Geology of Salars in Northern Chile

GEOLOGICAL SURVEY PROFESSIONAL PAPER 811

Prepared in cooperation with the
Instituto de Investigaciones
Geológicas de Chile

U.S. DEPARTMENT OF THE INTERIOR
MARCH 3, 1849

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By GEORGE E. STOERTZ *and* GEORGE E. ERICKSEN

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Description of the distribution, geology, and environmental setting of salt-encrusted playas and their closed drainage basins in Atacama, Antofagasta, and Tarapacá Provinces

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GEOLOGY OF SALARS IN NORTHERN CHILE

By George E. Stoertz and George E. Ericksen

ABSTRACT

Northern Chile, which includes the extremely arid Atacama Desert and the semiarid Andean Highlands, has more than 100 basins with interior drainage; most contain salars (salt-encrusted playas). The area of interior drainage totals more than 38,000 square miles, within which salars and clay playas extend over a total area of about 2,800 square miles. In addition, hills and valleys in the Atacama Desert are extensively covered either with a thin hard saline crust, chiefly salt-cemented soil, or with a powdery soil that has a high content of saline material, chiefly anhydrite and gypsum.

The region has an exceptional variety of types of hard saline crusts that are generally rare in other deserts, and many morphological and structural salt features, some of which may be unique. Soft saline crusts and clay playas, more characteristic of arid regions elsewhere, are also present. Hard salar crusts have formed by deposition of saline material in open water or by capillary migration and evaporation of near-surface ground water. Such crusts generally range from a few inches to several feet in thickness. Locally, crusts may attain thicknesses of several tens of feet, and one salar, Salar Grande, is a basin filled with high-purity rock salt to a local depth of at least 560 feet.

Six general types of hard salar crusts are distinguished: (1) layered massive rock salt with a rugged surface, (2) slabby or nodular silty rock salt, (3) rugged gypsum or anhydrite, (4) massive coarsely crystalline rock salt, (5) smooth rock salt, and (6) silty nitrate-bearing saline crust. Soft surfaces or crusts include moist gypsum-bearing crusts, which commonly contain nodules and layers of ulexite in Andean salars, and moist to dry puffy soils and crusts that contain gypsum, thenardite and mirabilite as the principal saline constituents. An unusual chemical feature of the salars and the desert soils of northern Chile is the general paucity of carbonate minerals (for example, trona, calcite, and aragonite) which are widespread in other desert regions.

Among the many morphological and structural features that can be recognized in and near salars of northern Chile, the most unusual occur in hard rock-salt crusts, which in themselves are scarce in other arid regions. Included are features due to corrosion of rock-salt crusts by windblown water or free-flowing surface water, such as: (1) salt cusps and crenulate margins of salars, (2) salt channels, (3) salt pseudobarchans, and (4) salt tubes. Constructional features in the salars include: (1) gypsum buttresses at borders of saline ponds, (2) salt veins, (3) salt stalactites, and (4) salt cones. In some salars, new fresh-water springs have formed steep-walled brine pools in thick rock-salt crusts. Prominent salt cascades and constructional salt terraces have been built up in one Andean valley by springs that are fed by brine from a nearby salar (Salar de Pedernales). Sag basins and prominent scarps occur along faults that cut through the salt mass of Salar Grande.

Of the 67 closed basins in the Andean Highlands of northern Chile, at least 35 show shorelines or deltas of former perennial lakes. Today only five perennial lakes occur in this area. The former lakes probably formed at one or more times during the Pleistocene and perhaps continued to form into Holocene time. They indicate a climate that was either more rainy or cooler, or both, during the time of their formation. However, the absence of glacial features throughout most of the northern Chilean Andes indicates that the climate during the Pleistocene glacial stages was not greatly different from today's climate. It is estimated that perennial lakes would form in nearly all the Andean basins if the mean annual rainfall of the region above 10,000 feet in altitude were increased to 15 inches from its present 8 inches, and if the mean annual temperature were about 2° F. less than it is at present.

INTRODUCTION

Northern Chile is predominantly an area of interior drainage where surface and ground water flow into closed basins to salars,[1] saline marshes, saline lakes, or clay playas. The region discussed in this report is in the northern Chilean provinces of Tarapacá, Antofagasta, and Atacama (fig. 1). It includes the extremely arid Atacama Desert, a coastal area in which are found the well-known Chilean nitrate deposits, and the semiarid Andean Highlands to the east. The area of interior drainage covers more than 38,000 square miles in Chile and extends eastward and southward into Argentina, eastward into Bolivia, and northward into Peru (fig. 2). More than 100 closed basins occur within the Chilean part of this region, and approximately 100 of these contain salars, of which only the largest are shown in figure 1. These salars extend over a total area of about 2,800 square miles.

This report describes the distribution, geology, and environmental setting of Chilean salars. Special emphasis is placed on the morphology, physical character, and mineralogical composition of salar crusts and on the geology of the adjoining basin floors.

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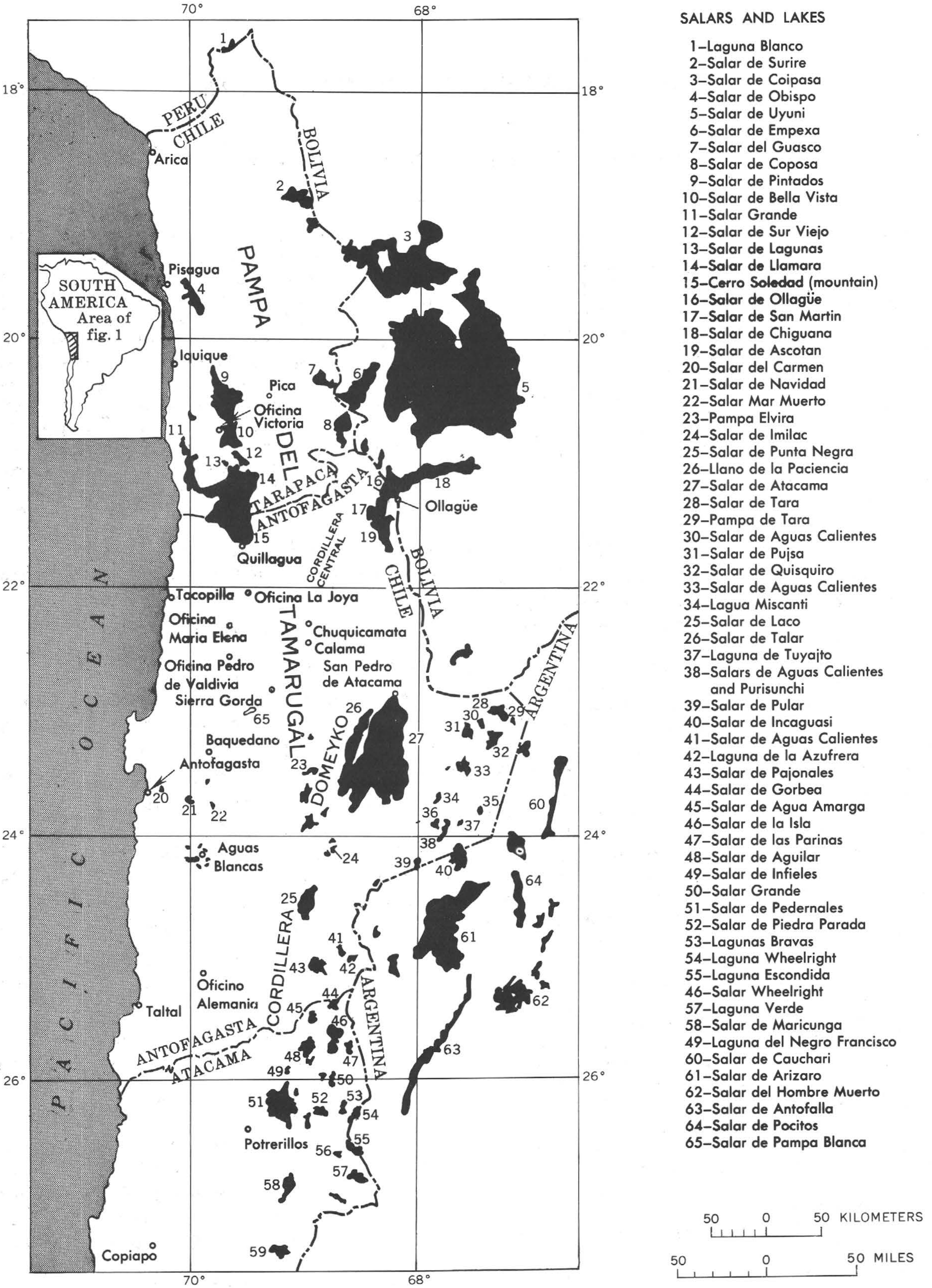
[1] Salars, the term used in South America and in this report, are salt-encrusted playas. Similar landforms in the United States have been termed salt flats, or, less frequently, salt pans.



SALARS AND LAKES

1–Laguna Blanco
2–Salar de Surire
3–Salar de Coipasa
4–Salar de Obispo
5–Salar de Uyuni
6–Salar de Empexa
7–Salar del Guasco
8–Salar de Coposa
9–Salar de Pintados
10–Salar de Bella Vista
11–Salar Grande
12–Salar de Sur Viejo
13–Salar de Lagunas
14–Salar de Llamara
15–Cerro Soledad (mountain)
16–Salar de Ollagüe
17–Salar de San Martin
18–Salar de Chiguana
19–Salar de Ascotan
20–Salar del Carmen
21–Salar de Navidad
22–Salar Mar Muerto
23–Pampa Elvira
24–Salar de Imilac
25–Salar de Punta Negra
26–Llano de la Paciencia
27–Salar de Atacama
28–Salar de Tara
29–Pampa de Tara
30–Salar de Aguas Calientes
31–Salar de Pujsa
32–Salar de Quisquiro
33–Salar de Aguas Calientes
34–Lagua Miscanti
25–Salar de Laco
26–Salar de Talar
37–Laguna de Tuyajto
38–Salars de Aguas Calientes and Purisunchi
39–Salar de Pular
40–Salar de Incaguasi
41–Salar de Aguas Calientes
42–Laguna de la Azufrera
43–Salar de Pajonales
44–Salar de Gorbea
45–Salar de Agua Amarga
46–Salar de la Isla
47–Salar de las Parinas
48–Salar de Aguilar
49–Salar de Infieles
50–Salar Grande
51–Salar de Pedernales
52–Salar de Piedra Parada
53–Lagunas Bravas
54–Laguna Wheelright
55–Laguna Escondida
46–Salar Wheelright
57–Laguna Verde
58–Salar de Maricunga
49–Laguna del Negro Francisco
60–Salar de Cauchari
61–Salar de Arizaro
62–Salar del Hombre Muerto
63–Salar de Antofalla
64–Salar de Pocitos
65–Salar de Pampa Blanca

FIGURE 1.—Index map of northern Chile showing location of salars and lakes.

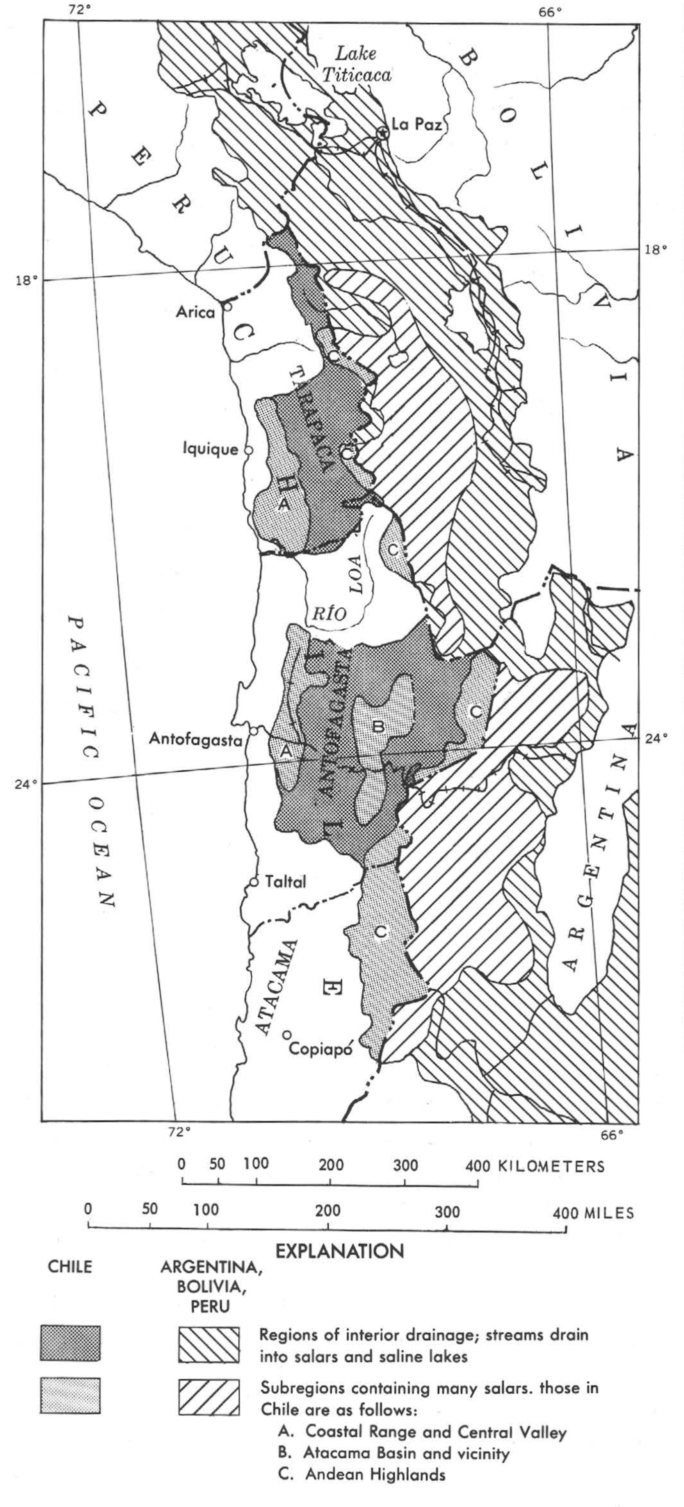


FIGURE 2.—Regions of interior surface drainage in northern Chile and nearby areas in Argentina, Bolivia, and Peru.

Because salars receive the drainage from large basins and lose this moisture chiefly by evaporation, they are responsive to many aspects of the environment, including geologic, hydrologic, topographic, and climatic factors. An ultimate objective is to interpret the features of the salars in terms of the environment.

PRESENT STUDY

The study of the salars of northern Chile has been carried out in cooperation with the Instituto de Investigaciones Geológicas (the national geological survey) of Chile. The work was initiated by Ericksen in 1961 as part of a reconnaissance investigation of the saline deposits, mainly nitrate deposits, of northern Chile. This early fieldwork, carried out during a period of about 6 months in late 1961 and in 1962, was sponsored partly by the U.S. Technical Aid program and partly by the United Nations Special Fund. The results of this work were presented in a report prepared for the United Nations (Ericksen, 1963).

Stoertz (unpub. data, 1966, 1967) made a study based on detailed examination of aerial photographs of about 75 of the salars of northern Chile, together with a review of published and unpublished data available in Washington. As part of this work, photogeologic maps were made of about 35 of the salars. This investigation was supported by the U.S. Air Force Cambridge Research Laboratories and the U.S. Geological Survey.

A field reconnaissance study, also supported by the U.S. Air Force Cambridge Research Laboratories, of 20 salars in northern Chile was undertaken during the period May to July 1967. Interpretations of crustal types, previously distinguished on aerial photographs, were field checked, and maps of the salars were corrected and amplified on the basis of new field data. Morphological and structural features of salars were also studied, and samples of saline crusts, associated clastic sediments and of saline waters from springs, lakes, and salars were collected for laboratory study.

Fifteen samples of clastic sediment were mechanically analyzed, including samples of playa clay or lake clay, playa silt, playa sand, dune sand, and beach sand and gravel from shores of former lakes. Laboratory determinations included sieve analyses, hydrometer analyses, liquid limit, plastic limit, specific gravity, and salt content. In addition, approximately 75 samples were examined microscopically for microfauna (diatoms and ostracodes), for identification of principal saline minerals, and for study of clastic grains.

High-altitude vertical aerial photographs of excellent quality are available for nearly all of northern Chile, at scales from 1:45,000 to 1:65,000. Maps of the salars (figs. 6 and 8–15), tabular data, and many other interpretations are based on aerial photographs taken during the periods March 25 to April 30, 1955, and March 15 to May 15, 1961. This is likely to be a period of maximum flooding at most of the salars in the Andes, for it follows the summer rainy season of December through March. Therefore, these photographs were particularly useful for study of flood patterns in the salar crusts. It is estimated that flooding shown in photographs taken in 1961 is typical of the average year because rainfall was average. From available records at Ollagüe, precipitation during the year prior to May 1961 was approximately 69 mm, close to the 7-year mean of 78.5 mm. San Pedro de Atacama also appears to have had a typical rainy season during the summer before the photographs were made. The average annual rainfall here for 1959–1961 was 20.4 mm (Fuenzalida, 1966, table 1).

The most up-to-date maps of northern Chile are topographic maps, at the scale 1:100,000, published by the Instituto Geográfico Militar of Chile, which cover the Coastal Range and Central Valley, and Operational Navigational Charts (ONC), at the scale 1:1,000,000, published by the U.S. Air Force, which cover the whole area.

PREVIOUS INVESTIGATIONS

Geological investigations of salars in northern Chile have been scanty; consequently, published reports are few and deal with only a few of the salars. A larger number of reports give more general information on geology, geomorphology, and hydrology of northern Chile.

The principal reports on salars follow: Both Gale (1918) and Brüggen (1918) described the potash deposits of Salar de Pintados. Bowman (1924) discussed the geography and climate of the Central Valley and Andes, described Salar de Atacama, Salar de Punta Negra, and others, and provided useful discussions of climate, former lakes, flooding, geomorphology, and surface conditions. Vila (1953) gave the most comprehensive description of the borate deposits in salars of northern Chile. He also briefly described deposits of sodium sulfate, potash, and rock salt of several salars. Stuven (1888) and Chamberlin (1912) also described a few of the borate deposits. Ericksen (1963) described the geology and mineral resources of several of the salars.

The most up-to-date information about the geology of northern Chile is in Brüggen (1950) and Ruiz (1965). In addition to the discussion of regional geology, Brüggen (1950) gave considerable information about geomorphology, hydrology, and former lakes of the area. Darapsky (1900) described the geology and geography of the department of Taltal, the southernmost part of Antofagasta Province. The most comprehensive report on ground water in northern Chile is by Castillo (1960); it deals with the Pampa del Tamarugal in the Province of Tarapacá. Taylor (1947a, b, 1948, 1949) described ground-water resources of several areas in northern Chile. Fuenzalida (1965, 1966) summarized information about the climate.

Harrington (1961) studied the geology of parts of the Atacama Basin and part of the basin of Salar de Pedernales. Segerstrom (1962, 1963, 1964) described the Quaternary geology and geomorphology of northern Chile. Dingman and Galli (1965) and Dingman (1967) reported on the geology and ground water in the regions of Pica and San Pedro de Atacama, respectively, including the northern parts of the Llano de la Paciencia and the Salar de Atacama. Salas and others (1966) described the geology and mineral resources of the Arica region, including Salar de Surire. Tricart studied the geomorphology of Salar del Guasco (unpub. data, 1967).

ACKNOWLEDGMENTS

Members of the Instituto de Investigaciones Geológicas (IIG) aided the work in many ways. Ing. Carlos Ruiz F., former director of the IIG, gave direct support and valuable advice during all phases of the work. Thanks for aid and information is given to the following geologists of the Instituto who accompanied us at various times during the field investigations: Nelson Bravo, Guillermo Chong, Hugo Conn, Francisco Ortiz, Gabriel Perez, Raul Salas, Jaime Sayes, and Arturo Thomas. Fernando Munizaga and Mauricio Tabac, respectively, made semiquantitative spectrographic analyses and X-ray diffractometer determinations of saline material from the salars. Hernán Cusicanqui made chemical analyses of saline waters and brines from salars and saline lakes.

We wish to express our gratitude to the following mining companies in northern Chile who offered hospitality and aid during fieldwork: Anglo-Lautaro Nitrate Corp.; Borax Consolidated, Ltd., owner of borate deposits at Salar de Ascotán and Salar de San Martín; and Cia. Azufrera Ollagüe, owner of sulfur deposits at Volcan Ollagüe.

The late Frank H. Humberstone supplied unpublished reports and information about explorations for potash in several of the salars. This information was essential to the understanding of the chemistry of salars in the Coastal Range and Central Valley of northern Chile.

Thanks are given to Major James T. Neal, U.S. Air Force Academy, and to Daniel B. Krinsley and Lawrence D. Bonham, U.S. Geological Survey, for their support and advice during the investigation of Chilean salars and in the preparation of this report.

ENVIRONMENT OF INTERIOR DRAINAGE BASINS

Information about physiographic and climatic features for each drainage basin and salar is given in table 1 to show broad relationships and regional variations. Physiographic data were taken largely from the U.S. Air Force Operational Navigational Charts, scale 1:1,000,000, supplemented by data from aerial photographs. Climatic data for northern Chile are scanty; data given in table 1 are estimated or extrapolated from information given by Fuenzalida (1965, 1966). Several parameters selected for showing regional variations in this table are based on unpublished data of Jerry Harbour (1963), U.S. Geological Survey.

DISTRIBUTION AND PHYSIOGRAPHY

Within the region of interior drainage, the salars tend to be concentrated in three distinct subregions (fig. 2): (1) about one-sixth of the salars are in the

TABLE 1.—*Physiographic and climatic features of interior drainage basins and salars in northern Chile*

(*A*) Basin No. (figs. 6, 8–12)	(*B*) Basin area (sq mi)	(*C*) Salar area[1] (sq mi)	(*D*) Basin/salar ratio	(*E*) Elevation of salar (ft)	(*F*) Mean elevation of divides (ft)[2]	(*G*) Mean elevation of basin: $(F+E)/2$ (ft)[2]	(*H*) Mean basin relief: $(F-E)$ (ft)[2]	(*I*) Equivalent basin radius $(B/3.14)^{1/2}$ (miles)[2]	(*J*) Effective basin slope, percent (H/I)[2]	(*K*) Estimated mean annual precipitation (in.)	(*L*) Estimated mean annual temperature (°F)	(*M*) Estimated index of potential evaporation	(*N*) Subregion[3]
2	224	40	6	14,000	16,100	15,000	2,100	8.4	4.7	7	34	19	C
4	182	*4.2*	43	13,500	16,000	14,750	2,500	7.6	6.2	7	35	20	C
7	691	*96*	7	2,300	3,300	2,800	1,000	14.8	1.3	0	62	60	A
8 9 10	6,280	*280*	22	3,000	10,300	8,500	7,300	44.7	3.1	1	55	45	A
11	624	*16*	39	12,500	14,600	13,500	2,100	14.1	2.8	5	40	26	C
12	434	*34*	13	12,205	14,800	12,500	2,600	11.8	4.2	5	40	26	C
14A	176	1.1	160	13,500	14,900	14,250	1,400	7.5	3.5	5	37	23	C
15	211	*44*	5	12,500	14,600	13,500	2,100	8.2	4.8	5	40	26	C
16	640	*96*	7	12,220	15,500	14,000	3,000	14.3	4.0	5	38	24	C
17A	1,442	0.4	3,600	2,300	4.800	3,500	2,500	21.4	2.2	0.4	62	60	A
17B	183	0.2	915	3,600	5,200	4,500	1,600	7.6	4.0	0.4	61	55	A
17C	40	0.4	100	3,500	4,700	4,000	1,200	3.6	6.3	0.4	61	55	A
17D	135	0.2	675	3,300	4,700	4,000	1,400	6.6	4.0	0.4	61	55	A
19A	550	1.3	423	2,300	5,300	3,500	3,000	13.2	4.3	0.4	62	55	A
21	165	*0.9*	183	8,500	9,700	9,000	1,200	7.2	3.2	0.8	54	44	B
22	479	*5.8*	83	8,000	9,700	8,750	1,700	12.4	2.6	0.8	55	45	B
22A	83	0.4	208	6,500	8,400	7,500	1,900	5.1	7.1	0.6	58	49	B
23	135	*2.0*	67	7,500	10,500	9,000	3,000	6.6	8.6	1	54	44	B
24	731	*118*	6	7,500	9,400	8,500	1,900	15.3	2.4	1	55	45	B
25	4,529	*1,225*	4	7,500	13,900	10,750	6,400	38.0	3.2	2	49	36	B
25A	45	0.8	56	10,500	11,400	11,000	900	3.8	4.5	2	48	36	B
26	436	*15*	29	6,500	9,500	8,000	3,000	11.8	4.8	0.7	57	47	B
26A	91	0.1	910	7,500	9,000	8,250	1,500	5.4	5.3	0.6	56	46	B
27	324	*9.3*	35	7,500	10,000	8,750	2,500	10.9	4.3	0.8	55	45	B
28	75	*12*	6	12,500	14.500	13,500	2,000	4 9	7.7	10	40	22	C
29	156	*21*	7	12,500	14,000	13,500	2,000	7.0	5.4	10	40	22	C
30	175	*2.3*	76	13,500	16,000	14,750	2,500	7.5	6.4	10	35	18	C
31	400	*56*	7	13,500	16,000	14,750	2,500	11.3	4.2	10	35	18	C
31A	91	0.8	114	13,500	15,800	14,750	2,300	5.4	8.1	10	35	18	C
31B	15	0.2	75	14,500	15,700	15,000	1,200	2.2	10.3	10	34	17	C
31C	55	0.2	275	14,500	15,500	15,000	1,000	4.2	4.5	11	34	16	C
31D	61	1.5	41	14,500	15,700	15,000	1,200	4.4	5.2	11	34	16	C
31E	124	6	21	13,500	16,600	15,000	3,100	6.3	9.3	11	34	16	C
31F	29	0.1	290	13,500	15,000	14,250	1,500	3.0	2.7	10	37	19	C
32	252	*7.6*	33	14,500	16,000	15,500	2,100	8 9	4.5	11	32	15	C
33	104	*6.6*	16	12,500	15,200	13,750	2,700	5.8	8.8	10	39	21	C

See footnotes at end of table.

TABLE 1.—*Physiographic and climatic features of interior drainage basins and salars in northern Chile*—Continued

(*A*) Basin No. (figs. 6, 8–12)	(*B*) Basin area (sq mi)	(*C*) Salar area[1] (sq mi)	(*D*) Basin/salar ratio	(*E*) Elevation of salar (ft)	(*F*) Mean elevation of divides (ft)[2]	(*G*) Mean elevation of basin: $(F+E)/2$ (ft)[2]	(*H*) Mean basin relief: $(F-E)$ (ft)[2]	(*I*) Equivalent basin radius $(B/3.14)^{1/2}$ (miles)[2]	(*J*) Effective basin slope, percent (H/I)[2]	(*K*) Estimated mean annual precipitation (in.)	(*L*) Estimated mean annual temperature (°F)	(*M*) Estimated index of potential evaporation	(*N*) Subregion[3]
33A	49	0.2	245	14,500	16,400	15,500	1,900	4.0	9.0	10	32	16	C
34	118	*6.7*	18	13,500	15,800	14,750	2,300	6.1	7.1	11	35	17	C
35	264	*37*	7	13,500	15,000	14,250	1,500	9.2	3.1	11	37	18	C
36	711	*19*	37	12,500	16,000	14,250	3,500	15.0	4.4	11	37	18	C
37	105	*3.0*	35	13,500	14,800	14,250	1,300	5.8	4.2	11	37	18	C
38	1,528	*2.8*	546	4,000	7,700	6,750	3,700	22.1	1.7	0.6	58	55	A
38A	81	0.2	405	7,500	8,200	7,750	700	5.1	2.6	0.4	57	48	A
38B	110	0.2	550	6,500	7,700	7,000	1,200	5.9	3.9	0.5	58	49	A
38C	107	0.4	268	6,500	7,600	7,000	1,100	5.9	3.5	0.5	58	49	A
38D	54	0.2	270	7,500	8,000	7,750	500	4.1	2.3	0.5	57	48	A
38E	62	0.2	310	6,500	7,700	7,000	1,200	4.4	5.2	0.5	58	39	A
38F	45	1.2	38	3,500	4,200	3,750	700	3.8	3.5	0.4	61	55	A
38G	271	1.7	159	3,500	4,500	4,000	1,000	9.3	2.0	0.4	61	55	A
39	1,668	*99*	17	9,534	13.100	11,250	3,600	23.0	3.0	2	47	35	B
39A	115	0.4	288	9,500	11,200	10,250	1,700	6.1	5.3	1	51	40	B
39B	122	1.0	122	10,500	11,300	11,000	800	6.2	2.4	1	48	37	B
39C	54	0.5	108	10,500	11,000	10,750	500	4.1	2.3	1	49	37	B
40	37	*3*	12	9,500	10,800	10,250	1,300	3.4	7.2	1	51	40	B
41	310	*3.6*	86	9,500	12,500	11,000	3,000	9.9	5.7	2	48	36	B
41A	144	0.2	720	11,000	14,300	12,750	3,300	6.8	9.2	7	42	27	C
41B	36	0.2	180	12,000	12,800	12,500	800	3.4	4.4	7	43	28	C
41C	75	0.1	750	10,500	13,000	11,750	2,500	4.9	9 6	3	46	34	C
42	104	*1.4*	74	9,500	10,800	10,250	1,300	5.8	4.2	1	51	40	B
43	97	*1.0*	97	12,000	14,500	13,250	2,500	5.6	8.4	9	40	23	C
44	283	*13*	22	11,500	15,900	13,750	4,400	9.5	8.8	10	39	20	C
44A	181	0.4	452	12,500	14,500	13,500	2,000	7.6	5.0	10	40	22	C
45	412	*85*	5	11,400	15,400	13,500	4,000	11.5	6.5	10	40	22	C
47	97	*1.8*	54	12,500	14,200	13,500	1,700	5.6	5.7	4	40	28	C
49	244	*31*	8	10,500	14,600	12,500	4,100	8.8	8.8	3	43	31	C
49A	60	2.6	23	11,500	13,500	12,500	2,000	4.4	8.6	3	43	31	C
50A	80	1.1	73	12,500	13,800	13,250	1,300	5.0	4.9	4	40	28	C
51	152	*9.4*	16	11,500	13,800	12,750	2,300	7.0	6.2	3	42	30	C
51A	102	0.6	170	11,500	13,800	12,750	2,300	5.7	7.6	3	42	30	C
52	690	*40*	17	11,500	13,800	12,750	2,300	14.7	3.0	3	42	30	C
52A	36	0.2	180	12,500	14,800	13,750	2,300	3.4	12.8	7	39	24	C
53A	17	0.6	28	13,500	15,200	14,250	1,700	2.3	14.0	7	37	22	C
54	283	*13*	22	13,500	15,500	14,500	2,000	9.5	4.0	7	36	21	C
55	139	*12*	11	12,500	15,200	13,750	2,700	6.7	7.6	7	39	24	C
56	210	8.4	25	12,500	15,100	13,750	2,600	8.2	6.0	6	39	25	C
56A	57	0.7	81	12,500	15,200	13,750	2,700	4.3	11.9	6	39	25	C
57	333	*75*	4	13,500	15,100	14,250	1,600	10.1	3.0	8	37	21	C
58	94	*3.3*	28	14,000	15,900	15,000	1,900	5.5	6.6	8	34	18	C
58A	23	0.1	230	15,000	16,000	15,500	1,000	2.7	7.0	8	32	17	C
59	168	*10*	17	13,500	15,300	14,500	1,800	7.3	4.7	8	36	20	C
60	1,464	*93*	16	11,500	15,100	13,250	3,600	21.6	3.2	4	40	27	C
60A	49	1.0	49	12,500	14,400	13,500	1,900	3.9	9.2	4	40	27	C
61	866	*56*	15	11,500	15,400	13,500	3,900	16.6	4.5	11	40	21	C
63A	31	0.3	103	13,500	15,300	14,500	1,800	3.1	11.0	8	36	20	C
65	180	*9.5*	19	14,500	16,800	15,750	2,300	7.6	5.7	8	31	17	C
65A	25	0.4	62	15,500	17,800	16,750	2,300	2.8	15.5	8	27	13	C
67	125	*2.4*	52	14,500	17.800	16,250	3,300	6.3	9.9	9	29	14	C
67A	35	0.4	88	15,500	17,700	16,500	2,200	3.3	12.6	8	28	14	C
68	154	*4*	38	14,500	16,000	15,250	1,500	7.0	4.1	8	33	18	C
69A	33	1.7	19	14,500	16,000	15,250	1,500	3.2	8.9	8	33	18	C
70	42	0.4	105	14,000	15.700	14,750	1,700	3 7	8.7	8	35	19	C
70A	34	0.2	170	14,500	16,000	15,250	1,500	3.3	8.6	8	33	18	C
70B	37	0.4	92	14,500	16,000	15,250	1,500	3.4	8.3	8	33	18	C
71	72	*1.5*	48	15,500	16.700	16,000	1,200	4.8	4.7	9	30	16	C
71A	134	0.3	447	14,500	17,000	15,750	2,500	6.5	7.3	9	31	16	C
71B	58	0.2	290	16,000	17,300	16,750	1,300	4.3	5.7	9	27	14	C
72	684	7.0	98	14,500	17,400	16,000	2,900	14.8	3.7	13	30	12	C
74	360	8.0	45	13,500	15,500	14,500	2,000	10.7	3.5	15	36	14	C
76	103	0.5	206	15,500	18,000	16,750	2,500	5.7	8.3	13	27	11	C

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[1] Italicized figures of salar areas were determined from large-scale aerial photographs and have fair to good accuracy; areas of other salars were determined from maps and are generally less accurate.

