarugal. During the epeirogenic movements, tensional fracturing occurred in the plateau area and especially in the brittle welded tuffs of the Altos de Pica Formation. These movements are probably of upper Pliocene or Pleistocene age. The mountain complex thus formed was then exposed to the Quaternary cycle of erosion which is presently active in the area.

Along the Chilean border, east of the area, is a line in which there has been very recent volcanic activity. In this area pyroxene-andesite lavas and pyroclastics have formed high volcanic cones, some of which rise to altitudes of more than 5,000 meters.

ECONOMIC GEOLOGY

There are no known rock or mineral deposits of economic value within the area of this investigation. The only mineral exploited is that found in an impure deposit of gypsum 3 km north of Pica. Only enough gypsum is excavated to meet the very limited needs of the village.

During the investigation, many old exploration pits were observed. Where the eastern limb of the Higueritas syncline is crossed by the quebrada of the same name, there are many small excavations made many years ago in search of copper. Apparently no workable deposits of copper or, for that matter, of any other metallic mineral was discovered.

Exploration pits were also dug in the carbonaceous shales of the Chacarilla Formation at various localities, particularly in the Quebrada del Carbón, 2 km south of the Chacarilla chacra. Perhaps these excavations were made in hope that the shale might become coal at depth. Tests conducted at the Instituto de Investigación y Ensayo de Materiales at the University of Chile confirmed that this carbonaceous shale was of no value as a fuel.

About 1 km south of Cerro Longacho are several old prospect pits, approximately 1 m deep, in highly altered greenish-gray lava which has light-reddish-brown bands and contains abundant chlorite. Apparently, the green chlorite was mistaken for copper.

A quarry is located 1½ km north of Matilla in outcrops of the dark-gray-welded tuffs of member 2 of the Altos de Pica Formation. The rock of this quarry was used in Matilla as a building stone. Samples of the welded tuffs of members 2 and 4 were polished in the laboratories of IIG. Fractures in these beds are widely spaced and blocks of a cubic meter or more could be quarried. These rocks are easily worked, and the polished surface is attractive. The possibility of using this rock as a building stone should be considered; it might be shipped outside of Tarapacá Province. The welded tuffs, in spite of the ease with which they may be worked and in spite of their beauty, are used very little in the Pica area. Most of the buildings consist of adobe and the gypsiferous material excavated north of Pica.

Gypsum is present as a very impure superficial layer in many localities in the depression of Pampa Pica between the Quebrada Seca and Puquio de Núñez. It was excavated from a locality southeast of Pica until a few years ago but now is obtained from a quarry 3 km north of Pica. The material is brought to Pica in fragments and large aggregates and is ground and sieved there. Its most notable quality is that it consolidates rapidly on addition of water which is characteristic of a high gypsum content. This material is used to make plaster for walls, to make sidewalks, and so on. A chemical analysis of a typical sample conducted at IIG gave the following results, in percent:

Analysis of gypsum from quarry near Pica

SiO_2	20.70	SO_3	34.35
Fe_2O_3	1.27	Na_2O	1.02
Al_2O_3	6.08	K_2O	1.02
CaO	26.02		
MgO	1.46	Total	101.56
		Loss on calcination	9.64

The above chemical analysis indicates that the rock is approximately 58 percent gypsum.

The exploitation of the calcareous beds exposed in the upper course of the Quebrada Chacarilla was suspended many years ago. There are other limestone deposits in Tarapacá Province which are presently being exploited under much more favorable conditions with respect to geographic location and accessibility. The calcareous beds of Chacarilla form a deposit approximately 20 m thick and 3 km long along the north wall of the quebrada. Muñoz M.[8] studied the economic possibilities of these deposits.

GROUND-WATER RESOURCES

GENERAL PRINCIPLES

The general regime of the recharge and discharge of ground water is known as the hydrologic cycle (fig. 16). The hydrologic cycle may be considered as a continuous process. For convenience, one may consider the cycle in northern Chile to start with the water vapor that results from the evaporation of the water of the Pacific Ocean, salars, plants, and other water reservoirs. The water vapor ascends into the atmosphere and condenses into water droplets to form clouds. From these clouds it is eventually returned to the earth's surface in one of the forms of precipitation, generally falling on the high area of the Altos de Pica. Of the precipitation that reaches the earth's surface, a part is returned to the Pampa del Tamarugal by the means of floods; a small part is intercepted by the leaves of the sparse vegetation and is evaporated; a part is trapped in the soil to fulfill soil moisture deficiencies and from the soil is returned to the air by evaporation and by transpiration; and a part passes downward through the soil to become recharged to the aquifers. The water that recharges the aquifers will eventually be discharged by natural or artificial means to again take its place in the hydrologic cycle.

The study of ground water is concerned with the part of the hydrologic cycle from the time that the water reaches the earth's surface until it is discharged from the aquifers.

RECHARGE

There are many factors that control the rate of recharge to the ground-water reservoir—such as, the permeability of the soil, subsoil, and bedrock; the antecedent soil-moisture content at the time of rainfall or snow melt; the duration and the intensity of precipitation; the topography; the seasonal changes in rate of evaporation and transpiration; and the type and the density of vegetation.

In a desert climate, such as that of the Pica area, some of these factors assume an importance which is far greater than that held in more moderate climates. Precipitation occurs in torrential showers separated by long dry periods, amounting to many years at lower altitudes in the area. During these long periods of drought, the soil moisture

[8] Muñzo M., E., 1953, El yacimiento de mármol de Chacarilla, Iquique: Santiago, Chile, Departamento de Minas y Combustible, 1–B, Iquique No. 1

