Geology and Ground-Water Resources of the Northern Part of the Salar de Atacama Antofagasta Province, Chile

GEOLOGICAL SURVEY BULLETIN 1219

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

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By Robert J. Dingman

ABSTRACT

The Salar de Atacama is an undrained topographic basin in east-central Antofagasta Province, Chile. This report describes the geology and ground-water resources of two 15-minute quadrangles in the northern part of the basin and the general features of the adjacent region.

The quadrangles are underlain by Mesozoic and Cenozoic continental sedimentary rocks, which are divided into four formations, and deposits of ash flows, piedmont deposits, basalt, alluvium, eolian sand, and salt. The Tonel Formation of Jurassic age is the oldest formation exposed and is composed of more than 500 meters of varicolored shale, sandstone, and conglomerate with intercalated beds of salt and gypsum. The Purilactis Formation of Cretaceous age is in fault contact with the Tonel Formation. The Purilactis Formation is divided into three unnamed members. The lower member includes 1,000 meters of reddish-gray medium- to fine-grained sandstone; the middle member 1,200 meters of reddish-brown sandstone, shale, and conglomerate; the upper member 1,700 meters of gray, brown, and olive-green shale, sandstone, and conglomerate.

The Tertiary rocks include the San Pedro Formation, which is composed of more than 2,100 meters of reddish-brown fine-grained basin-type sediments, and the Tambores Formation, which is composed of 500 meters of sandstone and conglomerate. These formations are overlain by ash-flow deposits, as much as 30 meters thick, of probable Pliocene age. The Quaternary sediments include piedmont deposits of an earlier cycle of deposition, alluvium, salt beds, and eolian sand.

The only intrusive rock exposed in the report area is a dark-green hornblendite which intrudes the Tonel Formation. Basaltic lava flows of Recent age overlie the Tertiary (Eocene) ash flows in the northwestern part of the quadrangle area.

Major structural features of the report area include a large horst which exposes the Tonel Formation, a broad syncline in the Purilactis Formation, salt domes in the Tonel and San Pedro Formations, and the structural basin occupied by the Salar de Atacama.

Aquifers having moderate to large development potential occur in sediments in the basin of the Salar de Atacama. A test drilling program demonstrated that wells flowing as much as 70 liters per second and capable of being pumped at much higher rates could be obtained in the vicinity of San Pedro. The quality

of the water, however, is rather poor, the dissolved-solids content is approximately 2,500 parts per million and includes 15 parts per million of boron.

Other mineral resources of the area include extensive salt and gypsum deposits in the San Pedro Formation and a small low-grade copper deposit.

INTRODUCTION

The Salar de Atacama,[1] an undrained topographic basin approximately 150 kilometers long and 80 kilometers wide, is in the east-central part of Antofagasta Province (fig. 1). The area is very sparsely populated and almost all the approximately 2,000 inhabitants live in the villages of San Pedro, Toconao, Peine, and Tilomonte. The economy of the area is based almost entirely on agriculture and on a very small mining industry (salt and copper near San Pedro and copper near Peine). San Pedro is the transportation hub of the area and has unsurfaced roads leading to Calama, the geysers of El Tatio, the sulfur mines of Toconce, east to Argentina, and south to the villages along the east border of the Salar de Atacama. This report describes the geology and ground-water resources of two 15-minute quadrangles, Túlor and San Pedro, in the northern part of the basin and the general features of the adjacent region (fig. 1).

PURPOSE AND SCOPE

All the crop production of the area is from irrigated land and is restricted by the very limited surface-water supply. The water is of poor quality and has much dissolved mineral matter. The quality of the water, coupled with the rigorous climate of the area, limits the crops that can be grown to a few hardy species such as alfalfa, corn, figs, pears, and in some localities wheat. The possibility of obtaining large quantities of ground water in the basin has been recognized for many years. In 1954 Carlos Galli [2] and Lorenzo Barraza made a preliminary study of the ground-water possibilities of the San Pedro quadrangle. In 1956 the author made a reconnaissance survey, and a test drilling program was planned. The objective of the program was to obtain water of better quality than that obtained from surface streams and thereby to permit diversification as well as expansion of agriculture in the area. The program included the drilling of six deep test wells (the deepest, 585 meters) and detailed geologic mapping of the Túlor and San Pedro quadrangles (Dingman 1963a and 1965a) at 1 : 50,000, as well as reconnaissance geologic mapping of parts of the basin north and south of these quadrangles (pl. 1). The construction of the wells was closely supervised, and numerous tests were conducted to determine the hydraulic characteristics of the aquifer and the quality of the water obtained from the wells.

[1] The term "Salar" as used in Chile means not only the salt lake, but also the basin that contains the salar.

[2] Galli O., Carlos, 1954, Posibilidades de agua subterránea en San Pedro de Atacama, Santiago, Chile: Unpub. rept. Corporación de Fomento de la Producción, p. 1–54.

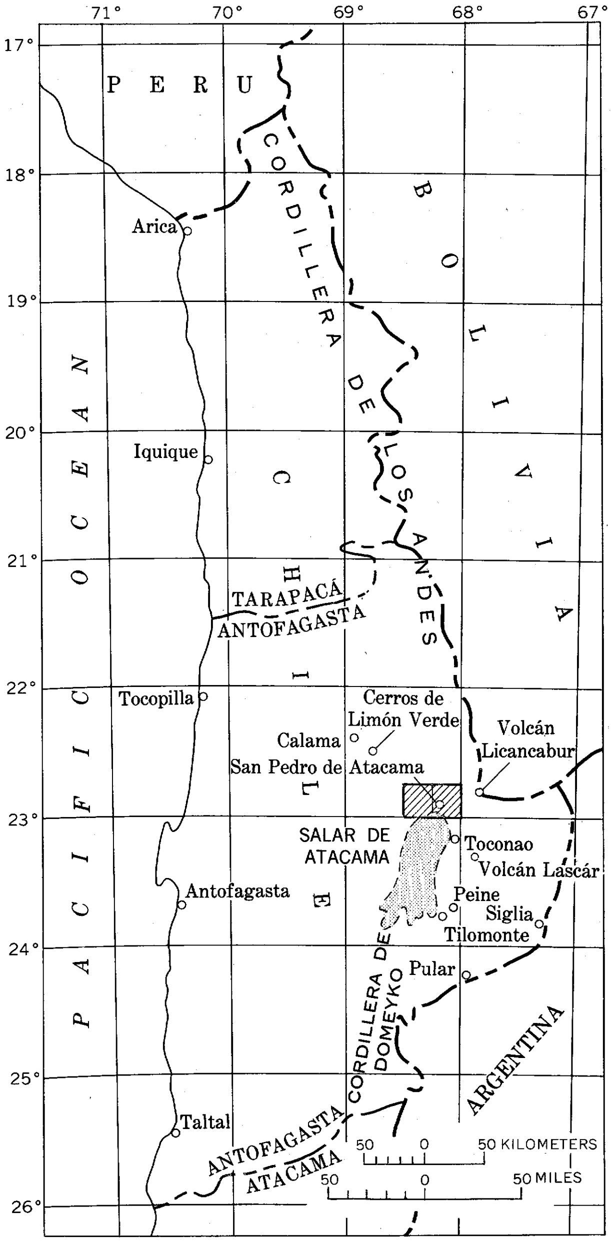

Figure 1.—Map of northern Chile showing area (diagonal-line pattern) of this report. Quadrangle on left is Túlor and that on right is San Pedro.

ACKNOWLEDGMENTS

The author is indebted to many persons for their assistance during various phases of this project. Special mention should be given to engineers Jaime Donoso, Raul Cobo, Fernando Alamos and Eugenio Seladón of the Sección de Aguas Subterraneas of the Corporación de Fomento de la Producción (CORFO) and to well drillers Renato Calatroni and Rene Guzmán for their complete cooperation during the test-drilling phase of the investigation. Many members of the Instituto de Investigaciónes Geológicas (IIG) assisted in the field and in the laboratory. Soñia Mehech studied numerous thin sections; Hernan Cusicanqui, IIG chemist, supervised the chemical analyses of water samples; Ernesto Peréz, Beatriz Levi, and Octavio Castillo spent some time in the field with the author. José Soto accompanied the author during the mapping of all the geology and deserves special thanks for his willing cooperation as chauffeur, cook, camp man, and field assistant. Professors S. E. Hollingworth and Roy Rutland of the University of London spent several days in the field with the author and made several very helpful suggestions regarding the structure of the area.

CLIMATE

The Salar de Atacama is a part of the Atacama Desert of northern Chile. This desert is one of the most arid in the world; at altitudes near 1,000 meters, the rainfall averages less than 1 millimeter per year for stations with many years of record. San Pedro, at an altitude of 2,438 meters, has an average rainfall of approximately 90 mm per year, but this average is based on 9 years of sporadic measurements and is of doubtful value. For 1920, a total of 409 mm of precipitation was reported; this amount is more than the cumulative total for the other 8 years of incomplete record. The villagers of San Pedro report that, typically, several years may pass between rains that are heavy enough to cause water to flow in the gutters. If judged by the discussions with the villagers and by the lack of vegetation, annual rainfall might be more nearly 20–30 mm per year, rather than the 90 mm indicated by the short period of record. Precipitation is much greater at higher altitudes and probably reaches an average of 400–500 mm per year on the high plains (puna) east of San Pedro, which have an average altitude of 4,300 meters.

The precipitation occurs during the summer months of December to March, when moisture laden airmasses from the jungle basins to the east in northern Argentina pass over the puna. Most of the precipitation on the puna falls in the form of snow, and even though the season is midsummer, this period of precipitation is known as the Bolivian winter.

The temperature range varies greatly as altitude increases or decreases. At San Pedro the maximum summer temperature is near 40°C (centigrade), and the minimum near 10°C; during the winter the temperatures are approximately 15° lower, and occasional severe freezes occur during the nights. In the Cerros (hills) de Purilactis and in the puna the temperature range is greater, and much lower temperatures occur at night and during the winter.

The winds can be very strong during the winter months. In July 1957, while the author was conducting a pumping test, winds of 100 kilometers per hour with gusts to 150 kilometers per hour were reported at San Pedro by Father Lepage, a priest who was making meteorologic observations. Winds were also very high in June 1962, while the author was mapping geology. Winds of this force can carry a load of medium to coarse sand and make it impossible to survive without shelter.

GEOGRAPHY AND PHYSIOGRAPHY

The Salar de Atacama is a completely enclosed basin bounded on the west by the Cordillera de Domeyko, which has an average altitude of approximately 3,000 meters; to the north by the high Andes, which have peaks over 5,000 meters, to the east by the puna, which has a plain surface at 4,300 meters; and on the south by high plains and hills having altitudes of more than 3,000 meters. The basin is elongated in a north-northeast direction. The lowest part of the basin is near 2,300 meters and is occupied by salt flats and a small salt lake. The gently sloping floor of the basin is broken by a range of hills (Cerros de la Sal) trending N. 30° E. The transition between the basin and the Cordillera de Domeyko on the west is abrupt; canyons as much as 200 meters deep are being eroded in this mountainous area, and youthful topography is being formed in the divides. To the north and east, great sheets of ash-flow deposits slope gently down from the high plains and disappear beneath the sediments of the basin. The surface of the ash-flow deposits is youthful, and many minor consequent streams cut downward through the flows. Quaternary andesitic volcanoes have been built on the ash flows east of the basin. Volcán Licancabur, west of San Pedro is a perfect cone that reaches an altitude of 5,650 meters. Southeast of Toconao, Volcán Lascár is active, and steam and smoke issue constantly. During August 1961, an eruption of ash from this volcano blanketed the puna and the volcanoes to the east of Lascár. South of Toconao several outliers of old rock are exposed along the east border of the basin.

Several streams drain into the basin. The largest of these is the Río San Pedro, which has a flow of approximately 500 liters per sec-

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ond. Other streams in the report area include the Río Vilama, Río Blanco, and the unnamed stream flowing in the Quebrada Hecal at Toconao.

STRATIGRAPHY

All the sedimentary rocks of Mesozoic and Cenozoic age exposed are continental in origin and seem to have been deposited under arid conditions similar to those of the modern desert. The fine-grained sedimentary rocks, ranging from sandstone to shale, tend to be reddish gray or reddish brown and contain beds of salt and gypsum. The conglomerates have angular to subangular clasts and are similar to the piedmont deposits now being formed. Table 1 summarizes the stratigraphic units identified within the quadrangles.

TABLE 1.—*Geologic formations in the San Pedro area*

System	Series	Formation	Approximate maximum thickness (meters)	Lithology
Quaternary	Recent	Eolian sand deposits	10	Medium to fine windblown sand.
		Salt deposits	50	Salt and salty silt or clay; well stratified.
		Alluvium	300	Clay, silt sand, and gravel; unconsolidated and poorly stratified.
		Basalt flows	20	Porphyritic; phenocrysts of plagioclase as large as 3 mm.
	Pleistocene	Terrace deposits	5	Sandstone and conglomerate, poorly sorted with subrounded to rounded clasts.
		Piedmont deposits	50	Sandstone and conglomerate, poorly sorted and poorly stratified with angular to subangular clasts.
Tertiary	Pliocene(?)	Ash-flow deposits	30	Ash flows and welded tuff. Tuff ranges from poorly lithified to dense and welded.
		—Conformable on the Tambores Formation; unconformable on older rocks—		
	Lower Tertiary	Tambores Formation	500	Sandstone and conglomerate, poorly sorted and poorly stratified.
		Conformable, unconformable, or intertongued		
		San Pedro Formation	2,000+	Shale, siltstone, and fine-grained sandstone; reddish brown; a few conglomerate beds. Thick beds of salt and salty clay.
		Unconformity		
Cretaceous		Purilactis Formation: Upper member	1,700	Shale, sandstone, and conglomerate; gray, brown, and olive-green; very hard.
		Purilactis Formation: Middle member	1,200	Sandstone and shale, scarce conglomerate; reddish brown to grayish green, well stratified, crossbedded. Few thin evaporite beds.
		Purilactis Formation: Lower member	500	Sandstone, medium- to fine-grained, medium-gray to grayish-red.
		Unconformity		
Jurassic		Tonel Formation	500+	Varicolored shale, sandstone, and conglomerate with intercalated beds of salt and gypsum.
Triassic(?)		Unnamed formation	500	Quartzite, slate, shale, and graywacke interbedded with andesite flows.

The rocks of Triassic(?) age exposed south of Toconao may have been marine in origin, at least in the lower, finer grained part of the section.

TRIASSIC SYSTEM

Rocks of an unnamed formation crop out in several outliers exposed along the east border of the Salar de Atacama between Toconao and Tilomonte. The rocks are soft tones of green, gray, and red and consist of highly metamorphosed sedimentary rocks including quartzite, graywacke, shale, and slate interbedded with thick beds of andesitic lava. The metamorphic rocks are intruded by a few cryptocrystalline mafic dikes and a few coarse-grained diorite dikes. The structure is fairly complex and has numerous north-trending faults that have downdropped blocks to the west; there is some complicated folding. In one stratigraphic section, 5 kilometers north of Peine, at least two definite angular unconformities and one probable unconformity were observed. Rocks of several ages are probably included in these outcrops. The rocks in the western part of the outcrops are continental in origin, coarser grained, and include crossbedded sandstones and conglomerates.