[2] Parameters described by Jerry Harbour (unpub. data, 1963).

[3] Subregions are as given in figure 2.

Coastal Range and Central Valley at elevations of 1,700 to 7,500 feet; (2) about one-sixth are in a belt along the Andean front, including the Atacama Basin, at elevations of 6,500 to 10,500 feet; and (3) two-thirds are in the Andean Highlands at elevations of 10,500 to 16,000 feet. A southwest-northeast profile across Antofagasta Province between lat 23° and 24°S. (fig. 3) illustrates the general setting of salars in relation to the major geographic subregions.

COASTAL RANGE AND CENTRAL VALLEY

The Coastal Range is characterized by subdued to moderately dissected terrain, generally consisting of rounded hills and rolling uplands at elevations of 3,000–6,000 feet. Small mountains locally rise above the general level of the uplands, but relief is generally low. Much of the region has the character of an undulating plateau, which is fairly level when seen from a distance but which is dissected by shallow broad valleys and basins having a relief of generally not more than a few hundred feet. The western side of the Coastal Range is bounded by an abrupt escarpment, commonly 2,000–3,000 feet high, that shows evidence of recent faulting. The eastern side of the Coastal Range slopes gently eastward toward the Central Valley, where it either merges with the valley fill or terminates at a low escarpment. The eastern margin has the appearance of being partly covered or "drowned" by the sediments of salars and clay playas.

The Central Valley is a broad longitudinal depression between the Coastal Range and the Andean Highlands. Its total length, from the Peruvian border near Arica southward to lat 27°S., is about 600 miles, and its maximum width is about 50 miles. It is a continuous broad valley in the northern part of Antofagasta Province and southern Tarapacá province, where it is known as the Pampa del Tamarugal (fig. 1). Here, it consists of a broad gently sloping alluvial plain at elevations mainly between 3,000 and 7,000 feet. In Tarapacá, north of the Río Loa (fig. 2), the valley contains large salars in its lowest part along the western edge adjacent to the Coastal Range. From here the surface rises eastward toward the Andean Highlands at slopes ranging from less than 1 percent at the base to as much as 8 percent at

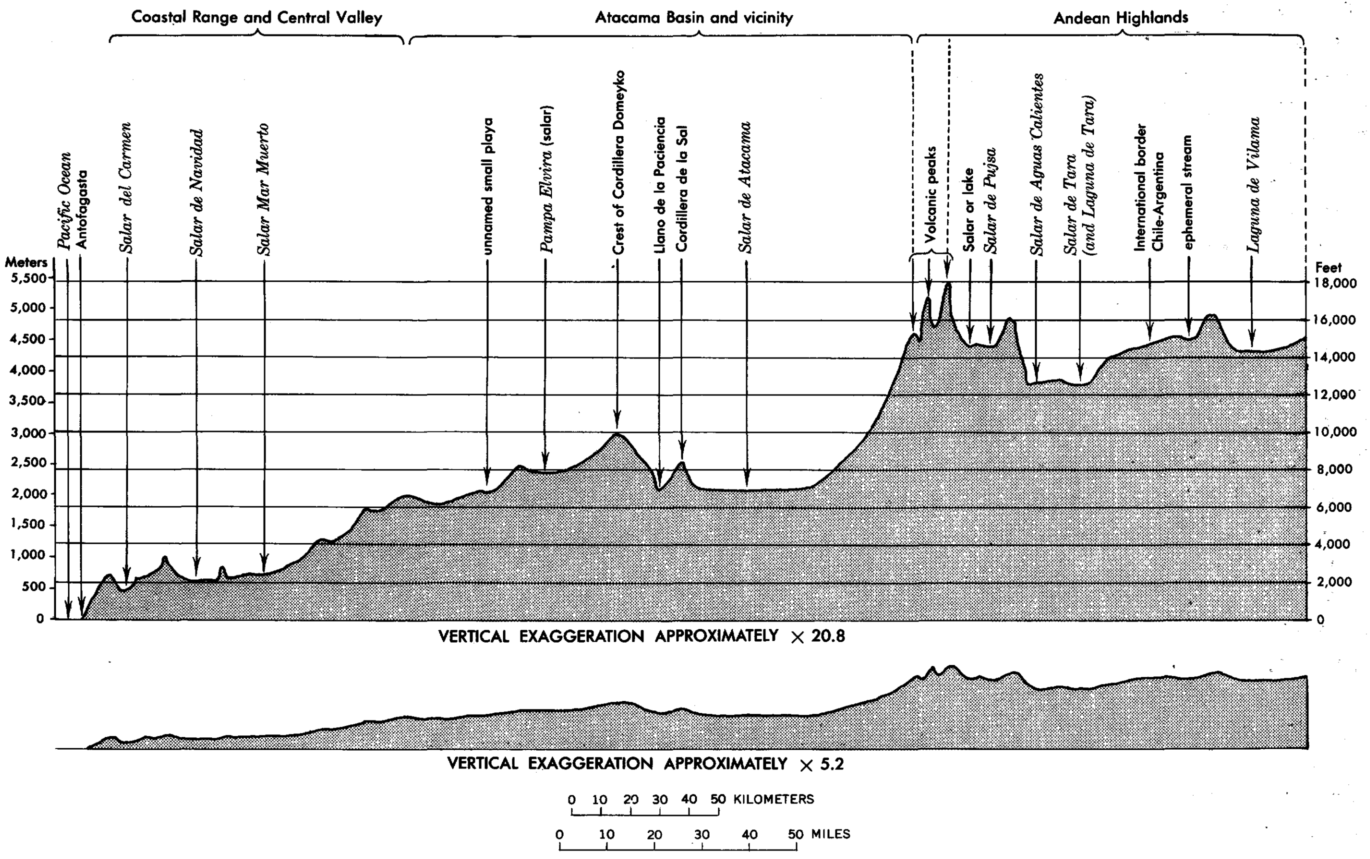


FIGURE 3.—Southwest-northeast profile across Antofagasta Province, northern Chile, between lat 23° and 24° S., showing positions of three subregions of interior drainage.

higher elevations. In addition to its distinct westward slope, the lowest part of the Pampa del Tamarugal slopes gently southward from an elevation of about 3,600 feet at a point east of Pisagua (lat 19°40′S.) to about 2,700 feet in the northernmost part of Antofagasta Province (fig. 1). It again slopes gently upwards to the south and ends at about the latitude of Sierra Gorda. The Central Valley is interrupted by a broad transverse valley extending from Sierra Gorda, passing Baquedano, and draining into Salar del Carmen (fig. 1). Farther south it is represented by a large elongate basin of interior drainage that centers near Aguas Blancas and gives way southward to upland piedmont plains and broad alluvial valleys.

In the subregion of the Coastal Range and Central Valley (fig. 2), many salars and clay playas are found from the latitude of Pisagua in the north to near Antofagasta in the south, a distance of about 300 miles. This region is interrupted by the exterior drainage basin of the Río Loa. Drainage basins in this subregion are large in comparison with those of the Andean Highlands of northern Chile. Sixteen basins having interior drainage are present; each of these has an average area of 960 square miles, and together they have a total area of about 15,360 square miles. This is an area larger than the combined areas of 67 basins in the Andean Highlands. Basins of this subregion (table 1) have relatively low salar elevations (median 3,500 ft), low basin divides (median 6,000 ft), low basin relief (median 1,200 ft), and low basin slopes (median 3.3 percent).

ATACAMA BASIN AND VICINITY

The eastern part of Antofagasta Province is marked by mountain ranges in front of the main Andes, the Cordillera Central in the north and the Cordillera Domeyko in the south (fig. 1). The Cordillera Central is separated from the main Andes by the broad valley of the Río Loa, whereas the Cordillera Domeyko is separated by an elongate closed depression which contains the Salar de Atacama in the northern part and the Salar de Punta Negra in the southern part.

Salars in the subregion of the Atacama Basin and vicinity, east and southeast of Antofagasta, are found over an area 20–50 miles wide and about 150 miles long (fig. 2). Seventeen basins of interior drainage occur in this area, the Atacama Basin being by far the largest. They extend over a total area of about 9,500 square miles. These basins have the following characteristics (table 1): median elevation of salars is 8,500 feet; median elevation of basin divides is 10,800 feet; median elevation of basins is 9,600 feet; median relief of basins is 1,700 feet; and median slope of basins is 4.3 percent.

ANDEAN HIGHLANDS

The Andean Highlands of northern Chile constitute an undulating plateaulike region having several north-trending ridges and hundreds of volcanic peaks with intervening broad, relatively shallow valleys and basins, many of which have internal drainage. Topography is relatively gentle, although relief is locally great. Base altitude of the region is 13,000–14,000 feet, and the highest volcanic peaks range from about 18,000 to 22,000 feet.

Salars occur in the Andean Highlands of Chile from Salar de Maricunga (northeast of Copiapo) in the south to Salar de Surire in the north (fig. 1), a distance of nearly 600 miles. There are 67 closed basins in this region. Salars also occur in the Andes of northern Argentina, western Bolivia, and southern Peru, within the areas of internal drainage shown in figure 2. Salar de Uyuni in western Bolivia (fig. 1) is by far the largest salar in South America. In Chile, the Andean Highlands are separated into two areas of interior drainage by the through-flowing drainage system of the Río Loa. The basins in these two areas tend to be small, in comparison with basins in the other two subregions in Chile, averaging only 205 square miles per basin. The total area of interior drainage in the Chilean Andes is about 14,060 square miles. Among the general characteristics that distinguish the Andean basins from those to the west (table 1) are high salar elevations (median 13,500 ft), high basin divides (median 15,400 ft), high basin elevations (median 14,250 ft), high basin relief (median 2,100 ft), and steep basin slopes (median 6.2 percent).

CLIMATE

Northern Chile is characterized by extreme aridity and sparse vegetation at elevations below 6,000 feet. This region, which includes the Coastal Range and Central Valley, corresponds to the approximate limits of the Atacama Desert, reputed to be the world's driest desert. Furthermore, the high Andes of northern Chile are extremely arid in comparison with other mountain ranges of equal elevation. The snowline is near 20,000 feet on the high volcanic peaks, perhaps the highest snowline in the world. Perennial snow and ice fields are found on only a few peaks extending above 21,000 feet in elevation. These are relatively small in area and in depth of snow and ice.

The aridity is due to the cold Humboldt Current, which flows northward along the coast in conjunction with a counterclockwise pattern of air circulation around a permanent high far to the west, resulting in prevailing south to southwest winds along the coast, bringing air that has blown for great distances over the cold ocean current. Near the coast this air is cool and even though it may be relatively humid, considering its cool temperature, when it blows over the warm land, the relative humidity drops to extremely low levels. Furthermore, the Andes Mountains inhibit movement of moist air into northern Chile from the east.

Meteorological data for northern Chile are scanty and incomplete, particularly for the Andean Highlands where climatic variability is greatest. The more uniform climate of the coastal desert is better known. The most up-to-date discussion of the climate of Chile is that of Fuenzalida (1965, 1966). We have used these reports and an earlier report by the Corporación de Fomento de la Producción (1950) in our attempt to evaluate the climate under which salars formed and continue to form in northern Chile.

The estimated relation between mean annual precipitation and elevation for several parts of the region have been plotted graphically (fig. 4). Although average temperature varies from region to region, the main curve (solid line) in figure 4 represents an estimated average for the entire region of closed basins. The interrelation among mean annual temperature, precipitation, and rate of evaporation has been explored by Langbein (1961), and data from his report have been used to estimate the relation between potential evaporation and elevation as shown in table 1.

PRECIPITATION AND TEMPERATURE

Coastal Range and Central Valley.—The driest region is a narrow strip along the coast where mean annual precipitation, which increases southward, ranges from about one-twentieth of an inch in Arica to about one-sixth of an inch in Antofagasta, and is about an inch in Taltal (Fuenzalida, 1966, table 1). Here, as elsewhere in the Coastal Range and Central Valley, rainfall may occur as infrequently as only once every 5–10 years. The Coastal Range is only slightly less arid than the immediate coast, even though it rises above the inversion associated with the cold coastal waters (Weischet, 1966).

The Coastal Range is characterized by heavy winter (May–September) fogs known as camanchaca. The fog blows in over the coast, appearing as a solid overcast, generally several hundred feet above ground level, but frequently reaching the ground at night, and extending roughly to the elevation of the highest peaks of the Coastal Range. The fog may extend inland as far as 50 miles, an area that encompasses all the salars in the Coastal Range and Central Valley. Precipitation of fog moisture on the ground surface has promoted the formation of a nodular surface that characterizes the perennial rock-salt crusts of this region. Only rarely do the fogs extend eastward across the Central Valley and up to elevations of 5,000–6,000 feet along the Andean front. At times, condensation of water from the fog is heavy, being sufficient to moisten soil surfaces, to trickle down car windshields, and to accumulate as films and tiny pools in depressions on asphalt road surfaces.

The lowest part of the Central Valley, where large salars occur, is somewhat drier than the Coastal Range, and average annual precipitation may be less than one-tenth of an inch. Mean annual precipitation for the Central Valley as a whole, from the latitude of Taltal to Arica, is probably less than one fourth of an inch.

Compared with other deserts of the world, the Atacama Desert is characterized by relatively low mean annual temperature, about 60°F, 5°–15° cooler than the mean annual temperature of most other deserts. Summer temperatures are even more anomalous, daytime temperatures being about 20°F cooler than those in most deserts. Winter temperatures are mild, generally dropping to freezing during winter nights at the east side of the Central Valley only at elevations above 5,000 feet. Therefore, the Atacama Desert, in spite of being the world's driest desert, is probably one of the world's mildest deserts in terms of temperature extremes.

Atacama Basin and vicinity.—The Atacama Basin and vicinity have a climate more humid than that of the Central Valley but more arid than the Andean Highlands. Furthermore, the climates of the western and eastern rims of the basin, even at the same elevations, differ markedly. The western side is extremely arid, whereas the eastern side is semiarid. Because of its large size, the Atacama Basin has its own unique microclimate, sufficiently distinct to create a prominent pattern on high-resolution infrared

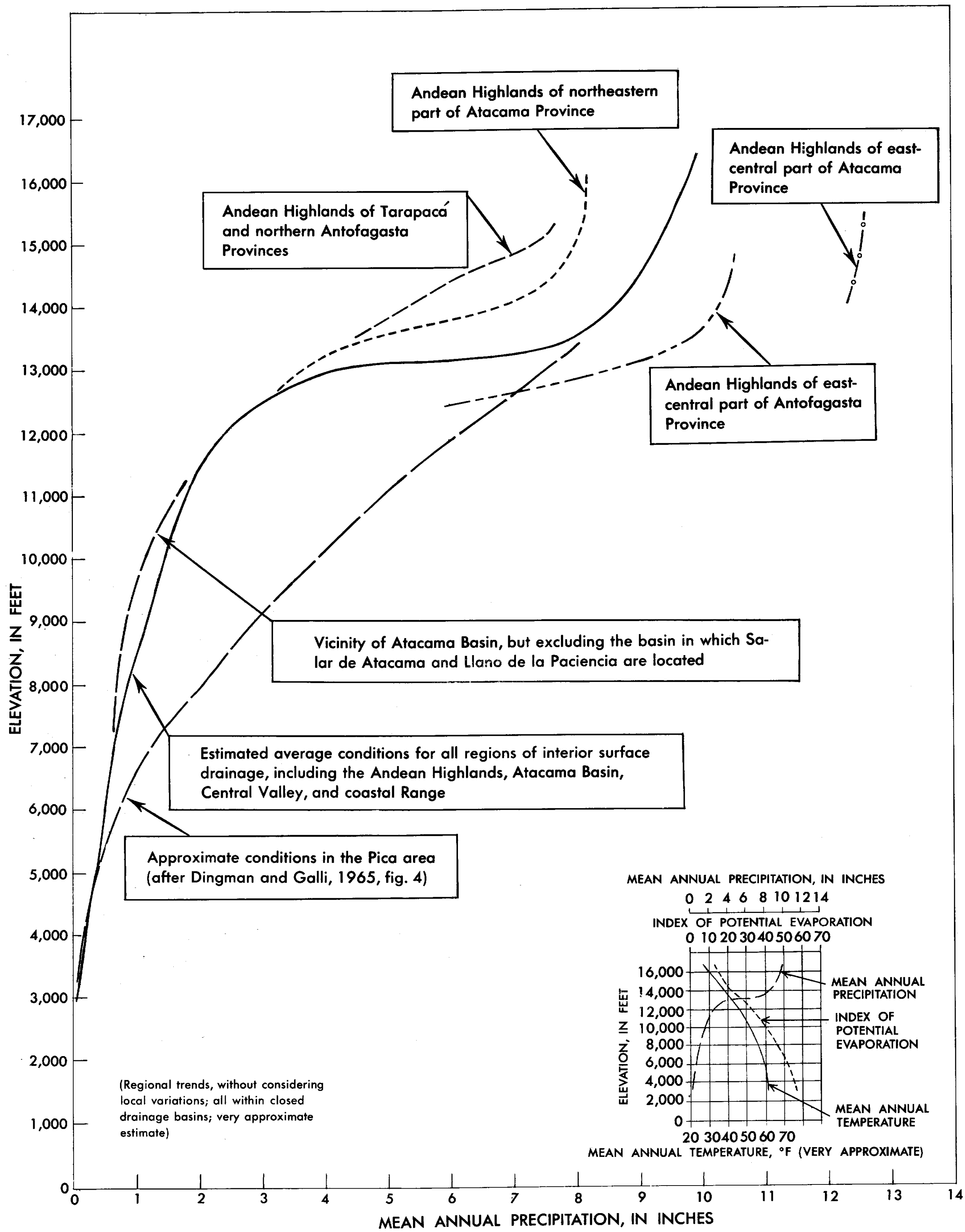


FIGURE 4.—Estimated relation between elevation and mean annual precipitation in five regions of northern Chile.

radiometer imagery made from an earth-orbiting satellite. On the basis of interpretation of this imagery, the thermal regime of the basin is estimated to be comparable in many aspects to that of Death Valley, Calif., though somewhat cooler. Temperatures at night are probably cooler on the floor of the basin than on the surrounding slopes, and on these slopes temperatures are undoubtedly much warmer than on the high rims and adjoining highlands.

In general, closed basins in and around the Atacama Basin are estimated to have a mean annual precipitation ranging from 0.6 to 2 inches. The mean annual temperature is estimated to range from 47°F to 58°F, probably averaging about 52°F (table 1).

Andean Highlands.—The climate becomes progressively cooler and less arid toward the east as elevation in the Andes increases. The heaviest rainfall is in the northernmost Chilean Andes near Peru, and rainfall decreases southward to the east-central part of Antofagasta Province and then increases again towards the south. In northern Tarapacá Province, precipitation is largely during the summer months of December to March; in Atacama Province it is during the winter months of May to September. At elevations of about 12,000 feet, the mean annual precipitation probably averages about 8 inches, but the lower marginal parts of the Andean Highlands receive much less precipitation. In the north, precipitation is rain from convectional storms in the summer months, but snow may fall in the high mountains, generally above 14,000 feet, and may account for as much as one-third of the total precipitation of some basins. Winter precipitation in Atacama Province is largely snow. Precipitation is extremely variable from year to year at a given place; commonly, wet years have two or three times as much precipitation as dry years.

A factor in the climate of this region which is difficult to evaluate in terms of overall basin precipitation is the amount of snowfall. The highest peaks may receive considerably more precipitation than might be inferred from the graph (fig. 4). Furthermore, a large percentage of the snow that falls at high elevations, as well as that falling during the winter months at lower elevations, evaporates directly rather than melting to form runoff. As a consequence, plants are much sparser in these areas than would be expected. This is particularly noticeable in the region of Salar de Maricunga, which appears to be one of the driest areas of the Andes, even though precipitation is probably greater than it is to the north in Antofagasta.

In general the interior-drainage basins of the Andean Highlands are estimated to have a mean annual precipitation ranging from 3 to 15 inches, and probably averaging about 8 inches. Mean annual temperature in individual basins in the Andes is estimated to range from 27°to 46°F, probably averaging about 36°F.

EVAPORATION

Very little information is available about rates of evaporation in northern Chile. At María Elena, a nitrate plant in the Central Valley, evaporation of brines in large shallow tanks averages about 85 inches annually. Brines evaporate less readily than fresh water, which is used in pan evaporation measurements (Harbeck, 1955, p. 1). A rough comparison with evaporation in the Atacama Desert is afforded by such measurements in the driest deserts of the United States. For example, lake or free-water evaporation at Yuma, Ariz., has been measured as approximately 77 inches annually, whereas pan evaporation in Death Valley, Calif., averages more than 120 inches per year (Kohler and others, 1959).

Langbein (1961, p. 3) devised a method for estimating mean annual lake or free-water evaporation from known values of mean annual temperature and mean annual precipitation. He presented curves showing the correlation between these factors and net evaporation, defined as "the difference between gross evaporation and precipitation on the lake," and therefore a measure of the rate of removal of water from a closed lake. These curves were utilized to estimate the relative rates of potential evaporation or evaporativity in closed basins in northern Chile. The resulting values serve as the index of potential rates of evaporation (shown in table 1) in different basins on the assumption that humidity, radiation, cloudiness, and wind are equal in each basin. That such an index is applicable to basins in northern Chile is indicated by the fact that among the 100 largest closed basins, the five that contain relatively large perennial lakes rather than salars are among those having the 14 lowest indices (table 1). On the other hand, only fair correlation was found between the presence of lakes and the factors of low temperature or high precipitation when they were considered separately.

In general, the potential rate of net evaporation from a free water body in the Atacama Desert is estimated to be about 60 inches annually, although the rate may be considerably higher in some areas of exceptionally low relative humidity such as at María Elena. An annual rate of 60 inches is somewhat lower than in other deserts of the world. For example, pan evaporation in the deserts of Iran, as reported by Krinsley (1970, p. 49), has been measured as 84 inches per year at Tabas and 134 inches at Varamin (30 miles southeast of Tehran).

WIND

Very little direct meteorological data are available regarding surface wind speeds and directions in closed basins of northern Chile. The general movement of air is from west to east across the region, but local and seasonal variations are great. Probably the best available evidence of dominant wind directions in most closed basins can be obtained by a study of wind erosional and depositional features visible in aerial photographs. Such features are visible on or adjacent to at least 80 percent of the salars in northern Chile and locally are clear enough to provide a detailed pattern of wind variations.

Measurement of wind directions at 40 salars resulted in the following conclusions:

1. Over the Coastal Range and Central Valley strong prevailing winds are from the west, but towards the coast they are more likely to be from the southwest. At the Mejillones Peninsula, north of Antofagasta, winds are predominantly from the south or south-southeast.
2. In the Andean Highlands and Atacama Basin, strong prevailing winds are from the northwest or west-northwest, and locally from the west.
3. Westerly winds evidently prevailed during the Quaternary, as indicated by asymmetrical development of shorelines of former lakes, which are commonly most prominent around the eastern and southeastern margins of salars. This is presumed to result from wave action due to prevailing westerly to northwesterly winds.

The entire region of northern Chile is characterized by extraordinary wind action. Within this region are at least two areas with outstanding accumulations of windblown sand, one in the vicinity of Pica and the other at the northern end of Salar de Atacama (Dingman, 1967; Dingman and Galli, 1965). We experienced a sand storm of 2-days' duration in June 1967 at San Pedro de Atacama. At times, wind velocities probably exceeded 60 mph. During one exceptionally strong wind blast, the rear window of our small truck was smashed by wind-driven pebbles. At the same time, the sand and dust in the air reduced visibility to a few feet, making it impossible to drive a car along the road.

REGIONAL GEOLOGY

Most of the closed basins in northern Chile formed as the result of late Tertiary to Holocene faulting, and fault movement has affected the configuration of salars and the morphology of their crusts. In general, the major subregions containing salars are closely related to major tectonic elements of northern Chile. The Coastal Range and Central Valley subregion (fig. 2) is within a zone of intensive block faulting associated with uplifting of the Coastal Range. The Atacama Basin and vicinity subregion lies to the east and partly within a fault zone trending north-northeast, associated with the uplifted tectonic block of Cordillera Domeyko. The Andean Highlands subregion is in the western Andes, an area of intensive volcanism and faulting during the late Tertiary and Quaternary.

Northern Chile is underlain chiefly by marine sedimentary rocks, volcanic rocks, and plutonic rocks of Jurassic and Cretaceous age, which are most widespread in the Coastal Range, and by rhyolitic to basaltic volcanic rocks of Tertiary and Quaternary age, which are most widespread in the Andean Highlands. Extensive areas are covered with thick alluvium and lacustrine sediments of late Tertiary and Quaternary age.

COASTAL RANGE

Rocks exposed in the Coastal Range are chiefly marine sedimentary rocks and andesitic volcanic rocks of Jurassic and Cretaceous age that have been intruded by granitic batholiths of Late Jurassic to Cretaceous age. Basement rocks of Paleozoic age are exposed in places, chiefly in the region west of the Río Loa. The stratified rocks have been gently folded and intensely faulted. Rhyolitic volcanic rocks of probable late Tertiary age are present locally. Hills and valleys in the Coastal Range are extensively covered with unconsolidated sediments that were derived largely from nearby bedrock. Alluvial fill in some basins is more than 100 feet thick.

An unusual feature of the Coastal Range that was originally described by Darwin as early as 1846 (Darwin, 1876, p. 302) is the widespread hard surficial layer consisting of relatively pure saline material, chiefly halite, or of saline-cemented regolith.

A widespread mantle of reddish windblown silt and sand, probably volcanic ash, has also been described (Brüggen, 1950, p. 142; Segerstrom, 1964, p. 163); this material occurs at places in the Central Valley and contributes to the reddish-brown color of many of the salars in this region.

Two major sets of faults can be observed in the Coastal Range. The principal faults trend north and the others east. Many of the valleys and the closed basins are structural features on these faults. A large fault apparently extends northward along the coast of northern Chile, and the steep cliff on the ocean side of the Coastal Range is an eroded fault scarp. The Atacama fault, the most prominent fault in northern Chile, can be traced for about 350 miles, from near Taltal to Iquique (fig. 1). It disrupts the salt crust of Salar Grande, intersecting the west edge of the salar at the old salt quarry of Salina Río Seco (fig. 13). South of this quarry the fault trace is marked in solid rock salt by subdued scarps and sag depressions that generally have relief of only a few feet. At another salt quarry, Salina Guanillos (fig. 13), a fault trending west-northwest has produced a prominent scarp 30–40 feet high (fig. 5).

Faulting appears to have had a profound effect on the hydrology and morphology of the Salar Grande basin. A field investigation and study of aerial photographs resulted in the following observations and conclusions. Formerly the basin must have been hydrologically closed, or nearly so; otherwise the solid halite body, as much as 560 feet thick, could not have accumulated by gradual evaporation. However, at present it has subsurface drainage, as indicated by the absence of ground water in the salt and in the alluvium below the salt. The salt and alluvium were penetrated by holes drilled during the 1920's in a search for potassium salts. Depressions having the appearance of solution pits or sinkholes occur near the eastern edge of the salar and may be sites of subsurface solution and collapse at places where ephemeral streams formerly drained into the salar. Large depressions at the western edge of the salar appear to be sag basins on faults. At places, the western side of the salar is characterized by abruptly truncated slopes ranging from less than a foot to about 30 feet high, which may be due to faulting and solution of salt. Scalloped perimeters of fans along the western margin, with local patterns reminiscent of a bird's-foot delta, apparently are alluvial fans along recent fault scarps.

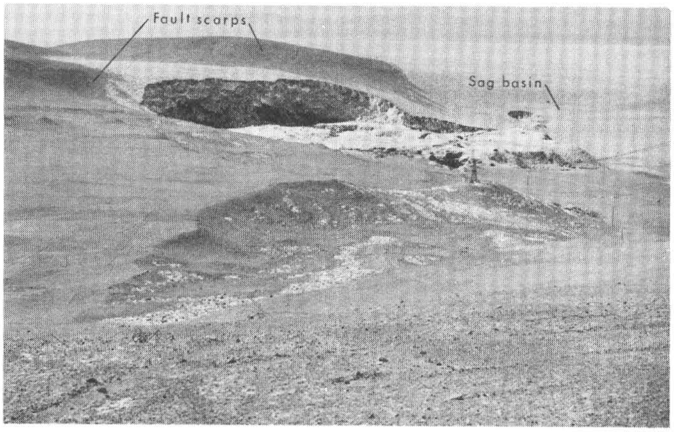


FIGURE 5.—Fault scarps and a sag basin in massive rock salt at Salina Guanillos, western border of Salar Grande; basin in foreground resulted from solution of rock salt below an alluvial cover.

CENTRAL VALLEY

The Central Valley has a thick fill of unconsolidated sediments ranging in age from middle Tertiary to Holocene. This fill consists of piedmont alluvial deposits of silt, sand, and gravel as well as playa and lacustrine sediments. These deposits, penetrated by an exploratory oil well near the east side of Salar de Bella Vista (fig. 1), are about 1,300 feet thick; they rest on older (probably Jurassic or Cretaceous) bedrock (Mordojovich, 1965). The uppermost layers of this 1,300-foot sequence of sediments, commonly several hundred feet thick, were described by Taylor (1947b, p. 26) as unconsolidated Pleistocene and Holocene stream deposits of interbedded gravel, sand, silt, and clay that make up the great alluvial fans of the Pampa del Tamarugal. Much of this part of the sequence may consist of mudflows. Dingman and Galli (1965, p. 74–75) stated that the underlying older sediments are apparently semiconsolidated and fairly permeable, consisting chiefly of "intercalated soft sandstone, siltstone, and clay with occasional beds of conglomerate." These deeper sediments beneath the Central Valley are generally considered correlative with the Altos de Pica Formation (probably late Tertiary age) that is exposed to the east at elevations generally above 5,000 feet. Part of the overlying, more coarsely clastic unconsolidated sediments also may be equivalent in age to the upper part of the Altos de Pica Formation, which consists mainly of torrential and mudflow deposits (Segerstrom, 1964, p. 165).

Along the western edge of the Pampa del Tamarugal the salar crusts and clay playa or lake sediments lap onto older rocks of the Coastal Range. Along this edge the valley fill is locally no more than

50 to 100 feet thick. Sediments are presently being deposited in the lowest parts of the Central Valley by infrequent floods from the Andes. Salar crusts also are being formed locally by evaporation of ground water. In contrast, farther north, where there is through-flowing drainage (fig. 2), sediments of the Central Valley are being eroded.

The Central Valley originated as a tectonic depression that is thought to be Pliocene to Quaternary in age. It is apparently a graben, bounded by north-trending faults to the east and west that are largely covered with valley fill. Downwarping or monoclinal folding evidently has contributed to the formation of the valley (Brüggen, 1950, p. 157).

The Central Valley in Tarapacá appears to have been tilted westward in late Pleistocene or Holocene time so that the lowest part of the valley is adjacent to the Coastal Range. The location of the flat salar crusts in this area indicates that the tilting has continued until recent times, resulting in nearly all clastic sediments from the Coastal Range being incorporated into the salar crust or gradually buried beneath its encroaching edge. In addition, the largest salars, Salar de Pintados for example, are lowest along their western sides, indicative of tilting since the salars first started to form. In many places along the eastern sides of Salar de Pintados and Salar de Bella Vista are broad surfaces partially dissected by shallow channels draining westward. These surfaces are interpreted as old parts of the salars that have been uplifted and tilted towards the west.