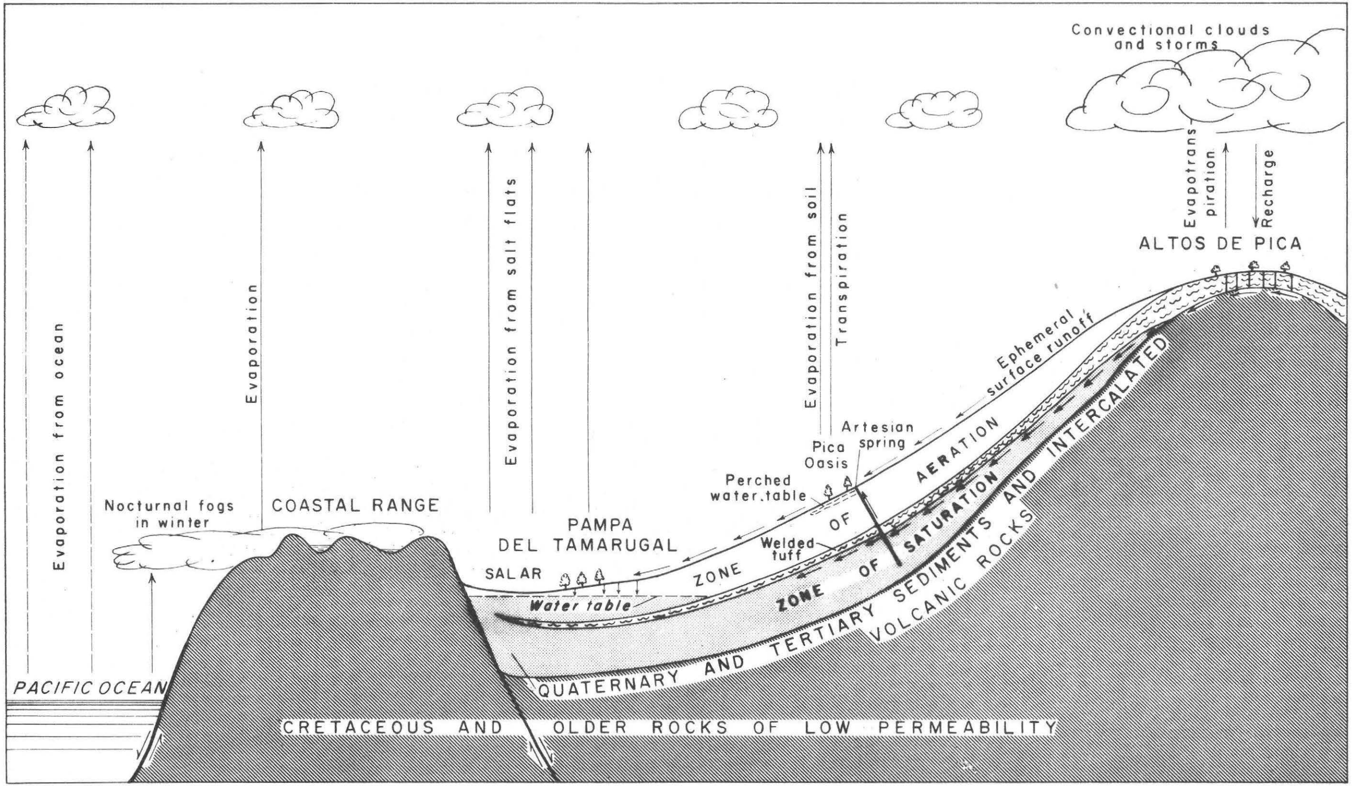

Figure 16.—Hydrologic cycle in central Tarapacá Province, Chile.

is greatly reduced by evaporation (and also at higher altitudes by transpiration). Before any of the precipitation can pass downward through the soil to become recharge to the ground-water reservoir, this deficiency in soil moisture must be satisfied. The deficiency may reach a value equivalent to several centimeters of rainfall. Therefore, the short intense showers over the low areas are probably of little value as an effective source of recharge for the reservoirs as this rainfall may be almost entirely retained in the soils and not transmitted downward to the aquifers.

The intensity of the rainfall has little effect upon the rate of absorption of water by the soil as long as the rate of precipitation exceeds the infiltration capacity (maximum rate at which a given soil in a given condition can absorb water as it falls). If precipitation occurs at a rate greater than the infiltration capacity, it will increase very slightly the rate of absorption—that is, in proportion to the hydraulic head of one or two millimeters that is built up as the water accumulates and seeks surface runoff channels.

Within the Pica area, the effect of topography in controlling the rate of infiltration into the upper few centimeters of the soil is relatively unimportant. During long periods of precipitation, the upper part of the soil becomes saturated regardless of topographic location, and, as the water moves downslope, the moisture in the soil is constantly replenished by precipitation whether the area is sloping or flat. Neal (1938) determined experimentally that slopes between 1 and 16 percent had little effect on infiltration rates. Slopes that have essentially no gradient increase infiltration rate in proportion to the head that is built up as water accumulates.

Interception is that part of rainfall that is intercepted by leaves of vegetation and that is later evaporated from the leaf surfaces and thus does not reach the ground. The first drops of rain during a storm strike against the leaves of vegetation and are almost completely retained either as droplets or as a film of water over the leaves. Only a small part of the water reaches the ground until the leaves overhead have reached their maximum capacity to store water. In areas which have a heavy vegetal cover, such as southern Chile, interception may significantly reduce the effectiveness of precipitation, and as much as 1 cm of precipitation may be intercepted depending on type and amount of vegetation. In the Pica area, interception has very little effect on recharge. On the lower slopes of the Altos de Pica Plateau and in the part of the Pampa del Tamarugal within the Pica area, the only vegetation is that on the few acres covered by the oases. On the slopes of the higher part of the Altos de Pica, from 2,600 m upward, the amount of vegetation increases, but even on these slopes, vegetation is sparse.

MOVEMENT AND DISCHARGE

The water that becomes recharge to the ground-water reservoir moves through the aquifers in response to gravity. The rate of movement depends upon the permeability of the aquifer and upon the hydraulic gradient. Essentially all the ground water is eventually discharged; however, due to a very slow rate of movement, a large amount of water is held in temporary storage in the aquifers. Rates of water movement through the aquifers probably ranges from about one meter per year to a few meters per day for aquifers that have high permeability[9] and high hydraulic heads. Discharge may be either artificial or natural—that is, through wells or drains or through springs, influent discharge to streams, transpiration by plants, or direct evaporation from soils in zones where the capillary fringe reaches the surface.

OCCURRENCE OF GROUND WATER IN THE SEDIMENTARY FORMATIONS

LONGACHO FORMATION

The Longacho Formation of Early Jurassic age is exposed in the Cerro Longacho area and in a few isolated outcrops to the north. No springs are known to originate in this formation. The rocks are very fine-grained sandstones, mudstones, and shales of evident low permeability. The sediments are folded, faulted, and intruded so that lateral movement of water through these formations must be restricted.

If the sediments of this formation were to be penetrated at lower relative topographic positions or at depth, small yields (less than 1 lps) probably could be obtained. However, in areas where the Longacho Formation is overlain by the much coarser sediments of the Altos de Pica Formation, there should be little reason to explore

[9] The coefficient of permeability is a measurement of the ability or capacity of a geologic formation to transmit water. The coefficient of permeability was defined by Meinzer (Stearns, 1928) as the rate of flow of water, in gallons per day, through a cross-sectional area of 1 sq ft under a hydraulic gradient of 100 percent at a temperature of 60°F. These units are presently used by the U.S. Geological Survey. A number of substitutions are possible in converting the above units to the metric system. However, inasmuch as permeability will be used primarily to indicate rate of movement of water through an aquifer under field conditions, the units of measurement used should carry a logical meaning to the ground-water geologists and also be easily comprehended by the technicians working with ground-water supplies. For these reasons, it is suggested that rate of flow of water be measured in cubic meters per day per square meter under a 100 percent hydraulic gradient [a hydraulic gradient of 1 meter per meter] at a temperature of 20° C. The metric units may be converted to the units of the U.S. Geological Survey (Meinzer units) by multiplying them by the factor 21.85, or Meinzer units may be converted to metric units by multiplying them by the reciprocal factor 0.0458.

these older sediments for ground water as large quantities of water would generally be available from the younger rocks.

CHACARILLA FORMATION

The sediments of the Chacarilla Formation of Late Jurassic age are predominantly fine-grained sandstones, siltstones, and shales. The formation crops out above altitudes of 3,000 m so that precipitation is available to furnish recharge to any potential aquifers in the formation. Probably very little recharge actually takes place, however, owing to the nearly impermeable nature of the sedimentary rocks as well as to the high relief of the area that causes rapid runoff of the rainwater.

As previously mentioned in the section on structural geology, the structural features of the area are oriented approximately north-south. The gradient of any ground-water movement in the rocks of the Chacarilla Formation would be, therefore, toward the west at right angles to the regional structure. Inasmuch as the sediments are strongly folded, overturned in some areas, faulted, and intruded, ground-water movement across these structures would be greatly restricted if not impossible.

No ground-water discharge, either natural or artificial, is known to take place from the rocks of the Chacarilla Formation. These rocks are probably saturated at depths below the levels of the quebradas; however, this water may be considered to be essentially trapped within the formation, and its movement must be very slow.