No fossils were found during several days of reconnaissance mapping, and no definite correlation can be made with formations of known age. Carlos Ruíz (oral commun., 1962) suggested that the outcrops might be Triassic in age. His opinion was based on the fact that the outcrops were lithologically similar to rocks interbedded in rhyolitic flows of Triassic age on the Pacific coast near Taltal. The author considers that the quartzites, graywackes, and slates in the lower part of the stratigraphic section indicate that the rocks are probably older than Jurassic inasmuch as Jurassic rocks of northern Chile have not undergone regional metamorphism. Possibly, however, detailed mapping might permit a lithologic correlation between the youngest part of the section and the Jurassic or Cretaceous formations of the area.

JURASSIC SYSTEM

TONEL FORMATION

The Tonel Formation of Jurassic age is exposed along and near the west border of the Salar de Atacama (pl. 1). The formation consists of more than 500 meters of unfossiliferous varicolored shales, sandstones, and conglomerates of continental origin (fig. 2). The rocks of this unit were first described by Brüggen (1942, p. 345) as the salinas de Purilactis Formation. To avoid confusion with the overlying Purilactis Formation, also named by Brüggen, (1934, p. 5), the author recommends that the name be changed to Tonel Formation.

This name is derived from the Cerros del Tonel, where the formation is well exposed. The total thickness of the Tonel Formation is unknown because the base is not exposed and the upper part of the formation is in fault contact with the younger Purilactis Formation.

The Tonel Formation was deposited in an undrained or poorly drained continental basin. Mud cracks, dust ripples, fine cross-bedding, salt, and gypsum layers are indicative of an arid or semiarid climate and of deposition in shallow saline waters. The lower part of the exposed portion of the formation consists of light-brownish-gray to medium-gray poorly consolidated shales, siltstones, and fine-grained sandstones intercolated with beds of gypsum and salt as much as 2 meters thick. Because of faulting and intense folding, the lower part of the formation was not measured in detail. The following is a section of the somewhat less disturbed upper part of the Tonel Formation:

Composite section of upper part of the Tonel Formation measured westward from the easternmost exposure on the west flank of the major syncline

Top of section.	*Thickness (meters)*
Sandstone, medium-grayish-red; in very well stratified layers 1.5 m thick intercalated with gypsiferous sandstone layers 0.3–0.5 m thick; composed of phenoclasts of quartz, plagioclase (andesine), and some orthoclase; has strongly banded appearance because of the erosion-resistant yellowish-gray-weathering gypsiferous layers	60
Sandstone, light-brownish-gray, fine-grained to very fine grained; in beds 1.5–2 m thick; has subangular phenoclasts of quartz, plagioclase, and orthoclase cemented by silica and calcite; erodes to smoothly rounded forms	10
Travertine, light-olive-gray, soft, very light and porous; more resistant to erosion than the sandstone	2
Sandstone, grayish-red, medium- to fine-grained; has slightly calcareous beds 1–2 m thick; composed of phenoclasts of quartz, plagioclase, and orthoclase cemented by silica and calcite. Section includes three very light gray soft and porous travertine beds 0.3–0.5 m thick	105
Sandstone, grayish-red, medium- to fine-grained; very well stratified; similar to overlying bed and intercalated with a few thin layers of gypsum, which forms approximately 5 percent of this part of the section	55
Total	232

Section lost in complicated zone of folding, faulting, and intrusion.

The section is incomplete but is typical of the upper part of the exposures of the Tonel Formation. The exposures total approximately 500 meters in thickness; however, the total thickness is unknown because all exposed contacts with adjoining rocks are either by faults or angular unconformity.

The Tonel Formation is considered to be of Jurassic age on the basis of its lithology and its stratigraphic position below the Purilactis Formation of Cretaceous age. The Tonel Formation is extensively

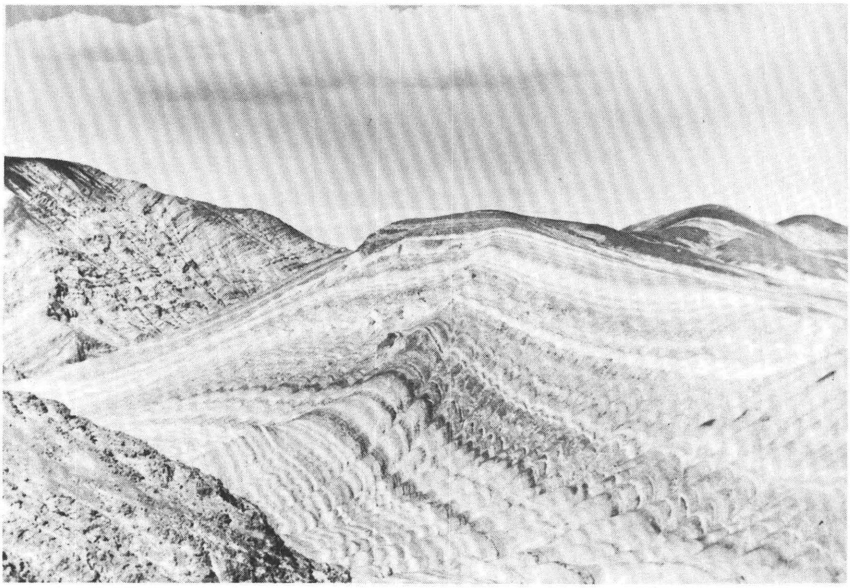

FIGURE 2.—Steeply dipping beds of the Tonel Formation. Approximately 250 meters of the formation is exposed.

intruded by dark-green perknite (hornblendite) dikes. Rocks of this composition are very sparse in northern Chile but occur in both of the known exposures of the Tonel Formation. The conglomerate of the overlying Purilactis Formation contains phenoclasts of perknite that are assumed to have been derived from the dikes that intrude the Tonel Formation, which must therefore have been deposited, intruded, uplifted, and eroded prior to the deposition of the Purilactis Formation. The sedimentary rocks of the Tonel Formation are relatively soft and unconsolidated in contrast to the hard, lithified rocks of Early Jurassic age exposed 40 kilometers to the east in the Moctezuma area (Pérez and Levi, 1961).

Galli and Dingman (1962) described continental deposits of the Chacarilla Formation, of Late Jurassic (Oxfordian) age, that are found in Tarapacá Province. The author believes that the Tonel Formation is the approximate equivalent of the Chacarilla Formation. Brüggen (1942) correlated the rocks of the Tonel Formation with those in the area of Siglia, 165 kilometers to the southeast, and with the sediments of the Pular area, 150 kilometers to the south-southeast.

CRETACEOUS SYSTEM

PURILACTIS FORMATION

The Purilactis Formation (Brüggen, 1934), of Cretaceous age, consists of approximately 3,500 meters of continental sedimentary rocks. The formation was divided by Dingman (1963a) into three unnamed members as follows: A lower member of medium- to fine-grained sandstone; a middle member of typical basin deposits that include "red beds" and evaporites; an upper member of coarse conglomerate which includes the only extrusive rock in the formation, an andesite flow 43 meters thick.

The formation name is derived from the Cerros de Purilactis, where the lower member is typically exposed. The other two members are exposed in the broad syncline that extends east of the Cerros de Purilactis. The base of the formation is unknown because the contact with the older Tonel Formation is a fault contact. The upper surface of the Purilactis Formation is eroded and is overlain with angular unconformity by the Tertiary and Quaternary formations (fig. 3).

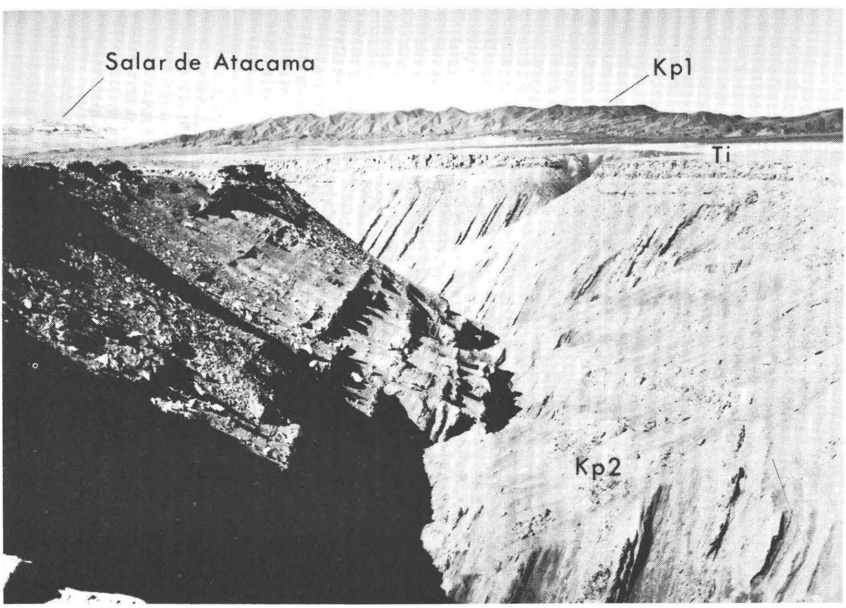

FIGURE 3.—Angular unconformity between the middle member of the Purilactis Formation (Kp2) and the overlying Tertiary rhyolitic tuffs (Ti). The ridge on the horizon is underlain by the resistant rocks of the lower member of the Purilactis Formation (Kp1).

LOWER MEMBER

The lower member consists of approximately 600 meters of massive medium- to fine-grained sandstone, which is medium gray to grayish red. Some of the beds are very hard and resistant to erosion and form cliffs and ridges. The subangular to subrounded grains consist largely of rock fragments and minor amounts of feldspar and quartz cemented by calcite and some hematite. The phenoclasts range from 0.1 to 0.4 mm, and scattered grains are as large as 0.7 mm.

Section of part of lower member of the Purilactis Formation in the eastern exposure of the member in a quebrada 2 kilometers southwest of the Calama–San Pedro road

Top of section is base of middle member Purilactis Formation.	*Thickness (meters)*
Sandstone, light-olive-gray, fine-grained, well-stratified, massive	5.7
Sandstone, grayish-green, fine-grained, massive, slightly calcareous	.5
Sandstone, light-olive-gray, fine-grained, intercalated with brownish-gray medium-grained sandstone; in beds 30–50 cm thick	4.9
Sandstone, green to red; in beds as much as 1 m thick. Similar to last described unit	7.2
Shale, grayish-red, very friable	.4
Sandstone, light-olive-gray to brownish-gray, medium-grained	12.2
Sandstone; joint planes space 1–10 cm. Similar to last described unit	27.3
Sandstone, medium-brownish-gray, medium- to coarse-grained; contains several layers of conglomerate 10–15 cm thick with pebbles 1 cm in diameter and possible but very poorly preserved fossil plants	1.7
Sandstone, reddish-gray (has a few greenish beds of same type sandstone), medium-grained. Red sandstone contains layers of mud fragments	28.1
Sandstone, grayish-red, fine-grained; intercalated lenses of silty shale of same color	36.5
Shale and siltstone, reddish-brown; intercalated in layers 10–20 cm thick	27.7
Siltstone and fine-grained sandstone, grayish-red; in well-stratified beds 20–80 cm thick	13.2
Siltstone, grayish-red; in well-stratified beds with a few layers of fine-grained sandstone 20 cm thick	21.0
Total	186.4

Base of section at axis of anticline.

MIDDLE MEMBER

The middle member of the Purilactis Formation consists of approximately 1,200 meters of sedimentary rocks, mostly sandstone and shale, intercalated with a few beds of conglomerate and gypsum. The sandstone is well stratified, is medium to fine grained, is reddish brown to grayish green, and has deltaic crossbedding.

Section of middle member of the Purilactis Formation in the first major valley south of the Calama–San Pedro road on east flank of a syncline

	Thickness (meters)
Top of section is base of the upper member of the Purilactis Formation.	
Sandstone, greenish-gray, medium-grained, very uniformly textured; has finely stratified individual beds that are several meters thick; shows massive deltaic crossbedding which suggests source area to the west	68
Sandstone, grayish-green, similar to preceding unit, intercalated with reddish-brown fine-grained to very fine grained sandstone. Phenoclasts are of rock fragments, feldspar, and quartz cemented by both epidote and hematite. Green sandstone, which is colored by the epidote that cements the grains, has coarser and more rounded grains than those of the reddish-brown sandstone	67
Sandstone and conglomerate, reddish-brown, intercalated in beds 1–2 m thick. Conglomerate has well-rounded clasts as much as 15 cm in diameter that include andesite fragments containing some diorite and fragments of hornblendite (from Tonel Formation(?))	53
Sandstone, grayish-red, medium- to fine-grained, crossbedded, massive, intercalated in beds 1–3 m thick with grayish-green coarse-grained sandstone and conglomerate similar to the last described unit	146
Sandstone, grayish-red, medium- to fine-grained; in beds 1–3 m thick alternating with grayish-red friable shale; intercalated with a few beds of medium-gray conglomerate 2 m thick that has subangular to subrounded phenoclasts of andesite, sandstone, diorite, and limestone as much as 20 cm in diameter	200
Covered slope. Rocks similar to last described unit are exposed in next valley to the south	133
Sandstone, grayish-red, fine- to medium-grained, intercalated with grayish-green medium-grained sandstone that occurs in beds as much as 4 m thick. Approximately 80 percent of this unit is composed of red sandstone	539
Total	1,206
Base of section at top of lower member of Purilactis Formation.	

Where exposed on the west flank of the syncline, the middle member is finer grained, grayish red, and does not include greenish beds. In this locality the conglomerate layers contain fragments of hornblendite and also many clasts of fossiliferous limestone. Gypsum, anhydrite, and salt are exposed in layers as much as 50 cm thick in the Cerros de Purilactis.

UPPER MEMBER

The upper member of the Purilactis Formation consists of approximately 1,700 meters of shale, sandstone, and conglomerate in shades of gray, brown, and olive green. Phenoclasts of the sandstone and conglomerate are angular to subangular. The conglomerate is identical in appearance with the Recent piedmont type of deposit of the area. In detail, stratification is poorly defined, crossbedding is scarce and is not well formed, cut-and-fill features are common. The shales contain fossilized mud cracks, dust ripples, and clay balls. In many localities the sand stone and conglomerate are indurated to the extent that fracturing crosses the clasts.