Five or more separate topographic basins within the Central Valley are attributable partly to faulting and partly to development of large alluvial fans where major valleys drain from the Andes. The basin of Salar de Pintados appears to be separated from that of Salar de Obispo to the north by a large alluvial fan built from Quebrada de Tarapacá (near lat 20°S.). Salar de Pintados and Salar de Bella Vista both seem to be bounded on their lower, southern edges by faults of probable Holocene age, trending approximately N. 50°W. and nearly west, respectively. These faults account for the resistant ridges of impervious older rocks, salients of the Coastal Range, that extend into the Central Valley. The ridges inhibit subsurface and surface drainage between these salars and between Salar de Bella Vista and Salar de Sur Viejo (fig. 1).

ATACAMA BASIN AND VICINITY

The Atacama Basin is a major structural basin occupying more than 5,000 square miles. The basin is bordered and underlain by upper Paleozoic to Cretaceous rocks and filled with Tertiary to Holocene continental sediments. Deposition of alluvium, saline deposits, and playa sediments continues.

An interior basin first originated in early Tertiary time and received terrestrial clastic sediments and evaporites that are now well exposed in a prominent ridge, the Cordillera de la Sal, which separates the Llano de la Paciencia from Salar de Atacama (fig. 11). These rocks belong to the San Pedro Formation of early Tertiary age and consist of interbedded fine-grained clastic sediments, gypsum, and rock salt (Dingman, 1962). The salt beds are described (Dingman, 1962, p. D94) as "apparently the result of redeposition and further concentration of the evaporite salts from the Jurassic(?) and Cretaceous formations." The San Pedro Formation has been deformed into plunging anticlinal folds and domes, including salt domes. Concentric banding, attributed to the deformed beds of this formation, is visible locally in the floors of Salar de Atacama and the Llano de la Paciencia, near the south end of the Cordillera de la Sal.

The present Atacama Basin probably formed in the late Tertiary (Pliocene) or early Pleistocene in response to the final uplift of the Andes. It postdates deformation of the San Pedro Formation. Diatomites were deposited in lakes that occupied the basin at one or more times during the late Tertiary or Pleistocene. Some diatomites on the east side of the basin are about 1,000 feet above present salar level, indicating either a former extremely deep lake, or more probably, that the basin has tilted westward and slowly subsided during the Pleistocene.

The western rim of the Atacama Basin is formed by the Cordillera Domeyko, made up chiefly of the Purilactis Formation, of Cretaceous age, which consists of coarse conglomerate and sandstone as well as "fine-grained red-bed sediments and evaporite deposits typical of deposition in continental basins under arid conditions" (Dingman, 1962, p. D94). Intrusive granitic rocks of Jurassic to Cretaceous age and marine sedimentary rocks of Jurassic age are exposed near Salar de Punta Negra in the Cordillera de Domeyko (Chile Inst. Inv. Geol., 1968, geologic map of Chile). The eastern side of the Atacama Basin is covered largely by volcanic rocks, of which major components are rhyolite ash-flow tuffs. These deposits, equivalent in age to the Altos de Pica Formation, slope uniformly 3°–5°W. (Dingman and Lohman, 1963, p. C69). The above-mentioned diatomites are younger than these volcanic rocks.

The configuration and crustal morphology of several salars in this subregion reflect the influence of geologic structure. The gradual subsidence of the Atacama Basin was apparently accompanied by upward tilting on the east. Among the effects of this are: (1) crowding of Salar de Atacama and Llano de la Paciencia against the western edge of the basin (fig. 11); (2) crowding of salt crusts, former lakeshores, and piedmont alluvial slopes in the same direction; (3) presence of the area of most frequent flooding, sometimes termed Laguna de la Sal (Taylor, 1947a, p. 14, map), in the southwestern part of Salar de Atacama; (4) the apparent diminishing in height of terrace scarps around salt crusts toward the west; and (5) presence of Quaternary lake sediments including diatomites along the eastern side of the basin, high above the level of the present salar.

Other basins and salars in the vicinity show a similar asymmetry. For example, Salar de Punta Negra (fig. 6) is close to the northwestern margin of its basin, near a probable fault zone trending north-northeast. The asymmetry of the salar is interpreted as resulting in part from gradual tilting of the basin downward toward the northwest as the result of fault movement.

ANDEAN HIGHLANDS

The Andean Highlands are underlain predominantly by volcanic flows, tuffs, and breccias ranging from Pliocene to Holocene in age. The older volcanic rocks, equivalent in age to the Altos de Pica Formation, are chiefly of rhyolitic composition and are thought to have erupted from fissures and volcanic centers no longer evident. The younger volcanic rocks are chiefly andesitic to basaltic and are associated mainly with volcanic cones or stratovolcanoes. In some regions, however, ash-flow tuffs are among the youngest volcanic rocks. Locally, ridges and hills consisting of Jurassic and Cretaceous sedimentary and volcanic rocks and Cretaceous plutonic rocks rise above the surrounding terrain of younger volcanic rocks.

There are reportedly about 800 volcanoes in northern Chile (Zeil, 1964, p. 199); more than 30 of these are between 19,000 and slightly more than 22,000 feet in elevation. Most date from the Pleistocene, although a few were probably active during the Holocene. Only a few now show fumarolic activity.

The Andean front in northern Chile rises eastward from the Central Valley, either as a gentle incline or as a series of steps, and is covered by piedmont alluvial deposits and mudflows in the lower region and volcanic tuffs and flows in the upper region. Deep valleys, which drain westward across the Andean front, expose underlying rocks of Jurassic and Cretaceous age.

Because most of the northern Chilean Andes are within the region of interior drainage, most of the erosional products of the region have remained within the closed basins. Sedimentary basin fill includes alluvium, lake and playa sediments, salines, windblown soil, and volcanic ash.

Many of the basins in the Andean Highlands appear to be due to faulting. Examples of salars whose configurations seem to be partly controlled by faults or by fracture systems are Salar de Surire, Salar de Pajonales, and Salar de Coipasa (figs. 8, 11). Much of the eastern perimeter of Salar de Surire is outlined by a series of springs that seem closely alined along an intersecting system of fractures or faults. Boiling springs and geysers, probably on a fault, were observed in the southeastern part of the salar (fig. 7). The western margin of Salar de Coipasa has one or more thermal springs that may also be on a major fault or fracture zone. The hot waters in both these areas are probably related to late Holocene volcanic activity.

Many of the salars in the Andean Highlands are asymmetrically situated in their basins and show asymmetrical zoning of the saline crusts because of faulting and tilting of basins during Quaternary time. Salar de Pedernales, Salar de Maricunga, and Salar del Guasco (fig. 6) are among those showing the clearest asymmetrical patterns. All three of these basins appear to have been tilted downward to the northwest as the result of movement along faults trending north to northeast. They are along a north-trending zone of intense block faulting near long 69°W. Harrington (1961, p. 180) reported the presence of at least nine large reverse faults in the region immediately west of Salar de Pedernales. Two or more faults cross this salar, trending generally northeast, and one of these, the Chapapote fault, may be associated with oil seeps and brine-pool springs in the northern part of the salar (Harding, 1926, p. 797, 799). A fault probably extends northeastward across the basin of Salar de Maricunga, as indicated by the pronounced elongation of the southern part of this salar and the straight southeastern edge (fig. 6). A major fault zone probably extends along the western edge of Salar del Guasco (figs. 6, 9). Five separate north-trending narrow basins of

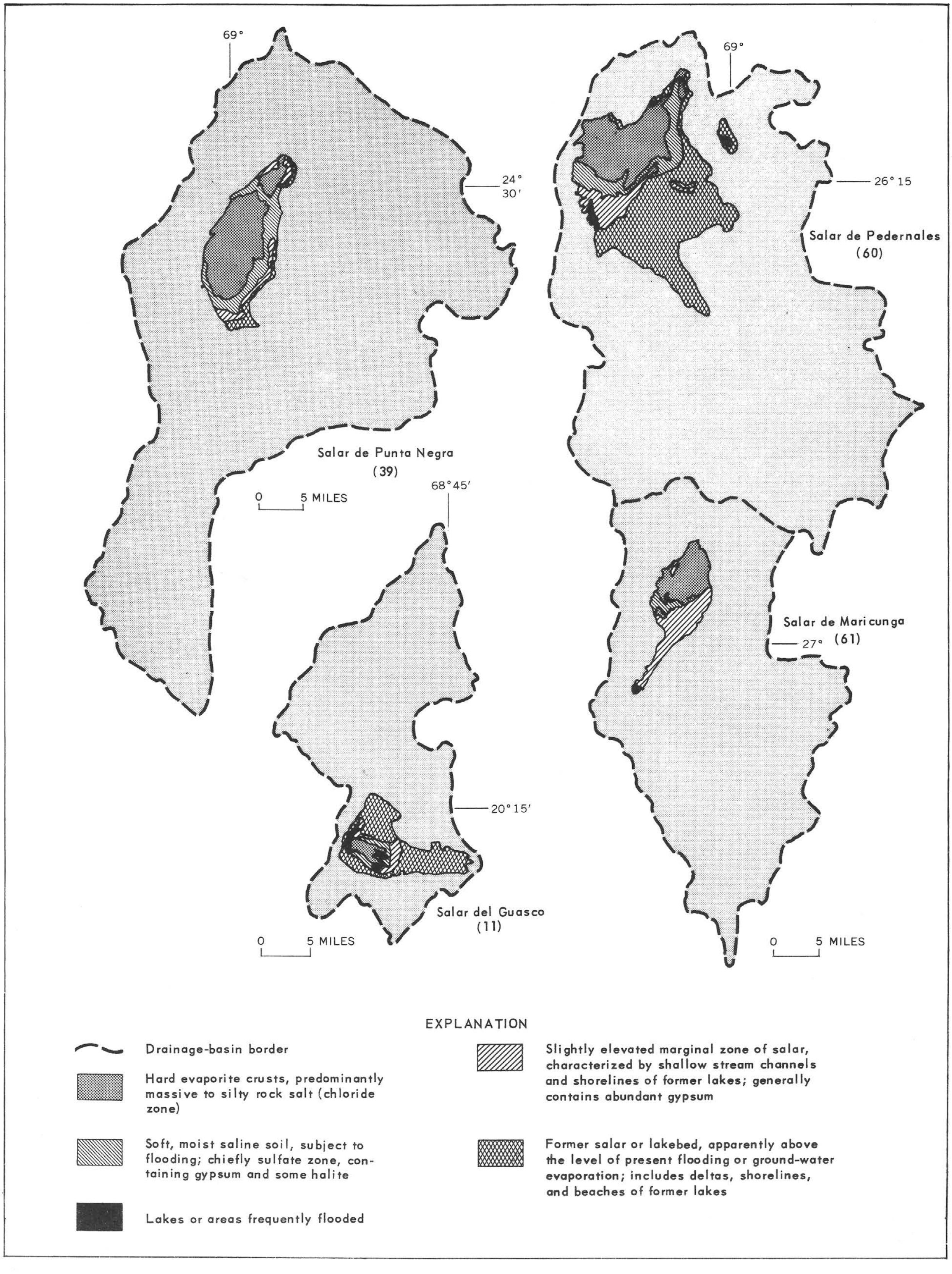


FIGURE 6.—Asymmetrical zoning of salars and drainage basins in northern Chile, attributed in part to faulting and tilting of basins. Numbers keyed to table 1.

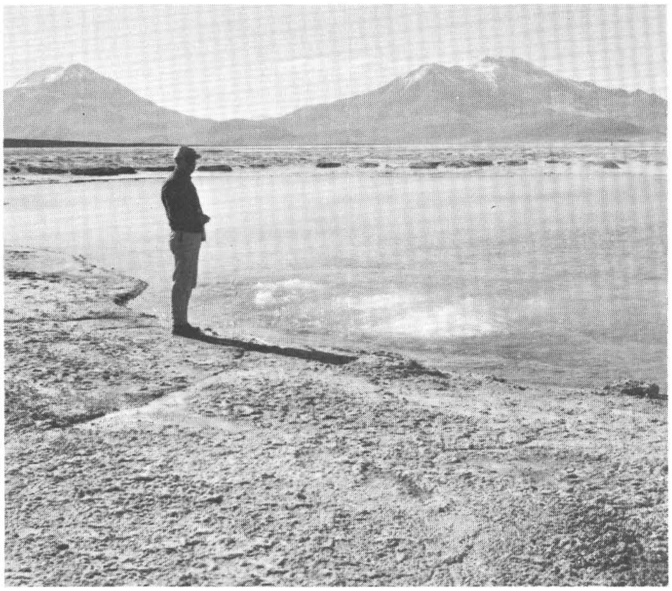


FIGURE 7.—Boiling spring and pool at southeastern edge of Salar de Surire.

interior drainage occurring within 6 miles west of this salar are probably fault valleys parallel or subparallel to the major fault at the western border of the salar.

CLAY PLAYA SURFACES AND SALAR CRUSTS

Maps showing types of salar and clay playa surfaces (figs. 8–12) are based on interpretation of aerial photographs, supplemented by field reconnaisance of about 20 of the salars. More detailed maps were made of 28 of the salars; five maps are shown as examples in figures 13–15. It was found that in many cases subtle differences between crustal types are more clearly visible in aerial photographs than on the ground. However, only the more general categories were identifiable from photographs alone without the benefit of a field check. Nine crustal types were mapped in the salars in northern Chile; however, intermediate crustal types can be recognized and could be shown in more detailed maps than we made in this study. Several of the crustal types are based on terminology suggested by Neal and others (1968, p. 74).

Two major crustal types can be recognized in the salars: (1) perennial hard crusts, which are permanently dry or infrequently flooded, and (2) soft crusts or saline soils which generally have near-surface ground water of comparatively low saline content and are subject to frequent flooding and (or) leaching by rain; crusts of the latter type may be either perennial or ephemeral. These two crustal types are distinguished in the maps of salars shown as figures 8–12. At most salars, the hard evaporite crusts are roughly equivalent to the zone of chlorides, whereas the soft crusts are roughly equivalent to the zone of sulfates, which in the Chilean salars consists chiefly of gypsum, mirabilite (or thenardite), and ulexite.

Other minerals are comparatively rare in Chilean salars. Glauberite and aphthitalite have been reported in Salar de Pintados (Gale, 1918; Pedro Alvear, oral commun., 1962). We found considerable amounts of calcium carbonate (aragonite or calcite), evidently of lacustrine origin, in Salar de Ollagüe. Trona (sodium carbonate) is rare in the Chilean salars, although Vila (1953) reported thin layers of trona in several salars in the Andes of eastern Antofagasta Province, including the following salars shown in figure 11: Tara, Pujsa, Quisquiro, and Laco. Small amounts of the newly described mineral hydroglauberite occur in association with mirabilite in Salar de Pintados (Ericksen and Mrose, 1970, p. 14).

CLAY PLAYAS

Size analyses and physical properties were determined for samples of playa clastic materials and lake sediments, as well as dune sand and beach gravels at or near several salars in northern Chile. The results of these determinations are listed in table 2, and size-gradation data are shown in figure 16.

Clay playas consist predominantly of clay, silt, and fine sand, and have surfaces ranging from hard and compact to somewhat soft. A small playa in the southern part of the Central Valley near the railroad station of Lacalle (fig. 10) might be termed a typical dry-clay playa, but the sediments are predominantly clayey silt rather than clay. Clastic sediment is deposited periodically on some parts of this playa by infrequent floods, whereas other parts are being eroded, having gullies as deep as 10 inches. The playa surface is marked by mud-crack polygons of a nonoriented type (fig. 17). A sample of the upper 4 inches of the playa (sample 19, table 2) consists of clayey silt (soil type ML), which, after leaching of soluble salt, consists of 43.2 percent silt, 40.5 percent clay, and 16.3 percent fine sand. This sample contained 4.0 percent water-soluble salt, chiefly halite. The surface is somewhat soft, as can be noted from the sunken vehicle tracks in figure 17.

TABLE 2.—*Gradation characteristics and physical*

[Soil type (Unified Soil Classification System): CL, clay of low plasticity; ML, poorly graded sand; SW, well-graded sand.

Sample identification, location							Atterberg Limits (fraction passing No. 40 sieve)		
Sediment type	Sample number	Name of salar	Depth of sample (cm.)	Geographic coordinates	Elevation (ft) (very approx.)	Specific gravity	Liquid limit (percent)	Plastic limit (percent)	Plasticity index
Playa or lake clay	52	Salar near Rosario.	0–10	24°15′S. 70°02′W.	3,950	2.92	26.3	22.0	4.3
	48	Salar del Carmen.	25–50	23°38′S. 70°17′W.	1,700	2.85	29.3	21.5	7.8
Playa silt	19	Playa near Lacalle.	0–10	24°28′S. 69°51′W.	4,750	2.91	23.5	±21.5	±2.0
	208	Salar Mar Muerto.	0–10	23°48′S. 69°49′W.	2,380	2.83	24.9	21.3	3.6
Playa sand	62	Salar near Imilac.	0–10	24°17′S. 68°50′W.	10,000	2.71	15.2	12.2	3.0
	92	Salar de Obispo.	30	19°39′S. 69°56′W.	3,500	2.62	29.2	±27.4	±1.8
	88	Salar de Llamara.	0–10	21°13′S. 69°33′W.	2,600	2.76	17.3	±17	±0.3
	91b	Salar de Pintados.	25–30	20°26′S. 69°43′W.	3,370	2.69	±20.5	±19	±1.5
Dune sand	99	Salar de Coposa.	0–10	20°38′S. 68°37′W.	12,300	---	---	---	--
	101	Salar del Guasco.	0–10	20°17′S. 68°49′W.	12,400	---	---	---	--
Beach sand and gravel	20	Salar de San Martin.	0–10	21°19′S. 68°18′W.	12,350	---	---	---	--
	37	Salar de Ollague.	0–10	21°13′S. 68°19′W.	12,350	---	---	---	--
Terrace Sand (various components)	98	Salar de Coposa.	0–10	20°41′S. 68°36′W.	12,500	---	---	---	--
	102	Salar del Guasco.	3–10	20°15′S. 68°52′W.	12,400	---	---	---	--
	36	Salar de Ollague.	0–10	21°13′S. 68°19′W.	12,350	---	---	---	--

Depth to the water table is unknown but is probably several tens of feet, or more.

A dry-clay playa south of Oficina La Joya (fig. 1) is several square miles in area and is thought to be the largest dry-clay playa in northern Chile. It differs from the playa near Lacalle in having a hard-clay and silt surface marked by mud-crack polygons as much as 3 feet in diameter. Smaller dry-clay playas are found at several other places in the Coastal Range and Central Valley of northern Chile.

Other dry-clay playas and areas of lake sediments are being eroded by gullying and by wind deflation. Such areas are found along the eastern edge of Salar de Llamara in the vicinity of Cerro Soledad (fig. 9; sample 88, table 2), and at Salar Mar Muerto (fig. 10; sample 208, table 2). Surface material in these areas consists of clayey silt or silty fine sand (soil type ML–SM) and is partially covered by a thin mantle of wind-rippled sand. These playas are estimated to be of Holocene age, representing the last episode of playa sedimentation in the basins. An old playa on the east edge of Salar de Llamara is dissected by steep-sided gullies to depths of at least 5 feet and by wind-eroded blowouts at least 2 feet deep. Salar Mar Muerto is chiefly a playa that has been strongly dissected by gullying and wind blowouts.

A clay playa in the Central Valley, several miles south of Salar de Obispo (fig. 8), is locally wind eroded; a scalloped surface has formed (fig. 18) that is similar to wind-eroded surfaces of other clay playas in northern Chile. At places in this same area, as shown in figure 18, the ground is covered with round boulders of rhyolite tuff that were derived from the wind-eroded playa sediments. These boulders were carried by floods from the Andes and evidently moved out onto the playa by rolling or floating along in sheet wash and thin mudflows.

The environment of deposition of the eroded clay playa sediments was similar to the present environ-

properties of clastic sediments from northern Chile

silt of low plasticity; SM, sand with appreciable amounts of silt; SP,
From U.S. Army Corps of Engineers (1953)]

	Mechanical analysis (combined hydrometer and sieve)							Gradation characteristics			Classification	
	Gravel (percent)	Sand (percent)		Silt (percent)		Clay (percent)		Diameters for given percent finer (mm.)				
Water-soluble salt (percent of original sample, by wt.)	Gravel (>4.76mm; >No. 4 sieve)	Coarse-medium sand (4.76–0.42 mm.)	Fine sand (0.42–0.074 mm.)	Coarse-medium silt (0.074–0.02 mm.)	Fine-very fine silt (0.02–0.004 mm.)	Coarse-medium clay (0.004–0.001 mm.)	Fine-very fine clay (<0.001 mm.)	D_{60} (60 percent finer)	D_{30} (30 percent finer)	D_{10} (10 percent finer)	Soil type	Soil name (all are inorganic soils)
6.7	0	0.9	5.2	12.5	20.9	35.6	24.9	0.0039	0.0013	est. 0.00057	CL-ML	Silty clay
12.3	0	0.5	5.8	4.7	28.5	44.0	16.5	.0039	.0016	est. .0008	CL	Do.
4.0	0	0.2	16.1	24.1	19.1	14.8	25.7	.021	.0013	est. .00034	ML	Clayey silt
4.6	0	0.3	9.2	22.0	36.3	12.3	19.9	.0099	.0035	est. .00038	ML	Do.
8.6	0.9	15.0	28.3	16.0	13.5	8.9	17.4	.099	.0055	est. .00054	ML-SM	Silty fine sand
0	6.6	3.6	32.8	12.1	17.1	18.2	9.6	.085	.0047	.0010	ML-SM	Do.
1.2	0	7.2	41.8	20.1	9.9	8.8	12.2	0.10	.016	est. .00071	ML-SM	Do.
0	0	2.5	58.8	5.3	8.6	12.5	12.3	0.18	.0081	est. .00073	SM	Do.
---	0	11.0	88.0	±1.0	0	0	0	0.25	.185	.135	SP	Poorly graded sand
0	0	33.0	58.0	9.0	0	0	0	0.34	0.17	0.08	SW-SM	Silty sand, well-graded
0	12.0	48.0	34.0	±6.0	0	0	0	2.7	0.19	0.11	SP-SM	Silty sand, poorly graded
0	20.5	49.5	24.2	±5.8	0	0	0	3.1	0.42	0.12	SP-SM	Do.
0	10.6	43.8	32.8	12.8	0	0	0	0.87	.205	.061	SM	Silty sand
0	8.5	45.5	41.5	±4.5	0	0	0	0.72	0.24	0.12	SP	Poorly graded sand
0	3.0	62.5	32.0	±2.5	0	0	0	0.99	0.36	.177	SP	Do.

ment in the Central Valley except that runoff from the mountains was sufficiently great or sufficiently frequent to create more extensive ephemeral lakes. Even today, ponds or small playa lakes form at a few places along the western border of the Pampa del Tamarugal, particularly in the area between Salar de Pintados and Salar de Obispo (fig. 1), every year or two, after exceptionally heavy rains in the Andes. These playa lakes dry up in a few days, leaving a thin deposit of silt, clay, and fine sand.

Clastic sediments are commonly found beneath the salt crusts of many of the salars in the Central Valley; these sediments probably were deposited during a former time of slightly greater rainfall in the mountains to the east, during which runoff was sufficient to form playa lakes. The sediments are of several types, as shown by samples in table 2. Silty clay (soil type CL) was found beneath a 10–inch salt crust of Salar del Carmen (fig. 10; sample 48, table 2), and silty fine sand (soil types ML–SM or SM), beneath the 10–to–12-inch salt crusts of Salar de Obispo (fig. 8; sample 92, table 2) and Salar de Pintados (fig. 13; sample 91b, table 2). Very fine, clastic sediment collected from Salar del Carmen and a salar near Rosario (fig. 10) consists of 60.5 percent clay, 33.2 percent silt, and 6.3 percent sand; the samples also contained 6.7 percent and 12.3 percent of water-soluble salts, respectively. Coarse playa sediments from Salar de Obispo and Salar de Pintados contain 25–28 percent clay, 14–30 percent silt, 36–61 percent sand, and as much as 7 percent gravel. Water-soluble salts occur in trace amounts only. These relatively coarse sediments probably resulted from torrential streamflow and mudflows, which still occasionally pour out into the Central Valley after especially hard rains in the Andes.

Layers of saline material, chiefly gypsum or anhydrite, are interbedded with clay playa or lake sediments beneath some salars (fig. 19). These layers are either remnants of old salar crusts or layers

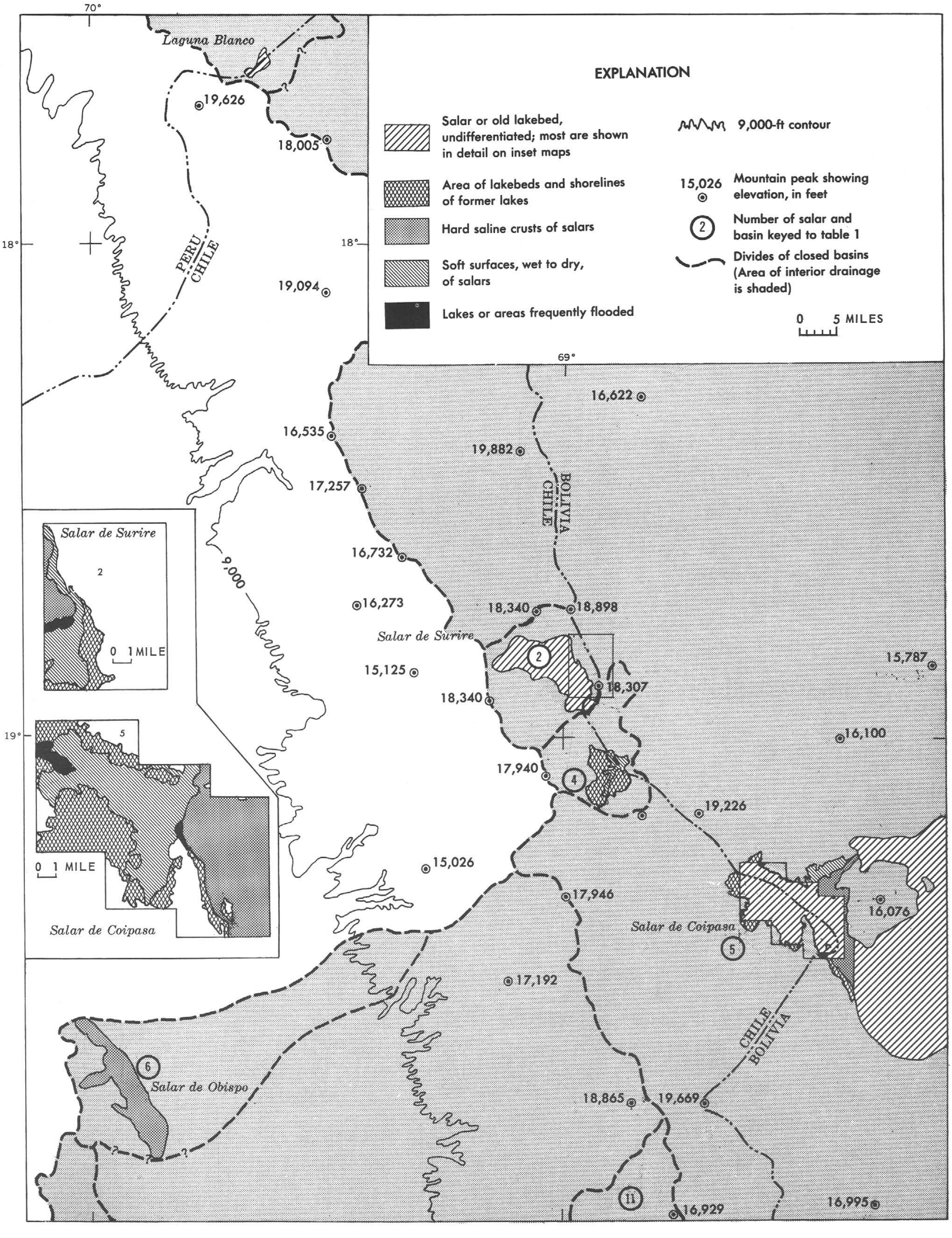


FIGURE 8.—Salars and basins of interior drainage in the northern part of Tarapacá Province, Chile.

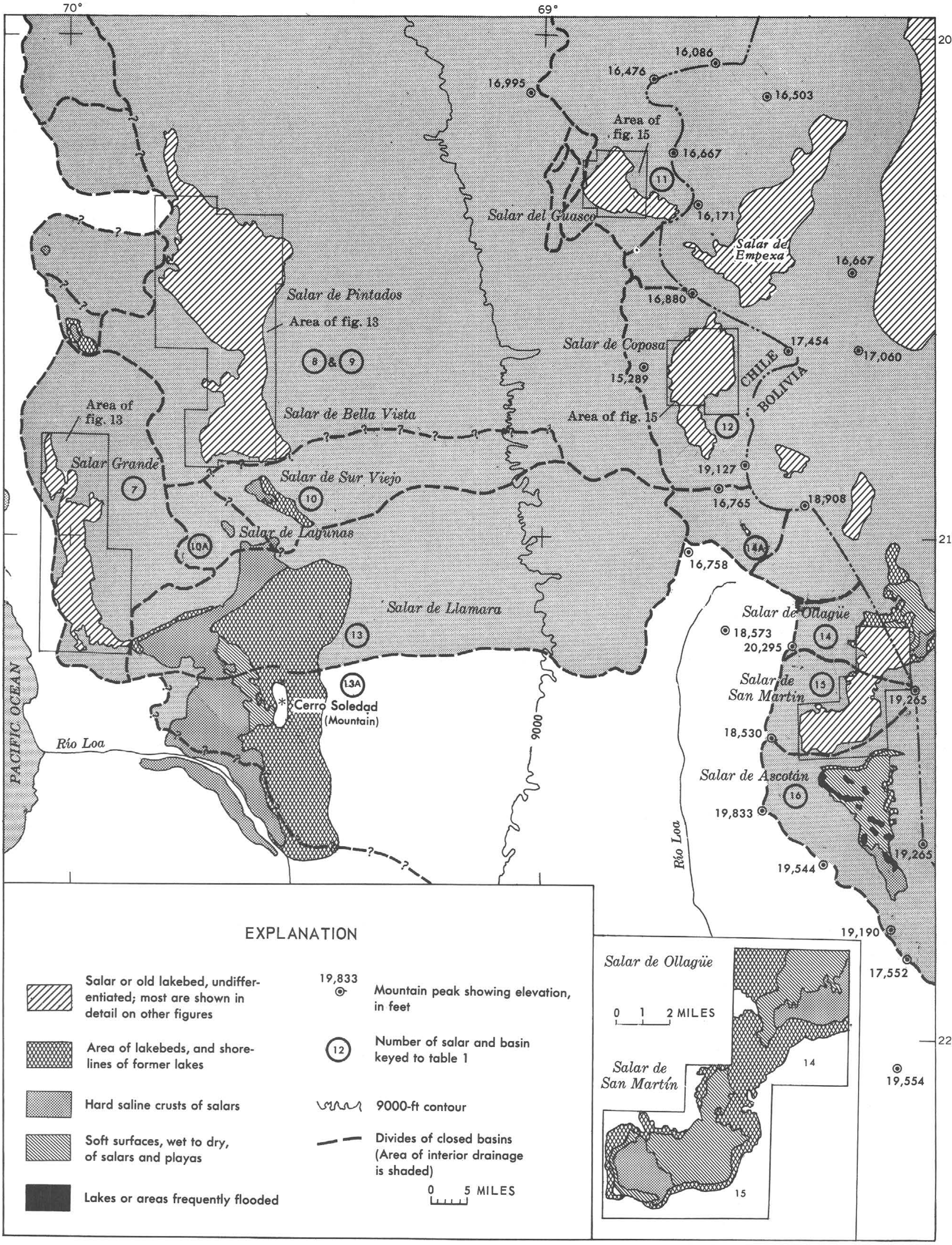


FIGURE 9.—Salars and basins of interior drainage in the southern part of Tarapacá Province and northeasternmost part of Antofagasta Province, Chile.