Wells drilled into this formation would almost certainly be unsuccessful. Maximum yield would probably be on the order of fractions of a liter per second. Static water levels in any such wells would be at or below the level of the water table in the alluvial fill of the quebradas that dissect the area.

CERRO EMPEXA FORMATION

The Cerro Empexa Formation of Cretaceous age unconformably overlies the Chacarilla Formation. The Cerro Empexa Formation is composed of fine-grained sediments similar to those of the Chacarilla and of thick beds of coarse, firmly cemented conglomerates. The fine-grained sediments are an unlikely source of ground water for the same reasons that were discussed under the Chacarilla Formation. The folding of this formation was somewhat less intense than that of the Chacarilla Formation; however, this is counterbalanced by the unfavorable topographic location in which the Cerro Empexa Formation occurs. Most of the outcrops of this formation are found at high altitudes in the divides between the major quebradas.

At the time they were deposited, most of the sediments of the Cerro Empexa Formation were probably highly porous and they, or at least the conglomerates, had a fairly high permeability. The original porosity has been greatly reduced by compaction and cementation until the rocks now have very low porosity and permeability. In the conglomerates the porosity and permeability of the unfractured rocks are probably comparable to those of a dense igneous rock. The conglomerates as deposited contained approximately 20 percent pore space, if one judges from the thin sections of the rock. These pores were filled by chlorite, chalcedony, quartz, calcite, and epidote, so that the present porosity of the rock is very small. A secondary porosity has formed owing to the fracturing of the rock. In the outcrop areas the fracturing has been intense, and thus some secondary permeability may have been formed. If this permeability is high enough, persists at depths, and is not a phase of weathering, then in some localities springs or seeps should occur at the contact of this formation with the underlying impermeable beds of the Chacarilla Formation. No such springs or seeps have been observed. Therefore it may be concluded that wells drilled into this formation would probably yield little or no water.

ALTOS DE PICA FORMATION

The Altos de Pica Formation of Tertiary and Pleistocene age is the only water-bearing formation that yields large quantities of water in the area covered by this report. In fact, with the exception of the underflow in the Quebrada Chacarilla, all the known ground-water discharge, natural and artificial, within the area comes from the various members of this formation or from the overlying beds that cannot be differentiated from the formation.

RECHARGE

The recharge of ground water to the aquifers of the Altos de Pica Formation is derived entirely from the precipitation that falls on the Altos de Pica Plateau. These highlands, known as the Altos de Pica, consist of a relatively flat area, 8–10 km wide and approximately 40 km long, which forms the divide between the surface drainage westward to the Pampa del Tamarugal and eastward to the Salar de Guasco (fig. 1). The Altos de Pica have an average elevation of more than 4,000 m and form a saddle between Cerro Yarvicoya (5,180 m) and Cerro Chacarilla (4,540 m).

As shown in figure 4, the average annual precipitation continues to increase with altitude; at 3,000 m it reaches an average of 100 mm per year, and at 4,000 m, approximately 200 mm. The curve for the maximum annual precipitation also indicates a rapid increase with increasing elevation, and an extrapolation of the curve shows that it would reach approximately 500 mm at 4,000 m.

No experiments have been conducted in the Altos de Pica area to determine what percent of the precipitation becomes recharge to the aquifers of the Altos de Pica Formation. Very little soil has been formed, and in most areas of the Altos de Pica the surface material consists of fine sand and silt that has numerous fragments of welded tuff weathered from member 4 of the Altos de Pica Formation. The spacing of the vertical joint system in member 4 and the width of the joint openings must be one of the controlling factors in recharge. As seen in outcrops, member 4 has a well-defined set of vertical joints, probably resulting from tensional forces formed during the cooling and contraction of the rock. Width of the joint openings is extremely variable and ranges from zero to several centimeters. If the joint systems as seen in outcrop are typical of the unexposed rock, the vertical permeability of member 4 probably is sufficiently high to permit the passage of recharge water as fast as or faster than it can be accepted by the underlying rocks. The same conditions probably exist in member 2 in the recharge area.

An approximation of the recharge to the formation may be obtained by assuming an average annual precipitation of 200 mm for the 400 sq km of the Altos de Pica Plateau that lie above 4,000 m and 100 mm for the approximately 600 sq km that lie between 3,000 and 4,000 m. If 20 percent of the precipitation becomes recharge, the average recharge would be approximately 4,000 lps.

MOVEMENT

The water that becomes recharge to the Altos de Pica Formation moves slowly through the formation to the discharge areas near Pica or continues to move through the formation and out of the area to recharge the aquifers of the Pampa del Tamarugal. The rate of movement of the water through the aquifer is very slow, probably a few meters or less per year. Water that enters the aquifer in the recharge area of the Altos de Pica may reach the discharge areas hundreds or even thousands of years later. Rainfall deficiencies during the dry years or even during fairly long cycles of drought will have little effect on the average discharge from the formation. It is for this reason that the famous springs at Pica are reported to have a constant discharge. The principal movement of water appears to be through member 1 of the formation. As previously mentioned, the recharge passes down through member 4 and member 2 in the recharge area and then moves laterally through member 1. Where the base of member 3 is exposed, as in the Quebrada Chintaguay, it is dry, and there are no springs or seeps at its contact with the underlying member 2.

The ground water moves westward, down gradient through member 1 toward the Pampa del Tamarugal. The westward movement of the water is interrupted by the upthrown fault block of the Longacho Formation which has surface expression in the Sierra Longacho (pl. 1). The rocks of the upthrown block are much less permeable than the sediments of the Altos de Pica Formation; therefore, they act as a ground-water dam preventing the westward flow of ground water. In the Cerro Longacho area the Lower Jurassic rocks reach the surface so that there is no possibility for the ground water to pass over the barrier. The water is deflected southward, and in the area of Matilla or a short distance to the south of the village, the water passes over the Lower Jurassic rocks and through the more permeable Cenozoic sediments to form a ground-water cascade. From this area the ground water continues to move west to recharge the aquifers of the Pampa del Tamarugal.

DISCHARGE

Ground water is discharged from the Altos de Pica Formation to the surface through the springs, galleries, and wells of the Pica area; the water moves through the formation westward to recharge the aquifers that underlie the Pampa del Tamarugal. The amount of water discharged to the surface either by natural or artificial means is approximately 140 lps. Essentially all the discharge is in the Pica–Matilla area, the only exceptions being the spring at Chacarilla and the galleries at Puquio de Núñez and La Calera which have a total discharge of approximately lps.

The discharge of the Pica area is approximately as shown in table 8.

TABLE 8.—*Discharge of springs, galleries, and wells in the vicinity of Pica*

Springs	Flow (lps)	Temperature (°C)	Galleries	Flow (lps)	Temperature (°C)	Wells	Yield (lps)
Animas	5.5	32	Comiña	0.8	24	Chintaguay (well J).	40+
Concova	9.5	34	Comiñita	.5	23	Irrigation (several)	5+
Miraflores	8.0	33	Charcas, Martín	1.0	24	Domestic	1
Resbaladero	30.0	35	El Carmen	2.2	24	Pampa Esmeralda	5+
	53.0		El Sauque	7.0	23		51
			Espinoza, Fernando	.5	23		
			Jesús María	2.0	24		
			San Isidro	4.0	24		
			Santa Rosita	17.0	31		
			Santa Elena	1.3	23		
			Ultima Esperanza	.9	22		
				37.2			

Except for an area of approximately 1 hectare downstream from Salto Chico in the Quebrada Chintaguay, there is no natural vegetational cover in the area subirrigated by ground water from the Altos de Pica Formation. Therefore, virtually no water is lost from the formation by evapotranspiration in the Pica area.