Section of upper member of the Purilactis Formation along the line A–A′ (pl. 1) eastward from the axis of the syncline

	Thickness (meters)
Top of section is the eroded surface of the Purilactis Formation.	
Sandstone and conglomerate, medium-brownish-gray; poorly stratified in beds 3–5 m thick; siliceous cement. Sandstone is coarse grained and crossbedded. Very hard conglomerate has phenoclasts of subangular andesite, diorite, sandstone, and fossiliferous limestone as much as 20 cm in diameter; fractures across clasts	47
Shale, medium-brown, friable, initercalated in well-defined beds 20–50 cm thick with medium-brown medium-grained sandstone lenses 50 cm to 1 m thick. Sandstone constitutes 10 percent of unit	63
Sandstone, coarse-grained, and medium-brownish-gray conglomerate; similar to uppermost unit of section	126
Shale and sandstone, brownish-gray, well-stratified. Sandstone is medium to coarse grained and crossbedded	25
Shale and fine-grained sandstone, light-olive-gray, thin-bedded, easily eroded	33
Same as last described unit but some of the sandstone beds contain lenses of conglomerate as cut-and-fill features	262
Shale, friable, and grayish-brown medium- to coarse-grained sandstone; poorly stratified with a few thin beds of olive-gray conglomerate that contain clasts as much as 10 cm in diameter	99
Conglomerate and sandstone similar to top unit of section; very poorly stratified	326
Conglomerate and sandstone similar to last described unit, but conglomerate beds decrease to 20 percent or less of total thickness	164
Conglomerate and coarse sandstone, medium-brownish-gray, very hard, massive; phenoclasts as much as 20 cm in diameter	83
Conglomerate and coarse-grained crossbedded sandstone, medium-brownish-gray, very hard, massive; subrounded to rounded phenoclasts. In lower part of unit conglomerate beds become olive green and constitute less than 10 percent of total unit	257
Porphyritic andesite, medium-dark-gray; phenocrysts of feldspar and pyroxene (sparse) 0.5–2 mm in diameter. Plagioclase is altered to clay, sericite, and calcite. Upper part of unit contains flow(?)-breccia zones	13
Porphyritic andesite; medium-gray euhedral plagioclase crystals as much as 3 mm in length	23
Andesite breccia, similar to last described unit but brecciated	7
Sandstone, reddish-brown, medium- to coarse-grained, finely stratified. Contact with overlying lava is concordant	8
Sandstone, grayish-green, medium- to coarse-grained, well-stratified, crossbedded; grades downward into medium- to fine-grained sandstone	206
Total	1,742

The age of the Purilactis Formation is considered by most authors to be Cretaceous. Felsch (1933) identified various species of middle and upper Jurassic fossils from limestone phenoclasts of the conglomerate beds of the middle and upper members of the Purilactis Formation. These fossils include *Perisphinctes*, *Pholadomya*, *Gryphea*, *Vola*, *Posidonia*, several species of *Ostrea*, *Trigonia*, and *Exogyra*. The author collected specimens of *Weylalata* from the clasts of the middle member of the Purilactis. In northern Chile a major orogeny occurred at the close of the Jurassic; therefore, if the Purilactis Formation contains redeposited fossils of the Late Jurassic age, it must have been deposited after Nevadian folding and subsequent erosion of the fossiliferous beds. Other indications that the Purilactis Formation is of Cretaceous age are that it is lithified to a greater extent than any known Tertiary sedimentary rock of northern Chile and is so intensely folded that 60°–70° dips are not unusual. The last major orogeny in northern Chile apparently occurred during the very Late Cretaceous or earliest Tertiary periods. Although the Purilactis Formation is considered to be of Cretaceous age, insufficient evidence is available to determine more precisely the epoch in which it was deposited.

TERTIARY SYSTEM

SAN PEDRO FORMATION

The San Pedro Formation of Late Tertiary age (Brüggen, 1950) is composed of more than 2,000 meters of continental, basin-type sediments including consolidated shale, siltstone, fine-grained sandstone, a few conglomerate beds, and thick deposits of salt. The salt of the San Pedro Formation is almost pure sodium chloride. Some of the sediments, particularly the more permeable sandstone and conglomerate beds that have been cemented by salt, are hard and resistant to erosion. The only exposures of the San Pedro Formation are in the Salar de Atacama where it underlies the Cerros de la Sal and in a narrow anticlinorium near the mouth of the Quebrada Tambores.

A complete section of the San Pedro Formation is not exposed in any one locality, and it is difficult to estimate the total thickness because a certain amount of plastic flow may have occurred in the salt beds and thereby exaggerated their true thickness. Without attempting to compensate for salt flow, the generalized section of the San Pedro is as follows:

Generalized Section of San Pedro Formation

	Thickness (meters)
Sandstone, fine, siltstone, and shale; reddish brown; interlayered with a few thin conglomerate beds. A few beds of salt and very salty silt	1,050
Salt, relatively pure and a few silty beds	500
Shale and fine-grained sandstone	250
Salt and silt	300
Total	2,100

Rest of formation not exposed.

Anlayses, in percent, of nine samples of salt from the San Pedro Formation

[Samples 1, 2 and 9 are typical of salt beds of the San Pedro Formation; samples 3-8 are selected samples from salt mines. Symbols used: T, trace; X, not present]

Sample	NaCl	Ca	Mg	SO_4	NO_3	CO_3	Insolubles	Total
1	94.26	0.83	0.007	2.02	0.004	X	2.68	99.83
2	94.96	1.88	.05	.80	T	T	2.21	99.90
3	99.85	.004	.002	X	.013	T	.033	99.902
4	99.90	X	.005	X	.016	X	.027	99.948
5	99.70	.02	.006	.04	.009	X	.18	99.955
6	99.90	.004	.002	X	.01	X	.07	99.986
7	99.85	.01	.066	X	.005	X	.07	99.941
8	99.80	.004	.005	.066	.007	X	.07	99.952
9	87.37	.63	.01	1.61	X	T	10.20	99.98

The high percentage of salt in the formation and its relative purity in terms of concentration of sodium chloride are due to a combination of factors. The sediments of the San Pedro Formation undoubtedly were derived, at least in part, from the rocks of the Mesozoic Tonel and Purilactis Formations; both contain evaporate deposits so that the sediments derived from their erosion and dissolution were abnormally high in salts. The two Mesozoic formations have very little calcium carbonate, but the piedmont deposits derived from these deposits are relatively rich in $CaCO_3$. A possible explanation for the concentration of $CaCO_3$ on the slopes and its almost complete absence in the basin deposits may lie in the mode of deposition of the piedmont deposits. The piedmont deposits were transported and deposited by sheet wash, and the sporadic rainfall of the desert in combination with low relative humidity, caused a high percentage of the available water to be evaporated or absorbed before reaching the basin. The remainder of the water contained such a high concentration of salts that the relatively insoluble $CaCO_3$ was deposited on the slopes. The more soluble sulfates may have been deposited farther toward the center of the basin beyond the zone represented by the exposed sediments of the San Pedro Formation.

Section of upper part of the San Pedro Formation measured in the northeastern part of the quadrangle along old road to San Pedro

	Thickness (meters)
Top of section is angular unconformity with ash flow.	
Conglomerate, pale-reddish-brown; has matrix of sandy clay cemented with salt; phenoclasts 0.1–5 cm in diameter and scattered boulders as large as 20 cm	4.8
Shale, light-brown, finely stratified	6.6
Siltstone, pale-reddish-brown, finely stratified, soft, easily eroded	9.7
Sandstone, pale-grayish-red, medium- to coarse-grained, slightly calcareous	1.5
Siltstone and fine sandstone, pale-reddish-brown, intercalated in beds 10–20 cm thick	7.4
Shale, light-brown, massive, very slightly calcareous with a few concretions	1.2
Sandstone, pale-grayish-red, fine-grained	.9
Shale, light-brown, massive	1.2
Siltstone and fine-grained sandstone, pale-reddish-brown; in layers 10–30 cm thick	3.4
Siltstone, pale-reddish-brown, very soft and unconsolidated with bedding obscured by weathering; has about 5 or 6 thin beds of grayish-red fine-grained sandstone 5–15 cm thick	60.0
Sandstone, grayish-orange-pink, medium- to coarse-grained	.2
Siltstone, pale-reddish-brown, unconsolidated; bedding obscured by weathering	37.5
Sandstone, pale-yellowish-brown, medium-grained; shows crossbedding that indicates deposition from the northwest	12.4
Siltstone, reddish-brown, unconsolidated	32.2
Sandstone, reddish-brown, very hard; cemented with salt; has a few partings of gypsum 1 cm thick parallel to bedding. Hardness of strata is directly related to salt content	41.9
Shale and siltstone, reddish-brown, very hard; cemented with salt, and salt mantles surface; very massive individual beds 3 cm thick; gypsum veins 3 cm thick; stands in vertical cuts	86.2
Siltstone and shale, reddish-brown, massive; in beds 1–3 m thick; gypsum (satin spar) in veins 1–10 cm thick	182.5
Siltstone and silty shale, reddish-brown; has sandstone beds 5–15 cm thick increasing in number downward in unit	45.8
Sandstone, grayish-brown, medium-grained; has fine conglomerate lenses; phenoclasts as much as 2 cm in diameter	.7
Siltstone and sandstone, reddish-brown; in beds 10–30 cm thick	12.1
Sandstone, yellowish-gray, medium- to coarse-grained, crossbedded	9.1
Siltstone and sandstone, reddish-brown, fine-grained; in beds 10–30 cm thick	72.8
Conglomerate, very coarse grained; boulders as large as 25 cm; phenoclasts that mostly have been redeposited from the Purilactis conglomerate	.4
Sandstone, grayish-orange-pink, medium- to coarse-grained, well stratified	6.3
Conglomerate, medium-gray; phenoclasts as much as 10 cm in diameter and matrix of sand and clay	2.6

Section of upper part of the San Pedro Formation measured in the northeastern part of the quadrangle along old road to San Pedro—Continued

	Thickness (meters)
Sandstone, grayish-red, medium- to coarse-grained, crossbedded; has conglomerate lenses composed of phenoclasts as much as 10 cm in diameter. Conglomerate constitutes approximately 10 percent of this unit	52. 5
Conglomerate, grayish-orange-pink; in beds 0.5–1 m thick; rounded to subrounded noncalcareous phenoclasts as much as 10 cm in diameter; interbedded with coarse sandstone beds 10–50 cm thick of the same color	49. 9
Sandstone, grayish-orange-pink, fine- to medium-grained	17. 2
Sandstone and conglomerate, grayish-orange-pink, interbedded; subangular to subrounded phenoclasts as much as 10 cm in diameter. Conglomerate is slightly less than 50 percent of unit	126. 5
Conglomerate, medium-brownish-gray, very poorly stratified; angular to subangular phenoclasts as much as 15 cm in diameter but mostly 1–5 cm; matrix of silt and sand. Unit forms conspicuous dark band on aerial photographs	41. 0
Conglomerate, light-yellowish-gray; finer grained but similar to last unit described	5. 1
Sandstone, grayish-orange-pink, coarse- to medium-grained, well-stratified	5. 5
Conglomerate, light-yellowish-gray; subangular phenoclasts as much as 5 cm in diameter	10. 4
Sandstone and conglomerate, grayish-orange-pink. Predominantly sandstone with conglomerate beds 0.20–1 m thick	21. 5
Fault(?).	
Siltstone and claystone, pale-reddish-brown, poorly stratified, soft and easily weathered; has one conglomerate bed, 30 cm thick, near base; many thin beds and veins of gypsum	119. 5
Total	1,088. 5

Base of section is at fault.

Brüggen (1950) correlated the San Pedro Formation with the Corocoro Formation of Bolivia and with the Areniscas Superiores of Argentina. The Corocoro Formation of Bolivia has been redefined as a group by Ahlfeld and Braniša (1960). The continental arenaceous Coniri Formation of Oligocene(?) age is the oldest formation of the Corocoro Group and consists of 2,000–4,000 meters of sandstone, shale, and conglomerate. The Corocoro Formation was later divided by Meyer and Murillo (1961), and the lowermost unit was named the Chuquichambi Formation. The Chuquichambi Formation is composed of lacustrine sediments and is folded into salt domes or anticlines similar to those of the San Pedro Formation. The lacustrine sediments were deposited in intermontane basins and may be the age equivalent of the San Pedro Formation. Both the San Pedro and the Coniri Formations contain tuffaceous material only in the uppermost beds. The widespread distribution of tuff beds of ash-flow origin in the upper part of the Tertiary System indicates that regional vulcanism was renewed at approximately the same time throughout the Andes of Chile, Bolivia, Peru, and Argentina.

TAMBORES FORMATION

The Tambores Formation of Late Tertiary age was first named and described by Brüggen (1934) from typical exposures in the quebrada of the same name. The formation consists of approximately 500 meters of poorly consolidated sandstone and conglomerate that wedge out to the west and interfinger with the sediments of the San Pedro Formation to the east. The Tambores Formation is the piedmont equivalent of the basin deposits of the San Pedro Formation.

The coarse-grained sediments of the Tambores Formation were deposited on the upper slopes of the ancestral Cordillera de Domeyko. Downslope the grain size of the deposits became progressively finer because of abrasion, reduced gradient, and reduced competency of the ephemeral streams and sheet floods resulting from the occasional rains of the desert. Therefore, clay, silt, and evaporites were deposited in the basin, whereas gravel and sand were deposited on the piedmont slopes. Periods of heavy rainfall caused the advance of coarse sediments farther into the basin while periods of lighter rainfall caused deposition of finer material farther up the slopes. Thus, the two formations are probably intercalated over a broad zone; however, this intercalation is not exposed. The Tambores Formation is exposed within the Túlor quadrangle in three small areas west of the Llano de Paciencia; to the north of the quadrangle the formation underlies an area of many square kilometers characterized by distinctive badland topography.

The Tambores Formation was deposited with angular unconformity over the truncated beds of the Purilactis Formation. In the type locality in the Quebrada Tambores, just north of the Túlor quadrangle, all the clasts of the conglomerate beds seem to have been derived from the Purilactis Formation. The clasts are, in general, slightly more rounded than those of the conglomerates of the Purilactis Formation but are classified as subangular to subrounded. In the westernmost exposures, high on the slopes of the Cerros de Purilactis, the phenoclasts of the Tambores Formation are almost as large as those of the Purilactis Formation. The sediments in this area were transported only a short distance from the locality where they were derived from the Purilactis and very little abrasion occurred.