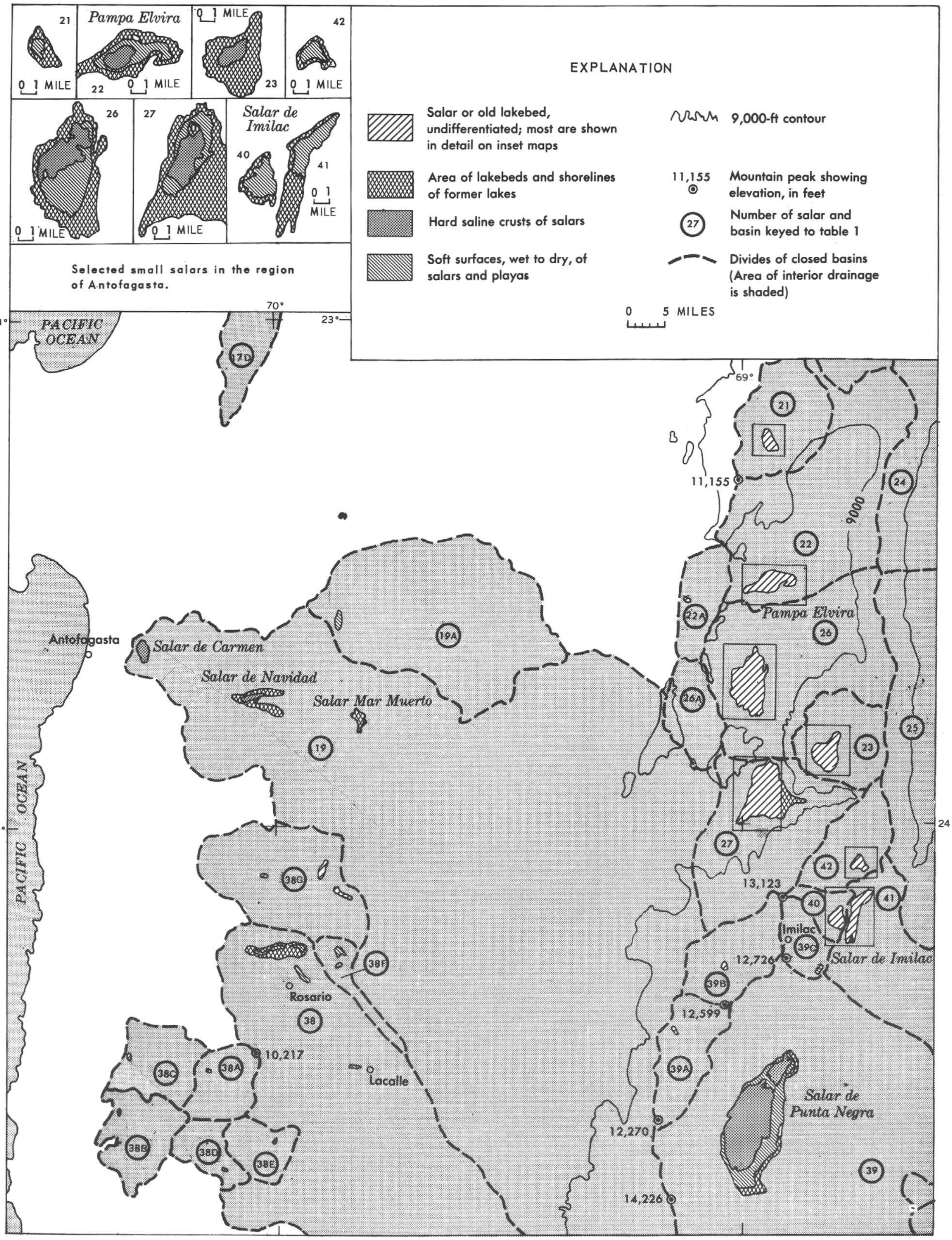


FIGURE 10.—Salars and basins of interior drainage in the western central part of Antofagasta Province, Chile.

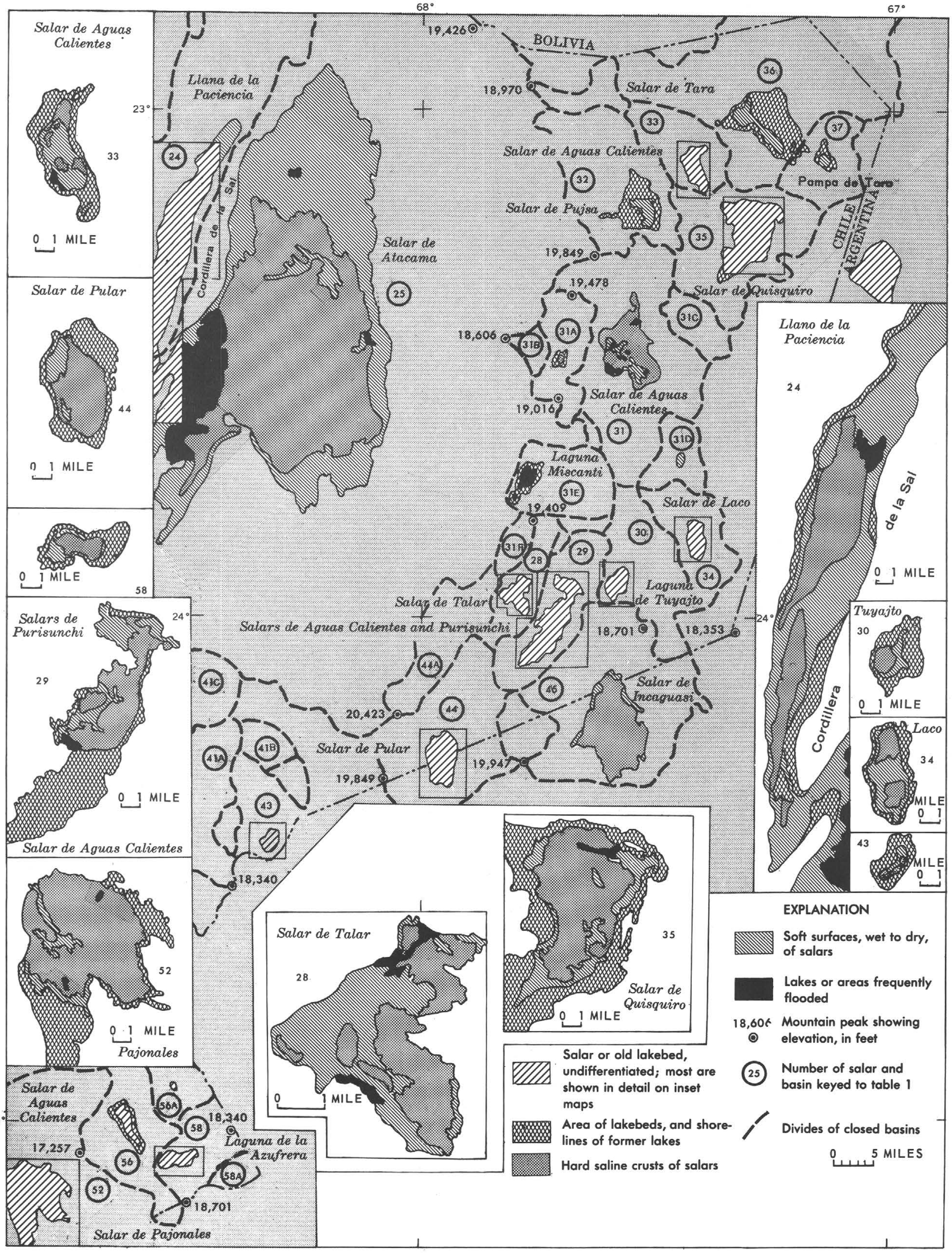


FIGURE 11.—Salars and basins of interior drainage in the eastern central part of Antofagasta Province, Chile.

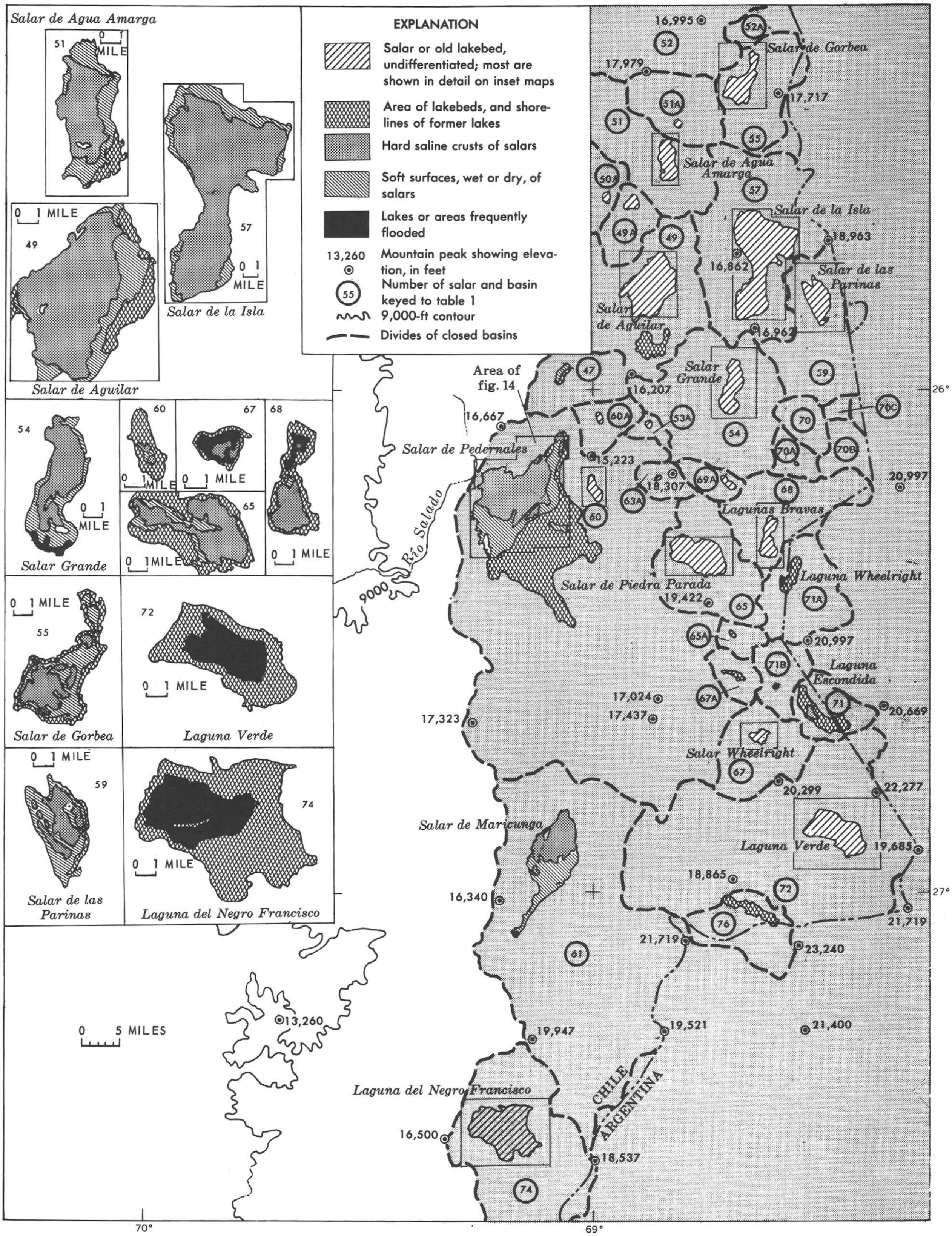


FIGURE 12.—Salars and basins of interior drainage in the northeastern part of Atacama Province, Chile.

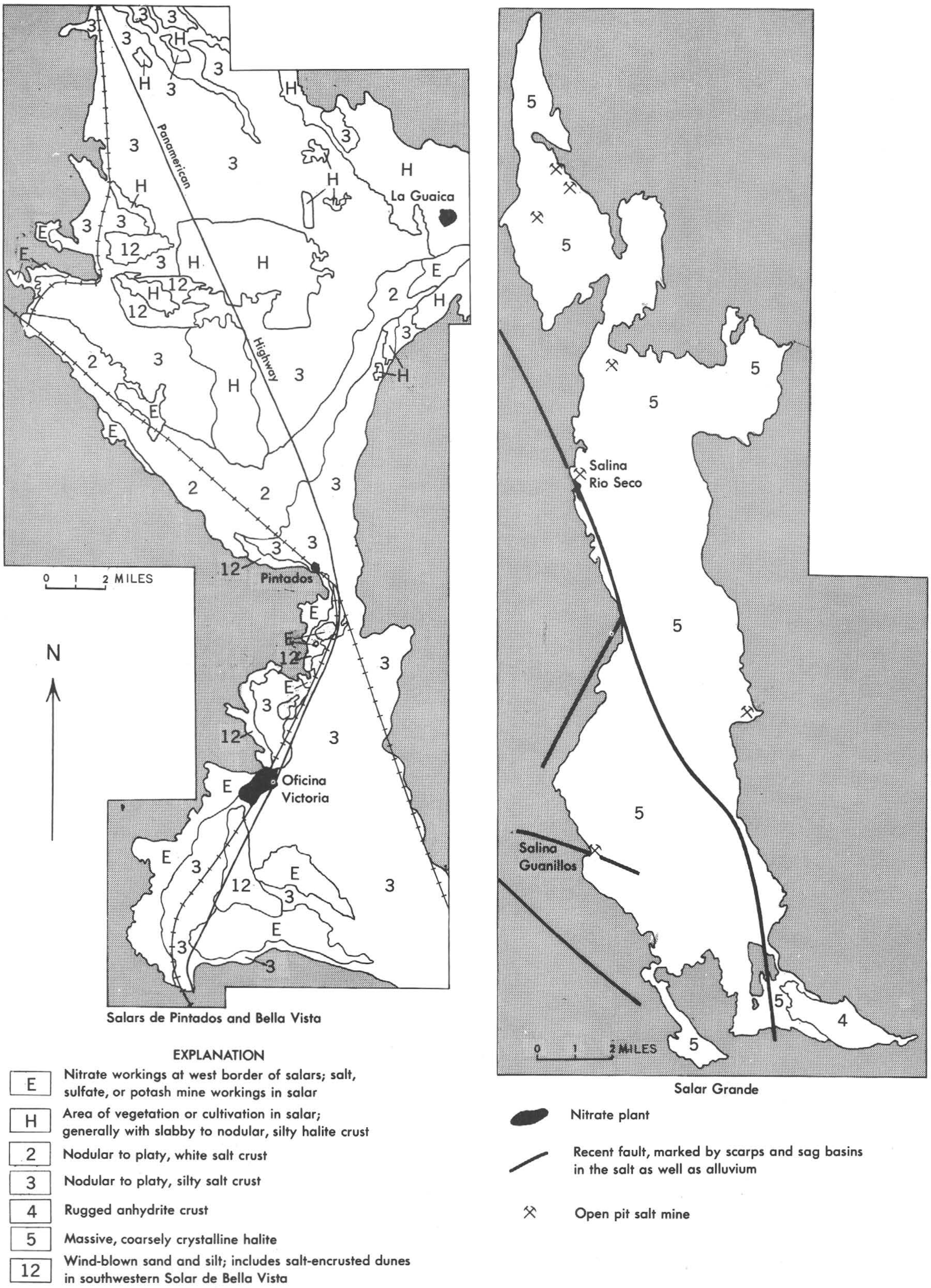
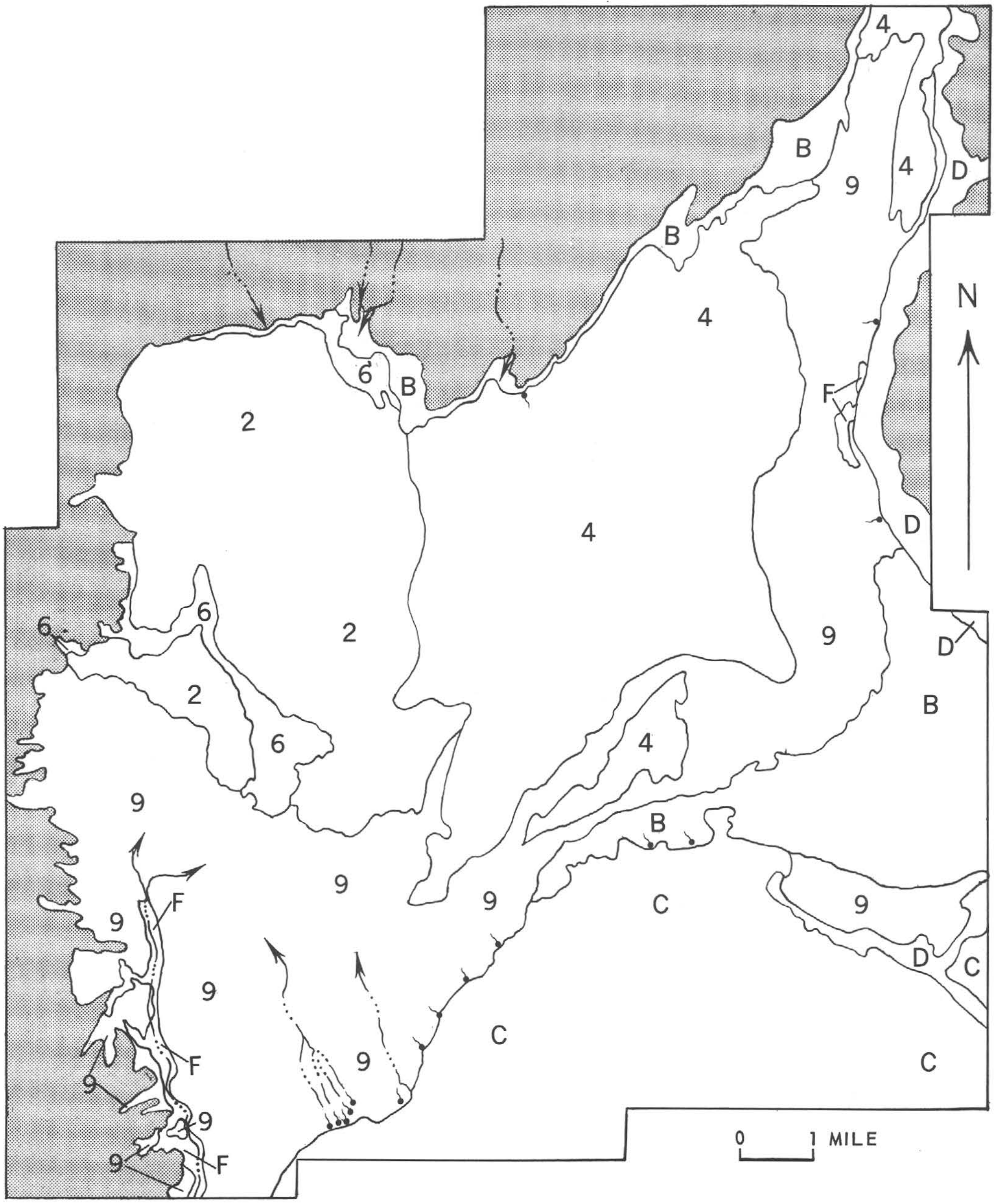


FIGURE 13.—Geologic maps of Salar de Pintados, Salar de Bella Vista, and Salar Grande. Location shown in figure 9.



EXPLANATION

B	Undifferentiated lacustrine sediments, includes saline to gypseous soils
C	Delta of former lake
D	Area showing shorelines of former lake
F	Pond or area frequently flooded
2	Knobby, massive white rock salt
4	Rugged gypsum crust
6	Smooth halite flood plain
9	Sulfate zone, undifferentiated; consists chiefly of soft moist gypseous soil
⟶•	Spring
—···⟶	Intermittent stream showing direction of flow

FIGURE 14.—Geologic map of Salar de Pedernales. Location shown in figure 12.

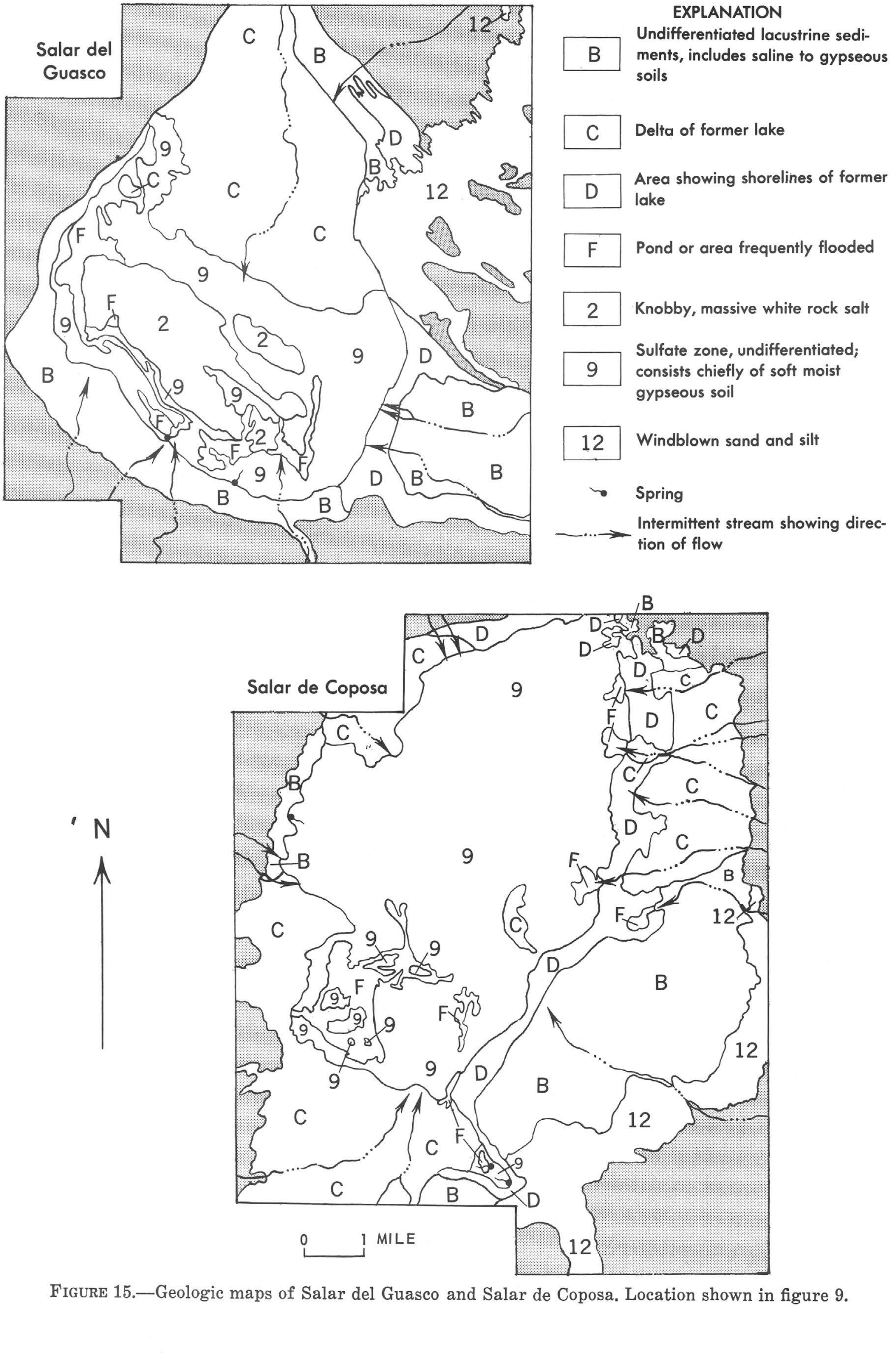


FIGURE 15.—Geologic maps of Salar del Guasco and Salar de Coposa. Location shown in figure 9.

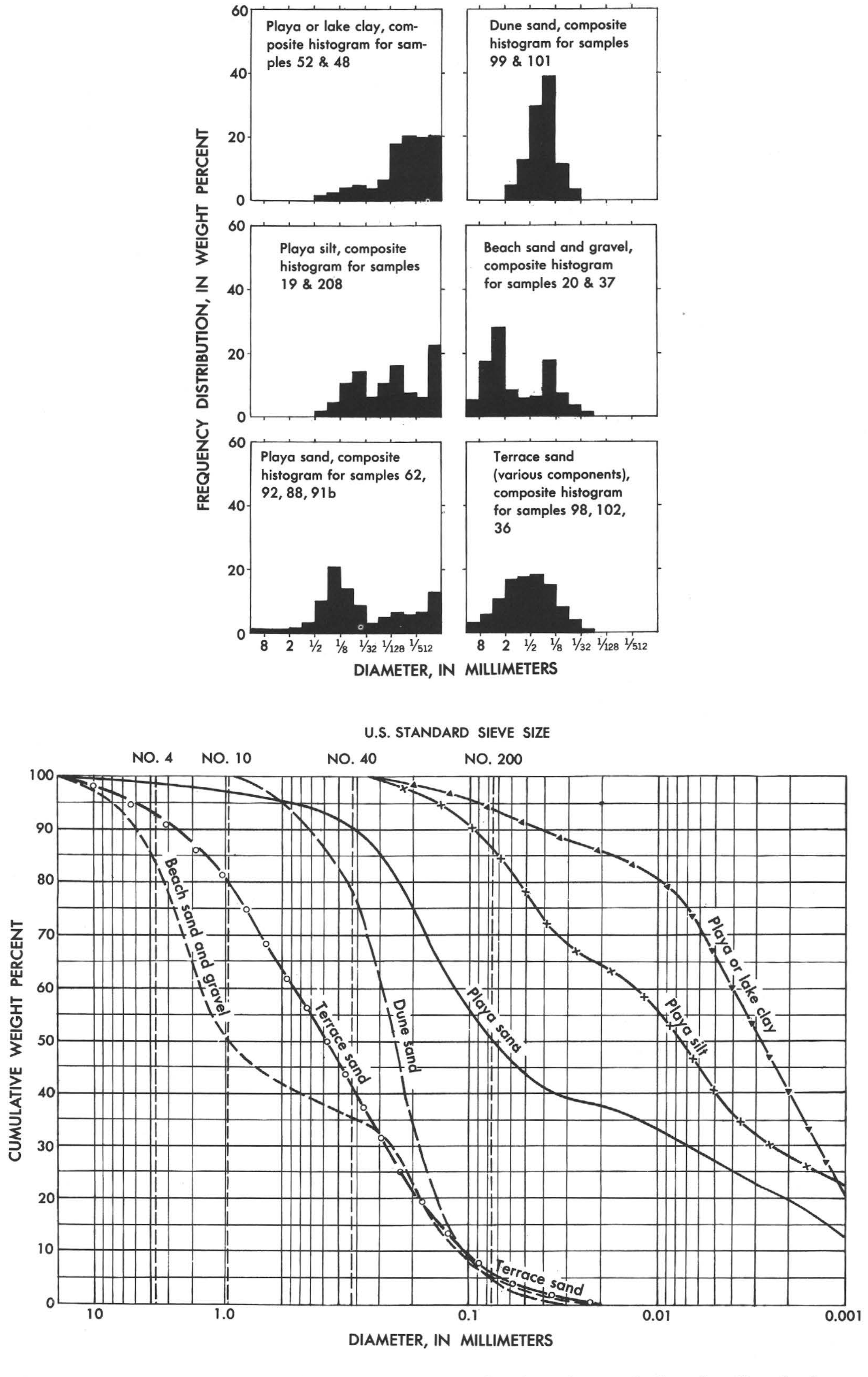


FIGURE 16.—Histograms and cumulative curves showing size-gradation for the six types of clastic sediments listed in table 2.

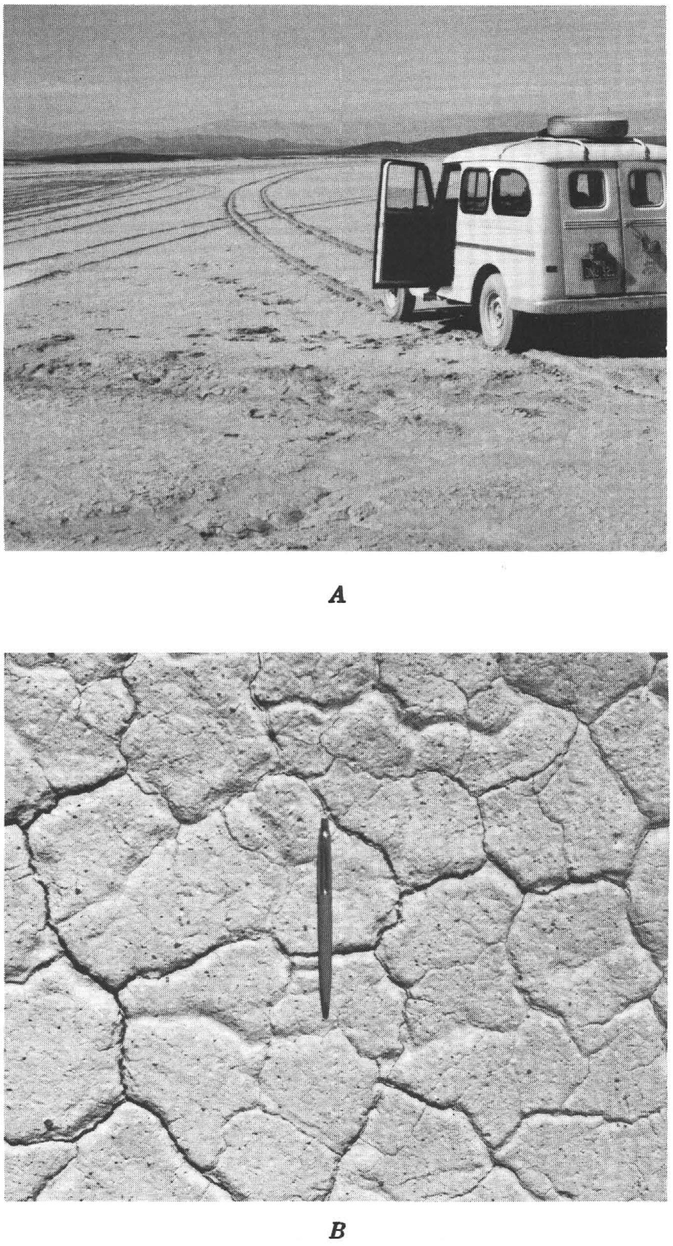


FIGURE 17.—Active mud-cracked dry-clay playa near the Lacalle railroad station. *A*, Soft surface showing car track 1–2 inches deep. *B*, Surface of playa showing randomly oriented mud-crack polygons.

of saline material deposited in the soil at the top of a temporary ground-water level.

HARD EVAPORITE CRUSTS

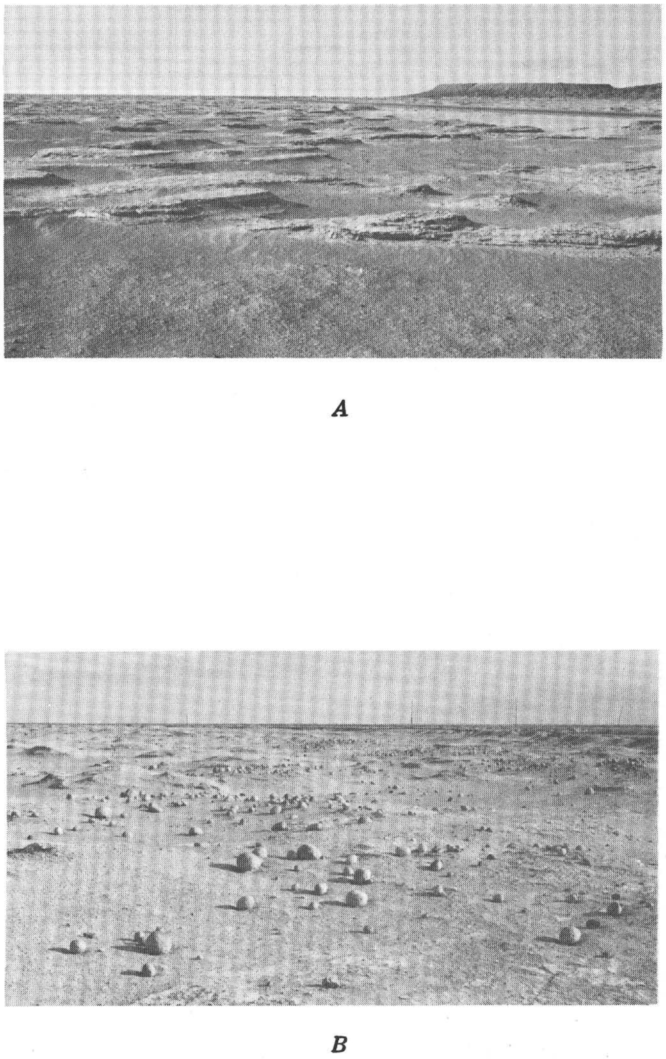


FIGURE 18.—Wind-eroded dry-clay playa sediments in the Pampa del Tamarugal several miles south of Salar de Obispo. *A*, Wind blowouts 2–3 ft deep in thinly layered playa sediments. *B*, Rounded boulders, averaging 6 in. in diameter, of rhyolite tuff eroded from the playa sediments. The boulders were rafted into the area by muddy flood waters or thin mudflows.