The discharge in the Pica area is probably less than 5 per cent of the quantity that is passing through the formation to recharge the aquifers of the Pampa del Tamarugal.

DEVELOPMENT AND USE

Water from all the springs in the vicinity of Pica is of potable quality and is used to some extent for domestic purposes. The three major sources of potable water are as follows:

1. The Concova springs, which provide water for both domestic use and irrigation.
2. The galleries of the Compañía Agua Potable Particular.
3. Privately owned shallow domestic wells.[10]

The Compañía Agua Potable Particular provides water for 140 families who are stockholders in the company. The water is obtained from a gallery located east of Pica within the chacras (small farms) of Concova. The water from the galleries is collected in a sheet metal tank which has a capacity of 12.5 cubic meters. The distribution system reaches most of the principal streets. In some localities the pipes of the distribution system are above land surface. Each house has a tank of 100 liters which is filled every other day. The inhabitants take the water from the tanks by means of jars and other vessels. It is prohibited to have a tap from the water system within a house. The average family consists of six to eight persons, and the daily average potable water supply is about 7 liters per person. At the time this report was being written, there was no chlorination of the water supply, but chlorination equipment was being requested from the Dirección de Obras Sanitarias.

Pica has no sewage system; each house has an outhouse although a few houses have a cesspool or a septic tank. Many of the houses also have shallow wells, which are used for domestic water supply, located within a few meters of their sanitary facilities. The possibility of contamination of these wells by the untreated sewage is very high.

In Matilla there are also three sources of potable water:

1. The gallery used for potable water.
2. Water from the gallery of the Dirección de Obras Sanitarias "El Sauque". The village has water rights of 400 cubic meters per day, and it is actually receiving approximately 600 cubic meters per day, most of which is used for irrigation.

[10] Records of dug wells were published in Galli and Dingman (1962).

TABLE 9.—*Records of drilled wells located in the Pica area*

Method of lift: N, none; B+W, bucket and winch; C, centrifugal. Use of water: D, domestic; N, not used; PS, public supply; Ir, irrigation.

Well [1]	Owner or name	Driller	Date completed	Altitude above sea level (meters)	Depth of well (meters)	Diameter of well (inches)	Water level: Meters below land surface	Water level: Date of measurement	Method of lift	Use of water	Remarks
130	Government of Chile	Ernesto Niemann	1930	1,461.05		6	41.18	3-29-56	N	N	
131	San Andrés Society	do		1,352.26	14.00	10	8.30	3-28-56	N	N	
132	Gregorio Palacios	do		1,355.30	21.37	10	20.95	3-30-56	B+W	D	
137	Government of Chile	do	1917	1,420.00	265.00	16-8	Flow	1917	N	N	Well C, abandoned and caved.
138	do	do	1919	1,420.00	110.00	?-5⅝	28	1920	N	N	Well D, abandoned and caved. Information obtained indicates that level of the water raised to within 5 m of surface when pipes were installed. Yield 1 lps (liters per second).
139	do	do	1922	1,350.00	320		Flow	1922	N	N	Well E, abandoned Yield 4 lps.
140	do	do	1926	1,312.00	65		Flow	1926	N	N	Well G, abandoned. Yield reported 4 lps.
141	do	do	1926	1,305.00	181		Flow	1926	N	N	Well H, abandoned. Yield reported 5 lps.
142	do	do	1926	1,303.00	64		Flow	1926	N	N	Well I, abandoned. Yield reported 2.5 lps.
143	do	do	1928	1,289.00	35	12	Flow	1928	N	PS	Well J. Yield 44 lps. In Iquique is used as potable water.
144	do	do	1930		50		40.40	1930	N	N	Well M, abandoned. Yield 0.7 lps.
145	do	do	1931		131		39	1931	N	N	Well N, abandoned. Yield reported 2 lps.
146	do	do	1936	1,213.00	200	10-6	Flow	1936	N	N	Well O, abandoned. Yield reported 1 lps.
147	do	do	1937	1,208.00	295	10-6	Flow	1937	N	N	Well P, abandoned. Yield less than 1 lps.
148	do	do	1939	1,470.00	100.2	16-6	41.40	1939	N	N	Well L, abandoned. Yield reported 35 lps. Aquifer is the dark-gray welded tuff of member 2 of the Altos de Pica Formation.
149	do	do	1939	1,453.00	50.7		26.20		N	N	Well Q, abandoned.
150	do	do	1939		77.00		59.95		N	N	Well R, abandoned. Yield 2.5 lpm (liters per minute).
151	do	do	1939	1,459.00	54.00	8-6	40.6		N	N	Well S, abandoned.
152	do	do	1939		81.1				N	N	Well T, abandoned.

153	do	Manuel Rodríguez	1957		325.00	12	173		N	N	Pampa Brüggen 1, abandoned and caved. Yield less than 1 lps.
154	do	V. Moris	1956		270.00	4			N	N	Pampa Pica 1 (CORFO), abandoned and caved.
155	do	do	1956		90.00	4			N	N	Pampa Pica 2 (CORFO), abandoned and caved.
156	do	D. Meneses and N. Plaza.	1959		338.00	10–14	100	1959	N	N	Charcarilla 1, abandoned. Insignificant yield.
157	do	do	1916	1,352.00	52.2		48.90	1916	N	N	Well A in Quebrada Seca, near Puquio Nüñez. Hand-dug well.
158	do	do	1916	1,205.00	52.3		11.60	1916	N	N	Well B in Puquio Nüñez, abandoned.
159	do	A. Meneses	1958	1,300.00	162.00	14	14.20	1960	N	N	Sanquecito 1, abandoned. Yield 0.25 lps.
160	do	do	1953		448.00				N	N	Pampa Esmeralda 1, abandoned.
161	do	do	1953		178.00				N	N	Pampa Esmeralda 2, abandoned.
162	do	do	1954		226.00				N	N	Pampa Esmeralda 2, abandoned.
163	do	do	1954		350.00		32		N	N	Pampa Esmeralda 4, abandoned.
164	do	H. Gómez	1955		380.00	12	28	1960	N	N	Pampa Esmeralda 5, abandoned.
165	do	do	1954		235.00				N	N	Pampa Esmeralda 6, abandoned.
166	do	L. Torrepa and M. Rodríguez	1955		361.00	10–14	41.50	1956	N	N	Pampa Esmeralda 7, abandoned. Yield 1 lps.
167	do	G. Juschkewitz	1956		486.00	10–12	45	1957	N	N	Pampa Esmeralda 8, abandoned Yield 1 lps.
168	do	H. Gómez	1955		312.00	12	47	1956	N	N	Pampa Esmeralda 9, abandoned. Yield 0.5 lps.
169	do	do	1955						N	N	Pampa Esmeralda 10, abandoned. (This well is not indicated on the maps.)
170	do	C. Olivares and M. Rodríguez.	1956		315.00	10–16	23	1960	C	Ir	Pampa Esmeralda 11. Yield 8 lps.
171	do	A. Meneses	1957		150.00	10	16	1957	C	Ir	Pampa Esmeralda 12. Yield 6 lps.
172	do	do	1960		93.00	10	35	1960	C	Ir	Pampa Esmeralda 13. Yield 15 lps.

[1] Well locations are shown on pl. 1.