Section of the Tambores Formation measured in the Quebrada Tambores starting 600 meters west of the west side of the rhyolite (tuff) mesa on the south side of the quebrada

	Thickness (meters)
Gravel, light-grayish-brown; made up of subangular to subrounded phenoclasts of diorite, limestone, and andesite and phenoclasts of hard sandstone, 6–8 cm in diameter, from the Purilactus Formation; has matrix of medium to fine sand and some clay	50.8
Same as the last described unit but has very irregular bedding and many lenses of coarse sand	3.6
Gravel, similar to last described unit, and coarse sand. Sand layers make up 30–40 percent of unit	117.0
Gravel and sand, light-reddish-brown. Sediments gradually become finer grained and more rounded and consolidated downward in unit. Individual coarse sand beds are 10–20 cm thick, make up 30–40 percent of unit, are lenticular, and contain rock fragments as large as 1 cm in diameter. Gravel has phenoclasts, mostly subrounded, as large as 6 cm	147.6
Conglomerate and sandstone, light-reddish-brown; similar to last described unit but cemented by $CaCO_3$; has lenticular but massive bedding; stands in vertical cliffs 30 m high	145.6
Sandstone and conglomerate; similar to last described unit but very massive; stands in overhanging cliffs	45.2
Sandstone and conglomerate, medium-brown; has fine-grained sandstone beds intercalated with massive lenticular beds of coarse-grained sandstone and conglomerate; shows pronounced stratification	3.6
Total	513.4

This section conformably overlies well-stratified massive medium- to dark-brown fine-grained sandstone beds of the San Pedro Formation. The two formations probably interfinger at depth. Inasmuch as the Tambores Formation is of the same age as the San Pedro Formation it may also be correlated with the Coniri Formation of the Corocoro Group. It may also be correlated, on the basis of lithology and stratigraphic position, with member 1 of the Altos de Pica Formation of Tarapacá Province (Galli and Dingman, 1962). This member of the Altos de Pica Formation was deposited directly on the eroded surface of Mesozoic rocks and is composed of piedmont deposits.

ASH-FLOW DEPOSITS

Both the San Pedro and the Tambores Formations are overlain by a deposit of rhyolitic tuff of Pliocene age that ranges in thickness from a few centimeters to approximately 30 meters. In some localities the lower tuff lies with 90° angular unconformity over the San Pedro Formation whereas in other areas the contact between the two formations is conformable. The tuff overlies the older formations with strong angular unconformity as shown in figure 3. The origin of the tuff is an ash flow which came from a source east of San Pedro.

The tuff is progressively more welded to the east as it changes from a poorly consolidated relatively low density rock having incipient welding in the Cordillera de Domeyko to a fairly dense hard rock in the eastern part of the Cerros de la Sal (fig. 4). Farther to the east, as indicated by drill cuttings and exposures on the slopes of the Andes, this deposit is a typical vitreous welded tuff.

Potassium-argon age determinations made by the Branch of Isotope Geology of the U.S. Geological Survey seem to eliminate the possibility of the tuffs being of Pleistocene age (Dingman 1965b). An average age of approximately 7.5 million years (Pliocene) is indicated for the four samples analyzed.

The tuff deposits exposed in the San Pedro area are part of the extensive sheets that cover much of the mountainous region of northern Chile. East of San Pedro the tuff sheets are almost continuous over 15,000 square kilometers. These sheets are interrupted only where the tuffs are buried by Recent andesitic or basaltic lavas and where a few small windows of older rock are exposed. Assuming an average thickness of 50 meters, which is a very conservative figure, there seems to be at least 750 cubic kilometers of tuff in the area east of San Pedro. No source vents for these tremendous sheets are obvious; therefore, the tuffs probably originated from fissures that were buried by their own extrusives.

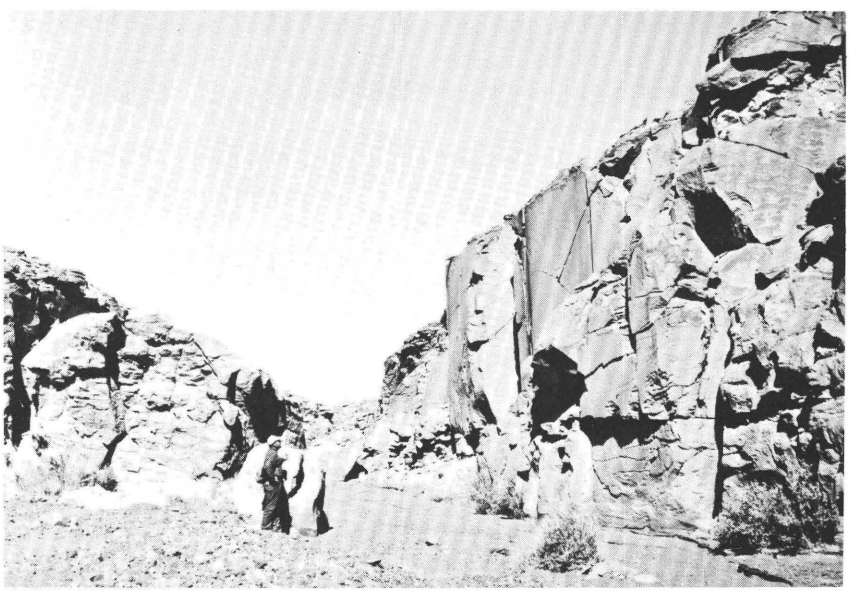

FIGURE 4.—Ash-flow deposits near San Pedro de Atacama.

Brüggen (1950) named the deposits of this type in northern Chile the Formación Liparítica and assigned them a Miocene age on the basis of their stratigraphic position with respect to the San Pedro Formation and to their supposed folding. He did not recognize the ignimbritic, or ash-flow, origin of these deposits but considered them to be lavas. Inasmuch as the tuffs mantled the preexisting topography, which was very similar to the modern surface, Brüggen was forced to postulate late Tertiary or Quarternary folding and a Miocene age for the tuff sheets to account for their existence in the Cerros de la Sal and in the Cordillera de Domeyko, for in the Cordillera de Domeyko they are exposed 1,000 meters above the floor of the Llano de Paciencia. Prior to the deposition of the tuff, a broad valley had been eroded in the less resistant middle member of the Purilactis Formation. As shown in plate 1 this old valley trends south and curves to the east following the curvature of a major syncline. The valley floor was graded to the surface of the basin that is now the Llano de Paciencia. In many localities the crossbedded alluvial sediments of the old valley are overlain by the ash-flow deposits. In Figure 3, the tuff is shown on the valley floor and slopes eastward toward the salar. This photograph was taken toward the south. The old surface of the valley is well preserved, and there is no evidence of uplift or tilting after deposition of the tuff. The ash flow apparently crossed the Salar, the Cerros de la Sal, and the Llano de Paciencia before continuing upslope to cross the eastern ridge of the upper member of the Purilactis Formation at 1,000 meters above the llano. If this hypothesis is correct the tuff sheet was not deposited as an avalanche but must have been deposited, at least in part, directly from the nuée ardente.

Of the two major ash-flow sheets exposed in the mapped area, the older (Ti1, pl. 1) is the thicker, more extensive, and more thoroughly welded. The tuff 1 sheet crosses the Cerros de la Sal and the Llano de Paciencia to reach the west edge quadrangle. The tuff is approximately 61–77 percent glassy groundmass that has an index of refraction of 1.59–1.51 and is 67–72 percent SiO_2; in composition it corresponds to rhyolite.

Tuff 1 is 44.5 meters thick where it was penetrated during the drilling of well 1. As indicated in the geologic section (pl. 1), the tuff was reached in this well at 280 meters below the surface. The same tuff sheet in the Cerros de la Sal is exposed 420 meters higher. Although there is a major fault between the two points, the difference in altitude is considered to be at least in part depositional and is not indicative of hundreds of meters of vertical movement across the fault.

The younger of the two ash-flow sheets (Ti2, pl. 1) is whiter, softer, and less extensive than the older tuff; however, it is at least 50 meters thick along the east border of the quadrangle. It was also deposited as an ash-flow tuff, although in some localities it has many of the characteristics of a mudflow or a lahar. In figure 5, most of the clasts shown are rounded fragments of pumice, however, there are also a few fragments of andesite and rhyolite. Microscopically tuff 2 is seen to be only slightly welded, having minor curving of the glass shards. The tuff increases in hardness toward the south and becomes a moderately dense welded tuff. As the hardness increases, the pumice fragments are less frequent and are somewhat elongated. The volcanic ash layer reported in well 1 at 158–224 meters and in well 2 at 123–212 meters includes not only the original deposit tuff 2 but also the detrital material consisting almost entirely of ash which was deposited in the basin after the ash flow. (See table 2.)

The oldest tuffaceous material is intercalated as thin lenses in the upper 30 meters of the San Pedro Formation. Some of these lenses are water deposited, as indicated by crossbedding, whereas others may be airborne ash. The largest of the tuff deposits intercalated in the San Pedro Formation consists of approximately 15 meters of very light gray very poorly consolidated tuff. The lower 90 centimeters to 1 meter of the bed is crossbedded. The rest of the stratum seems to be a direct-fall ash deposit although the many angular fragments of

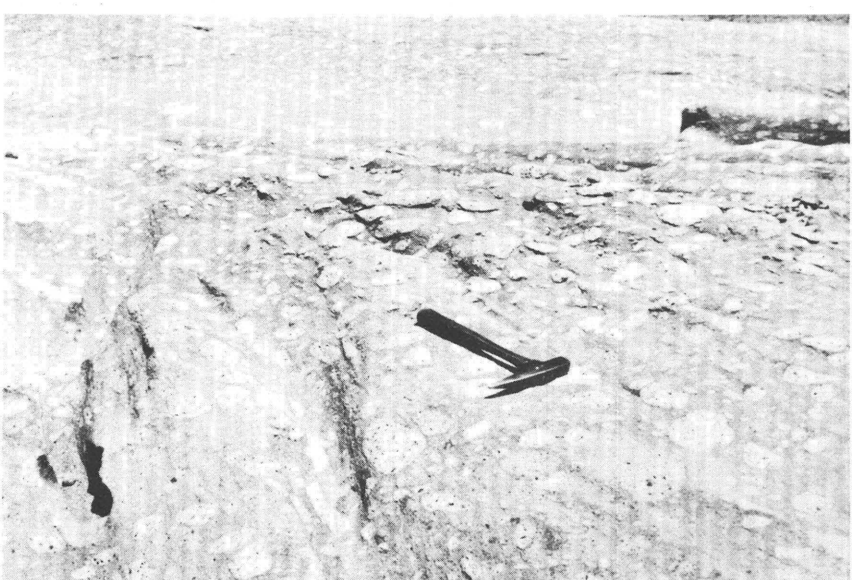

FIGURE 5.—Ash flow or lahar exposed on the east border of the Salar de Atacama.

rhyolitic to andesitic lava and the lack of stratification suggest an ash-flow origin. This tuff layer was involved in Quaternary folding of the salt domes and is well exposed in a vertical bed that crosses the road from Calama to San Pedro approximately 100 meters east of the west border of the Cerros de la Sal. This lower bed of tuff was completely eroded from the higher areas in the period that elapsed before deposition of tuff 1 of Pliocene age. During this period, 20–40 meters of basin sediments were deposited over the lower tuff bed in some localities.

TABLE 2.—*Drillers' logs of deep wells near San Pedro de Atacama*

Well 1

	Depth (meters)		Depth (meters)
Sand, gravel, and boulders	3.5 - 13.0	Sandstone	101.0 -122.0
Conglomerate, sand, and clay	13.0 - 24.0	Sand and fine gravel	122.0 -123.6
Gravel, fine sand; water	24.0 - 26.0	Ash, volcanic	123.6 -132.0
Conglomerate and clay	26.0 - 28.8	Ash, volcanic, and sand	132.0 -148.0
Gravel, coarse, unconsolidated	28.8 - 32.0	Clay and sand	148.0 -158.0
Conglomerate and clay	32.0 - 33.5	Ash, volcanic	158.0 -224.0
Gravel, fine, and sand; water bearing	33.5 - 37.5	Clay	224.0 -267.5
Conglomerate and clay	37.5 - 59.0	Sand, fine, and gravel; artesian aquifer	267.5 -271.5
Clay	59.0 - 62.0	Clay	271.5 -275.3
Sandstone	62.0 - 69.0	Sand	275.3 -276.2
Clay	69.0 - 73.0	Sandstone	276.2 -280.0
Rock, unidentified	73.0 - 76.0	Tuff, welded	280.0 -324.5
Conglomerate	76.0 - 91.0	Clay, dense	324.5 -528.3
Ash, volcanic, and clay	91.0 -101.0	Sandstone	528.3 -575.0

Well 2

Gravel and sand	3.8 - 9.0	Conglomerate	73.0 - 90.0
Conglomerate, sand, and clay	9.0 - 21.7	Clay and sand	90.0 - 96.5
Gravel, fine, and sand; water	21.7 - 24.4	Sandstone	96.5 -123.0
Conglomerate, sand, and clay	24.4 - 35.0	Ash, volcanic	123.0 -212.0
Gravel, fine, and sand; water bearing	35.0 - 37.0	Clay	212.0 -254.0
Conglomerate	37.0 - 70.0	Gravel, fine, and sand; artesian aquifer	254.0 -259.0
Clay	70.0 - 73.0	Clay	259.0 -264.0

Well 3

Clay	0 - 0.6	Sand and volcanic ash	90.0 - 95.0
Sand	0.6 - 1.2	Ash, volcanic and sand	95.0 -101.0
Clay	1.2 - 3.6	Sandstone	101.0 -107.0
Gravel, sand, and clay	3.6 - 26.5	Ash, volcanic, yellowish white	107.0 -131.0
Gravel and sand; water bearing	26.5 - 29.0	Ash, volcanic, white	131.0 -160.0
Conglomerate	29.0 - 40.0	Clay	160.0 -185.0
Gravel and sand; water bearing	40.0 - 45.0	Sandstone	185.0 -187.5
Sand and some clay	45.0 - 73.0	Sand, gravel, fine; artesian aquifer	187.5 -191.0
Clay and some sand	73.0 - 76.0	Clay	191.0 -202.0
Sandstone	76.0 - 80.0	Sand, gravel; artesian aquifer	202.0 -220.2
Clay	80.0 - 90.0	Tuff, welded	220.2

TABLE 2.—*Drillers' logs of deep wells near San Pedro de Atacama*—Continued

Well 4

	Depth (meters)		Depth (meters)
Gravel, sand, and some clay	0 - 18.00	Ash, volcanic	91.80-108.80
Sand and gravel, fine	18.00- 26.00	Tuff, welded	108.80-117.10
Sandstone	26.00- 52.40	Sandstone	117.10-131.00
Sandstone and volcanic ash	52.40- 61.00	Conglomerate	131.00-132.60
Tuff, welded	61.00- 62.50	Rock, unidentified	132.60-133.30
Tuff, welded, fractured	62.50- 64.80	Sandstone	133.30-157.00
Tuff, welded	64.80- 91.80	Tuff, welded	157.00-196.40