Six types of hard evaporite crusts can be recognized in the salars of northern Chile, of which five have very rugged surfaces and one a relatively smooth surface. Most of the hard crusts consist chiefly of halite, but a few consist of anhydrite or gypsum. The rugged types are characterized by predominantly dark tones on aerial photographs because they are generally either covered by a thin mantle of windblown or waterborne silt and fine sand or contain clastic material incorporated from underlying playa or lake sediments. The smooth type appears white to light gray on aerial photographs, evidently because it consists of a hard perennial layer of relatively fresh pure salt that is not covered with windblown sediment. The rugged perennial crusts appear to be above the highest local level generally reached by flood waters, either from surface runoff or from rising ground-water tables, whereas

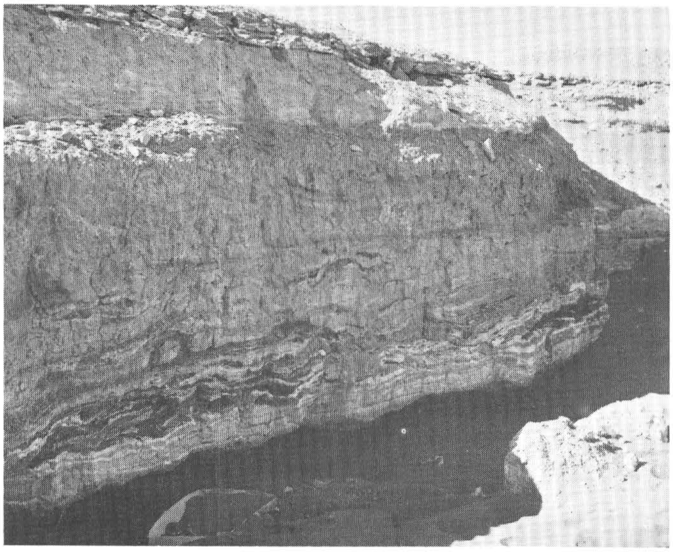


FIGURE 19.—Pit about 6 ft deep in clay playa near north end of Salar de Pintados showing layers of anhydrite, the white bands in lower part of pit wall.

the smooth white crusts are subject to rather frequent, perhaps annual, flooding. Some hard crusts are in a state of change from smooth to rugged or rugged to smooth in response to changing patterns of flooding and consequently are gradational or intermediate types. Hard evaporite crusts evidently cover more than 1,500 square miles, more than 50 percent of the total area of Chilean salars. This is in marked contrast to closed basins in the United States, for example, where hard evaporite crusts are comparatively rare. Although there are as many closed basins in the United States as in Chile, the only good examples of hard evaporite crusts are in Death Valley, Calif. (Devil's Golf Course and similar areas); the Bonneville Salt Flats, Utah; Searles Lake, Calif.; Bristol Lake, Calif.; and possibly a few other dry lakes in the Mojave Desert of southeastern California.

LAYERED MASSIVE ROCK SALT WITH A RUGGED SURFACE

The most prevalent of the six types of hard evaporite crusts in the Andean region is a rugged perennial massive rock-salt crust deposited during evaporation of Quaternary lakes. These crusts are commonly in a relatively inaccessible setting, being surrounded on nearly all sides by the soft water-saturated soil of the sulfate zone. Their extremely rugged surfaces prevent travel by vehicle and make foot travel difficult; consequently, they are poorly known. On recent maps, made in the early 1960's (U.S. Air Force, Operational Navigational Charts, for example), many of these areas are erroneously shown as lakes.

The rock salt is massive, consisting of layers of hard white fine-grained salt, generally more than 4 inches thick, separated by thin layers of silty salt. Near the northwestern edge of Salar de Pedernales (fig. 14) two prominent layers within the upper 3 feet of the rock-salt crust can be seen (fig. 20). The uppermost is about 10 inches thick and is separated by a silty parting from an underlying layer, which is more than 18 inches thick, extending below the bottom of the pit. The parting is irregular and probably is an old surface of the salar that was thinly blanketed by windblown silt, just as the present surface is. The salt crust here appears to be exceptionally thick in comparison with that of other salars. Layered white high-purity rock salt can be seen in the walls of brine pools such as the one shown in figure 21. The brine level here was about 2 feet below the salt surface at the time of our visit in May 1967, as is shown in figure 21. Depth of this pool was estimated to be 25–30 feet; the vertical to overhanging walls are composed of pure white salt. The bottom could be seen covered with fragments of the salt, visible beneath the perfectly clear brine. The exceptional thickness of salt may result from gradual subsidence of the northwestern part of the salar, which is near a large fault zone, from repeated flooding, and from intermittent deposition of rock salt. The pool probably formed by solution of the

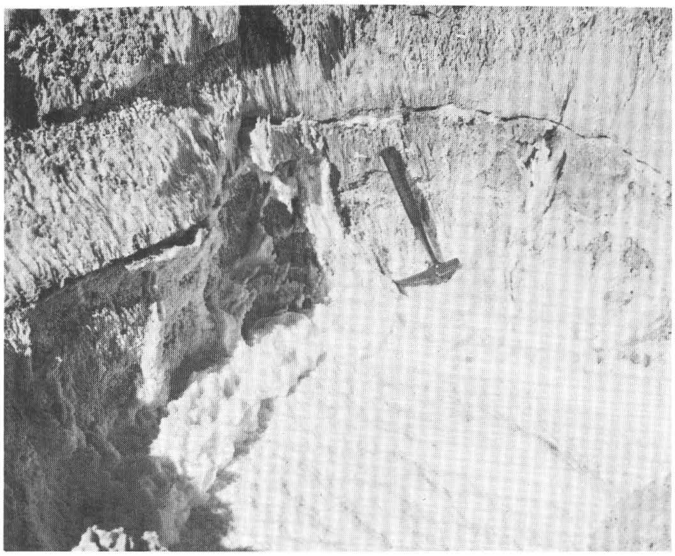


FIGURE 20.—Layering of massive rock salt near the northwestern edge of Salar de Pedernales. The upper 10-in. layer of salt is separated from the underlying salt by a ¼- to 1-in. layer of silty salt.

FIGURE 21.—Brine pool in thinly layered high-purity rock salt in the northern part of Salar de Pedernales. The pool, 25–30 ft deep, is probably formed by solution of the crust by a recently developed fresh-water spring in the clastic sediments underlying the salar crust. The pinnacled surface around the pool is due to periodic (annual?) flooding as the water table rises.

crust by water from a newly developed spring in the clastic sediments below the salt crust. Such a spring could have formed on one of the recent faults known to exist in this area.

Infrequent flooding of the massive rock-salt crusts and periodic leaching by rainfall generally form extremely rugged and pitted surfaces. These surfaces may have delicate pinnacles and knobs like the surface near the salt pool shown in figure 21, or, more typically, they may be rugged and hummocky, as shown in figure 21 at a greater distance from the pool, where the surface has an average relief of about a foot. More rarely, the leached surface has an extremely irregular network of pits and knobs with a delicate clinkerlike texture, as shown in figure 22.

SLABBY OR NODULAR SILTY ROCK SALT

Silty rock-salt crusts consist chiefly of halite with varying but generally lesser amounts of clay, silt, and sand. They have formed by capillary evaporation of subsurface moisture that deposited salt at the surface and as a cement in the surface layer of the fine-grained clastic sediments. In this way, a silty salt crust forms, and deposition of salt continues by evaporation of ground water at the base of the crust. Silty rock-salt crusts are characteristic of the extremely arid Central Valley and Coastal Range. Typical silty crusts are those of Salar de Obispo (fig. 8), Salar de Pintados (fig. 13), Salar de Bella Vista (fig. 13), Salar de Lagunas (fig. 9), and Salar del Carmen (fig. 10). Similar crusts were seen in the northern part of Salar de Punta Negra (fig. 10) and at the eastern edge of Salar de Atacama (fig. 11).

FIGURE 22.—Rugged perennial rock-salt crust showing delicate clinkerlike texture, southeastern part of Salar de Atacama.

This type of crust consists of salt-cemented clastic material that commonly makes up more than 25 percent of the crust. The crusts are underlain by uncemented fine-grained playa and lacustrine sediments that appear similar in color and composition to the clastic material within the crust. The transition from hard crust to soft underlying sediment is abrupt (fig. 23). Although the term silty rock salt has been used for convenience, the clastic material may range from clay to coarse sand. The crust consists of a partially cemented rubble of irregular to polygonal slabs and nodular fragments (see fig. 39) that formed by breaking of the older crust as a new crust formed below and pushed it upwards. Thermal expansion and contraction in response to diurnal and seasonal temperature changes contributed to the breaking and heaving of the crust. The crust is generally 1–4 feet thick but locally exceeds 5 feet. The nodular surface is attributed in part to modification of salt fragments by winter fog, the camanchaca.

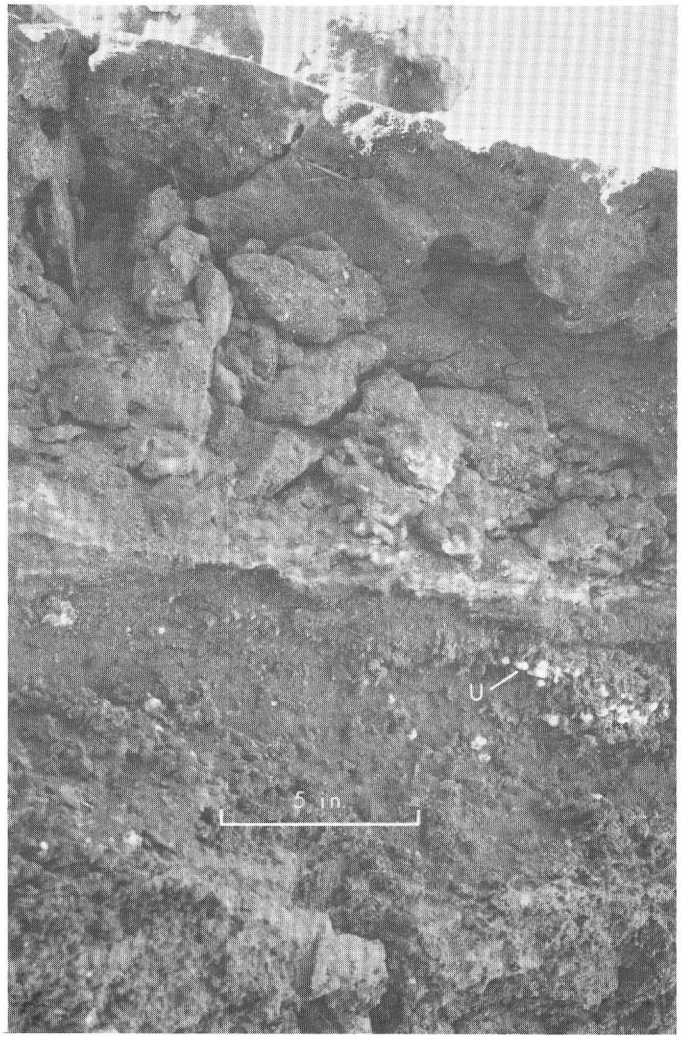


FIGURE 23.—Section of slabby and nodular silty rock-salt crust exposed in cut along Pan-American Highway, Salar de Obispo. The crust is underlain by silty sand, which is loosely cemented by a meshwork of gypsum crystals and contains blebs and small nodules of white ulexite (U).

Salars having crusts of this type are in basins that formerly had ephemeral lakes in which fine clastic sediments and saline material were deposited. When the climate became more arid, the lakes dried, and deposition of saline minerals by ground water began. The water came from the Andes in sufficient quantity to maintain a near-surface ground-water table. The high rate of evaporation inhibited accumulation of surface water. Deposition of such salar crusts is taking place today in parts of several salars, including Salar de Pintados and Salar de Bella Vista.

Evaporation of ground water has played a role in past deposition of silty rock-salt crusts in the Andes, as it does today, but because of flooding and washing by rains, such crusts tend to be ephemeral. Salar crusts formed by surface water and by ground water are believed to be extensive and intimately associated in the Death Valley salt pan, California (Hunt and others, 1966, p. B64), where their differentiation required detailed mapping. The two types appear to be identical in aerial photographs of that area, as they do in Chile.

RUGGED GYPSUM OR ANHYDRITE

Rugged gypsum or anhydrite crusts are exceptional types that occur in only five or six salars. They vary widely but appear to have the common characteristic of being composed in large part of sulfate minerals, chiefly gypsum in the Andes and anhydrite in the more arid coastal region. They are moderately hard and coherent. Hard rugged crusts of sulfate minerals in salars of the Andean Highlands are rare. The sulfate zones in these salars tend to be soft, varying from a plastic gypsum mud to a moist sand consisting of subhedral gypsum crystals in areas of very shallow ground water, to a dry and friable, locally layered or laminated, very fine grained to crystalline gypsum meshwork in slightly elevated areas above the water table or capillary fringe.

The principal occurrences of the rugged dry anhydrite crust are at Salar de Llamara (fig. 9), the southeasternmost end of Salar Grande (fig. 13), the eastern part of Salar de Pedernales (fig. 14), an area along the eastern edge of Salar de Atacama (fig. 11), and an area in the western part of Salar de Surire (fig. 8).

Large areas of Salar de Llamara have a crust composed mainly of anhydrite, which has been severely eroded by wind into fluted hummocky forms and intervening irregular pits and basins that commonly have a relief of 5–10 feet. The resulting surface is the most rugged of all salar surfaces in northern Chile, being highly variable in both thickness and relief. The northern border of Salar de Llamara is several tens of feet higher than the central and southern part of the salar. Tentative conclusions regarding a possible sequence of events in formation of this crust, on the basis of a reconnaissance along the northern margin, and published information by Brüggen (1950), are as follows: (1) the anhydrite represents the original sulfate zone (gypsum) deposited on the floor and around the edges of Gran Lago Soledad, a former deep lake that periodically may have overflowed into the basin of Salar Grande; (2) at a high lake level, drainage across the Coastal Range began and ultimately cut the present sharp canyon of the Río Loa and drained the lake to the point that only a small lake remained in a subsidiary basin northwest of Cerro Soledad; (3) final evaporation of this lake resulted in deposition of high-purity rock salt; (4) movement on east-trending faults, of Quaternary age, along the northern margin of the basin caused uplifting here and tilting toward the south; (5) extensive erosion of the salar by wind deflation and gullying.

The gypsum crust in the eastern part of Salar de Pedernales (fig. 14) was not seen during the present study, but was described by Harding (1926) as a severely wind-eroded remnant of a former layer, now consisting largely of isolated mounds containing large gypsum plates and crystals. It seems probable that the gradual tilting of the Pedernales basin, upward in the southeast with respect to the northwest, has elevated an old sulfate zone. Well-preserved lake-shore lines occurring in the eastern and southern sides of the basin, as much as several hundred feet above the level of the present salar, are convincing evidence for such tilting. A gypsum layer probably covered the floor and margins of the former lake before the deposition of massive halite.

Part of the southeastern border of Salar de Atacama (fig. 11) consists of a rugged clinkerlike crust of gypsum (fig. 24) similar in appearance to the nearby rugged rock salt crust shown in figure 22. This is the only area where this type of gypsum crust was seen in northern Chile. The surface was evidently formed by the erosion, resulting from rainfall and infrequent flooding, of a hard granular gypsum crust. The crust was exposed either as the result of lowering of the ground-water table or of tilting due to faulting.

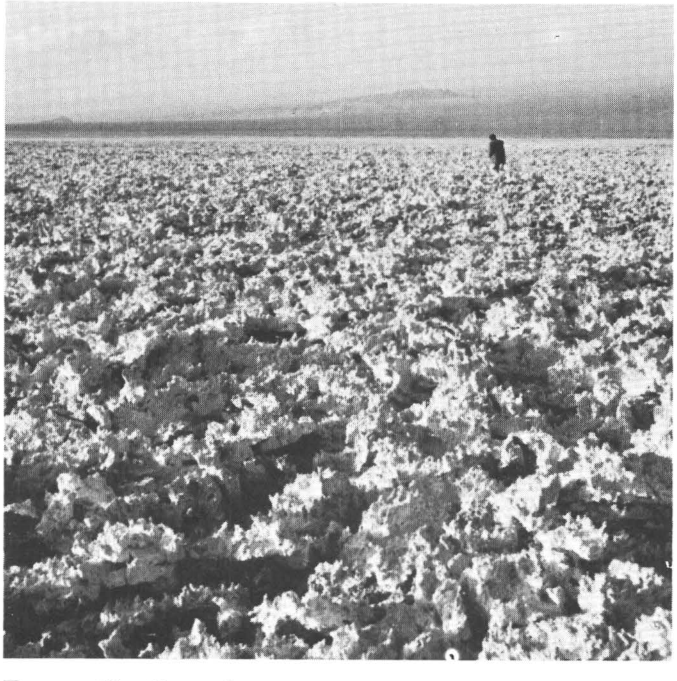


FIGURE 24.—Rugged gypsum crust showing a clinkerlike texture, eastern side of Salar de Atacama.

Another type of rugged gypsum crust, observed in the northwestern part of Salar de Surire (fig. 8) consists of a dry hard granular layered gypsum with a pitted surface. Relief is on the order of 1–3 feet, and the surface is 3–4 feet above the main level of the salar, which here consists of relatively smooth moist gypsum sand containing nodules and lenses of ulexite.

MASSIVE, COARSELY CRYSTALLINE ROCK SALT

Massive, coarsely crystalline rock salt occurs only in Salar Grande (fig. 13), a salt-filled basin, shown by drill-hole core to average more than 99 percent halite to a depth of as much as 560 feet. The surface is nodular and silty to depths of 1–3 feet, appearing similar to some of the nodular silty halite crusts of salars in the Central Valley. Thenardite is present locally as tan subhedral to euhedral crystals as much as 2 inches long in irregular zones of white sugary salt that are distinct from the more typical coarsely crystalline halite of the salar. The salt in Salar Grande has been mined in open pits for many years and presently is the source of most of the salt used in Chile.

The salt is cut by deep vertical joints (fig. 25) that are generally spaced 5–15 feet apart and, as seen in the salt quarries, may extend to depths of more than 20 or 30 feet. Silt from the surface has stained the joint surfaces reddish brown. The salt contains abundant small fluid inclusions but otherwise is dry. Drilling during the 1920's showed the presence of dry cavities and porous zones to the bottom of the salt layer. Loss of drilling water indicated that the underlying alluvium also was dry. Distinctive giant oriented polygons, hundreds of feet across, are faintly visible in aerial photographs in nearly all parts of Salar Grande. These giant polygons, as well as the smaller polygons that are outlined by the above-mentioned joints in quarries, are not apparent on the ground, being obscured by the eroded nodular surface of the salar.

SMOOTH ROCK SALT

Rock-salt crusts that are subject to periodic flooding may become covered by a relatively smooth crust of freshly deposited white halite (fig. 26). In large part, the salt is leached from an older crust near or

FIGURE 25.—Massive, coarsely crystalline rock salt in an active salt quarry, northern part of Salar Grande, showing prominent vertical joint surfaces (J) coated with silt and sand.

at the site of the new smooth crust. Smooth rock-salt crusts generally range from a few inches to a foot or two in thickness. They are underlain by a sticky mud that inhibits subsurface drainage and tend to be in shallow depressions bordering older rugged crusts.

This type of crust is found in the United States at the Bonneville Salt Flats, Utah, and in parts of the Death Valley salt pan, California. In these places the salt reportedly attains maximum thickness of more than 10 inches. The Bonneville Salt Flats appear to be subject to seasonal flooding, largely by rising ground water which is such a concentrated brine that it dissolves little or none of the perennial salt crust. Evaporation of the surface water deposits a thin smooth new layer of salt on the old crust. A halite flood plain in the Death Valley salt pan west of Badwater apparently is subject to less regular flooding, the salt probably surviving intact for periods of several years, and therefore being essentially perennial.

In Chile, smooth rock-salt crusts occur in the northern part of Salar de Maricunga (fig. 12), in the western part of Salar de Pedernales (fig. 14), and in the southern part of Salar del Carmen (fig. 10). Salar de Uyuni in Bolivia (fig. 1) consists largely of a smooth rock-salt crust, which extends over an area of many hundreds of square miles. This crust, which is commonly 10 feet or more in thickness, owes its smoothness to annual flooding by a rising ground-water table and annual deposition of a thin layer of salt. During the dry season, trucks can cross this salar at high speed in almost any direction.

The flooding of salars may originate from surface-water runoff, from a rise in the water table, or both. The salt is initially flat, but as it dries it may form polygons (fig. 26) or sharp pressure ridges (fig. 27). It tends to become rough with age if periodic flooding does not occur, as a result of cracking due to thermal expansion and contraction, and of weathering. The smooth salt crust in the southern part of Salar del Carmen (fig. 27) weathered over a period of 5 years (1962–1967) into scattered nodular fragments. This was attributable largely to condensation of fog.

SILTY NITRATE-BEARING SALAR CRUST

An unusual type of salar crust that is probably unique to the Atacama Desert of northern Chile, is one containing soda-niter ($NaNO_3$) as a significant

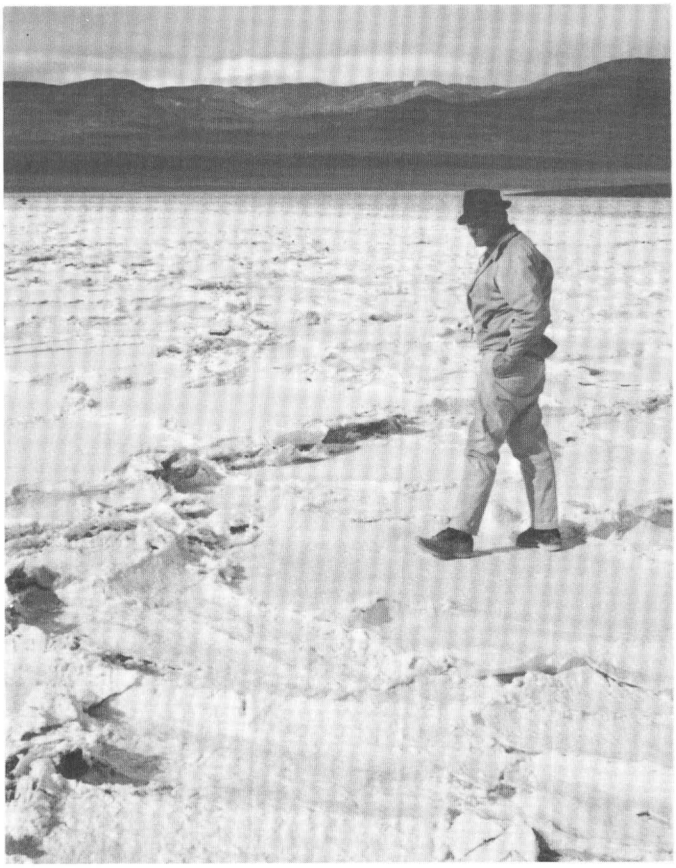


FIGURE 26.—Smooth rock-salt crust in flood plain, northwestern part of Salar de Maricunga. Salt crust is about one-half inch thick; newly formed salt polygons have upturned edges as much as 5 in. high.

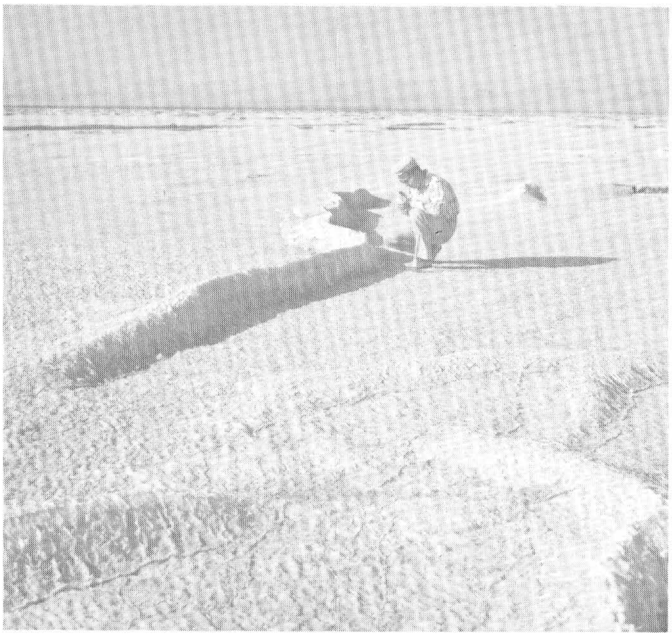
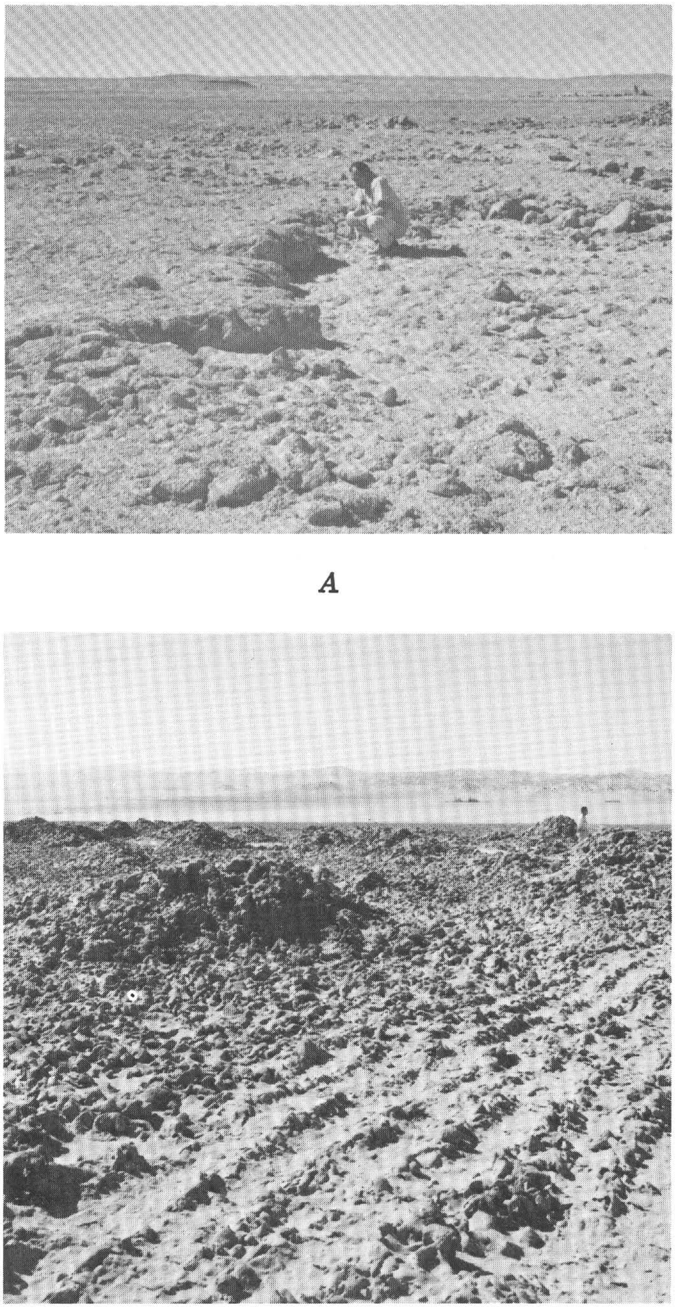


FIGURE 27.—Pressure ridges in newly deposited thin (1–2 in.) layer of white salt, southern part of Salar del Carmen.

saline constituent. Five salars in the region have been mined as a source of commercial nitrate: Salar de Lagunas, Salar de Pampa Blanca, a small unnamed salar just north of Sierra Gorda, Salar del Carmen, and another small unnamed salar near Oficina Rosario (figs. 1, 9, 10). The content of sodium nitrate in these salars ranges from a few percent to about 25 percent; those parts of the salars that were mined probably had average grades of 10–20 percent $NaNO_3$. The crusts contain considerable silt and sand from underlying sediment, thus resembling the more typical silty rock-salt crusts of other salars in the region; they also contain halite and sulfate minerals, including thenardite and gypsum, as part of the saline cement. Samples 48 and 52 (table 2) show the nature of the clastic material in the area of nitrate workings at the salar near Oficina Rosario and at Salar del Carmen. The saline complex of nitrate-bearing salars resembles the more normal nitrate caliche of this region in containing small amounts (a few hundredths to a few tenths of a percent) of perchlorate (ClO_4^-) and iodate (IO_3^-).

The silty nitrate-bearing crusts resemble the silty rock-salt crusts but tend to have smoother surfaces. They generally are not more than a few feet thick, and the richest nitrate ore is commonly in the upper part of the crust. Figure 28 shows mine areas in the southern parts of Salar del Carmen and of Salar de Pampa Blanca. Fragments in the ore piles at Salar del Carmen were tested in the field and were estimated to contain as much as 20 percent $NaNO_3$.

Salar del Carmen was mined periodically during the later part of the 19th century; according to people familiar with the nitrate industry (Frank H. Humberstone, oral commun., 1962), the nitrate ore



A

B

FIGURE 28.—Silty nitrate-bearing salar crust. *A*, Shallow nitrate workings in the southern part of Salar de Pampa Blanca. *B*, Piles of nitrate ore in the southeastern part of Salar del Carmen.

in areas that had been mined would regenerate itself in 5–10 years. Evidently regeneration involved capillary migration of ground water and evaporation to deposit $NaNO_3$ in the upper part of the crust and on the surface.

The above-mentioned salars are in closed basins; some of these basins have extensive nitrate deposits on the hillslopes surrounding the salar (Salar de Lagunas, Salar de Pampa Blanca, and the small salar near Oficina Rosario), whereas Salar del Carmen is at the terminus of a transverse valley that drains the area of extensive nitrate deposits northeast of Baquedano (fig. 1). These salars probably differ in composition from others in northern Chile because they represent deposition from ground waters containing saline materials leached from nitrate deposits. Saline minerals, including nitrates, are still being deposited in Salar del Carmen and Salar de Lagunas which have near-surface ground water, but not in the other three salars, which are dry and in which the water table is at depths of 20 feet or more.

SOFT SURFACES OR CRUSTS

MOIST SALINE SOIL

Soft moist salar surfaces occur in parts of salars that are subject to flooding by surface water and that have a shallow fluctuating ground-water table that keeps the surface moist. Underlying sediments tend to be permeable moist to water-saturated silts and sands, rather than relatively impermeable muds.

The surfaces of these salars contain only small quantities of saline minerals. On aerial photographs these surfaces generally appear dark gray to black, commonly showing smooth bands of differing shades, indicating different degrees of soil saturation. The moist soils are characteristic of the lowest parts of Andean salars, which are subject to frequent flooding. During the rainy season, and for a few weeks or months thereafter, these areas are likely to be shallow lakes. Evaporation and decrease in groundwater levels expose the moist soils during the dry season. However, some areas of deeper water in Andean salars tend to be covered with water during most if not all the year. Such areas are really perennial or intermittent lakes.

A good example of a soft moist soil surface is in the central part of Salar de Maricunga (fig. 12). In May 1967, the time of our visit to this locality, this entire area was flooded by shallow water, as was a part of the smooth halite flood plain to the north. This temporary lake disappears partly or entirely during each dry season, whereas ponds at the southern end and southeastern edge of this salar appear to be perennial.

MOIST GYPSEOUS CRUST

Moist to water-saturated crusts containing a large percentage of gypsum are widespread in Andean salars. They are the dominant crustal type of some salars such as Salar de Ascotán (fig. 9), and in others form the bordering zones around hard evaporite crusts of rock salt. The gypseous zone commonly contains moderate amounts of halite and mirabilite either as surface incrustation or admixed with the granular gypsum in the crust. Nearly all the gypseous crusts of the Andean salars contain disseminated fibers, blebs, nodules, and layers of ulexite; at several salars this ulexite has been mined from shallow pits such as those shown in figure 29.

The soft gypseous crust generally is made up of a loose accumulation of tan to cream-colored subhedral gypsum crystals of sand size. The gypsum is moist to within a few inches of the surface, and the saturated zone is generally within 10 or 20 inches of the surface. The surface is smooth to hummocky, with a microrelief of as much as 3 or 4 inches. The bearing strength is variable, ranging from an extremely soft surface impossible to cross with a

FIGURE 29.—Soft gypseous crust underlain by a 10–20-in. layer of high-purity ulexite that was mined in shallow pits now filled with water, Salar de Ascotán. The pond is about 10 ft wide.

4-wheel drive vehicle, to a compact surface that can be crossed by car. A typical example of this type of crust is the eastern side of Salar de Punta Negra (figs. 10, 30). A similar crust on the western side of Salar de Surire (fig. 8) is 18 inches to 3 feet thick and is underlain by reddish-brown moist to water-saturated silt and clay.

Some of the soft gypseous crusts also may contain small amounts of sodium or calcium carbonate. For example, Sayes (written commun., 1968) found that marginal zones of Salar del Guasco and Salar de Coposa (fig. 15) contained carbonates, sodium bicarbonate being prevalent in Guasco and calcium carbonate in Coposa.

Practically all the salars in the Andean Highlands appear to be bordered by crusts of this type on one or more sides. The crust tends to be much better developed on one side than the other, an asymmetry attributable either to basin tilting or to greater inflow of water on one side of the salar than on the other.