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3. Overflow from the pipeline between Chintaguay and Iquique, amounting to approximately 150 cubic meters per day, is used primarily for irrigation.

Water from the gallery serves approximately 20 families, each of which receives a quantity of water somewhat larger than is distributed to the consumers in Pica. The rest of the population obtains its domestic water from the irrigation system or from private wells. It is a curious situation in that the drinking water is not chlorinated nor analyzed bacteriologically; however, the irrigation water is chlorinated, containing approximately 0.5 parts per million free chlorine. The situation exists because the irrigation water is obtained as a result of water rights which were granted when the ground-water development for Iquique reduced the natural water supply of Matilla. This irrigation water is obtained from the pipelines to Iquique and has already been chlorinated before reaching Matilla.

The sewage situation in Matilla is the same as in Pica. Each family must arrange its own methods of sewage and garbage disposal. There are no regulations for disposal of sewage and no plans for construction of a sewage system.

IRRIGATION

The cutivated areas of Pica, Matilla, Puquio de Núñez, and La Calera are irrigated with ground water derived from the springs and galleries. The low rate of discharge from these sources necessitates the collection of the water in tanks or pools so that the water may be released at a sufficiently high rate of discharge to provide efficient irrigation. The water is conducted from the tanks to the fields through canals, many of which are lined with concrete. Water from the water-table aquifer has been pumped for irrigation during the past few years by the Cervellinos brothers at their chacras west of Pica.

The Dirección de Riego is using water pumped from well 5 to irrigate the land of their experimental station.

In Chacarilla and Jucuma, a few hectares are irrigated from springs. Here the water is also accumulated in small pools and distributed through unlined canals.

Small areas, in the vicinity of Chacarilla and El Algarrobal, were at one time irrigated with the surface water of the Quebrada Chacarilla, but were abandoned many years ago. The high salinity of the water in the Quebrada and the occasional violent floods probably discouraged the irrigation of these tracts.

A comprehensive survey of the ground-water development and use of water from springs and galleries in the vicinity of Pica was made by Brüggen (1918). Very little work has been done in the way of further development since that time. A few wells have been dug, others have been deepened, and a few galleries have been extended and lowered as the water table has declined. However, the description as made in 1918 is still applicable, and the reader is referred to this report for detailed descriptions and sketches of the individual galleries. Brief descriptions are given as follows.

LA CALERA

At La Calera, 17 km north of Pica, a short gallery driven into member 5 of the Altos de Pica Formation produces approximately 1 lps. The water is used to irrigate an area of 2–3 hectares, mainly for the production of green vegetables.

PUQUIO DE NÚÑEZ

Several galleries have been excavated in member 5 of the Altos de Pica Formation at this locality (Brüggen, 1918), but only one was producing water at the time of this investigation. The rest of the galleries have collapsed or have been covered by windblown sand. The present yield of the gallery is approximately 1 lps, and the water is used to irrigate approximately 3 hectares.

CHACARILLA

At this locality, a spring issues from the contact of member 1 of the Altos de Pica Formation with the underlying Chacarilla Formation. The yield of this spring is approximately 1.5 lps. The water is used to irrigate an area of less than 1 hectare. The small fields irrigated are on remnants of a high terrace, and most of the usable land is under cultivation.

PICA

All the ground water in the vicinity of Pica has its origin from member 1 of the Altos de Pica Formation. The diversion of ground water to the south by the ground-water dam of the Cerro Longacho fault block and the westward movement of water downslope through member 1 has resulted in an artesian pressure sufficient to bring the water to the surface in the springs of the area. Water is confined in member 1 between the overlying rhyolitic tuffs of member 2 and the nearly impermeable beds of the underlying rock (Chacarilla Formation?). The water moves upward, probably passing through member 2 along fracture zones resulting from late Tertiary or Pleistocene faulting. Some water may be lost through horizontal movement in the sedimentary beds of the formation. However, the vertical permeability of the faults is apparently sufficiently greater than the permeability of the sediments of members 3 and 5 to allow the water to reach the surface. Silica precipitated from the rising water has cemented the sedimentary beds through which it has passed and thus reduced their permeability. Samples of a sandstone taken from the Resbaladero spring show that approximately 40 percent of the rock is composed of a siliceous cement in the form of chalcedony and microgranular quartz. This cement was apparently deposited by ground water. Possibly a long period elapsed between the fracturing of the formation and the appearance of the springs, and the rising water gradually cemented off members 3 and 5 until the water finally was forced to the surface. In the Resbaladero Spring the water issues from north-trending fractures in the cemented sandstones. The fractures along which the water rises may have been kept open by continued movement along zones of weakness.

All the ground water in the vicinity of Pica has its source in the system described in the preceding paragraph. There are four large springs near Pica (table 10). The water in all four springs has a temperature of approximately 33°C. The shallow wells and galleries of the area produce water that is considerably colder; however, the water temperatures range from 14°C to approximately the temperature of the warmer spring water. This water is obtained primarily from return flow of irrigation and from the discharge of the springs. The temperature of the water in shallow water-table aquifers should closely approximate the mean annual air temperature of the area, which in Pica is 14°C. Anomalies in the water-table map (pl. 2) and the water-temperature data indicate that there may be other subsurface "springs" in the area which do not reach the surface but which contribute warm water to the unconfined water body that forms the water table in the area.

There has been a very long history of ground-water development in the Pica area. The Geographic Dictionary of Chile states that Pica was "discovered" by the Spanish conquistadores in 1536. Carbonaceous material resembling peat excavated from wells at Pica at a depth of 15 m indicates that the area around these springs has been an oasis for thousands of years. There were undoubtedly Inca and pre-Inca villages at this location before the arrival of the Spaniards. The villagers claim that some of the galleries were constructed by the Indians before the time of the conquistadores. Only one gallery, Matriz, which discharges water to Ultima Esperanza, is irregular and meandering. This is probably the oldest of the galleries, and may have been constructed soon after the arrival of the conquistadores. The principle of ground-water development by means of galleries is typically Spanish and was used in other Spanish colonies. The technique was undoubtedly brought to Spain by the Moors who had learned it from the Arabic nations to the east. It is interesting to note in passing that Tolman (1937, p. 13) mentioned that the Arabic word for