Well 5

Clay, sandy	0 - 0.50	Gravel and boulders	64.85- 67.00
Sand	0.50- 1.10	Sandstone	67.00- 81.30
Sandstone and volcanic ash	1.10- 1.80	Conglomerate, fine	81.30- 83.30
Sand	1.80- 2.25	Sandstone	83.30- 97.00
Sandstone	2.25- 2.85	Sandstone and thin beds of volcanic ash	97.00-109.00
Ash, volcanic	2.85- 4.00	Sandstone, poorly cemented	109.00-142.00
Sand and gravel	4.00- 8.00	Ash, volcanic	142.00-149.20
Sandstone and volcanic ash	8.00- 9.55	Sandstone, poorly cemented	149.20-152.00
Sand, gravel, and clay; water bearing	9.55- 15.30	Ash, volcanic	152.00-154.00
Clay and volcanic ash	15.30- 17.00	Sandstone	154.00-156.00
Clay, sandy	17.00- 18.50	Sandstone, coarse, and clay	156.00-161.00
Sandstone	18.50- 19.30	Ash, volcanic	161.00-237.00
Ash, volcanic	19.30- 31.47	Clay, compact, thin beds of volcanic ash, and rhyolitic sand	237.00-294.45
Sand and gravel	31.47- 44.60	Sand and gravel, fine; artesian aquifer	294.45-297.63
Sandstone and volcanic ash	44.60- 53.00	Sandstone and clay	297.63-298.40
Gravel, fine	53.00- 58.65	Tuff, welded	298.40-303.50
Clay and volcanic ash	58.65- 60.10		
Ash, volcanic	60.10- 62.70		
Sandstone	62.70- 64.85		

Well 6

Sand, gravel, clay, and boulders	0 - 3.00	Sandstone and beds of volcanic ash, brown	125.00-131.00
Sand and clay; some gravel	3.00- 32.00	Sandstone, coarse, and clay and thin beds of ash	131.00-138.00
Sand and gravel; water bearing	32.00- 34.00	Clay and volcanic ash	138.00-144.50
Sandstone, fine	34.00- 42.00	Sandstone, fine, yellow	144.50-147.50
Sand and gravel; little clay	42.00- 53.00	Sandstone, coarse	147.50-148.80
Sandstone and clay	53.00- 69.00	Clay, sand, and gravel, fine	148.80-165.50
Sand, coarse	69.00- 72.50	Clay and sand, fine	165.50-205.80
Sand, coarse, and fine gravel; water bearing	72.50- 74.60	Sand and gravel, fine; artesian aquifer	205.80-212.70
Sandstone and thin beds of clay	74.60- 85.00	Sand, coarse and clay	212.70-217.00
Sandstone and clay	85.00- 96.00	Sand, gravel and clay	217.00-232.00
Sandstone and beds of volcanic ash and clay	96.00-116.40	Sandstone and clay	232.00-241.00
Sandstone, yellow, and thin beds of clay	116.40-125.00	Tuff, welded, dense	241.00-246.50

Tuff 1, as exposed in the Cerros de la Sal, is typical of ignimbrite deposits. In some localities it is welded into a dense vitreous rock having a groundmass of curved glass shards and phenocrysts of plagioclase (oligoclase and andesine), biotite, amphibole, magnetite, and zircon. Sparse quartz crystals are present. Axiolitic structure is fairly common but is not well formed. The groundmass makes up 50–60 percent of the rock.

Tuff 2 is not exposed in the Cerros de la Sal. Either the hills were too high to be crossed by the nuée ardente and the accompanying avalanche at the time of deposition of this tuff or else the softer tuff bed was completely eroded off the Cerros de la Sal.

In the Cerros de la Sal tuff 1 contains rounded clasts as much as 15 cm in diameter (fig. 4). The form of these clasts is that of an oblate spheroid. The structure is concentric: an outer layer of 0.5 cm or less is light-gray finely crystallized rhyolitic tuff; a second thicker layer is medium-grained rhyolitic rock with included fragments of ash; an inner ring is light-gray ash and a central cavity is about one-fifth of the diameter of the clast. The central cavity is partially filled with an aggregate consisting of microcrystaline quartz, epidote, and fragments of altered volcanic glass. These clasts are particularly common near the tunnel on the old road from San Pedro to Calama. In this locality the ash flow is at least 100 meters above the desert floor and probably was deposited in its present position on a topographic high. The topographic position would seem to eliminate the possibility of deposition by avalanche or mudflow. The clasts must therefore have formed in place by a process of cementation as concretions or by some process of fusion, or they must have been transported into their present position through the air. The nearest probable source for the ash flow is 30 kilometers to the east. A tremendous velocity of ejection would have been required to hurl these clasts, weighing as much as 5 kilograms, that many kilometers. The possibility should be considered that these clasts originated within the nuée ardente and owe their shapes and long transportation to the violent turbulence of the cloud. Once a nucleus was formed, clasts would grow by a process of agglutination similar to that by which a hailstone grows.

S. E. Hollingworth (oral commun., 1961) suggested that the short axis of the oblate spheroids may represent the axis of rotation of the clasts during their transportation. The spinning of a plastic mass would tend to cause distortion of a spheroidal form, and accretion might be more rapid normal to the spin axis.

QUATERNARY SYSTEM

PIEDMONT DEPOSITS

The Quaternary (Pleistocene?) piedmont deposits which were formed after the deposition of the ash flows are lithologically very similar to the westernmost exposures of the Tambores Formation. Deposits of poorly sorted gravels that have angular clasts interbedded with lenses of sand and clay attain thickness of at least 100 meters. Many of the clasts of the peidmont deposits were derived either directly from the Mesozoic rocks or from the clasts of the Tambores

Formation; however, the deposits also contain clasts of welded tuff, as well as ashy material, in the matrix. As a result of this material, the sediments are a light brownish gray as compared to the darker reddish browns of the Tambores Formation. The sediments were deposited by overloaded, braided streams flowing down the aggrading piedmont slope. Mudflow deposits are intercalated with the sand and gravel lenses. Stratification is very poor and lenticular, individual beds wedging out in a few meters. Crossbedding is uncommon; however, the crossbedding in the few places where it is exposed, as well as the imbricate structure of the gravels, indicates deposition from the west or northwest.

The decision to date these sediments as Quaternary is arbitrary. They are obviously younger than the Pliocene(?) ash-flow tuffs deposits but older than the alluvial sediments now being deposited. The piedmont deposits are remnants of an earlier cycle of deposition; they have been uplifted and are now being actively eroded. In the roughly circular outcrop in the west-central part of the quadrangle, this uplift has been more than 100 meters. The possibility should also be considered that these beds could be upper Pliocene in age, their deposition commencing immediately after deposition of the ash-flow deposits and continuing until climatic changes in the Pleistocene caused a change in effective base level and erosion of the piedmont deposits.

TERRACE DEPOSITS

A well-formed terrace occurs in the San Pedro River valley at approximately 20 meters above the flood plain. The surface of the terrace is graded to the surface of the piedmont deposits near the village of San Pedro. The terrace deposits are coarse grained and poorly stratified. The clasts are mostly of rhyolite (welded tuff), andesite, basalt, and diorite, however, many of the smaller fragments are redeposited clasts from the conglomerates of the San Pedro and Purilactis Formations which are exposed in the drainage basin of the river. The clasts are subrounded to rounded and are in decided contrast to the subangular fragments of the piedmont deposits. The swiftly moving water of the river was apparently very effective in producing rapid abrasion of the clasts.

ALLUVIUM

Alluvial sediments are being deposited in all the major valleys of the area. These deposits are composed of poorly sorted gravels, sand, and clay derived almost entirely from the Tertiary and Quaternary piedmont deposits; they comprise both piedmont and stream deposits. At the mouths of the quebradas the alluvial sediments are deposited in fans that are difficult to distinguish from the piedmont deposits. In the courses of the quebradas the alluvium was deposited by rapidly flowing water during periods of rainfall. As a result, stratification and sorting is, in general, much more pronounced in the stream-deposited alluvium than in the piedmont deposits; however, mudflow deposits are also present. All the major quebradas are actively being eroded in the upper reaches, and deposition is occurring in the lower courses to compensate for the upgrading of the surface of the basin as a result of the accumulation of sediments.

Thick deposits of alluvium occur in the lower part of the Salar de Atacama and are added to during each of the infrequent floods. These floods carry large quantities of poorly sorted sediments from the mountains to the basin. The thickness of the deposits is at least 280 meters as shown by the log of well 1 (table 2).

The alluvial deposits in the Salar de Atacama contain thick beds of clay, silt, sand, and gravel; the coarser grained deposits are poorly sorted but the silt and clay beds are relatively well sorted. Thick strata of volcanic ash are also included. The ash was probably partially air dropped and partially water deposited.

EOLIAN SAND DEPOSITS

Large dunes of windblown sand occur in the lee of cliffs and ridges in the area. All these dunes are on the east or southeast side of the topographic highs and thus indicate the prevalence of westerly winds.

The sand of the dunes is medium to fine and is composed primarily of quartz phenoclasts and fragments of rhyolite derived from the ash-flow deposits. In many localities, dark areas on the lee face of the dunes indicate an eolian separation of heavy minerals (magnetite and ilmenite) from the sand.

Extensive sand sheets have accumulated in the southwestern part of the mapped area. In some localities the surface of the sheet is warped into complicated dune forms; however, most of the surface is relatively flat and has small ripples and windrows formed in the lee of small desert shrubs. The sand is fine grained and so loosely packed that it is difficult to cross some of these surfaces even in 4-wheel-drive vehicles.

Small deposits of very coarse quartz sand have been formed in the lee of the tuff hills on the west side of the Llano de Paciencia. In this area the downslope wind is funneled through the quebradas that cross the tuff and becomes an effective agent of erosion and transportation. The coarse sand deposits are common on the east side of the large tuff deposit which is located 3–5 kilometers west of where the highway crosses the Llano. Here the sand is composed almost entirely of quartz grains, 1–2 mm in diameter, which are frosted and pitted by abrasion.

BASALT FLOWS

Basalt flows of Recent age extend from the base of Volcán Licancabur westward into the San Pedro area. The basalt was deposited directly on the ash-flow deposits and flowed downslope following local surface depressions.

The basalt is porphyritic in texture and has phenocrysts of plagioclase (labradorite) ranging in size from 0.3 to 2.7 mm and of pyroxene ranging from 0.2 to 0.7 mm. The groundmass is composed of feldspar microlites and a black pigment.

The basalt occurs as a typical aa lava flow. In at least one locality the liquid tongue of the lava followed a canyon in the underlying ash-flow deposit which was not large enough to contain the entire flow, and the blocky upper fraction of the flow spilled out over the edge of the canyon creating a reversal of the topography (fig. 6).

SALT DEPOSITS

Salt, very salty silt, and clay beds have been and are being deposited in the lower part of the Salar. The salt is very impure, and the impurities cause the deposits to be light olive gray; white zones are present only where the salt has been dissolved and recrystallized. Outcrop zones of these salt beds are very irregular, the closely-spaced depressions being 15–20 cm in diameter and 10–15 cm deep. The surface is very hard because of the cementing action of the salt and is dry even where the zone of saturation is within a few feet of the

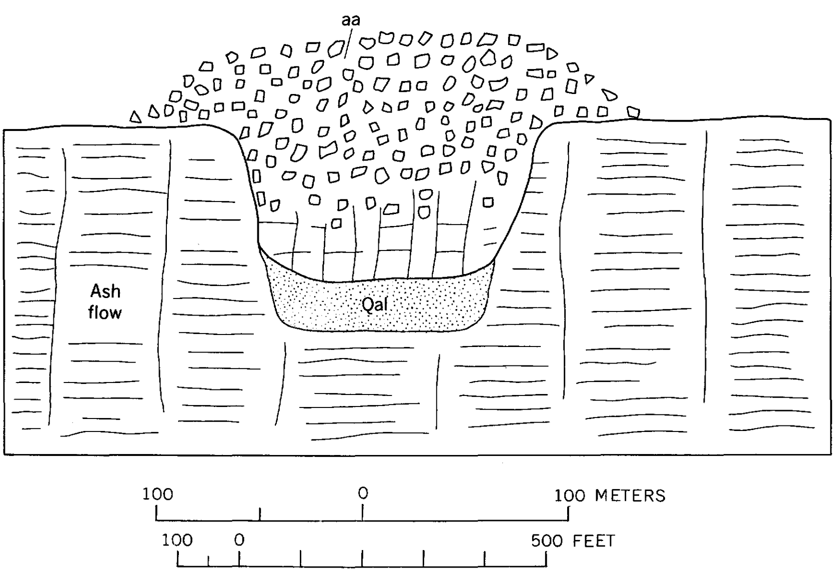

FIGURE 6.—Tongue of aa lava flow.

surface. According to the local inhabitants, this surface is very treacherous because it remains dry and hard but forms only a thin crust over the mud of the salar. An auto may be driven over the crust with ease until the surface sags, cracks, and breaks dropping the auto into the mud of the salar. The author did not venture far enough out on the salt crust to test the accuracy of these reports.

The salt is derived principally from the solution of the older salt strata of the area. Inasmuch as salt beds are present in the Jurassic, Cretaceous, and Tertiary Formations of the area, the Recent salt deposits may represent a second or third cycle of redeposition of the salt.

In contrast to the salt of the San Pedro Formation, the Recent salt is relatively impure. A typical sample is as follows:

Constituent	*Percent*
Insolubles	31.86
Sodium Chloride (NaCl)	63.14
Sulfate (SO_4)	1.95
Nitrate (NO_3)	.57
Carbonate (CO_3)	Trace
Calcium (Ca)	1.02
Magnesium (Mg)	0
Potassium (K)	.14
Total	98.68

The thickness of the salt deposits is unknown. Only the surface of the deposits is exposed, and no wells or excavations have been made in these strata. It seems reasonable, however, to assume a depth of several tens of meters, or more, for these deposits.

INTRUSIVE ROCKS

Mafic dikes less than 1 meter thick intrude the Tonel Formation and are the only intrusive rocks within the mapped area. They consist of a dark-green fine- to coarse-grained perknite (variety of hornblendite). Inasmuch as this rock is much more resistant to erosion than the sediments of the Tonel Formation, the dikes tend to be exposed along the ridges and tops of small hills where fragments of the weathered hornblendite form a dark green mantle over the slopes. The dark-green debris from the intrusive is in striking contrast with the soft grays and grayish pinks of the sedimentary rocks.

Microscopically, the hornblendite is panidiomorphic in texture. The amphibole crystals are approximately 5–10 mm in length and contain inclusions of pyroxenes, epidote, and muscovite. The groundmass is composed of crystals, 0.3–0.5 mm in length, of the same amphibole and of plagioclase, orthoclase, and probably scapolite. There is slight alteration to serpentine and to chlorite.

Dikes of a very similar rock are reported to intrude sedimentary rocks exposed near Siglia, 165 kilometers southwest of the exposures of the Tonel Formation in the Túlor quadrangle (Floreal García, oral

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commun., 1961) and also to intrude sediments exposed some 50 kilometers north of this area (Brüggen, 1950). Fragments of the hornblendite are relatively common in the conglomerates of the Purilactis Formation.

No intrusive rocks are known to penetrate the sediments of the Purilactis Formation within the limits of the area mapped by the author. Approximately 15 kilometers south of the area, dikes of unknown composition were observed to penetrate the unnamed formation which underlies (unconformably?) the Purilactis Formation and overlies unconformably the Tonel Formation.