DRY FRIABLE CRUSTS

Soft dry friable crusts are characterized by a porous, puffy surface consisting of fine-grained clastic sediments and varying but generally considerable amounts of halite and gypsum and lesser to trace amounts of other saline minerals such as ulexite and thenardite. The upper few inches are typically composed of a loose dry powder covered by a very thin crust which is easily crumbled in the fingers. At depths of 8–10 inches the soil tends to be moist and contains relatively little saline material. The surface is evidently kept in a puffy condition by crystallization of salts in the capillary fringe of the water table and by periodic leaching of the salts by rainwater or by flooding; these factors inhibit formation of a hard salar crust.

FIGURE 30.—Soft moist gypseous crust, eastern side of Salar de Punta Negra.

A small salar near Imilac, north of Salar de Punta Negra (fig. 10), is typical of this type of crust. Parts of the crust show evidence of being smoothed by recent flooding, and others show transitions between such a surface and the typical puffy surface. The upper 6 inches of soil from this salar (sample 62, table 2), after leaching, was found to consist of 26.3 percent clay, 29.5 percent silt, 43.3 percent sand, and 0.9 percent gravel. The unleached sample contained about 9 percent water-soluble salts. This crustal type also is extensive around the eastern edge of Salar de Atacama (fig. 11), where it may be the remnant of a marginal sulfate zone that has dried because of a decline in the water table.

FEATURES OF SALAR CRUSTS IN CHILE

Northern Chile offers unique opportunities for study of morphological and structural features that form in salt crusts in response to unusual climatic and hydrologic environments and to fault movements in an active seismic region. Such structural features appear to be more varied and better shown in the Atacama Desert and the Andean Highlands than in other deserts of the world, and some of the features may be unique to this area. Because of the extreme aridity of the Atacama Desert, rock salt tends to be relatively stable; in most other deserts, salt that is deposited during an annual dry season tends to be washed away during the following wet season. Not only are perennial rock-salt crusts widespread in the Atacama Desert, but soils generally contain a high content of halite, gypsum, and soda-niter. Furthermore, this is one of the few areas of the world where rock salt is sufficiently stable to make a satisfactory building stone, and hygroscopic saline soil, a good road-surfacing material. Building walls constructed of rock salt or saline-cemented soil (saline caliche) may remain standing, with little change, for 50 years or more.

In spite of the very arid climate, salar crusts of the Atacama Desert are in a state of gradual but continual change. Agents operating to bring about these changes are (1) surface water, (2) ground water and springs, (3) rainwater and fog, (4) faulting and fracturing, and (5) wind action. Examples of morphological and structural features that are recognizable in aerial photographs are shown in figure 31.

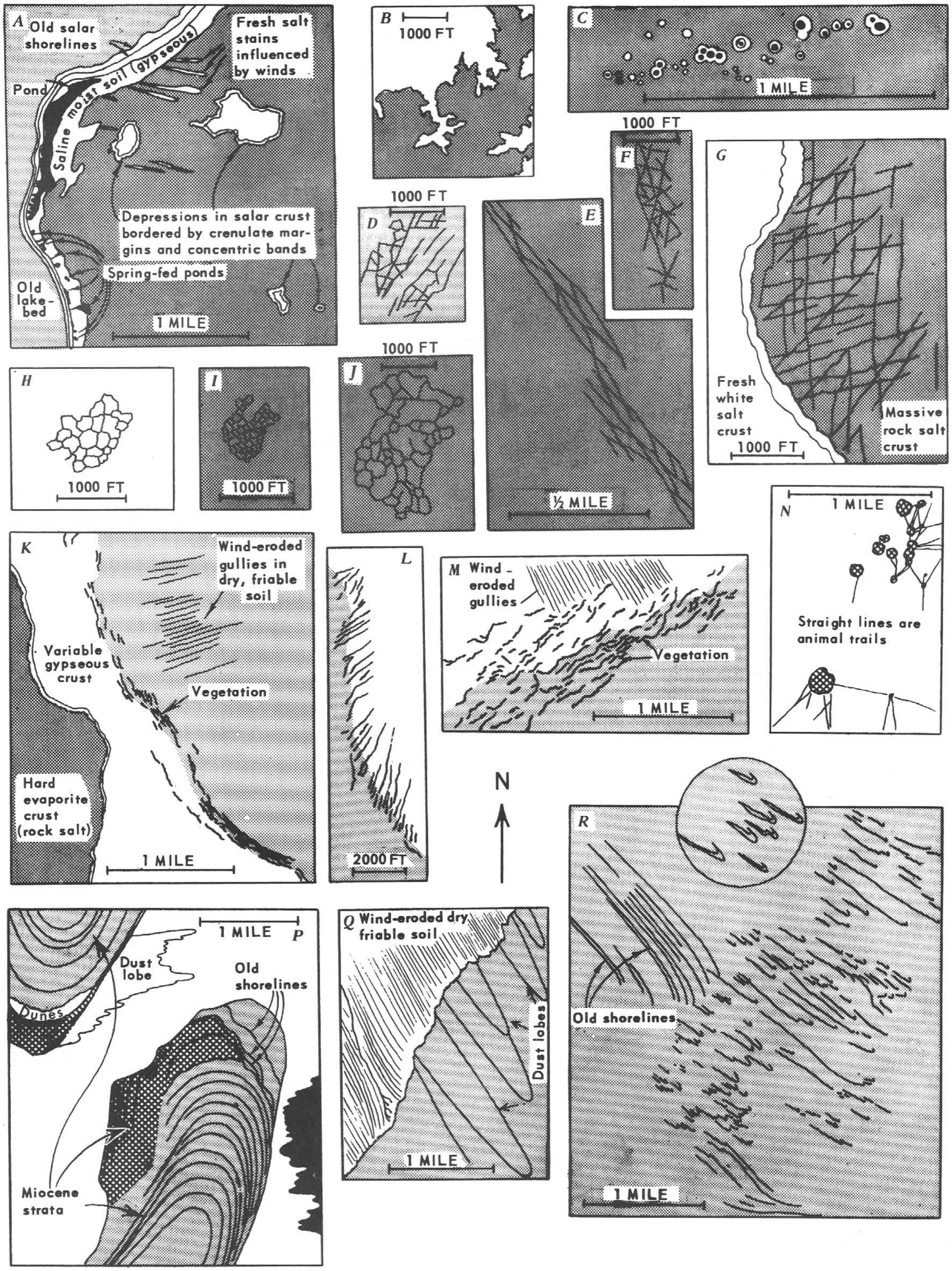
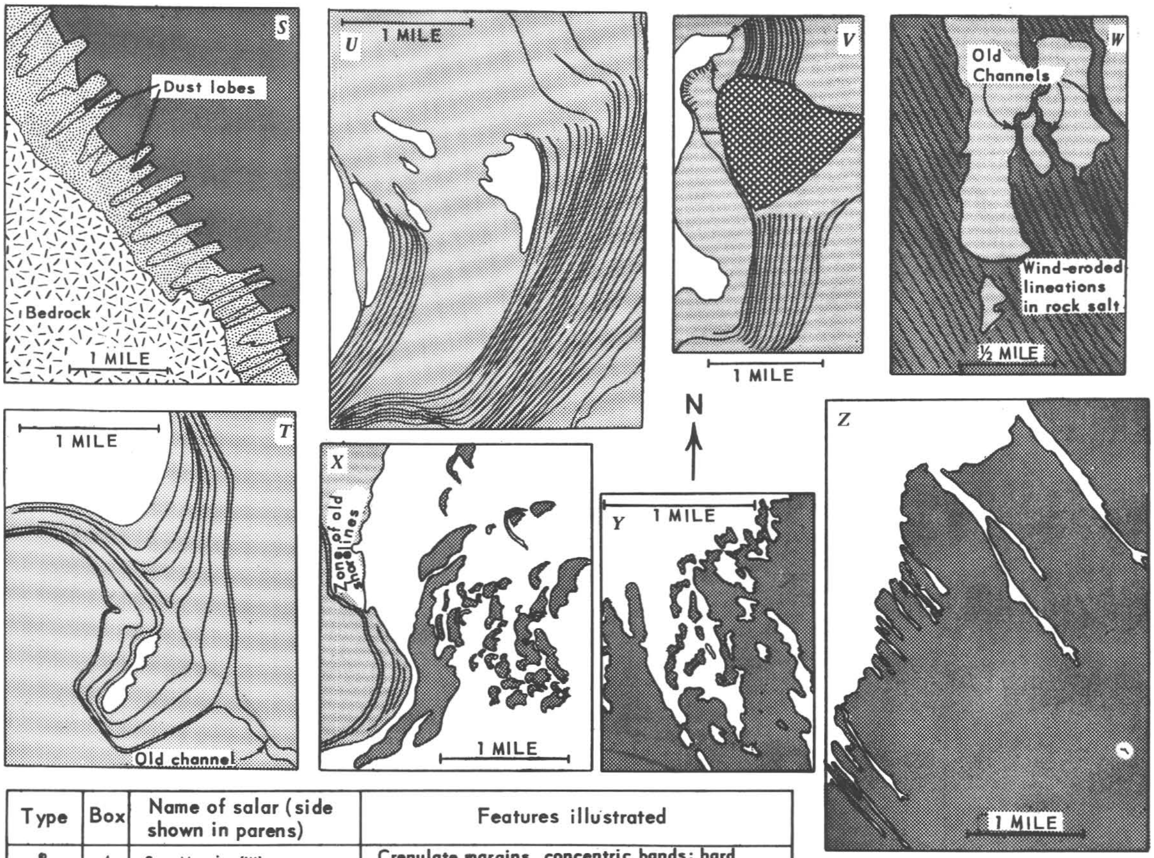


FIGURE 31.—Distinctive patterns observed on aerial photographs



Type	Box	Name of salar (side shown in parens)	Features illustrated
Hard evaporite crusts	*A*	San Martin (W)	Crenulate margins, concentric bands; hard evaporite crust, salt channels.
	B	Atacama (NE)	Crenulate margin; hard evaporite crust.
	C	Atacama (NW)	Pools ringed by white saline soil; hard evaporite crust.
Oriented nonorthogonal polygons	*D*	Pampa de Tara (E)	Polygons in tuff(?) swept bare by wind.
	E	Grande (7, fig. 9, E)	Polygons in faulted, exceptionally thick massive rock salt.
	F	Llano de la Paciencia	Polygons in Miocene evaporites(?) exposed in salar.
	G	Pedernales (W)	Polygons in very thick massive rock salt(?).
Giant random orthogonal polygons	*H*	Talar (NW)	Polygons in smooth fresh white salt crust.
	I	Pedernales (W)	Polygons in old hard evaporite crust, probably rock salt.
	J	Atacama (N)	Same as I; both I and J show on photographs as light networks on dark salt.
Vegetation patterns	*K*	Atacama (SE)	Vegetation along old salar shores; hard evaporite crust of rock salt.
	L	Atacama (S)	Vegetation along spring-fed moist zones.
	M	Atacama (S)	Vegetation along old salar shores, probable spring zones.
	N	Atacama (SE)	Marshy vegetation around springs; vegetation cross-hatched.
Wind deposition patterns	*P*	Atacama (SW)	Wind-blown salts on salar; polygons (cross-hatch pattern) similar to F above.
	Q	Pedernales (S)	Wind-blown salts (gypsum?); old delta shaded.
	R	Guasco (NE)	Longitudinal dunes and barchans (enlarged in inset).
	S	Pintados (SW)	Dust lobes on salt.
Relict drainage features	*T*	Aguas Calientes (33, fig. 11, SE)	Former lakeshores; old channel to Salar de Quisquiro nearby.
	U	Tara (E)	Former lakeshores, at north partly obliterated by wind.
	V	Laguna de Tuyajto (E)	Former lakeshores; old delta cross-hatched, newer delta hashured.
	W	Grande (7, fig. 9, SE)	Old drainage channels(?) buried by salt.
Wind-eroded features	*X*	Aguas Calientes (31, fig. 11, W)	Remnants of hard evaporite crust(?).
	Y	Ollagüe (SW)	Remnants of hard evaporite crust(?); 2 wind directions(?).
	Z	Incaguasi (NW)	Eroded and corroded margin of hard evaporite crust, salt channels.

EXPLANATION

☐ Soft, moist saline soil of salar, subject to flooding; chiefly sulfate zone containing gypsum and some halite

░ Predominantly clastic sediment, including alluvium, and lacustrine sediments; also consolidated or semiconsolidated sediments (all areas other than salars)

▓ Hard evaporite crusts, predominantly massive to silty rock salt (chloride zone)

■ Ponds, open water; frequently flooded areas

of salars and basins of former lakes in northern Chile.

FEATURES DUE TO FLOODING BY SURFACE WATER

SALT CUSPS AND CRENULATE MARGINS WITHIN SALARS

Rugged rock-salt crusts that abut against younger smooth rock-salt crusts generally have crenulate margins (fig. 31*A*, *B*) consisting of intersecting cusplike curves that are concave toward the younger salt crust. Borders of this type may be highly irregular, having a dendritic form such as in figure 31*B*, but commonly they are more regular. This type of salt interface shows clearly in aerial photographs. It forms by corrosion of older salt and redeposition of new salt by floodwaters, the flooding generally resulting from a gradual rise in water level. The younger salt, which is in an area of periodic flooding, forms a slight depression, whereas the older salt, which is slightly above flood level, is slowly corroded; solution and gentle wave action apparently combine to produce a cuspate crenulate interface between the two types of salt.

Salt cusps and crenulate margins are found in nearly all salars of the Andean Highlands that have a rugged perennial rock-salt crust. They are well developed in the north-central part of Salar de Atacama (fig. 31*B*) where the points of the intersecting cusps are typically 10 to 50 feet apart in the most strongly crenulate margins and 100 to 200 feet apart in those more gently crenulate. Good examples of crenulate margins can also be seen in aerial photographs of Salar de Punta Negra, Salar de Pedernales, and Salar de Maricunga. In the United States, a similar crenulate "pattern" can be seen around the margin of the Devils Golf Course, Death Valley, Calif.

SALT CHANNELS

Rugged rock-salt crusts that are immediately leeward of springs or ponds in regions of strong prevailing winds are likely to have lobate margins in which parallel or subparallel channels, floored with fresh white salt, extend into the rugged crust (fig. 31*A*, *Z*). Such channels are commonly hundreds or even thousands of feet long. We have termed them salt channels. They result largely from corrosion of the older salt by windblown water.

Salt channels of this type are best developed at the western margin of Salar de Incaguasi (fig. 11) where there are many prominent southeast-trending channels, the two largest being 2 miles long and 100–500 ft wide (fig. 31*Z*). Salt cusps and crenulate margins occur at places in the salt channels, being best developed at the leeward ends of the channels. Salt channels also can be seen in aerial photographs of Salar de la Isla (fig. 12), and small or incipient salt channels can be seen in several other salars in the Andean Highlands.

Salt channels are believed to indicate: (1) strong prevailing winds, (2) large flows of spring water having only low to moderate salinity, (3) presence of a rugged perennial rock salt crust that is above flood level or otherwise protected from flooding, and (4) proximity of the rugged salt crust to the windward side of the basin, with little or no development of a bordering sulfate or carbonate zone.

SALT PSEUDOBARCHANS

As interpreted from aerial photographs, an old rugged salt crust in the western part of Salar de Aguas Calientes (fig. 31*X*) is in an advanced stage of corrosion by windblown surface water, the remnants of the former crust being characterized by rounded cuspate forms, which in aerial photographs appear to have the form of barchan dunes. We have called them salt pseudobarchans. They appear to be surrounded on all sides by fresh white salt that is periodically flooded. Flow lines and shallow channels in the white salt curve around the windward sides of the pseudobarchans and trail off to leeward. The pseudobarchans appear dark in the photographs, indicating that they have a mantle of windblown silt and sand. Crenulate margins at leeward edges that were corroded by standing water and smoothly rounded windward edges that were corroded by windblown water indicate that the pseudobarchans are remnants of an old salt crust.

Salt pseudobarchans are not known to occur elsewhere in Chile and may be unique. However, dunelike forms along the southern edge of Salar de Ollagüe (fig. 31*Y*) appear to be partly the remnants of a hard evaporite crust and partly dunes of clastic saline material, mainly gypsum, and silt.

The pseudobarchans in Salar de Aguas Calientes are thought to be due to strong winds, somewhat variable from west to northwest, to large flows of spring water from the western margin of the salar, and to presence of a crust of perennial rock salt that is being corroded.

SALT BLISTERS

Newly deposited thin layers of rock-salt crust locally form blisterlike mounds as the result of expansion of the salt layer during crystallization and drying. Typical salt blisters are shown in figure 32. The blisters are a variation of pressure ridges that also form in newly deposited thin salt layers, as shown in figure 27.

Salt blisters are found at many places in the Andean salars of Chile. They are undoubtedly common to seasonally flooded salars elsewhere. Hunt, Robinson, Bowles, and Washburn (1966, p. B65–B66) described blister crusts in the Death Valley salt pan, California.

GYPSEOUS RAMPARTS

Saline ponds along the western edge of Salar de San Martín (fig. 31*A*) are rimmed on the east by a low ridge that consists chiefly of hard nodular fine-grained gypsum (fig. 33), which we have termed a "gypseous rampart." This ridge separates the ponds from the soft gypseous crust of the salar to the east. The rampart is 10–20 feet wide and is 2–5 feet high, being highest near the pond edge, and slopes gently eastward to the level of the gypseous crust, which during the dry season is a few inches to about a foot above the level of the pond.

The rampart formed by evaporation of windblown spray from the pond that was carried by the prevailing westerly winds. Other salines, chiefly halite, are also deposited from this spray but are leached by seasonal rains.

FEATURES FORMED BY GROUND WATER AND SPRINGS

SALT CASCADES AND SALT TERRACES

Near the head of Río Salado, 25 miles northeast of Potrerillos (fig. 1), are found unique cascades and terraces of rock salt. Here, the stream valley is within 1,000 feet of the border of Salar de Pedernales (fig. 12), and the valley floor is about 300 feet lower than the brine level in the salar. Brine springs on the valley wall, fed by subsurface seepage through permeable strata and along fractures in a probable fault zone have deposited salt on the side and bottom of the valley. This natural flow has been augmented by a higher level, manmade tunnel, apparently driven to increase the water flow into the Río Salado. The salt cascades are along the steep side of the Río Salado valley; on the floor of the valley are constructional salt terraces, reminiscent of hot-spring deposits (fig. 34). A copious flow of brine can be heard flowing in salt tunnels beneath the terraces, in spite of the fact that the manmade tunnel was closed at the time of our visit.

FIGURE 32.—Salt blisters on rock-salt flood plain, northern end of Salar de Maricunga. Newly deposited salt layer is ¼–½ in. thick; hollow blisters shown are as much as 6 in. high.

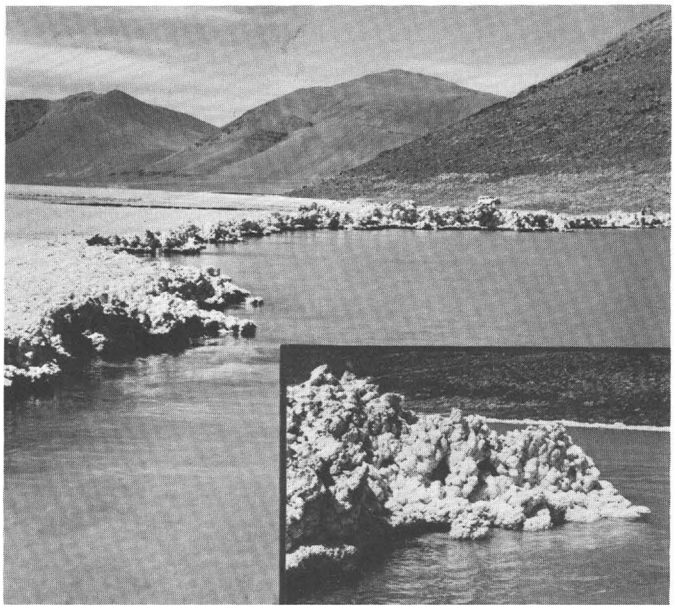


FIGURE 33.—Gypseous rampart (maximum height of 4 ft) bordering saline pond at western edge of Salar de San Martín. Inset photograph shows the nodular character of the hard fine-grained gypsum, which is the chief saline component of the rampart.

The water level within the adjoining part of the salar is approximately 3 feet below the surface of the salt crust. The decline in water level in this area, presumably since construction of the tunnel, must have been at least 1 foot, as indicated by horizontal shelves of fresh salt in the sides of a trench.

BRINE POOLS

Perennial circular pools 3–30 feet across occur in salars of northern Chile where springs of relatively fresh water have dissolved holes in a salt crust and

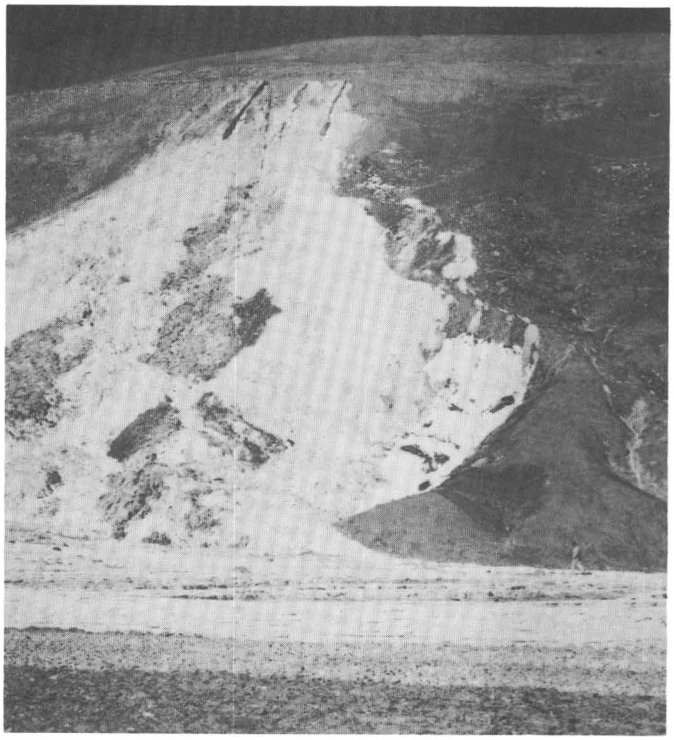


FIGURE 34.—Salt cascades and constructional salt terraces at the eastern side of the valley of Río Salado, near the northwestern corner of Salar de Pedernales.

maintained them against the growth of new salt from the sides (fig. 21). The pools are most common near the margins of perennial rock-salt crusts, where they are thought to be maintained by springs in permeable layers at the foot of adjoining piedmont slopes, and along faults below the crusts.

Many well-developed brine pools, thought to be along faults, are in the northwestern part of Salar de Pedernales. The largest pools (fig. 21) are as much as 30 feet wide and 30 feet deep, having vertical to overhanging walls of white rock salt clearly visible beneath the brine. Smaller brine pools, 3–15 feet across, occur along the eastern edge of Salar de Atacama (fig. 35). They are apparently associated with fresh-water springs supplied by subsurface flow from the large alluvial fans to the east, or along a fault zone in this area. The pools are in a marginal zone having a thin hard rock-salt crust overlying water-saturated plastic gypseous clay. The crust around the pools is smoother and whiter than the surrounding crust (fig. 35), indicative of seasonal flooding.

SALT CONES AND CUPS

Among the most unusual salt structures found on salar crusts in the northern Chilean Andes are salt cones, of which typical examples are shown in figure 36. Salt cones are best developed on perennial rock-salt crusts where the ground-water table is within the crust and near the surface. They are centered over salt-solution tubes (fig. 40) leading down to the ground-water table. The best examples seen in the present study were in the northwestern part of Salar de Pedernales, where three general types can be observed, as shown in figure 36. Here, the water table was only about 2 feet below the surface of the salt crust at the time of our visits in May 1967, which was near the end of the dry season. Low salt rims, the vestiges of salt cones, surround vertical tubes on the perennial salt crusts of Salar de Atacama and of Salar de Pintados.

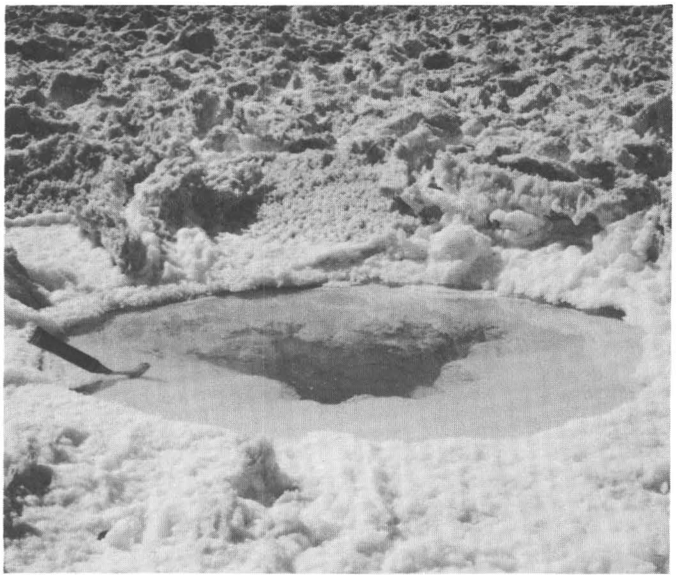


FIGURE 35.—Small brine pool in a thin, 1–2 ft rock-salt crust, eastern side of Salar de Atacama.

The salt cones at Salar de Pedernales are as much as 8 inches high and 10 inches in diameter at the base and have walls as much as an inch thick. They consist of granular to fibrous halite. Specimens of thick-walled cones, examined in the laboratory, appear to consist chiefly of microscopic elongated, twisted, interwoven fibers of halite. The fibers tend to be rather uniform in diameter and are of roughly the same dimensions and gross appearance as the fibers in bond paper. The salt cones are solid closed structures (fig. 36*B*), cones with a small opening on the top, or more open structures such as that shown in figure 36*C*. An intermediate type, such as figure 36*A*, may have a subsidiary opening on the side. Cones, once formed, may later be partially eroded or corroded so much that only a vestige of the cuplike

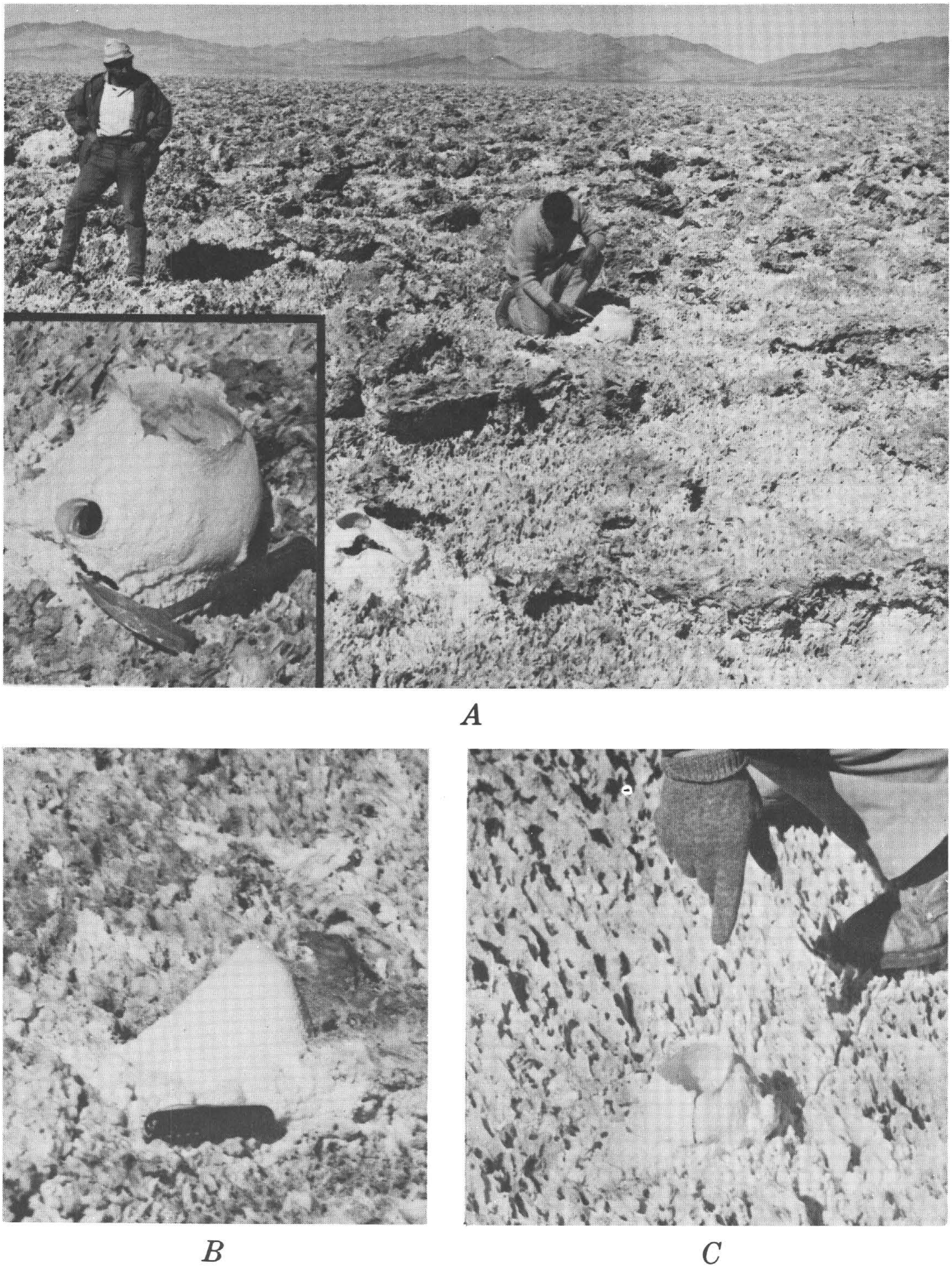
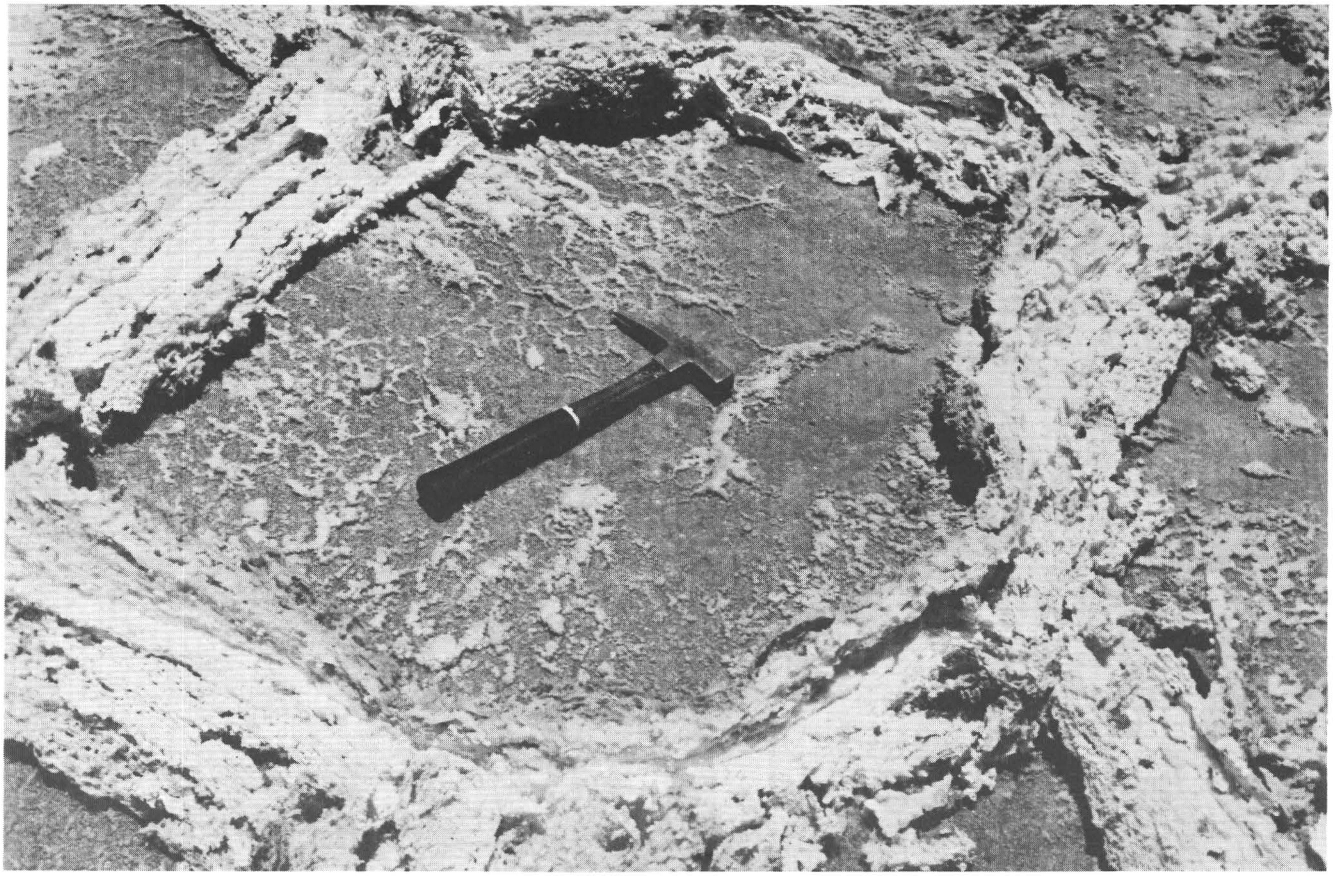
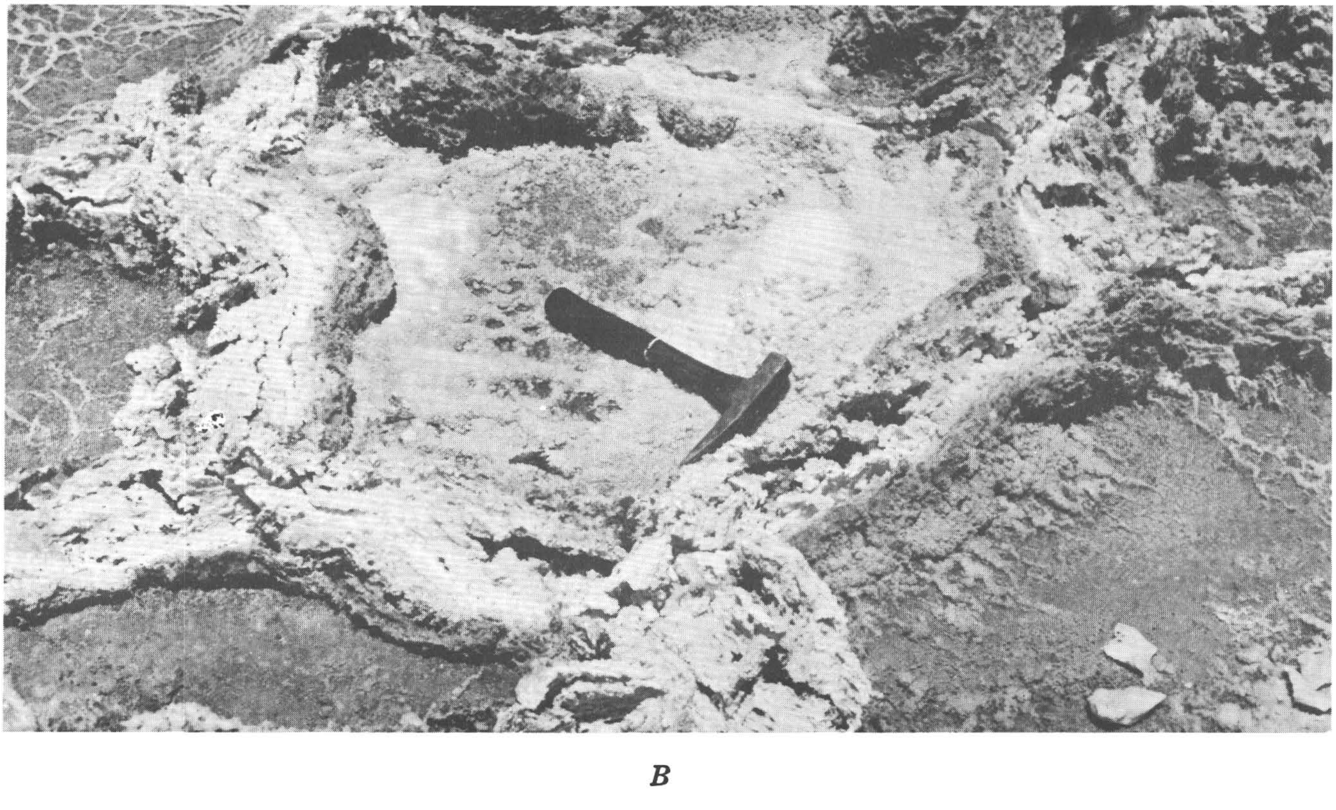


FIGURE 36.—Salt cones on rugged perennial rock-salt crust in the northwestern part of Salar de Pedernales. *A*, Rugged rock-salt crust typical of area; enlarged inset is of complex cone, shown in photograph, which has a breached top and tubular side opening. *B*, Salt cone in an early stage of development. *C*, Remmant of salt cone, a salt cup.