TABLE 10.—*Records of springs and galleries in the Pica area*

Name	Location	Topography	Geologic situation	Yield (lps)	Temperature (°C)	Remarks
Springs						
Animas	Oasis of Pica	Piedmont slope	Issues from Quaternary wind-blown sand, locally cemented by silica.	5.5	32	
Chacarilla	Oasis of Chacarilla	Small tributary valley to the Quebrada Chacarilla.	Contact between the Altos de Pica Formation (member 1) and the Chacarilla Formation.	1.0		
Concova	Oasis of Pica	Piedmont slope	Quaternary sand, locally cemented by silica.	9.5	34	
La Calera	Oasis of La Calera	Small broad valley on piedmont slope.	Sand of the member 5 of the Altos de Pica Formation.	.7		Water issues from short gallery. It is unknown whether a spring existed at this place before excavation of gallery. See table of chemical analyses.
Miraflores	Oasis of Pica	Piedmont slope	Quaternary sand, locally cemented by silica.	8.0	33	See table of chemical analyses.
Puquio de Núñez	Oasis of Puquio de Núñez.	Small east-west gallery on piedmont slope.	Member 5 of the Altos de Pica Formation.	1.0		Water issues from short gallery; a spring probably existed at this locality before excavation of the gallery.
Resbaladero	Oasis of Pica	Piedmont slope	Quaternary sand, locally cemented by silica.	30.0	35	Water issues from fractures in bottom of two short galleries that were dug to increase original yield of spring.
Galleries						
Bellavista	6 km north of Pica	Broad open valley between piedmont slope and the Longacho Ridge.	Member 5 of the Altos de Pica Formation.			Gallery collapsed, reported to have yielded 7.5 lps.
Charcas, Martin	Matilla	Slope	Quaternary eolian sand deposit.	1.0	24	
Comiña	2.5 km southwest of Pica.	Piedmont slope	do	.8	24	
Comiñita	3 km west-southwest of Pica.	Slope	do	.5	23	
De Gregory	Pica	Piedmont slope	do	1.4		
El Carmen	1 km southwest of Pica.	do	do	2.2	24	See table of chemical analyses.
El Sauque	Matilla	do	do	7.0		
Espinoza, Fernando	do	Slope	do	.5	23	
Jesús María	1 km southwest of Pica.	Piedmont slope	do	2.0	24	Do.
Loreto	3 km north of Pica	do	do	.5		
San Isidro	2 km southwest of Pica.	do	do	4.0	23	
Santa Cruz and Santa Rosita.	2.5 km west of Pica	do	do	15.6	31	
Santa Elena	2 km southwest of Pica.	do	do	1.3	23	
Ultima Esperanza	3 km southwest of Pica.	do	do	.9	22	

these galleries is "kanat" or "ghanat" which has also been euphoneously translated by some other authors as "kharez" or "kahriz". One might speculate that the naming of the gallery Matriz may be the result of the corruption of one of these pronunciations. The word "matriz" in Spanish means matrix or origin, which is not particularly applicable to its use as a name for the gallery.

Many galleries have been constructed in the Pica area during the more than 400 years that have passed since the arrival of the Spanish. Some of these are described by Brüggen (1918), but there were probably many more that have collapsed or been buried by the drifting sands of the area and thus have been lost to knowledge of the local inhabitants.

Many exploration wells have been drilled in this area. In the period from 1916–42, approximately 20 wells were drilled in the Pica–Matilla–Quebrada Chintaguay area. These wells ranged in depth from 35 to 320 m. Many of the well locations have been lost because the casings were removed and because the locations were covered with sand. Only one of these wells (J), located in Quebrada Chintaguay, is now in use. This well flows approximately 40–50 lps and is used for a part of the potable water supply of Iquique. This was by far the best yield obtained; the rest of the wells produce less than 1 lps. Approximately in 1952 the Department of Irrigation began a test-drilling program on the eastern border of the Pampa del Tamarugal, northwest of Matilla. This is one of the poorest areas that could have been selected for exploration because of its location in the lee of the Cerro Longacho fault block which forms a barrier to the westward movement of the ground water. As a result of the fault block, the water levels are much lower west of this fault than they are east. The fault block also acted as a barrier to the surface streams that deposited the sands and gravels of the Altos de Pica Formation. The sediments penetrated in the drilling program were the fine-grained materials that had been deposited on the far edges of the alluvial fans that formed north and south of the previously mentioned barrier. As would be expected, the results of this program were unfavorable; the best well produced a reported 15 lps, and most of the wells produced 1 lps or less.

In 1956, an exploratory well was drilled by the Department of Irrigation in Pampa Pica approximately 10 km due north of Pica. A well was drilled at that location by the engineers of that department because of the seismic studies that had been made in the area. When the well was drilled, the rhyolite of member 2 was penetrated at a much greater depth than had been expected, and therefore drilling terminated before the member was completely penetrated. Drilling was terminated at approximately 325 m in the dark-gray lower phase of the member. At the same time, an attempt was made to drill two observation wells 100 m from the large well, a very light rotary drill being used for the perforations. The maximum depth that could be reached with this machine was 270 m, and the deepest observation well was abandoned at this depth (fig. 17). The water table in this area is

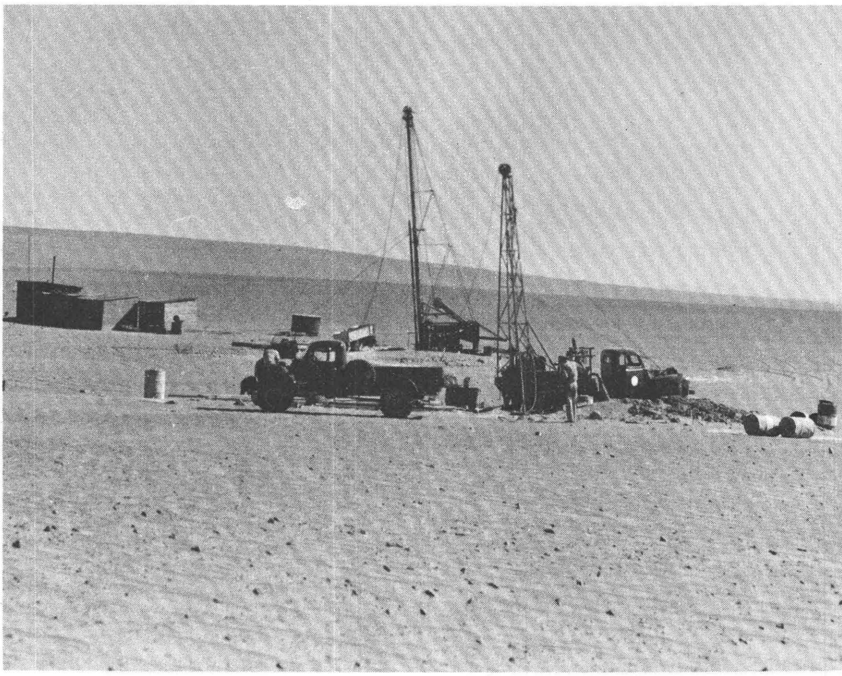

FIGURE 17.—Typical desert morphology in Pampa Pica.

in the cemented sandstone overlying the rhyolite. Artesian pressure in the rhyolite as measured in the exploratory well is sufficient to bring the water to within 10–15 m of the land surface.

As part of the fieldwork in connection with this report, the dug wells of Pica were inventoried and a map of the water table was constructed on the basis of the information thus derived (pl. 2). The water-table contours indicate the configuration of the water table and in general indicate zones of recharge and discharge as well as the direction of movement of the water. Zones of recharge are indicated by "high" areas of the water table and, conversely, discharge zones are indicated by "low" areas. Movement of ground water is essentially at right angles to the contour lines in the direction of the steepest gradient. Thus, it may be observed from the water-table map that the zones of recharge correspond to the irrigated areas of the village.

This recharge is derived from the water that is applied for surface irrigation, a part of which passes through the soil and subsoil and eventually reaches the water table. The percentage of irrigation water that becomes recharge is difficult to determine unless exhaustive studies are made of evaporation, plant use, soil permeability, and so on.