STRUCTURE

FAULTING

Faults of regional importance are along the west boundary of the area. Three of these north-trending faults delineate the scarp along the west flank of the major syncline in the Purilactis Formation and border the exposures of the Tonel Formation. The westernmost fault of this series is so poorly exposed that the scarp at the contact of the lower member of the Purilactis Formation with the Quaternary piedmont deposits may be either a fault scarp or a faultline scarp. The exposures are not extensive enough to determine the magnitude of the relative horizontal or vertical displacement along this fault.

The faults bounding the horst in which the Tonel Formation is exposed are left-lateral strike-slip faults as indicated by the large-scale drag folds formed in the sediments of the Purilactis Formation (fig. 7) and also by the complicated folding in the relatively incompetent beds of the Tonel Formation.

The San Pedro basin is probably a graben; however, the border faults are not exposed within the area of investigation. Just to the north of the mapped area, along the west border of the basin, are exposures of a system of imbricate normal faults having a downthrown blocks toward the basin. These faults are concealed beneath the alluvium in the area that was mapped geologically and could not be located. Brüggen (1950) reported the existence of major faults along the west border of the basin farther to the south. The author was unable to locate these faults in the field; however, their existence is inferred as the southward extension of the previously mentioned imbricate fault system.

The existence of north-trending normal faults along the east side of the basin is postulated even though the exact location of these faults is problematical. The only direct evidence for these faults is the northward trend of the inliers of old rock along the southeast border of the basin. The western limit of these outcrops may represent the approxi-

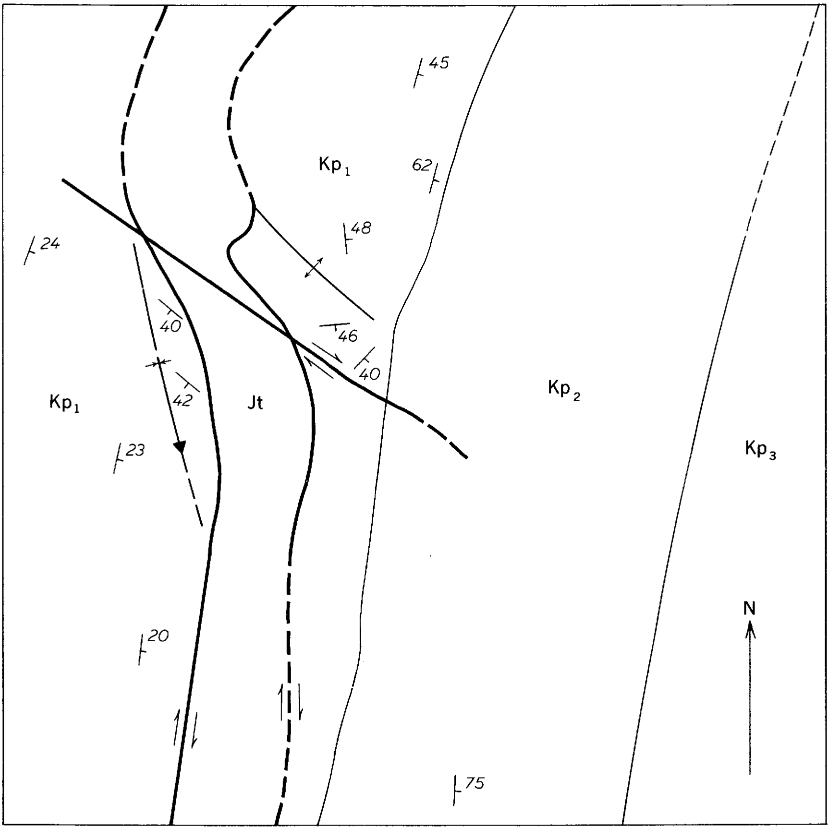

FIGURE 7—Drag folding of the Purilactis Formation, 4 kilometers north of the Túlor quadrangle. Strike-slip faults separate the Tonel Formation (Jt) and the lower (Kp_1) member of the Purilactis Formation.

mate location of at least one of the supposed faults. There is no evidence of late Tertiary movements of the east border faults, at least within the limits of the present basin. Section *A–A′* (pl. 1), based on data from wells and outcrops of the ash-flow deposits, is evidence of the smooth, unbroken westward dip of the late Tertiary volcanics. Several north-trending normal faults which form west-facing scarps 5–10 meters high are near the easternmost edge of the basin where the puna surface begins to slope rather abruptly toward the San Pedro basin. The total displacement of these faults is minor compared to the hundreds of meters of downfaulting in the basin. Most of the tectonism which formed the basin was accomplished before the deposition of the ash-flow deposits.

The normal faults which border the Cerros de la Sal are considered to be related to the origin of the salt domes and therefore are not of regional significance. These faults probably do not extend downward into the basement (Mesozoic?) rocks that underlie the basin. The vertical displacement along the easternmost of these two faults may be as much as 420 meters, as indicated by the relative position of the ash-flow beds in the Cerros de la Sal and in the deep wells drilled near the village of San Pedro. It is likely, however, that at least part of the apparent displacement is the result of the deposition of the ash flows over a preexisting topography of considerable relief. The nearly vertical faults within the Cerros de la Sal are local, shallow faults related to the upfolding of the salt domes that underlie the cerros.

The low-angle thrust faulting which occurs on both sides of the Llano de Paciencia and on the east slopes of the Cerros de la Sal are shallow features formed by horizontal stresses which occurred as a result of gravitational gliding of underlying sediments (Dingman 1963b). The ash-flow deposits are moderately to slightly welded and therefore react to compression as brittle and easily fractured beds. The fracturing that occurred in the ash flows resulted in a well formed set of conjugate joint sets intersecting at an angle of 28°–30°. The ash-flow beds in most localities are almost horizontal and the fracture planes dip from 13°–15°. Under the continued application of stress, faulting took place along one of the joint sets, usually along the joint set that dipped toward the center of the basin.

FOLDING

The Tonel Formation is folded into a complicated synclinal structure that has a north-trending fault which follows the trace of the axial plane. The syncline probably predates the uplift of the horst in which the formation is exposed. Relatively small folds having nearly vertical axial planes that intersect the axial plane of the major fold at high angles have been formed on the west flank of the syncline. These minor folds were probably a result of drag related to the strike-slip movement of the faults that bound the horst. On the east flank of the syncline, the stress that resulted from the horizontal movement along the eastern boundary fault produced a series of faults that almost form a conjugate system with the axial planes of the minor folds on the west flank of the syncline. The structure of the Tonel Formation becomes extremely complicated in the zone within 200-meters of the faults that border the horst. The effect of drag folding in these areas was intense and produced very tight folds, including recumbent and overturned anticlines.

A small diapiric salt dome is exposed in the eastermost outcrops of the Tonel Formation. In this outcrop area, a domal structure having nearly vertical bedding surrounds a plug of salt that has flowed upward, distorting and penetrating the overlying strata. The salt core contains fragments of rock that are typical of the Tonel Formation as well as fragments of the dark-green perknite that intrudes the Tonel Formation. The lack of older sediments in the salt core suggests that the salt which flowed to produce the dome is one of the lower, unexposed strata of the Tonel Formation. The lower member of the Purilactis Formation is also arched upward in the exposures just north of the salt dome, and this arching indicates that the diapiric movement continued after the emplacement of the horst.

The Purilactis Formation is exposed in an extensive flat-bottomed syncline in the northwestern part of the area. Steep dips occur along the flanks of the syncline and produce a continuous exposure of 3,700 meters of the three members of the formation. The axis of the syncline strikes N. 25° E. The syncline is doubly plunging and has closure both to the north and south. A small anticline is on the east flank of the syncline.

The series of small tight folds that cross the lower part of Quebrada Tambores is a narrow anticlinorium. Near the quebrada the anticlines are slightly overturned; however, in the next quebrada to the north the flanks of the folds are nearly vertical but are not overturned.

The salt domes and synclines that underlie the Cerros de la Sal were formed as a result of gravitational gliding of the unconsolidated sediments of the San Pedro Formation toward the center of the basin (Dingman, 1962). The horizontal forces produced by the gliding caused the upfolding of the domes but relatively little distortion of the sediments involved. Diapiric flow or intrusive action of the salt was probably relatively unimportant. The preservation of bedding within the salt cores, the complete lack of fragments of older rock, and the lack of clastic sediments of the San Pedro Formation within the salt cores of the domes are considered to be strong arguments against large scale flowage of the salt strata involved in the formation of the domes.

The gentle westward homoclinal dip of the ash-flow beds and associated sediments is considered to be depositional and does not represent folding.

GEOLOGIC HISTORY

The known geologic history of the area begins with the deposition of the Jurassic sediments. Only a few scattered bits of evidence indicate the earlier history of this area or that of the whole of northern Chile. Marine sediments of Ordovician age have been identified at the Aguada de Perdiz, 150 kilometers southwest of San Pedro (Pérez and García, 1962), and sediments of Pennsylvanian age have been described by Galli (1956) from a locality near Cerro Juan de Morales some 400 kilometers to the north of the area. The Triassic(?) sediments and extrusive rocks exposed along the east border of the Salar de Atacama represent an undeciphered chapter of the geologic history of the area. The age of these rocks is not known with any certainty, and, in reality, several periods of deposition are probably indicated by at least two angular unconformaties in the section northeast of Peine. Owing to the advanced metamorphism of the rocks and to their highly weathered condition, very little could be determined concerning the environment which prevailed at the time of their deposition. It is probable that both marine and continental sediments are included in the exposed sequence of rocks. The scattered rhyolitic and andesitic lava beds in the sequence indicate that volcanic activity was common throughout the period or periods represented by these rocks.

Fossiliferous marine sediments of Lower Jurassic (Liassic) age are exposed in several areas in northern Chile. The nearest of these exposures to the San Pedro area is approximately 40 kilometers to the west at Cerros Limón Verde. In this locality the Liassic sediments were deposited on an eroded surface of Paleozoic granitic rock (Pérez, and Levi, 1961). It is strictly a matter of conjecture as to whether marine sediments underlie the San Pedro area; however, the exposures of older marine sediments of several ages, both to the east and west, would indicate that there is a reasonable possibility that one or more of these sequences might extend under the area.

The Jurassic sediments of the Tonel Formation were deposited in an arid climate and probably as continental sediments in an area of low topographic relief. The evaporite beds in the formation are evidence of deposition either in a closed basin or in a shallow coastal lagoon. Eolian crossbedding in some of the fine-grained sandstones and "dust ripples" in some of the siltstones, as well as fossil mud cracks are further evidence of deposition in an arid climate. There is scattered evidence that deposition may have occurred from a source area to the west but the evidence is inadequate to make a definite statement to this effect.

The Jurassic Period closed with a major orogeny throughout northern Chile as indicated in all the areas where the relationship of the Jurassic and the overlying Cretaceous beds can be clearly determined. In the San Pedro area the contact between Jurassic and Cretaceous is by faulting. The complexity of the folding in the Tonel Formation as compared to that of the Purilactis Formation is probably due, at least in part, to orogenic folding of the Tonel Formation prior to the deposition of the Cretaceous sediments and presumably at or near the end of the Jurassic.

The orogeny at the close of the Jurassic apparently created a highland or mountainous area to the west of San Pedro, probably a north-trending range, in the general vicinity of Calama. Exposures of

Paleozoic granites and Liassic rocks in this vicinity may be the roots of a Cretaceous mountain chain. The tremendous thickness of sediments of the Purilactis Formation was caused by deposition from a source area to the west and northwest. Hundreds of clear exposures of cross-bedding, the imbricate structure of the clasts, and a general reduction in grain size from west to east all confirm the direction of deposition. The Purilactis Formation contains clasts that have Liassic fossils of the same suite as those of Limón Verde and that are contained in rock fragments of similar lithology. Clasts of perknite identical with intrusive hornblendite found in the Tonel Formation are also included in the middle and upper members of the Purilactis Formation.

The rather abrupt change from the medium- to coarse-grained sandstones of the lower member of the Purilactis Formation to the shale, siltstone, and evaporite sequence of the middle member of the formation probably indicates tectonic activity which caused a reduction in the relative altitude between the basin of sedimentation and the source area of the sediments. The reddish beds of the middle member, the fine-grained clastic sediments, and the intercalated evaporites are evidence of the deposition of the formation in a closed basin under arid continental conditions.

The coarse-grained sediments of the upper member of the formation are lithologically very similar to the piedmont (fanglomerate) deposits now being laid down in the San Pedro basin, and therefore similar climatic and topographic conditions may be assumed to have existed at the time of deposition of the two sediments. The increase in grain size of the clastic sediments from the middle to the upper member indicates an uplift or rejuvenation of the source area. The one andesitic flow interbedded in the thick sequence of sediments of the upper member probably records a single brief period of volcanism as volcanic strata and volcanic ash are entirely missing from the rest of the formation.

In other parts of northern Chile the Cretaceous Period closed with a period of strong orogeny and the San Pedro area was no exception. The great syncline of the Purilactis was formed at this time as well as the upthrusting of the horst in which the Tonel Formation is now exposed. The downwarping and block faulting which began the formation of the San Pedro basin also occurred, or at least began, at this time.

The Tertiary Period was characterized by the deposition of continental sediments in closed basins under extremely arid climatic conditions. As the thick mantle of clastic sediments and evaporites accumulated in the basin further downwarping occurred, probably as a result of isostatic adjustment to the ever-increasing sedimentary load. The amount of relative downwarp was greatest under the area of the greatest load of sediments which also corresponded to the area where the finest sediments and the evaporate deposits were thickest. The differential downwarping tilted the beds of the San Pedro Formation producing ideal conditions for gravitational gliding, as the thick mass of sediments and intercalated evaporites were tilted into a relatively unstable position. It is possible that movement along north-trending faults under the basin acted as a trigger to initiate the folding and faulting that accompanied the formation of the domes, anticlines, and synclines that underlie the Cerros de la Sal; however, this trigger is not considered to be necessary for the formation of these structural features. The deposition of the basin-type sediments of the Tertiary was interrupted by several short periods of explosive volcanic activity. The ash-flow deposits of the Pliocene were deposited in a geologic instant from glowing avalanches and clouds that crossed the landscape at speeds of many kilometers per hour. After deposition of the ash-flow deposits, the cycle of sedimentation was resumed with little change except for the increase in volcanic ash in the sediments as a result of the sudden availability of tremendous quantities of ash and tuff.

The formation of the folded structures of the Cerros de la Sal was seemingly intermittent in nature as periods of active construction alternated with long intervals of relative quiet while the topographic highs, which resulted from the upward movement of the sediments, were eroded into a predominantly smooth plain. The truncated structures resulting from these periods of planation may be seen where shallow water courses cut through the veneer of Quaternary alluvium adjacent to, but outside of, the limits of the present range of hills. The formation of the structures was not interrupted by the deposition of the ash flows.

The origin of the San Pedro basin was not related to the Pliocene volcanism; indeed, the basin existed throughout most of the Tertiary prior to the volcanism and was sufficiently deep to permit the deposition of at least 2,100 meters of sediments before the Pliocene. There is no indication of deepening of the basin during or after the deposition of the pyroclastic rocks and no evidence of any major structural changes in the area after deposition of the ash-flow deposits.