A



B

base, which may be filled with windblown sediment, remains.

The mode of formation of the cones we saw in Chile in 1967 was not clear because all were fully developed cones or cuplike remnants. However, in November 1970, Ericksen found cones in Salar de Pocitos, northern Argentina (fig. 1), that showed a complete sequence of cone formation and destruction. This sequence is shown in figure 37. The cones start to form as nodular veinlets of moist granular salt within polygons in rock salt, as is shown in figure 37*A*. These veins form in cracks resulting from diurnal expansion and contraction of the salt crust. Capillary rise of brine, which stands only about 2 feet below the surface, deposits the salt in the veins and causes the nodular efflorescences on the surface. These veins do not form at the margins of the polygons where diurnal expansion is greatest and where thin lacy sheets of salt (fig. 37*A*) may be squeezed out, making a rim around the polygon. Certain of the nodules continue to grow by capillary rise and deposition of salt from brine, forming a solid nodule of moist granular light-gray salt a few inches in diameter and height. At some point in this growth stage a small tube (fig. 38) forms in the vein, extending from brine level to the cone, and a white cap of dry salt appears on the top of the cone shortly thereafter.

Once the tube forms, the cone continues to grow by both capillary rise of ground water and diurnal pumping, wherein moist air moves out of the tube (and cone) during the warm day, and dry air moves into them during the cold nights. These processes cause the cone to expand (fig. 37*B*), eventually to become thin, and finally to develop openings at one or more places. Generally a simple opening forms on top of the cone (fig. 37*C*). While the cone grows, the tube below it increases in diameter to as much as 5 inches in large cones. Finally, an open cuplike structure forms (fig. 36*C*).

C

FIGURE 37.—Above and facing page. Formation of salt cones at Salar de Pocitos, Argentina. *A*, Nodular salt veins in salt polygons, the first stage of development. Note thin lacy sheets of salt squeezed upwards along polygon borders because of thermal expansion. *B*, New salt cone formed by growth of a nodule on one of the salt veins. *C*, Breached salt cone, the final stage of development.

FIGURE 38.—Salt saucers at Salar de Pocitos, Argentina, that result from corrosion of salt polygons by rainwater. Note hole of salt tube (T) at site of former salt cone and salt network (SN) in center of breached saucer. Also note salt pond in upper left of photograph.

Cones apparently form in a few weeks or a few months. Those shown in figure 37 were destroyed during the rainy season a few months after these photographs were taken, and their former presence is indicated only by the open tubes in the salt polygons.

Dingman (1963) described delicate salt cups on rock-salt beds of Tertiary age in the hills of the Cerros de la Sal between Salar de Atacama and the Llano de la Paciencia (fig. 11). Like those seen in the salars, these cups are centered over tubes leading downward into the salt. Dingman attributed formation of these cups to movement of moist air out of the tubes.

Hunt, Robinson, Bowles, and Washburn (1966, p. B62) reported delicate efflorescences of salt (incipient salt cups?) around tubes leading downward into the salt crust in the northern part of the Badwater Basin, Death Valley, Calif. These authors attribute the efflorescences to escape of moisture from underlying sediments through the tubes. During a visit in 1968, Stoertz found several small active salt cones in the Death Valley salt pan, about 2 miles southwest of Badwater.

FEATURES FORMED BY SOLUTION OF SALT BY RAINWATER AND FOG

SALT SAUCERS

Salt saucers are salt polygons that have a pronounced concave form and a prominent rim. They occur in Salar de Obispo (fig. 8) and other salars in the Central Valley in places where the crust of slabby and nodular silty rock salt is 1–3 feet thick. The saucers, which form a network, are generally 5–10 feet across, and their upturned rims range from 6 inches to about 2 feet in height (fig. 39). The saucer rims are commonly outlined by nodular rock salt, whereas the centers of the saucers are relatively smooth and consist of polygonal plates of silty rock salt 1–3 feet in diameter.

These salt saucers are pressure-ridge polygons that were leached by rain and fog, which dissolve surficial salt and carry it down into the rather porous silty crust. Loose silt and sand remaining at the leached surface is blown away by wind. Redeposition of salt from the surface and deposition of new salt by capillary evaporation of ground water at the base of the crust probably cause additional expansion of the salar crust and elevation of the saucer rims. Thermal expansion and contraction, due to diurnal temperature changes, open cracks that allow movement of salt into the crust and also expand and lift the polygonal plates.

FIGURE 39.—Salt saucers in slabby and nodular silty rock salt, Salar de Obispo.

Another type of salt saucer, shown in figure 38, formed by corrosion of polygonal salt cakes by rain. This type of saucer is characteristic of relatively thin salt crusts having abundant salt tubes and salt cones. Rainwater, which drains through the tubes, corrodes the polygon first to the saucerlike shape and then dissolves away the lowest part of the saucer (fig. 38), finally destroying it. Upturned edges of the saucers in part are due to cementation of extruded salt that had formed at polygon borders (fig. 37A, 38).

SALT NODULES

Rounded forms or nodules of salt are widespread and abundant in the soils and salars of the Coastal Range and Central Valley of northern Chile. They have formed by slow solution and recrystallization on surfaces of salt fragments, chiefly due to frequent wetting by the nightly winter fogs. Rainfall is so infrequent and sparse in this region that it little affects the formation of salt nodules. The nodules range from an inch or two to about a foot in diameter.

Two types of salt nodules can be distinguished. One type, as shown in figure 40*A*, forms from hard, dense, crystalline rock salt, and the other, shown in figure 39, forms from the porous silty salt typical of most salar crusts of the Coastal Range and Central Valley. In the first type, the fog condensate collects as a thin film on a relatively impermeable rock-salt fragment, dissolves a little salt, and then flows downward on the sides of the fragment where it evaporates and reprecipitates the salt as a sugary white porous mass. As can be seen in figure 40*A*, this new salt collects on the bottom and sides of the fragment. In a final stage it grows over the top, completely enclosing the remains of the original salt fragment. It is estimated that the fragments shown in figure 40*A* lay undisturbed for more than 30 years. Other fragments in this same area that were broken during salt mining in the 19th century are completely covered with white sugary salt, and some fragments less than 5 or 6 inches in diameter lack a crystalline salt core.

The nodules form in a slightly different way from porous silty salt. Fog condensate moistens the porous surface to depths of one-tenth of an inch or more, and dissolved salt moves into the fragment. Removal of the salt cement leaves loose silt on the surface that is carried away by wind. The nodule tends to be less porous than the original silty fragment. The end product is a white nodule of granular salt similar to that formed from the dense crystalline salt described above.

Ultimately the salt nodules are destroyed by fog and rain, the salt being slowly dissolved and carried down into the soil. This process is accelerated where hygroscopic saline minerals are present in the salt. It has been particularly effective in destruction of fragments of hygroscopic nitrate ore at mines in this area, fragments as much as a foot in diameter being completely dissolved in a few tens of years. Their former presence is now revealed by small piles of loose rock fragments and sand, the former matrix of the ore.

SALT PINNACLES

In the Andes, perennial rock-salt crusts that are infrequently flooded commonly are covered by a variety of jagged forms such as pinnacles and serrate ridges. These forms are characteristic of most perennial rock-salt crusts in the Andean Highlands and Atacama Basin, where flooding generally takes place only during exceptionally rainy years. These rugged crusts have a different appearance from the rounded nodular crusts typical of the Central Valley and Coastal Range. The pinnacles result from corrosion by rain, commonly windblown rain, as evidenced by the orientation of points and ridges in the general direction of the prevailing strong winds. Pinnacle height ranges from 1 to about 6 inches and is a rough measure of time since the last flooding.

The surface of the massive rock salt in the northwestern part of Salar de Pedernales (fig. 14) shows typical well-developed pinnacles ranging from about 2 to 5 inches in height (fig. 40*B*). Salt pinnacles are also shown in figures 21 and 36.

Jagged or pinnacled surfaces seem best developed in areas of thick rock salt on the largest salars, which are well drained, so that flooding is rare and crustal modification is largely or wholly by rainwater.

SALT SOLUTION TUBES

Massive rock-salt crusts in the Andes contain salt solution tubes through which rainwater drains (fig. 40*C*). The tubes are characteristically found in the lowest parts of relatively smooth basinlike depressions, which generally range from a few feet to 10 or 15 feet in diameter. They appear to have formed by drainage of rainwater that would otherwise collect in small shallow pools after rains. The tubes are generally not more than a few inches in diameter. They are nearly vertical, straight to curving, and lead down at least to the water level in the salt crust, which may be at a depth of as much as several feet.

Salt solution tubes are particularly numerous and widespread in the northwestern part of Salar de Pedernales in an area that is relatively smooth, evidently having been flooded more recently than the surrounding rugged crust. In this part of the salar, many solution tubes are in areas of more rugged rock-salt crust (less frequently flooded) and are capped by salt cones or cups (fig. 36). Solution tubes also occur in Salar Grande, where there is no known water table and where they are presumed to drain downwards to interconnecting fissures that extend to great depths and serve as channelways for subsurface drainage of the basin. Dingman (1963) described salt tubes as occurring in the massive rock salt of the Cordillera de la Sal where they are also associated with salt cups.

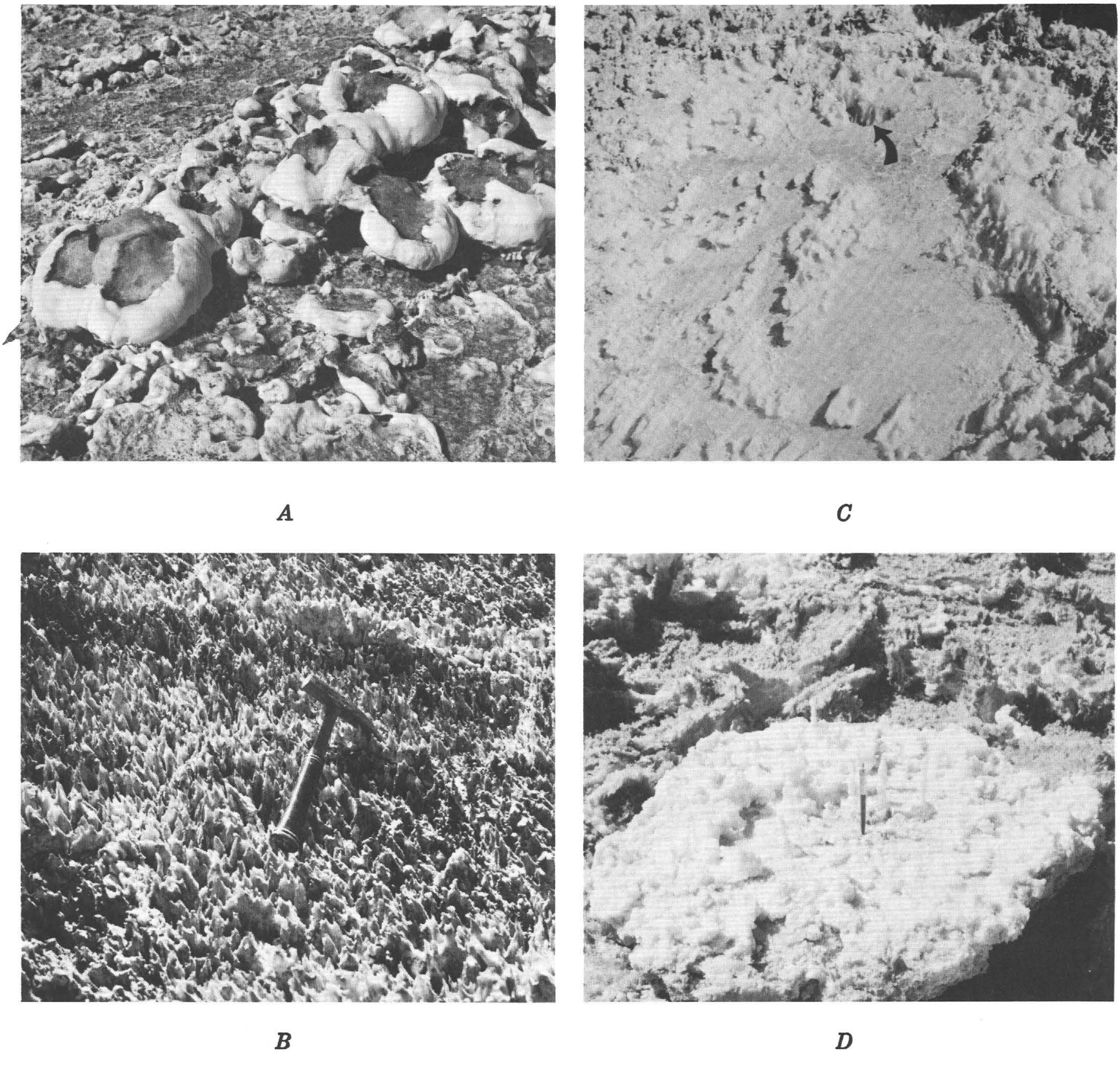


FIGURE 40.—Features formed by solution of salt by rainwater and fog. *A*, Salt nodules forming from fragments of coarsely crystalline rock salt, Salina Guanillos, west side of Salar Grande. *B*, Salt pinnacles in massive rock-salt crust, northwestern part of Salar de Pedernales. *C*, Orifice of a salt solution tube about 4 in. in diameter (at top of arrow) in relatively smooth massive rock-salt crust, northwestern part of Salar de Pedernales. Arrow indicates direction of surface flow of rainwater. *D*, Salt stalactites on overturned slab of rock salt, eastern side of Salar de Atacama (pen gives scale).

SALT STALACTITES

Cavities in salar crusts may contain stalactites such as those in the eastern part of Salar de Atacama (fig. 40*D*). Here, salt stalactites one-half of an inch in diameter and as much as 6 inches long are widespread. They are found beneath an upper layer of somewhat porous rock salt at the margin of the salar, and can be seen only by prying up individual polygonal cakes. Salt stalactites undoubtedly are present elsewhere in the crust of this salar and in the rock-salt crusts of other salars in northern Chile. They also have been found at a few places in cavities in the nitrate ore of the region. Salt stalactites occur in Death Valley, Calif. (Hunt and others, 1966, p. B110), on the overhanging edges of salt saucers in the flood plain west of Badwater.

The stalactites are formed by solution of a perennial rock-salt crust by rainwater, downward migration of solutions through pores and cracks in the crust, and deposition in cavities, most of which formed as the result of breaking of the crust during uplift because of thermal expansion and contraction.

FEATURES FORMED BY FAULTING AND FRACTURING

GIANT SALT POLYGONS

Oriented type.—Aerial photographs of some perennial crusts or thick bodies of rock salt locally show polygonal patterns formed by the intersection of two or three sets of subparallel lines spaced 200–500 feet apart. The lines are thought to be joints along which solution and recrystallization of salt has taken place. They commonly maintain a consistent orientation over areas of a square mile or more. These polygons are believed to be indicative of a perennial evaporite crust or body that is hard and brittle, and thick enough to transmit stresses for long distances. The more prominent and consistently oriented polygons are believed to be indicative of exceptionally thick bodies of salt and of regional stresses associated with faulting. The polygons are oriented according to the direction of these stresses.

The best examples of oriented giant polygons are in Salar Grande (fig. 31*E*), where the rock salt is several hundred feet thick, and in the northern part of Salar de Pedernales (fig. 31*G*), where the average thickness of salt is probably more than 20 feet. Similar polygons are faintly visible in aerial photographs of six other salars in northern Chile. Such oriented polygons appear to be absent in salars having crusts less than 5 or 6 feet thick, even though they are in basins showing evidence of recent faulting.

In Salar Grande, the giant oriented polygons are best developed near northwest-trending faults that displace the salt (fig. 13), and probably are genetically related to these faults. The joints that outline the polygons maintain a fairly consistent orientation throughout most of the salar. Near the center of the salar the dominant trend is approximately N.35°W., subsidiary trends being roughly N.70°W. and N.5°W.

Giant oriented polygons in the northwestern part of Salar de Pedernales extend over an area of at least 8 square miles. They are probably related to a northeast-trending fault believed to pass through the northwestern part of this salar. Oil seeps and salt pools within the rock salt here may be associated with this fault (Harding, 1926, p. 797, 799). Although the fractures that border these polygons are clearly visible in aerial photographs, they are obscure on the ground. We were not able to find them when we walked over part of this area. The joint sets, in order of prominence, trend north, N.80°E., and N.40°E., the last set tending to bisect the acute (80°) angle between the other two sets (fig. 31*G*).

Polygons of a similar type occur in the San Pedro Formation, a sequence of evaporites and interbedded clastic sediments that has been deformed into a series of domal anticlines and has been locally faulted. The polygons are visible in photographs of the eastern edge of the Llano de la Paciencia and of the area where it joins Salar de Atacama (fig. 31*F*, *P*). They are most clearly visible in areas where former saline lakes cut relatively smooth terraces into the older evaporites. Many of the polygons are triangular or rectangular and appear to be bordered by parallel joints 100–400 feet apart. Although these joints show consistent orientation at a single locality, no single regional trend seems to be dominant.

Randomly oriented type.—High-altitude aerial photographs reveal that rock-salt crusts locally have giant polygons, commonly 100–300 feet in diameter, bounded by randomly oriented fractures. These are similar to the small salt polygons that are dominant structural features in most salt crusts but that are generally too small to be visible in the aerial photographs.

The giant randomly oriented salt polygons appear to be best developed in areas of smooth halite flood plains, where the rock-salt crust is relatively thick and where solution due to periodic flooding is minimal. They were not seen on the ground in Chile but are visible in aerial photographs of several salars where they appear most clearly as a dark network in areas of white salt interpreted to be smooth flood plains. Polygons having the same form, but appearing on the photos as a white network on a dark background, occur locally on old perennial rock-salt crusts. They are most clearly visible in areas near the margins of salt crusts, where a former covering layer of silt and sand has been removed by wind or where there is occasional flooding.

The polygons on a white salt flood plain are well developed in the western part of Salar de Talar (fig. 11, 31*H*), where the largest are 100 to 300 feet across and the smallest discernible on the photos are probably about 10 feet across. Polygons of a similar type are widespread in the hard halite crust of Salar de Coipasa (fig. 8). Polygons in a perennial salt crust, showing as a white network on a dark background in aerial photographs, are well developed on the north-central part of Salar de Atacama (fig. 31*J*), and in the westernmost part of Salar de Pedernales (fig. 31*I*). The most conspicuous polygons range from 50 to 100 feet across in the latter locality and 100 to 500 feet across in the former.

SALT SAG BASINS AND ESCARPMENTS

Faults cutting Salar Grande (fig. 13) are marked by escarpments and by round to elongate depressions or sag basins. Escarpments are as much as 5 feet high and are rounded because of leaching of salt since the last fault movement, which occurred several tens to several hundreds of years ago. Many sag basins on the faults are a few feet to several tens of feet long and as much as 5–10 feet deep. A few larger basins are several hundred feet in diameter and 10 feet or more deep. The basins may be due to subsurface leaching and collapse along the fault as well as to differential fault movement. A prominent escarpment and a sag basin occur along a recent fault in Salar Grande at the old salt mine, Salina Guanillos (fig. 5). This figure also shows a conspicuous basin in foreground that appears to have formed largely by surface leaching of the salt.

SALT PRESSURE RIDGES

Expansion and contraction of thin salt crusts because of temperature changes cause breaking of the crust and may result in formation of polygonal pressure ridges. The breaking and heaving of salt blocks is aided by the crystallization of new salt, which generally occurs by capillary migration of saline ground water, in newly formed fractures and cavities. Pressure ridges are found in two types of salar crusts. One type, shown in figure 27, consists of a nearly continuous thin layer of rock salt, 1–2 inches thick; the ridges result from the buckling of this single layer. Such pressure ridges were seen only at Salar del Carmen. The other type, a slabby silty crust, typical of salars in the Central Valley, has ridges 1–4 feet high consisting of upended slabs and rubbly fragments (fig. 41). Especially well-developed pressure ridges in this type of crust are in Salar de Obispo, Salar de Pintados, and Salar de Bella Vista. Similar pressure ridges were also seen in the northern part of Salar de Punta Negra.

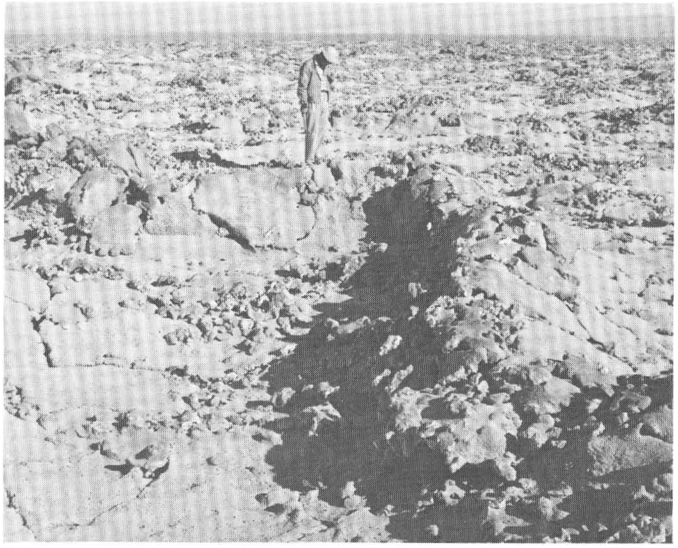


FIGURE 41.—Pressure ridges in slabby and nodular silty rock-salt crust, which averages about 3 ft in thickness, Salar de Bella Vista.

SALT VEINS

Salt veins occur in thick rock-salt crusts of salars in the Andes of northern Chile and may represent an early stage in development of salt polygons in such crusts. They also form in cracks within polygons in relatively thin crusts where they are associated with salt cones. They consist of granular salt formed along fractures in massive salt in the capillary fringe of the ground-water table. Some veins have banding parallel to vein walls.

White salt veins are widespread in the rugged rock-salt crust at the northern end of Salar de Maricunga (fig. 42). They are ½–2 inches wide and outline polygons that are generally 4–8 feet across. They cut across an older set of corroded polygons that are 2–4 feet across and that are bounded by ridges about 6 inches high. The rugged salt crust of this area borders a halite flood plain and was itself flooded by shallow water sometime in the past several years. The shallow-water flooding caused both the rugged crust to become slightly smoother and the old polygonal cracks to be firmly sealed before formation of the new polygons bounded by salt veins.

FEATURES FORMED BY WIND ACTION

DUST LOBES

Salars with extensive soft saline surfaces or granular gypseous crusts commonly trail elongate dust

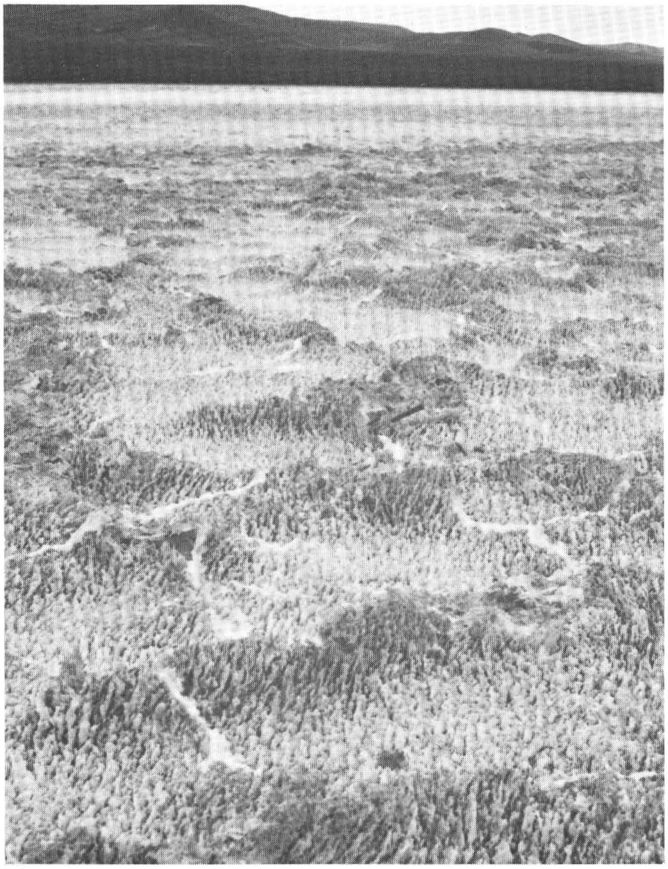


FIGURE 42.—Salt veins (white lines) outlining newly formed salt polygons in massive rock-salt crust, northwestern part of Salar de Maricunga; dark stripes outline old salt polygons.

lobes of windblown material from their leeward margins. The lobes consist chiefly of gypsum but also contain small amounts of more soluble saline minerals such as halite and thenardite. Large gypseous dust lobes extend southeastward from the edge of Salar de Pedernales for distances of a mile or more (fig. 31*Q*). The area from which the material in the lobes was derived is a gypseous zone which is marked by long straight southeast-trending furrows, parallel to prevailing wind direction.

At other places in northern Chile, dust lobes contain a large percentage of clastic sediment derived from the salar as well as from bordering areas. Such a dust lobe is visible on the western side of Salar de Atacama, near its junction with the Llano de la Paciencia (fig. 31*P*).

Lobes or dunes of sand and salt are found along the southwestern margin of Salar de Pintados and along the western margin of Salar de Bella Vista. In Salar de Pintados, the rugged perennial salt crust abuts against a gently sloping piedmont apron which is partly covered by prominent dust lobes trending northeast (fig. 31*S*). These lobes occur along the margin of the salar for more than 5 miles northwest of Pintados. The lobes are as much as a mile long and a quarter of a mile wide. Each lobe extends leeward from a gully in the adjoining hillside, which indicates that the gullies serve to channel windblown sediment. Some lobes extend out onto the hard salar crust for as much as a quarter of a mile. Some of these terminate abruptly at the margin of a low area in the salar that is subject to infrequent flooding.

SALT-STABILIZED DUNES

Sand dunes in the southwestern part of Salar de Bella Vista (fig. 13) are now stabilized by a slabby silty rock-salt crust that averages 1–2 feet in thickness. The salt crust on the dunes extends over them as a continuous layer, which merges with the crust of the surrounding flat salar and is identical in appearance (fig. 43*A*). The salt-stabilized dunes are scattered over an area of about 3 square miles, on both sides of the Pan-American Highway. They are mostly 5–10 feet high and appear as mounds rising above the otherwise level plain of the salar. Several of the dunes, which are cut by the highway, show excellent crossbedding in the sand and a sharp contact with the salar crust (fig. 43*B*).

The salt crust on these dunes apparently was deposited by capillary rise and evaporation of ground water. However, this took place at a time when the water level was higher than its present depth of 1–3 feet in this area. At the time when the salt crust was forming on the dunes, this area may have been subject to periodic flooding.

PHREATOPHYTE MOUNDS

Phreatophyte mounds (Neal, 1965, p. 23) are found in several salars and playas of northern Chile. They are best developed, however, in the northern part of Salar de Pintados where tamarugo trees are growing on mounds of windblown fine clastic sediment in an area of thin discontinuous crust (fig. 44). These mounds attain heights of as much as 5 feet and are 10–20 feet in diameter at their base. Smaller phreatophyte mounds are widespread in silt-clay playa areas in the eastern part of Salar de Llamara, where they have been built up of windblown sediment around low bushes.