The ground water is discharged from the shallow aquifer principally to the southwest toward the Matilla area and also to the northwest into the Tarapacá Water Works Gallery. The water table in the northwestern part of the village is controlled by the drainage toward this gallery, and some rather steep gradients have formed. The increased depths to water observed in the northwestern sector are due to the control exerted by this gallery. In addition, the water-table map indicates that there is considerable underground discharge from the area as the water moves south and southwest to be lost at depths under the sand. The ground-water recharge that is derived from irrigation has the same temperature as the earth through which it passes. This temperature is, at a depth of a few meters, essentially equal to the mean annual temperature of the area, or as indicated by the water temperatures measured in wells in or near the irrigated areas, approximately 14°–17° C. As the water moves away from the recharge areas and to greater depths beneath the surface, it would be expected to increase in temperature in response to the normal increase in temperature with depth. This increase in temperature is known as the geothermal gradient and, in areas not affected by geologically recent volcanism, averages approximately 1° C per 33 m. In the area of this investigation, the geothermal gradient should be somewhat higher as a result of the volcanic activity along the Andes Range. Water temperatures measured from the previously mentioned well drilled in Pampa Pica had a temperature of 38° C at approximately 300 m.

This would be approximately 1°C per 15 m. If this geothermal gradient prevails in the Pica area, with each increase of 15 m in the depth of the water table below land surface, there should be a corresponding increase of 1°C in the temperature of the water. During the inventory of the wells, the water temperature in each well was measured. After the completion of the inventory, the wells were revisited and all the temperatures remeasured. The remeasuring of the temperatures was completed in 2 days so that essentially all effects of seasonal changes in temperature were eliminated from the results. The data thus obtained indicate that temperature increases rapidly with depth as the water moves away from the area of surface recharge. This increase is approximately 1°C per meter. A geothermal gradient of this order is almost unknown except in recently active volcanic areas. The explanation must be that the water table is being recharged both from above and from below. Ground water must be moving up from depths of 200 to 300 m where the temperatures would be approximately 35°–40°C. This upward movement takes place along fractures or conduits of fairly high permeability so that sufficient time does not elapse during the movement of the water to permit it to reach the temperature of the surrounding rock. This phenomenon is observed in flowing wells where there is essentially no decrease in temperature between the uppermost aquifer and the surface. If the upward movement in the Pica area were diffused throughout the sandstone of member 3, then it would be so slow that the water would take on the temperature of the rock and would reach the surface, or the water table, at temperatures essentially corresponding to the mean annual temperature. On the basis of the present available data, it is impossible to determine the percentage of recharge due to the cold surface waters and as compared to that due to the upwelling warm waters. From the rapidity with which the temperatures increase away from the irrigation recharge areas, the recharge from below may be greater than the recharge from above.

QUALITY OF GROUND WATER

The chemical quality of ground water governs its suitability for the use to which it is being applied. In the Pica area there are essentially only two uses of ground water; it is used for irrigation and for domestic and municipal use. According to the eight analyses made of samples of ground water from wells, springs, and galleries (table 11), the water is satisfactory for irrigation. Total dissolved solids ranged from 211.6 to 2,038.1 mg per l (milligrams per liter). This is sufficiently low so that there is little danger of excessive salt deposition in irrigated areas, particularly in view of the highly permeable soils of the area. Boron, which is a problem farther to the west in the Pampa del Tamarugal, is 1 mg per l or less in the samples from the Pica area which were tested for this element (Castillo, 1960). Castillo reported that a sample from the Salar de Guasco had the highest boron concentration, that is, 1.7 mg per l. Figures 18 and 19 are two methods of graphically representing the chemical character of the water. The concentration of the points in figure 18 indicates that all the water has a similar source and that it is probably all derived from the deep aquifers of the Altos de Pica Formation.

CONCLUSIONS

As indicated in the preceding discussion of the occurrence of ground water in the Pica area, the overall permeability of the two upper and perhaps the lower sedimentary members of the Altos de

TABLE 11.—*Chemical analyses of water samples from wells, springs, and galleries in the Pica area*

[All values reported in mg per l except pH]

Analysis No.	Location	Date of collection	Dissolved solids	Silica (SiO_2)	Calcium (Ca)	Magnesium (Mg)	Sodium (Na)	Potassium (K)	Bicarbonate (HCO_3)	Carbonate (CO_3)	Sulfate (SO_4)	Chloride (Cl)	Nitrate (NO_3)	Boron (B)	Hardness as $CaCO_3$		pH
															Total	Noncarbonate	
1	Pampa Esmeralda, well 164 (well 5, MOP).	Dec. 1957	580.4	40.0	29.6	5.3	171.1	4.4	252.6	0	58.4	146.0	1.4	-------	96.0	0.0	7.98 at 25°C
2	Well 7, Pica, Owner M. de Cervellino.	June 1959	594.1	45.0	70.5	9.0	107.0	7.0	195.6	-------	172.6	71.2	14.6	0.9	213.2	52.9	7.12 at 16°C
3	Well 1, Pica SOCAPI.	do	500.0	46.0	53.3	3.6	101.0	8.6	180.6	0	111.9	69.5	16.1	1.0	148.0	0	7.34 at 16°C
4	Well 103, Pica. Owned by H. Oxa.	do	415.4	41.0	38.0	1.2	93.0	7.0	154.2	0	83.5	60.7	14.2	.9	100.0	0	7.24 at 16°C
5	El Carmen Gallery, Pica.	do	237.4	39.0	22.2	.7	49.0	1.6	101.2	0	42.8	27.9	4.0	.4	58.4	0	7.16 at 16°C
6	Jesús María Gallery, Pica.	Nov. 1956	543.6	43.2	61.6	5.0	100.6	3.2	162.8	0	138.4	80.3	25.0	-------	174.3	40.9	8.11 at 20°C
7	Miraflores Gallery, Pica.	do	211.6	33.2	19.6	.1	45.9	.4	95.3	0	35.4	25.8	4.0	-------	49.4	0	6.05 at 20°C
8	La Calera	May 1957	2,038.1	40.0	108.2	12.2	541.1	6.1	123.9	0	984.6	225.0	60.0	-------	320.0	219.0	7.65 at 25°C
9	Surface water, Quebrada Chacarilla.	Dec. 1957	5,531.4	33.0	380.8	132.5	1,406.7	71.4	207.5	-------	982.0	2,423.0	.0	-------	1,495.0	-------	7.19

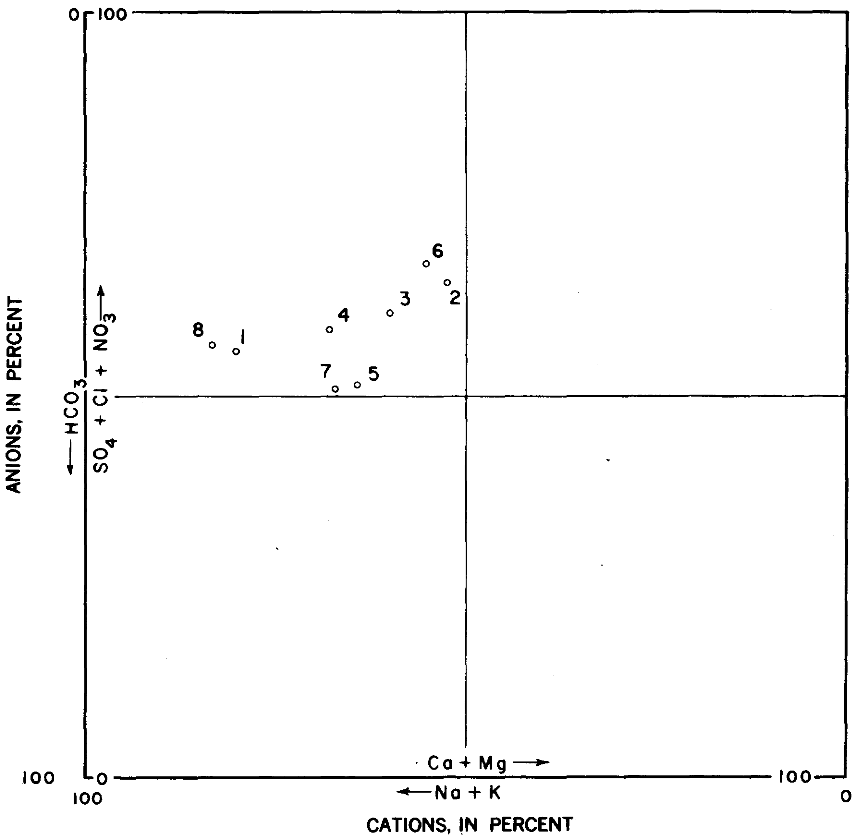

FIGURE 18.—The chemical character, by percent reacting value, of ground water in the Pica area.