The increased precipitation of the Pleistocene Period apparently had little effect in the San Pedro basin. No evidence of higher lake levels in the basin were noted by the author either in the field or after careful appraisal of the aerial photographs. In smaller closed basins in northern Chile strand lines, beach gravels, and small wave-cut scarps testify to lake levels during the Pleistocene that were as much as 20 meters higher than those of present lakes. Such indications of higher water levels are typical in the Salar de Guasco in the Andes east of Pica and some 350 kilometers north of San Pedro.

The entire geologic history of the San Pedro area from the Upper Jurassic to the Recent is that of relatively continuous deposition of continental sediments under arid conditions in closed basins. In short, the historical record indicates that conditions very similar to those of the modern desert extend all the way back to the Jurassic.

MINERALS

COPPER

A small abandoned copper mine is on the east border fault of the Cerros de la Sal approximately 6 kilometers west of San Pedro. The mine has not been worked for several years, and all the buildings and equipment have been removed.

The ore body is localized in the fault zone and in the overlying piedmont terrace gravels (fig. 8). The copper-bearing mineral atacamite is associated with aragonite as a coating on the clasts of the conglomerate and as a fissure filling between the fragments of rock in the fault breccia. The mineralizing solutions were carried upward along the fault by cold ground water. Where the water reached the relatively permeable beds of the piedmont deposits, it moved laterally to form horizontal mineralized zones in the conglomerates. The mineralization occurred after the faulting, after the piedmont deposition, and, inasmuch as the conglomerate contains clasts of welded tuff, after the deposition of the ash flows.

SALT

Salt has been mined from three localities in the Cerros de la Sal. At the time of this investigation, the largest mine, which is in the large dome near the west border of the cerros, was not in operation. At this mine, a circular shaft 5–7 meters in diameter had been sunk 20–30 meters. A horizontal excavation ranging from 5 to 15 meters deep, 10 meters wide, and approximately 200 meters long had also been dug. The salt of the wallrock at this locality contains as much as 5 percent clay and silt as impurities, and only the lenses and pods of very pure salt are mined. The chemical analyses of the salt show that, except for the insolubles, it is almost pure sodium chloride. (See the analyses of salt from the San Pedro Formation, p. 15.)

The other two mines were being worked by very primitive methods using pick, shovel, and wheelbarrow, and production was very small. Two or three men were employed at the northernmost of the two mines and approximately six at the southern mine.

Salt with less than 2 percent insoluble material is scarce in the San Pedro Formation, and no large bodies of pure salt were observed dur-

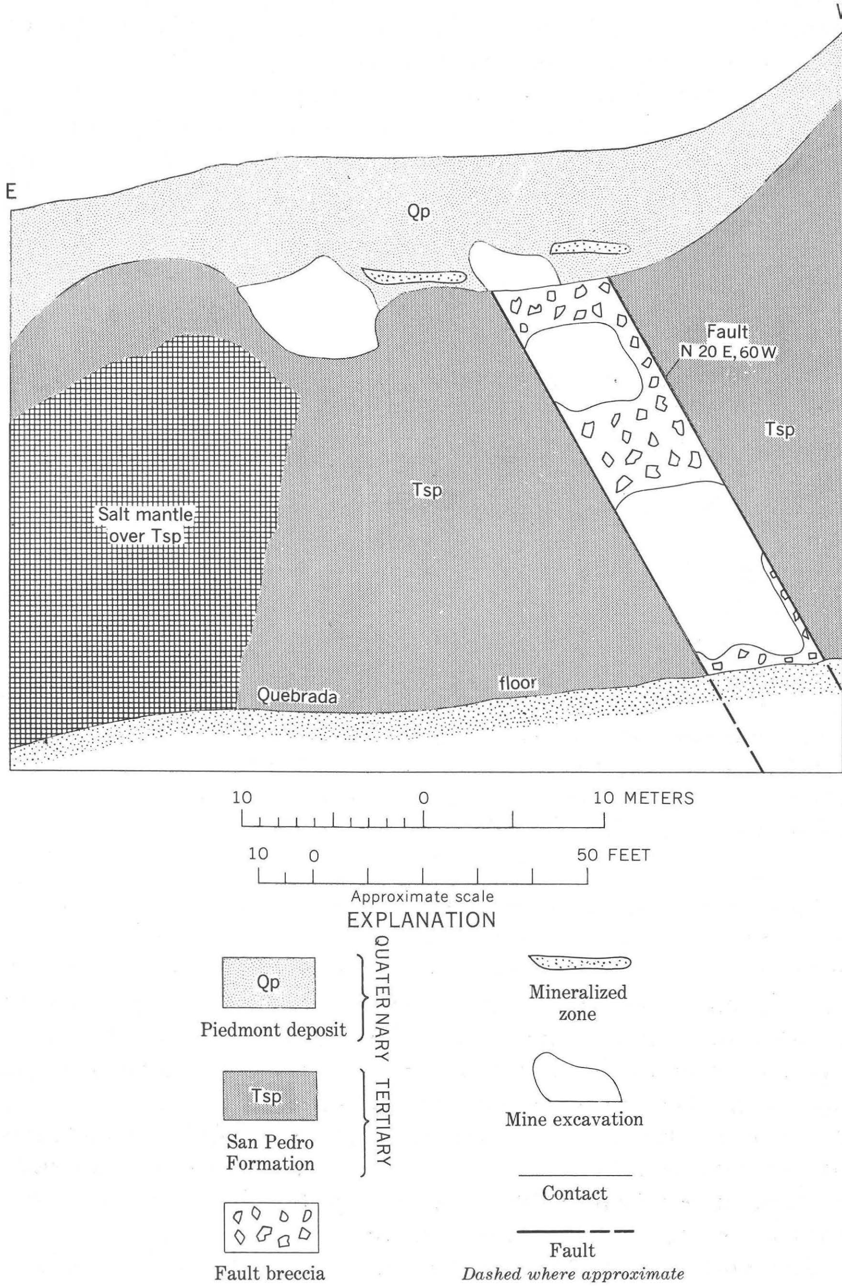

FIGURE 8.—Surface workings of the copper mine in the Cerros de la Sal near San Pedro de Atacama.

ing the geologic mapping. The salt reserves of more than 90 percent pure sodium chloride are tremendous, probably on the order of many billions of cubic meters.

The salt deposits of the Tonel, Purilactis, and the Recent deposits in the modern salt flats are all considerably less pure than those of the San Pedro Formation and probably are not worthy of investigation as a source of commercial sodium chloride.

There is an excellent possibility that other salts of commercial value occur in the Recent salt deposits. The principal source of the Recent salt deposits is from the crystallization of the residue remaining after the evaporation of water from the salt lake and from the shallow water-table aquifer. Most of the water in both the lake and water-table aquifer is derived from upward leakage of the water from the artesian aquifer. The salt deposits must, therefore, contain in some combination all the elements contained as dissolved solids in the ground water. Commercial deposits of borate minerals have been found in other closed basins in northern Chile; and in view of the high boron content of the ground water, it is very likely that borate deposits occur also in the Salar de Atacama.

GROUND-WATER RESOURCES

The basin occupied by the Salar de Atacama is underlain by artesian and water-table aquifers capable of yielding large quantities of water from flowing wells or from pumped wells that have shallow pumping levels. There are two separate aquifer systems in the San Pedro area. The upper aquifer is relatively shallow and contains water under unconfined or water-table conditions. The depth to water ranges from land surface, near the salt lake in the south-central part of the basin, to as much as 16 meters in dug wells near San Pedro. The unconfined aquifer is recharged by the San Pedro and Vilama Rivers whose waters disappear a few kilometers after the rivers emerge from the Cerros de la Sal; by return flow from irrigation (used water from the two rivers); by flood waters from occasional heavy rains in the surrounding highlands; and by upward leakage from the artesian aquifer. A few dug wells in the small villages surrounding San Pedro supply brackish water for domestic use and for the irrigation of a few tens of square meters of garden crops.

The shallow aquifer was not tested during the drilling of the deep wells in the basin as the driller reported the water to be salty to the taste. This aquifer was penetrated by wells 1 and 2 (table 3) at a depth of 21–26 meters. The aquifer is composed of fine to medium gravel and coarse to medium sand and, from the aspect of the drillers samples, should be capable of yielding several liters per second to properly constructed wells.

TABLE 3.—*Records of wells in the San Pedro area*

[Remarks: F, flows; B, bucket; W, windlass; N, none; Ir, irrigation; D, domestic; Dr, drilled; Du, dug; lps, liters per second. All wells are in alluvial valleys]

Well	Location	Owner	Driller	Date completed	Depth of well (meters)	Diameter of well (inches)	Principal water-bearing bed: Depth to top of bed (meters)	Principal water-bearing bed: Thickness (meters)	Principal water-bearing bed: Character of material	Depth to which well is cased (meters)	Water level: Above (+) or below (−) land-surface datum (meters)	Water level: Date of measurement	Temperature °C	Remarks
Exploration wells														
1	Lat 22°52′ S., long 68°12′ W.	Corporación de Fomento de la Producción.	Sección de Aguas Subterraneas de la CORFO.	1957	575	12–10	267.5	4.0	Gravel and fine sand.	273.0				Dr, F, N.
2	Lat. 22°51′ S., long 68°11′ W.	do	do	1957	264	12–10	254.0	5.3	Sand and fine gravel.	263.8			21.4	Dr, F, N; yield 40 lps in 1957.
3	Lat 22°51′ S., long 68°10′ W.	do	do	1957	220.2	16–10	202.0	18.2	Gravel and sand.	220.1	+15.22	9–17–58		Drawdown was 19.0 meters for 136 hour test. Yield 100 lps 9–12–58; Dr, Ir.
4	Lat 22°51′ S., long 68°08′ W.	do	do	1958	196.4	16–10								Casing removed and well abandoned; marked by stake; Dr.

5		do	do	Aug. 1958	303.2	12- 8	294.4	3.2	Gravel and sand.	303.2	+7.20	9- 7-58	30.7	Dr, F, N.
6		do	do	June 1959	246.5	12-10	205.8	6.9	Sand and gravel.	216.7			28.0	Dr, F.
Dug, domestic wells														
7	Túlor	Sebastián Avan Mamani.			12.0	40×200			Clay, silt, and sand.		−9.30	10- 6-62		Du, B, W, D Ir.
8	Túlor	Esteban Mamani Morales.			10.26	26×40			do		−9.86	10- 6-62		Du, B, W, D, Ir.
9	Coyo	Juan Romolo Agüero.			16.0	28×48			Sand and gravel.		−15.78	10- 6-62		Du, B, W, D, Ir.
10	Coyo	Fermín Reyes Mamani.			17.05	28×45			Clay and gravel.		−16.10	10- 6-62		Du, B, W, D, Ir.

The artesian aquifer system is recharged almost entirely by the rainfall that occurs on the Puna de Atacama (high plateau). This plateau extends eastward from the Salar de Atacama to the Argentine border. The average altitude of the puna is more than 4,000 meters above sea level. There are no stations reporting meteorological data on the puna; however, on the basis of the vegetation, it is likely that precipitation is the 200–300 mm per year typical for other regions of this altitude in northern Chile (Almeyda, 1949). Most of the precipitation at high altitudes in the desert occurs as short violent rain showers. In the zone immediately east of the Salar de Atacama, the water from these rains is drained off rapidly by the deep quebradas and is discharged as surface floods on the aluvial slopes of the basin. Farther east the surface of the puna is physiographically one of extreme youth, and the drainage is internal in the large shallow basins that contain ephemeral shallow lakes. Except for a few Recent volcanic cones of andesite or basalt and a few windows of older rock, such as those at Siglia and at the Aguada de la Perdiz, the surface of the puna is immediately underlain by thick deposits of ash flows. The ash flows in most localities are slightly welded, have very high porosity, moderate permeability, and thus are capable of absorbing much of the precipitation that falls as rain. In the localities where the upper tuff is dense and thoroughly welded, it has a strongly formed set of vertical joints that were probably created as tension fractures during the cooling of the tuffs. These joints are sufficiently open to permit the downward percolation of water.

The water that moves downward through the tuffs becomes, in part, recharge to the ground-water reservoir. In the uplands the ground water probably exists under unconfined conditions. The ground water moves westward downslope from the areas of recharge to enter the San Pedro basin from the east through the coarse clastic sediments that overlie the thick Pliocene densely welded rhyolitic tuff (pl. 1). The permeable clastic sediments of the aquifer are overlain by a thick sequence of silts and clays which have interbedded ash-flow deposits and beds of water-laid ash. Artesian pressure is created as the water moves downslope in the permeable beds between the welded tuff and the clay-silt sequence.

The San Pedro basin was a virgin artesian aquifer system prior to the drilling of the first test wells in 1957. The gradient of the piezometric surface, approximately 2 meters per kilometer, indicates that there was natural discharge from the system in its pristine condition. The small springs at Toconce west of the road to Toconao probably derive their water from the artesian system, but the quantity of water discharged to the surface is too small to have any appreciable effect on the piezometric surface. The discharge of the aquifer in the natural state must have been by a general upward seepage through the overlying confining bed so that the discharge became part of the water-table system and eventually moved laterally to the lowest parts of the basin where the water table intercepts the surface. In this part of the basin large salt lakes exist, and the water is returned to the atmosphere by evaporation. Large areas of the lower parts of the basin are covered by salt-tolerant vegetation, and large quantities of water are lost to the air through evapotranspiration.

Galli (1954) made the first scientific appraisal of the ground-water potential of the area and recommended that exploration wells be drilled to determine the subsurface geologic and hydrologic conditions of the area. In 1956 the author, accompanied by Carlos Galli and engineers of the Ground Water Section of CORFO, placed the first of six exploration wells. This well (well 1, pl. 1) was drilled to a depth of 585 meters, and a good aquifer was penetrated above the welded tuff at 267.5–271.5 meters. Well 2 was drilled simultaneously 500 meters to the northeast, and several performance tests were conducted to determine the hydraulic coefficients of the aquifer. The average of the tests as analyzed by the Thies nonequilibrium method indicated a transmissibility (*T*) of approximately 14,000 gallons per day per foot (1.92 liters per second per meter) and a storage coefficient (*S*) of 1×10^{-4}.

The water contained approximately 2,500 ppm (parts per million) of dissolved solids, which the CORFO agronomists considered as relatively high but usable in the sandy soil of the area. The boron content, however, was 14 ppm which is approximately five times the usually accepted limit for irrigation. In view of the high boron content of the first two wells, wells 3 and 4 were located approximately 3 and 7 kilometers farther east (fig. 9) on the theory that the boron, as well as the other salts) might have its origin in old salar deposits and that wells drilled nearer the borders of the basin might obtain water of better quality. The quality of water in wells 3 and 4 was actually very similar to that of the first two wells; so, this theory was disproved. The conclusion is reached that the water throughout the artesian aquifer in this area is probably of similar quality.