Pica Formation have been greatly reduced because the sediments have been cemented by silica deposited by ground water. Upward (and lateral) movement of ground water is along fractures which may be kept open by continued seismic activity or possibly along vertical conduits of rather high permeability in which for some reason cementation has not taken place. Therefore, the permeability of most of the formation is very low, but some small zones are of relatively high permeability. Exploration for ground water under these conditions becomes a special problem. Drilling of deep wells, at least into members 3 and 5, is very likely to be unsuccessful as the well must intercept one of the small zones of high permeability in order to obtain any appreciable yield. Inasmuch as these zones may be considered to be somewhat like tubes in a vertical position, the possibility of a well penetrating one of these tubes is very slight. This would explain the high percentage of failures in the wells which have been drilled up

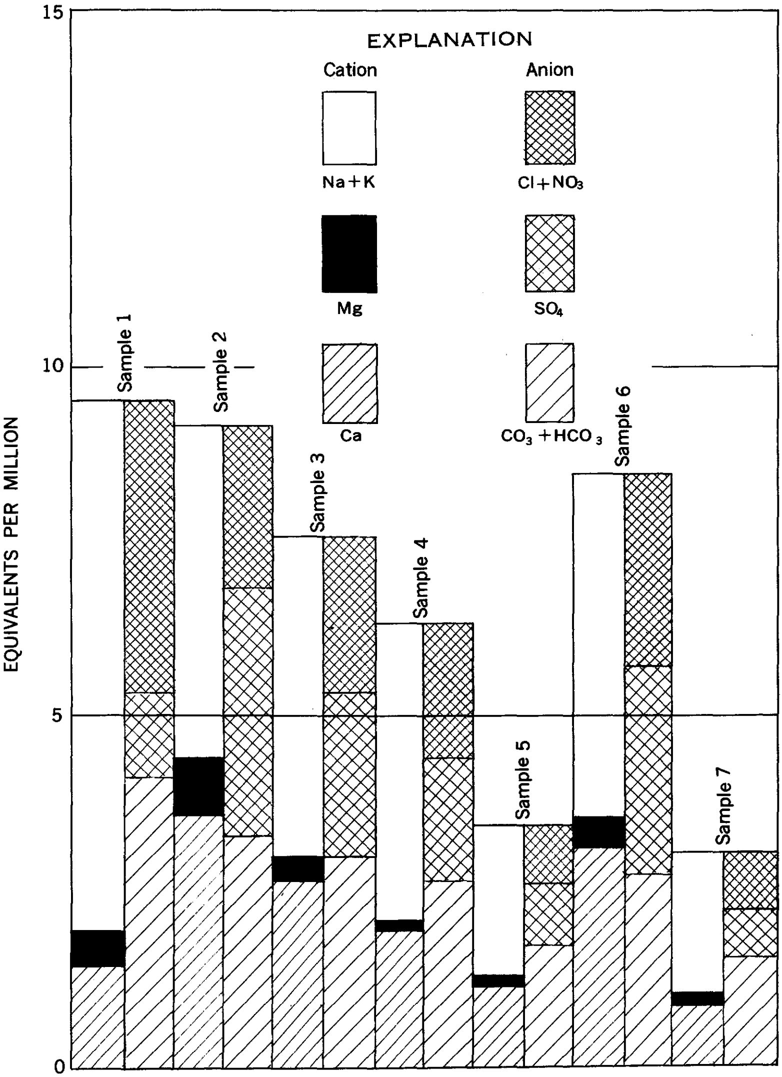

FIGURE 19.—Chemical analyses of water from the Pica area.

to this time. If exploration were to be undertaken, then the problem would be, obviously, to find some way to locate the passages through which the water is moving through the formation. In the Pica area, where the water in the lower members of the Altos de Pica Formation is known to be present under sufficient pressure to bring the water to or near the land surface and where such passages are known to exist, exploration could be done by sinking shallow small-diameter wells. Such wells would be drilled only to the water table. Water-level and temperature measurements in these wells could be used to construct water-table and temperature maps. Zones of high temperature and high water levels would be interpreted to indicate zones of recharge. Close spacing of wells in promising areas would provide the additonal data necessary to determinate points of recharge. Final exploration and development might be made by means of shafts. The cost of such a program would probably not be too great if the drilling were to be done by means of a light rotary drill of the type used for shot-hole drilling in the United States. With such equipment, a driller should be able to drill three to five shallow wells per day. The depths of such wells would probably be on the order of 25–30 m.

It is evident from the water-table map that an appreciable quantity of water is moving out of the Pica area through the water-table aquifer toward the west and southwest. For maximum development of the area, this discharge should be reduced. This could be accomplished by the construction of a gallery approximately 1 km southwest of Pica tangent to the water-table contours or at right angles to the movement of the water. Such a gallery should be oriented approximately northwest-southeast and should be excavated to sufficient depth to penetrate at least one meter into the cemented, relatively impermeable sandstone that underlies the windblown sand of the surface. The purpose of such a gallery would be to intercept the water moving out of the area through the water-table aquifer. Extension or deepening of the present system of galleries cannot obtain maximum development of the area as they are located parallel to the direction of ground-water flow and water escapes from the area between the galleries. In this area the galleries have been an extremely uneconomical method of development as may be seen if one considers the many kilometers of galleries that have been dug to obtain partial development of the water-table aquifer. Much more complete development could have been obtained by one relatively short, deep gallery at right angles to the direction of ground-water flow.

The conditions along the eastern border of the Pampa del Tamarugal probably are the same as in the Pica area with regard to cementing of the aquifers and the occurrence of water in fractures or conduits. However, the artesian pressures are less in this area than in the Pica area, the water table is much deeper, and the sediments are much finer. All these factors combine to make the eastern border of the Pampa del Tamarugal very unfavorable as a locality for developing water supplies from wells.

Any deep well which would intersect a conduit or a zone of sufficient permeability to obtain an appreciable yield would be almost certain to reduce the artesian pressure over a large area and, if located near the Pica springs, would reduce the flow of the springs. It is quite possible that the flowing well in the Quebrada Chintaguay has had an effect on the spring discharge in the Pica area.

Complete development of the shallow aquifer, including exploration for and development of the conduit discharge areas, should have little or no effect on the yield of the springs. The shallow aquifer is essentially a separate hydraulic system from the deep pressure system that feeds the springs. The surest and most rapid way to increase the quantity of ground water available in the area is by construction of the northwest-southeast gallery. This gallery should be located southwest of Pica 1 km or less from the village. Construction of this gallery will make more water available to the area but will reduce or stop the discharge of galleries located downslope from the new gallery. Dug wells located southwest of the new gallery would also be affected by the reduced water levels and would possibly go dry.

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