When first drilled, well 3 yielded a flow of 1,160 gallons per minute (70 l per sec) and had an artesian head of 42.9 feet (13 m) above land surface. Wells 5 and 6 were drilled as offset wells to well 3.

Additional tests were performed using wells 3 and 5 as pumping wells and the remaining four wells of the field as test wells. The validity of the figure for transmissibility (*T*) was confirmed; however, the storage coefficient (*S*) could not be calculated owing to a time lag

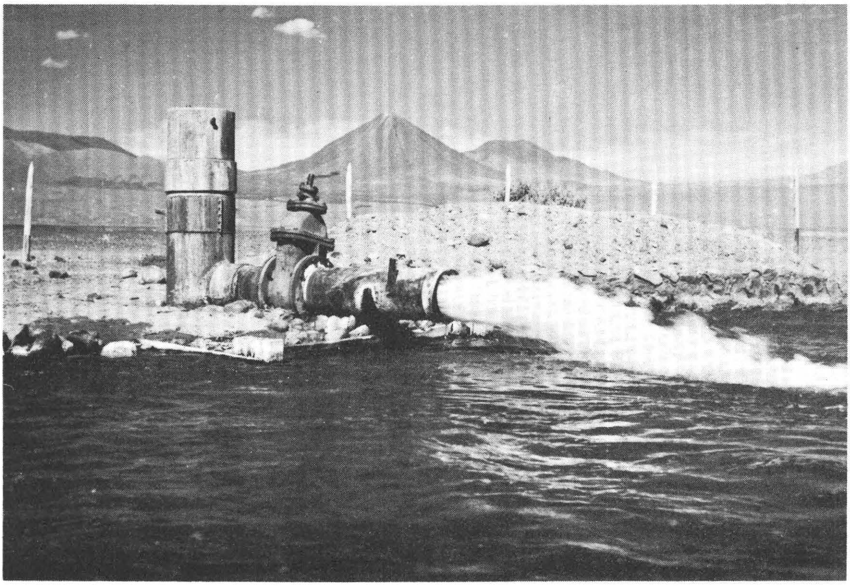

FIGURE 9.—Well 3, in the foreground, flows 70 liters per second. Volcán Licancabur, in the background, is 3,000 meters above the locality from which this photograph was taken.

of as much as 1,000 minutes between the time pumping commenced and the time the effect reached the observation wells.

After the exploration well-drilling program was terminated, CORFO agronomists reported that the water was unfit for irrigation use. Approximately 5 hectares, however, was irrigated by local farmers during the summer of 1961, and the results were reported to be satisfactory. As shown in table 4, the well water is of the same type as that of the Río San Pedro which has been used for irrigation for hundreds of years. The dissolved solids are approximately 50 percent higher in the well water (ranging from 1,910 to 3,380 ppm as compared to the approximately 1,600 ppm concentration in the Río San Pedro). The mineral content of water from the Pleistocene aquifer is remarkably similar to that of the water from the San Pedro and Vilama Rivers. The Stiff diagrams (Stiff, 1951) shown in figure 10 are a rapid means of demonstrating the similarity of the chemical content of water samples. The water from the rivers is slightly lower in concentration of chloride but in other respects is nearly identical with the water from wells 1 and 3. The similarity of the water from the surface and ground-water sources is further demonstrated by the very close grouping of the analyses when plotted on a Piper diagram (Piper, 1944), as shown in figure 11. The points on this diagram represent per-

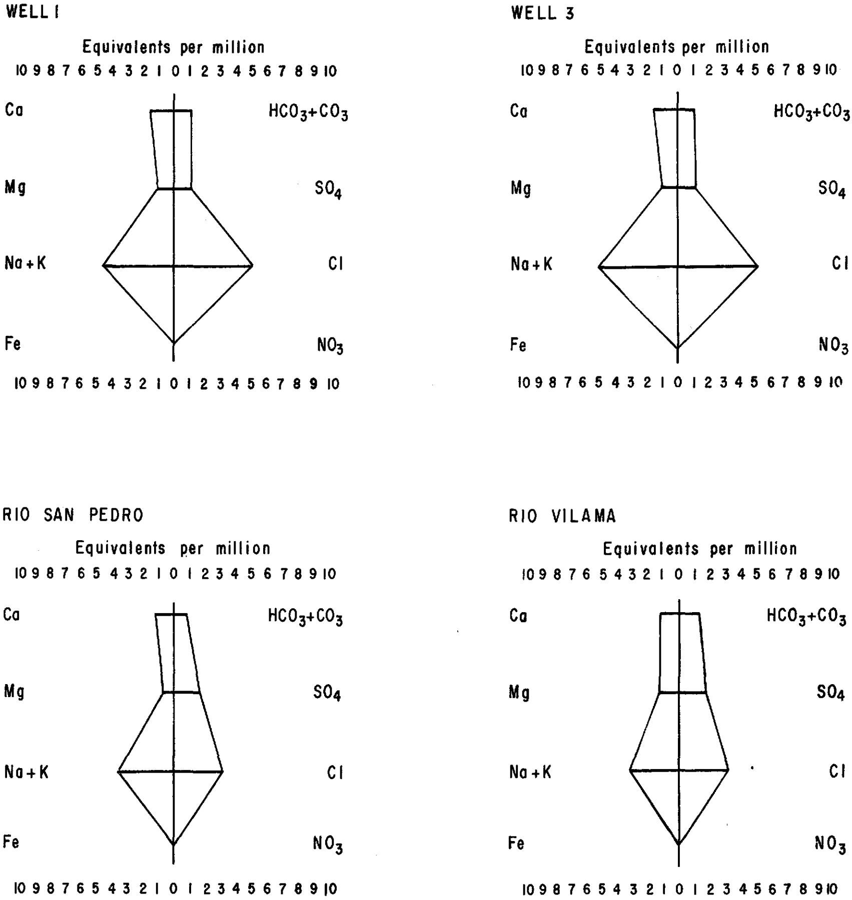

FIGURE 10.—Stiff diagrams of chemical analyses of selected water samples from the San Pedro area.

cent reacting values so that the effect of concentration of the mineral constituents is eliminated. Therefore, if the water in a river is diluted by the addition of relatively pure rain water, there will be little or no shift of the plot of the analysis on the Piper diagram. The results of plotting the analyses indicate that the surface water is almost identical chemically to the water from the major aquifer in the San Pedro basin. The low flow of the rivers is maintained by springs that flow from unconsolidated rocks and ash-flow deposits of Pliocene to Recent age. These rocks are of the same geologic unit that was penetrated in the deep wells of the area. The similarity in composition of the surface and ground water indicates that the quality of the water from the aquifer probably has little variation regionally.

TABLE 4.—*Chemical analyses of water from typical*

[Results in parts per million except as indicated. All analyses by Institutde

Location	Date of collection	Silica (SiO_2)	Iron (Fe)	Calcium (Ca)	Magnesium (Mg)	Sodium (Na)	Potassium (K)	Bicarbonate (HCO_3)	Sulfate (SO_4)
San Pedro well 1	1956	77	-----	146	63	532	56	296	296
	6-14-56	-----	-----	-----	-----	-----	-----	-----	539
	4-17-59	-----	-----	-----	-----	-----	-----	-----	-----
San Pedro well 2	11-5-56	-----	-----	-----	-----	-----	-----	-----	-----
San Pedro well 3	1957	80	-----	142	62	547	51	267	293
	3- -58	-----	-----	-----	-----	-----	-----	-----	-----
	9-7-58	-----	-----	-----	-----	-----	-----	-----	-----
	9-8-58	-----	-----	-----	-----	-----	-----	-----	-----
	9-9-58	-----	-----	-----	-----	-----	-----	-----	-----
	9-12-58	-----	-----	-----	-----	-----	-----	-----	-----
	11-26-58	-----	-----	-----	-----	-----	-----	-----	-----
	4-16-59	-----	-----	-----	-----	-----	-----	-----	-----
	8-24-59	70	-----	200	15	538	63	264	251
	8-30-59	70	-----	199	15	538	64	259	253
	1963	102	0	137	58	545	46	266	264
	10-19-63	112	0	160	54	690	59	290	280
	1963	103	0.08	136	54	546	47	266	266
San Pedro well 5	12-22-58	-----	-----	-----	-----	-----	-----	-----	-----
	4-17-59	-----	-----	-----	-----	-----	-----	-----	-----
	9-3-59	80	-----	214	32	640	75	303	294
	10-19-63	102	.01	137	54	544	48	265	262
San Pedro well 6	4-16-59	-----	-----	-----	-----	-----	-----	-----	-----
Río San Pedro	2-16-47	-----	-----	65	39	321	-----	128	296
	1963	81	.25	115	33	415	15	170	338
	1963	77	0	106	31	376	14	175	306
	1963	75	.01	111	29	395	14	174	312
Río Vilama	2-17-47	-----	-----	71	59	337	-----	207	354
	1963	106	1.0	102	54	341	32	388	208

wells and streams in the San Pedro de Atacama area

Investigaćiones Geológicas except as indicated in remarks column]

Chloride (Cl)	Boron (B)	Nitrate (NO_3)	Dissolved solids (residue at 103° C)	Hardness as $CaCO_3$ Calcium, magnesium	Hardness as $CaCO_3$ Noncarbonate	Specific conductance (micromhos at 25° C)	pH	Remarks
920	------	0	2, 550	242	382	------	6. 6	Lower aquifer.
1, 030	3. 0	-----	3, 380	------	------	------	7. 2	Aquifer from 33.5 to 37.5 m.
------	6. 6	-----	1, 910	------	------	------	------	Lower aquifer
------	17. 5	-----	2, 389	------	------	------	------	
930	11. 2	0	2, 300	235	375	------	7. 15	
------	15. 3	-----	------	------	------	------	------	
------	15. 8	-----	2, 532	------	------	------	------	
------	15. 7	-----	2, 474	------	------	------	------	Pumped 1 day
------	15. 8	-----	2, 424	------	------	------	------	Pumped 2 days
------	15. 8	-----	2, 422	------	------	------	------	Pumped 5 days
------	14. 0	-----	2, 460	------	------	------	------	
------	16. 6	-----	2, 550	------	------	------	------	
939	14. 2	9. 0	2, 300	216	345	------	------	Temp 81.5°F.
943	14. 2	4. 0	2, 300	212	349	------	7. 16	Sampled after 128 hr of pumping 100 l per sec; temp 81.5°F.
955	16. 0	0	2, 250	218	362	3, 710	------	Analyst, U.S. Geol. Survey.
1, 180	20. 0	0. 1	2, 700	238	382	4, 450	------	Do.
935	16. 0	0. 4	2, 230	218	342	3, 720	------	Do.
------	17. 3	-----	2, 926	------	------	------	------	
------	18. 4	-----	3, 050	------	------	------	------	
1, 134	17. 8	-----	2, 720	248	415	------	7. 21	Temp 84.0°F.
935	16. 0	0. 1	2, 230	217	348	3, 720	------	Temp 86.0°F.; analyst, U.S. Geol. Survey.
------	12. 5	-----	2, 620	------	------	------	------	
473	------	-----	1, 308	------	------	------	------	Analyst not known.
605	1. 5	0. 1	1, 690	146	276	2, 760	------	Analyst, U.S. Geol. Survey.
555	1. 4	0. 1	1, 550	144	248	2, 540	------	Collected from irrigation canal; analyst, U.S. Geol. Survey.
575	1. 4	0	1, 600	142	256	2, 590	------	Do.
500	------	-----	1, 408	------	------	------	------	Analyst not known.
515	8. 7	1. 1	1, 560	318	160	2, 530	------	Analyst, U.S. Geol. Survey.

Boron may be a more serious problem than the concentration of dissolved solids. The water from the drilled wells averaged approximately 14 ppm of boron as compared to 1.4 ppm of boron in the river water. The upper limit for boron-tolerant plants, such as alfalfa, is usually considered to be 3 ppm; however, boron-fixing ions in the soil may permit use of water with relatively high boron content for an extended period.

Water containing 22 ppm of boron was successfuly used for irrigation at Baquidano in the Pampa del Tamarugal for approximately 10 years before general salting of the soil made further irrigation impractical.

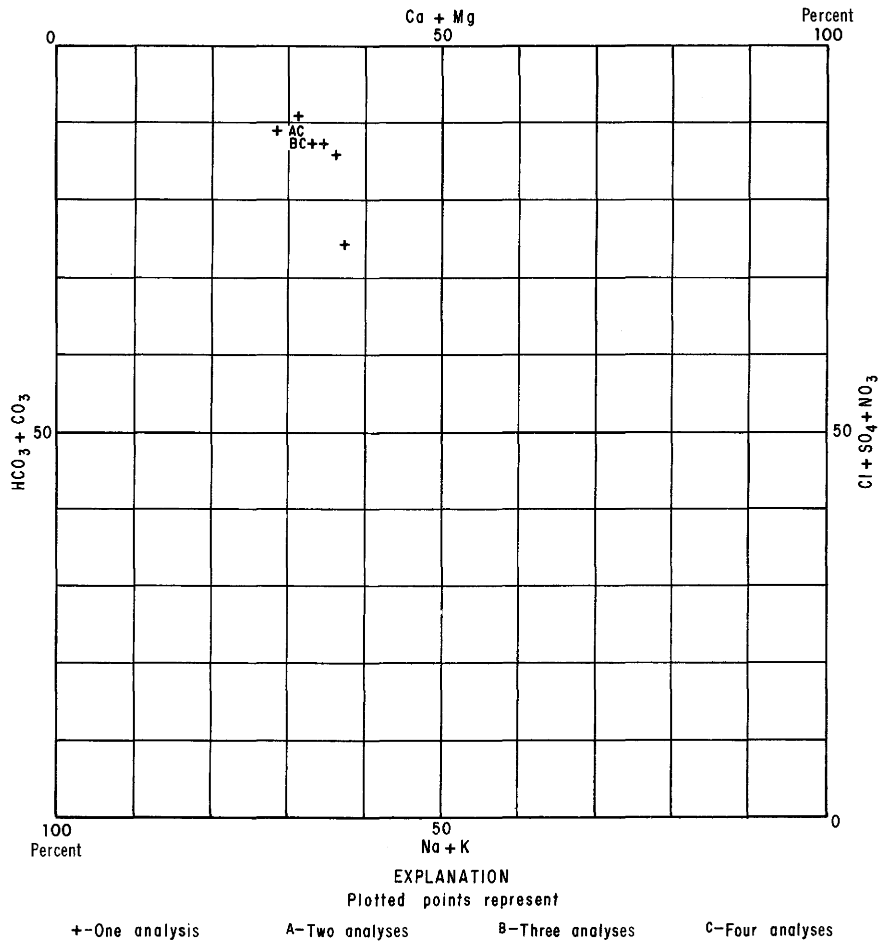

Figure 11.—Piper diagram of percent reacting values for chemical analyses of 15 water samples from the San Pedro area.

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