FORMER LAKES IN NORTHERN CHILE

ANDEAN HIGHLANDS

Deep lakes formerly occupied parts of many closed basins in the Chilean Andes where now only salars

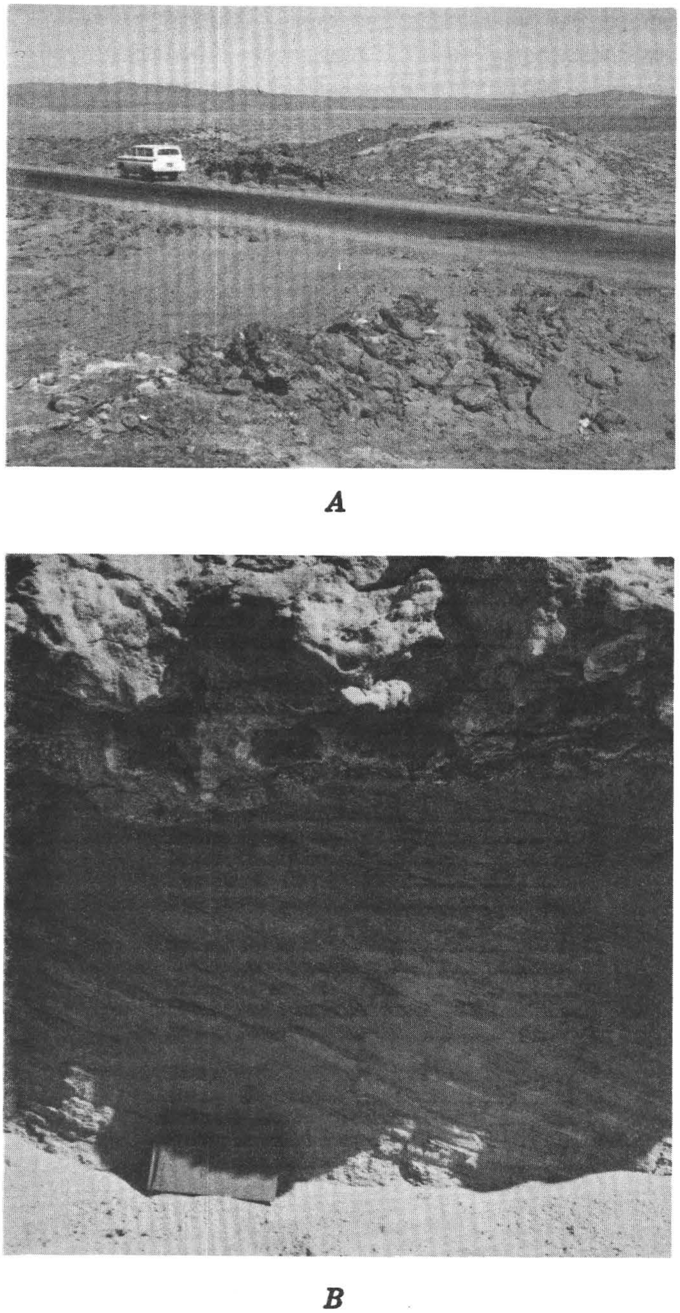


FIGURE 43.—Salt-stabilized sand dune, Salar de Bella Vista. *A*, Dune encrusted with platy silty rock-salt layer 1–2 ft thick. *B*, Crossbedded loosely cemented sand in sharp contact with overlying silty rock-salt crust. Notebook is about 9 in. long.

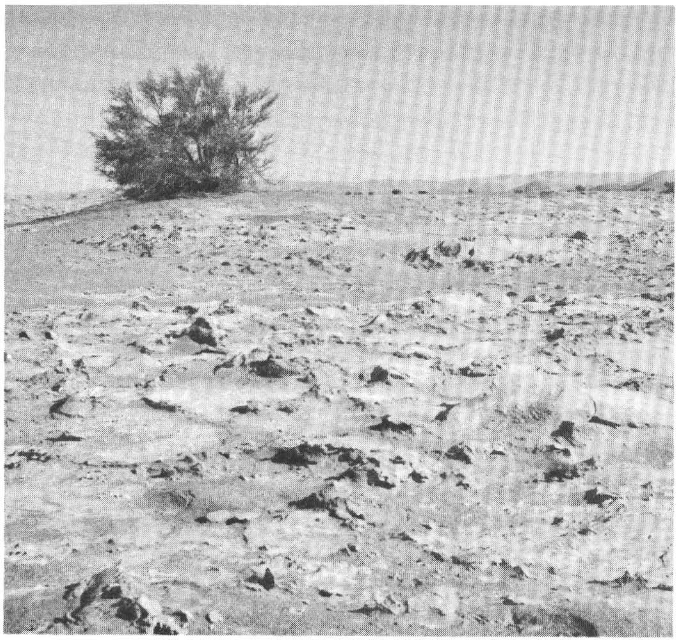


FIGURE 44.—Phreatophyte mound on which tamarugo tree (*Prosopis tamarugo*) is growing in area of thin discontinuous salar crust, northern part of Salar de Pintados. The tree is about 12 ft tall.

and shallow ponds remain. Shorelines and deltas of former lakes cut by more recent stream channels show clearly on aerial photographs but are less clear on the ground. Because detailed topographic maps of this region are lacking, it is difficult to interpret depth of former lakes, degree of tilting of lake basins, or changes in drainage divides due to tectonic movement or uplift during and after drying of former lakes.

Most former lakes in northern Chile and in the Andean region of adjoining countries were probably of Pleistocene age, but some may have existed during late Pliocene and others during Holocene time. For example, recent investigations of the paleontology and stratigraphy of lake sediments in the basin of Salar del Guasco indicate they are of Pleistocene age (Jaime Sayes, written commun., 1968).

Surprisingly little has been written about former lakes in northern Chile, considering their number, size, and, in some cases, great depth. These have been discussed by Bowman (1924), Ogilvie (1922), Brüggen (1950), Wurm (1940), Vita-Finzi (1959), and a few others.

During the present investigation, only a few of the basins containing relatively deep former lakes were visited. However, the aerial photographs show clear evidence that moderately deep perennial lakes formerly occupied parts of at least 35 of the 67 closed basins in the Andean Highlands of northern Chile. Most of these lakes are indicated in figures 8–12. However, in several basins, for example that of Salar de la Isla (fig. 12), the shorelines of the former lake are so close to the margin of the present salar that they could not be shown on the map. The lakes in such basins may have been large and deep, as was the lake that formerly occupied the basin of Salar de la Isla. The principal former lakes, shown in the above-mentioned illustrations, and their estimated maximum sizes are listed in table 3.

TABLE 3.—*Location and size of the principal former lakes in northern Chile*

Present salar or lake in basin (numbers refer to localities shown in figures 8–12)	Approximate size of former lake in basin (sq. mi)
Salar de Surire (2)	Unknown (incomplete photocoverage).
Unknown name (4)	29
Salar de Coipasa (5)	Unknown (largely outside Chile).
Salar del Guasco (11)	67
Salar de Coposa (12)	98
Salar de Ollagüe (14)	Unknown (largely outside Chile).
Salar de San Martín (15)	68
Salar de Ascotán (16)	104
Salar de Talar (28)	12
Salar de Aguas Calientes[1] and Purisunchi (29)	40
Laguna Tuyajto (30)	7
Salar de Aguas Calientes[1] (31)	56
Laguna Miscanti (31E)	11
Salar de Pujsa (32)	31
Salar de Aguas Calientes[1] (33)	14
Salar de Laco (34)	9
Salar de Quisquiro (35)	67
Salar de Tara (36)	78
Pampa de Tara (37)	7
Unknown name (43)	4
Salar de Púlar (44)	21
Salar de Incaguasi (45)	85
Salar de Aguilar (49)	47
Salar de Agua Amarga (51)	11
Salar de Pajonales (52)	66(?)
Salar Grande[2] (54)	13
Salar de Gorbea (55)	16
Laguna de la Azufrera (58)	7
Salar de las Parinas (59)	10
Salar de Pedernales (60)	210
Salar de Maricunga (61)	56(?)
Salar de Piedra Parada (65)	18
Salar Wheelwright (67)	3
Lagunas Bravas (68)	7
Laguna Escondida (71)	13
Laguna Verde (72)	20
Laguna del Negro Francisco (74)	30
Unknown name (76)	7

[1] Three salars in northern Chile are named Aguas Calientes.

[2] Two salars in northern Chile are named Salar Grande.

SHORELINES

Shorelines of former lakes appear in aerial photographs of many closed basins now containing a salar or a lake in the Andes of northern Chile, indicating more extensive flooding in the past. The shorelines appear to be best preserved where they are well above the present water level or salar margin and where the former lakeshores were fairly steep. Stream channels approaching many salars are graded to a level near that of the highest clearly recognizable shoreline, being less well defined below this level than above, thus indicating former larger streams. Some streams that now are deepening channels above the highest shoreline of a former lake apparently have little or no effect on channels below this shoreline because here the stream sinks into the highly permeable lake sediments. Such is the case at Salar de Aguas Calientes (fig. 11, no. 33), where channels with flowing streams end at the uppermost shoreline, the lower shorelines being virtually undissected.

Exceptionally well preserved shorelines can be seen in aerial photographs of the following Andean basins (figs. 9, 11, 12): Salar del Guasco, Salar de Coposa, Salar de San Martín, Salar de Tara, Salar de Pujsa, Salar de Aguas Calientes, Salar de Quisquiro, Pampa de Tara, and Laguna del Negro Francisco. The most detailed and extensive shorelines in all of northern Chile are in the basin of Salar de Tara (fig. 31*U*) where at least 24 terraces are recognizable around the eastern end of the salar. Their formation and preservation appear to be favored by the relatively soft porous material, probably tuffaceous sediments, in which they occur. The influence of prevailing westerly to northwesterly winds is indicated by the development of the most prominent shorelines in the eastern and southeastern parts of the above basins. Of the 27 most prominent shoreline areas that can be seen in aerial photographs, 11 are southeast and 9 east of the present salars.

Around the margins of many salars, particularly those at lower elevations in the Andes, the evidence of former lakeshores generally is obscure. Faint lineations around some salars seem to be the shorelines of very shallow or intermittent lakes. Shorelines in basins tilted by tectonic movement may appear to have the form of low terraces or steps crossed by many shallow channels flowing toward the lower parts of the basin. Such shorelines, which are apparently undergoing destruction, can be seen at the northern and eastern margins of Salar de Aguas Calientes (fig. 11, no. 31), the southwestern margin of Salar de Quisquiro (fig. 11), and the northwestern margin of Salar de la Isla (fig. 12).

The highest clearly recognizable shorelines at the southeastern side of Salar de San Martín (fig. 9) and at the western side of Salar de Ollagüe are between 12,400 and 12,500 feet and indicate the presence of a large former lake in these basins. This lake undoubtedly was connected with the former Lago Minchin, which covered much of west-central Bolivia, including the basins of Salar de Uyuni, Salar deCoipasa, Salar de Empexa, and Salar de Chiguana (fig. 1). The highest shorelines of Lago Minchin, measured far to the north in Bolivia, are reported to be at about 12,500 feet (Ogilvie, 1922, p. 42–44). At its greatest extent this lake was about 300 miles long, nearly connecting with Lake Titicaca at the Bolivia-Peru border, and had a maximum depth of more than 400 feet. It covered an estimated 10,000 square miles, an area roughly the same as Lake Erie in the United States.

Several altimeter measurements give an indication of the depth of the former lake in Chile and its relation to the divide between Salar de San Martín and Salar de Ascotán. Prominent beaches indicate a maximum depth of about 250 feet in the basin of Salar de San Martín and about 220 feet in that of Ollagüe. The lowest part of the pass between Salar de San Martín and Salar de Ascotán is about 12,680 feet, 260 feet above the nearby highest shorelines. Because of the height of this pass, it appears that lakes in these two basins were not interconnected at the time that Lago Minchin existed.

DELTAS

Prominent deltas, best seen in aerial photographs, are at the margins of several salars. Many of these deltas, including those at Salar de Tara (fig. 11), Salar del Guasco and Salar de Coposa (both in fig. 9), have well developed lakeshores at their upper edges, indicating that at the highest levels of former lakes the deltas were largely under water. As lake levels receded, the deltas were reworked, and lower shorelines formed. Some were dissected by streams, as can be clearly seen in aerial photos of Salar de Tara and Salar de Ollagüe. Stream dissection is generally greatest in the upper parts of the deltas where the stream channels commonly cut across steep-sided terraces. The lower parts show much less dissection, and in some cases none. Most of the present stream flow is commonly lost by seepage into the permeable deltaic sediments, reappearing again as springs along the margins of the salars.

Salar del Guasco (fig. 15) is the remnant of a much larger lake that left well-preserved shorelines, including prominent lake terraces, particularly northeast and southeast of the salar, and a large delta to the north. One prominent terrace at the eastern side of the salar was measured to be 100 feet above the salar. Brüggen (1929, p. 5) reported a terrace at that level. Still higher terraces, which we did not measure, are estimated to be at least 150 feet above the present salar. An extensive gently sloping plain extending for more than 5 miles north of the salar is interpreted as a delta. The highest shorelines are at the margins and above this delta, indicating that the delta was under water at the highest lake level. The delta is dissected by present stream channels, which are most prominent in its upper parts.

A decrease in streamflow that accompanied lowering of lake levels is well shown by a series of deltas on the east side of Laguna de Tuyajto (fig. 31*V*). The oldest delta was apparently below water at the highest former lake level. Successive lake shorelines are recorded by a series of terraces that are truncated by the delta plain, indicating that the delta continued to receive sediments while the lake receded. At a very low lake level, not far above the present salar, deposition on the emerged delta stopped, streamflow was confined to one or two steep-sided channels, and the lower edge of the delta was largely truncated at this lakeshore. During the final stage of lake desiccation, a small subsidiary delta (fig. 31) was apparently built out into the lake by a small stream. This small delta has now emerged and is inactive, but is crossed by a small intermittent stream which has built a new alluvial fan, approximately 300 feet wide, at the margin of the salar. The decrease in area of these successive deltas or fans gives a very rough indication of the decrease in runoff and of alluvial sediment that reached the lower part of the basin. The delta covered more than 600 acres at highest lake level but only about 40 acres at a very low lake level. The alluvial fan currently being formed is less than an acre in extent.

The northeast side of Salar de Tara (fig. 11) and westernmost end of Salar de Ollagüe (fig. 9) show a spectacular record of development of deltas and shorelines. The delta in Salar de Ollagüe is unique in having at its toe a series of cuspate spits that evidently formed in the shallow waters of the lake during its last stage of desiccation.

DRAINAGE CHANGES DURING HIGH LAKE LEVELS

From features seen in aerial photographs, several former lakes in the Andean Highlands appear to have overflowed their divides into adjoining basins. This is well illustrated by Salar de Aguas Calientes (fig. 11, no. 33), where the highest former lakeshore at the southeast side of the salar is cut by a steep-sided stream channel (fig. 31*T*) that connects southeastward with the basin of Salar de Quisquiro. Other drainage changes that appear to have occurred when lakes were at high levels are as follows:

1. A lake in the basin of Salar de Coposa (fig. 9) overflowed northward into a lake in the basin of Salar de Empexa.
2. A lake in the basin of Salar de San Martín (fig. 9) coalesced with one in the basin of Salar de Ollagüe, forming an arm of former Lago Minchin.
3. The lake in the basin of Salar de Tara (fig. 11) overflowed into one in the basin of Salar de Aguas Calientes. A lake in Pampa de Tara (fig. 11) appears to have coalesced with that in the basin of Salar de Tara.
4. A lake in the basin of Salar de Pujsa (fig. 11) apparently extended westward, joining a small lake at the salar that is about 4 miles to the west.
5. A lake at Laguna de Tuyajto (fig. 11), when at its highest level, probably overflowed into the basin of Salar de Incaguasi.
6. The basins of Salar de Talar and Salar de Purisunchi (fig. 11) were apparently formerly occupied by an interconnected lake.

LACUSTRINE SEDIMENTS

The lacustrine sediments in closed basins of the Andean Highlands of northern Chile consist of sand, silt, and clay, largely of volcanic origin, and locally of reworked volcanic ash. Diatomaceous earth layers have been found at several localities, and such layers may be widespread in lake sediments of the area. The sediments of a few of the Andean basins, described below, give an idea of the general character of the lacustrine sediments throughout the northern Chilean Andes.

Lake sediments in the basin of Salar del Guasco (fig. 15) consist of interstratified clay, silt, and diatomaceous earth layers having a probable maximum thickness of several hundred feet. A diatomite layer was sampled in a shallow cut (fig. 45) near the northwest side and 30–40 feet vertically above the present salar. The diatomite was estimated to consist of about 75 percent diatoms. At a late stage of desiccation of the former lake, large amounts of pyroclastic debris, including abundant pumice fragments, were deposited. A low terrace at the northern side of the salar, 5–10 feet above the present salar level, contains rounded pebbles of pumice, apparently washed up on the shore of the former lake.

FIGURE 45.—Diatomite layer deposited in a former lake, northwestern side of Salar del Guasco.

Salar de Coposa is in a basin that was once occupied by a large lake, as evidenced by well-preserved lake sediments and terraces at high levels around its margin, and by a large delta at the northeast side that is dissected by present streams (fig. 15). Two or more terraces presumed to be lake terraces are present along the western and southern sides of the salar, the highest prominent terrace being approximately 75 feet above present salar level. Terraces are most prominent along the eastern side, but on both sides they seem to be blanketed by volcanic material and possibly mudflows, which have obscured their outlines and particularly their upper limits. A valley south of the salar, Quebrada del Pabellón (not shown in fig. 9), appears to be occupied by lake sediments (Gabriel Perez, written commun., 1967) that extend nearly 9 miles to the south. Sediment from an area about 1.3 miles south of the salar was found to contain diatoms and to have small vertical tubes, evidently formed by roots of plants that grew in the shallow margins of a former lake.

The lake sediments have been blanketed by volcanic ash at several places around Salar de Coposa, the ash being deposited when the former lake had almost disappeared. The ash is thickest east of the salar; the volcanic source was probably in this direction. At the west side of the salar the lakebeds are overlain by a unit of white relatively undisturbed ash or pumiceous tuff, above which is a unit of reworked pyroclastic material. The upper unit appears to have been washed over the surface possibly as a mudflow, shortly after deposition of the underlying unit. Both units are variable in thickness and conform roughly to the slope of the present land surface. They have a total thickness of more than 20 feet.

The extensive tuffaceous deposits at the southeast side of Salar de Coposa (fig. 15) consist of loose to compact, light-gray, pink, and white pyroclastic material, including considerable pumice. The maximum exposed thickness is about 20 feet, but it is estimated that the tuff is generally many tens of feet thick and that it may attain a maximum local thickness of several hundreds of feet. Layering of the tuff is more or less parallel to present ground surface which is inclined gently to the west.

A special study was made of samples of beach deposits in the basins of Salar de Ollagüe and Salar de San Martín (Samples 20 and 37, table 2), to get an idea of the character of such deposits in the Andean Highlands. The samples were taken from about 10 feet below the highest prominent shorelines in both basins, at elevations between 12,400 and 12,420 feet.

The samples are similar in composition, consisting of about 94 percent sand and gravel and about 6 percent silt, and constitute a poorly graded silty sand (soil type SP–SM). Clastic grains in both samples are coated with calcium carbonate deposited after beach formation. Grains are predominantly subrounded in both samples; those larger than one eighth of an inch in diameter from the beach at Salar de Ollagüe are slightly more rounded, being classed as subrounded to rounded. The size gradation of the samples is comparable, average frequency distribution being shown on figure 16. The sediments are similar to mixtures of beach sand and gravel found on beaches elsewhere.

Near the settlement of Ollagüe (fig. 1), a beach terrace near the level of Salar de Ollagüe is covered with calcareous tufa. The terrace is well developed northwest of Ollagüe, and in aerial photographs it appears to form a broad plain extending for several miles northeast of that settlement. The tufa apparently was deposited in shallow water at the edge of a former lake. It includes abundant ostracodes that are incorporated in and partly encrusted by the concentrically banded calcareous tufa that may have been deposited by algae. Further desiccation of the lake initiated deposition of gypsum which predominates in the salar crust near Ollagüe.

ATACAMA BASIN AND VICINITY

The Atacama basin and nearby basins to the west and south along the east side of Cordillera Domeyko (figs. 10 and 11) differ from the basins in the Andean Highlands in lacking high shorelines and large deltas indicative of large former lakes. One might conclude that the lakes in these basins were not materially larger than the present salars, even when the largest lakes existed in the Andean Highlands. On the other hand, diatomaceous earth deposits in the Atacama basin seem to indicate that a former large lake extended 10 kilometers or more east of the present salar. Conversely, these deposits may have formed in a small lake, perhaps one of several that once existed in the Atacama basin. The diatomite deposits are nearly 1,000 feet above the level of the present salar and dip nearly 5°W., indicating sinking of the basin and tilting westward. Parameters of a former large lake that probably existed in the Atacama basin are listed in table 4.

TABLE 4.—*Comparison of probable former lakes in the Atacama Basin and in the Central Valley (Gran Lago Soledad)*

	Gran Lago Soledad	Atacama Basin
Drainage-basin area	12,870 sq mi (Río Loa only)	4,530 sq mi (Salar de Atacama only)
Maximum probable drainage area, including adjoining basin.	19,150 sq mi	5,260 sq mi
Former lake area (estimated).	770 sq mi(?) (excl. Salar Grande)	1,300 sq mi(?)
Maximum depth of former lake (estimated).	250 ft(?)	20 ft(?)
Mean depth of former lake (estimated).	100 ft(?)	15 ft(?)
Volume of former lake (gross estimate).	15 cu mi(?)	4 cu mi(?)
Elevation of former lake (approx.).	2,720 ft	7,500 ft
Mean elevation of drainage basin.	7,750 ft (weighted by percent of area)	10,750 ft (estimated)
Mean elevation of divides.	9,800 ft	13,900 ft
Mean annual precipitation in basin (estimated).	2 in.	2 in.
Ratio: Drainage area/volume of lake.	1.3 (approx.)	1.3 (approx.)

The only shorelines and lake terraces evident in the aerial photographs of the Atacama basin are along the east side of the Llano de la Paciencia and at the north end of an anticlinal dome bordering a low pass in the Cordillera de la Sal (fig. 31*P*). A lake in the Llano de la Paciencia once was connected to the main lake in the Atacama basin to the east, through this pass. The lake terraces are cut in the soft saline sediments and interbedded rock salt of the San Pedro Formation. Three distinct broad wave-cut terraces can be seen in the photographs. These terraces are 5–30 feet above present salar level. Less distinct terraces can be seen at higher levels, perhaps an additional 25–50 feet above the more distinct lower terraces.

CENTRAL VALLEY AND COASTAL RANGE

The Central Valley of southern Tarapacá Province and northern Antofagasta Province (fig. 1) once was occupied by a large lake known as Gran Lago Soledad (Brüggen, 1950, p. 151–152). This lake may have overflowed periodically into the basin of Salar Grande. Extensive deposits of gypsum and anhydrite in and around Salar de Llamara are attributed to this lake, as is the solid body of rock salt in Salar Grande. Extensive halite crusts and anhydrite-gypsum crusts elsewhere in this part of the Central Valley also are attributed to this lake. Estimated parameters of this former lake are shown in table 4.

At its highest level, Gran Lago Soledad apparently attained a depth as great as 250 feet, as indicated by shorelines on Cerro Soledad, an isolated ridge in the eastern part of the salar, and in the low pass between Salar Grande and Salar de Llamara (fig. 9). The highest former lake shorelines do not appear to be level at present, possibly the result of tilting due to tectonic movement. For example, the highest apparent shoreline in the pass near Salar Grande is estimated to be at an elevation of 2,720 feet, whereas a shoreline that appears comparable along the northernmost edge of Salar de Llamara is estimated to be about 100 feet higher, and farther north appears to rise to nearly 2,900 feet. At a high level the lake appears to have overflowed a divide in the Coastal Range, initiating the downcutting of the Río Loa (fig. 9), and subsequently cutting a steep-sided gorge several hundred feet deep.

Elsewhere in the Central Valley and Coastal Range, the presence of former lakes is indicated only by lake sediments. Shorelines and deltas, well shown in basins of the Andean Highlands, are absent. Consequently, our knowledge of size and distribution of the lakes is scanty; we do not know their relative ages, nor can we relate them to the period of lake development in the Andes.

Lacustrine sediments are widespread in the Pampa del Tamarugal (fig. 1), locally attaining thicknesses of 200 feet or more. These sediments are well exposed along the Río Loa in northern Antofagasta where they consist of interbedded fine-grained clastic sediments, limestone, diatomaceous earth, and evaporites. Salar del Miraje, in the Pampa del Tamarugal in the vicinity of Oficinas María Elena and Pedro de Valdivia (fig. 1), is covered with dissected lake sediments, apparently the upper part of the sequence exposed by the Río Loa. The sediments consist of interbedded silt and sand layers, some of which are firmly cemented with halite, anhydrite, or gypsum. Locally, the surface is covered by a dry friable soil consisting of clastic sediments and powdery gypsum or anhydrite. Still farther south, in the region near Aguas Blancas (fig. 1), widespread clastic lake sediments and interbedded anhydrite occur in an elongate closed basin that is a segment of the Central Valley. These sediments may attain thicknesses of several hundred feet.

Soft diatomaceous earth has been found as a surface layer or a layer just below thin salar crusts at several places in the Pampa del Tamarugal, indicating the presence of lakes during late Pleistocene or even Holocene time.

ENVIRONMENT OF PRESENT AND FORMER LAKES

It has been found that the relative sizes of former lakes in northern Chile, as indicated by basin/lake ratios, do not show a simple relationship to gross environmental factors such as mean annual precipitation, basin elevation, basin slope, or rate of evaporation. It is concluded that sizes of the former lakes were controlled by factors such as topography, hydrology, and geology, as well as by the above-mentioned gross environmental factors. Furthermore, the existence of lakes in certain basins and their absence in others cannot be correlated with present gross environmental factors. The following tabulation in which the basins showing clear evidence of former lakes are compared as a group with all the basins in the northern Chilean Andes, shows no significant differences between the two groups in elevations of basins, elevations of divides, mean annual precipitation, mean annual temperature, and index of potential evaporation.

Only five of the closed basins in the Andes of northern Chile have relatively large perennial lakes rather than salars. However, many of the salars of this region have small perennial ponds. These lakes and ponds provide a means of estimating gross environmental factors that favor their development

	Present gross topographic condition		Present gross climatic conditions		
Groups of basins	Mean basin elevations (in feet)	Mean elevation of divides (in feet)	Mean annual precipitation (inches, estimated)	Mean temperature (F, estimated)	Mean index of evaporation (estimated)
All 84 drainage basins in the Andean Highlands, and in the Atacama Basin and vicinity.	13,450	14,700	7.3	39	24
44 drainage basins having good evidence of former lakes.	13,400	14,300	6.7	39	25

and of estimating the climatic changes required to produce the more numerous and larger former lakes.

EXISTING LAKES

Basins in which perennial lakes rather than salars now are present are Laguna Miscanti, Laguna Wheelright, a small lake southeast of Lagunas Bravas, Laguna Verde, and Laguna del Negro Francisco (figs. 11, 12). A comparison of these five basins with 95 other closed basins in northern Chile shows that the five basins containing lakes have four of the 22 highest values of mean basin elevation (the fifth basin ranks thirty-third), five of the 29 highest values of mean annual precipitation (estimated), and five of the 14 lowest values of potential evaporation index (estimated).

Of the five basins with lakes, four are among the six basins in which all of the four critical values, listed below, are high. These values for the group of 100 basins in northern Chile are as follows:

1. Mean elevation of basin, 15,000 feet or more (22 basins).
2. Mean elevation of divides, more than 16,500 feet (9 basins).
3. Mean annual precipitation, 9 inches or more (29 basins).
4. Index of potential evaporation, 16 or less (14 basins).

Of all the basins, only 14 meet or exceed two of these critical values, and only six basins meet or exceed all four conditions. As the six basins having all four conditions include four out of five basins presently containing lakes, the four stated conditions might be considered the most critical values favorable for lake formation in northern Chile. Other factors may influence lake formation, but our information is too scanty to allow us to evaluate them.

The gross environmental factors favoring formation of perennial lakes in northern Chile are summarized in a circle graph (fig. 46). The graph shows that six to eight additional basins probably have conditions presently favorable for lakes. The absence of lakes in some of these basins is probably due to subsurface leakage of the basin, and in others to factors not yet recognized.

The basin of Laguna Verde (fig. 12) typifies the conditions favorable for perennial lakes in northern Chile. The mean elevation of the basin is approximately 16,000 feet; the lake itself is near 14,500 feet. The basin is rimmed by exceptionally high divides having a mean elevation of about 17,400 feet. The rim of the basin includes at least five peaks more than 19,500 feet high. The highest peak, Ojos del Salado, is reported to attain an elevation of about 22,580 feet, shown erroneously on a recent map (ONC) as 23,240 feet. The few peaks that rise above 21,000 feet have perennial snowfields, and Ojos del Salado is reportedly one of only three peaks in Chile north of lat. 30°S. having small glaciers (Lliboutry and others, 1958). Mean annual precipitation in the basin is estimated to be approximately 13 inches, and the index of potential evaporation would be about 12, probably the lowest of all the basins.

FORMER LAKES

Environmental factors favoring present-day lake formation in northern Chile give a clue to the past environment when perennial lakes were more numerous. The required increases in mean annual precipitation or decreases in mean annual temperature for different regions are shown in figure 47. The equivalent amounts of change of these two factors are based on their estimated relation to the potential rate of evaporation. These relations have been investigated by Langbein (1961) as an aid in estimating hydrologic regimes in areas of little meteorological data, the relative effect of precipitation and temperature varying in different climates.

The estimated changes in climate required to produce perennial lakes in each of the three major subregions containing salars are as follows: A very small to moderate increase in precipitation, or equivalent decrease in temperature, would favor the reestablishment of the former perennial lakes in the Andean Highlands. Large changes in one or both factors would favor perennial lakes in the Atacama

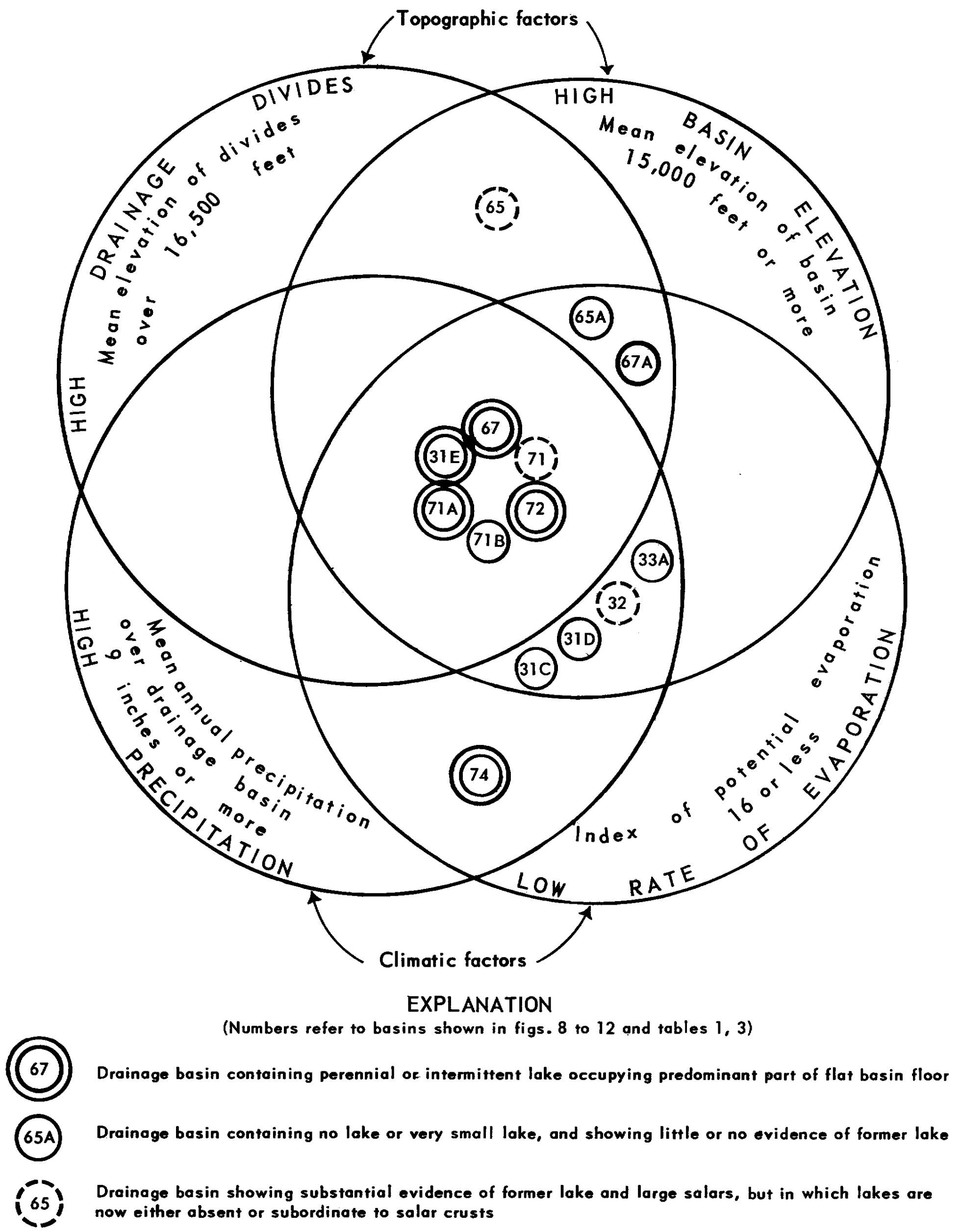
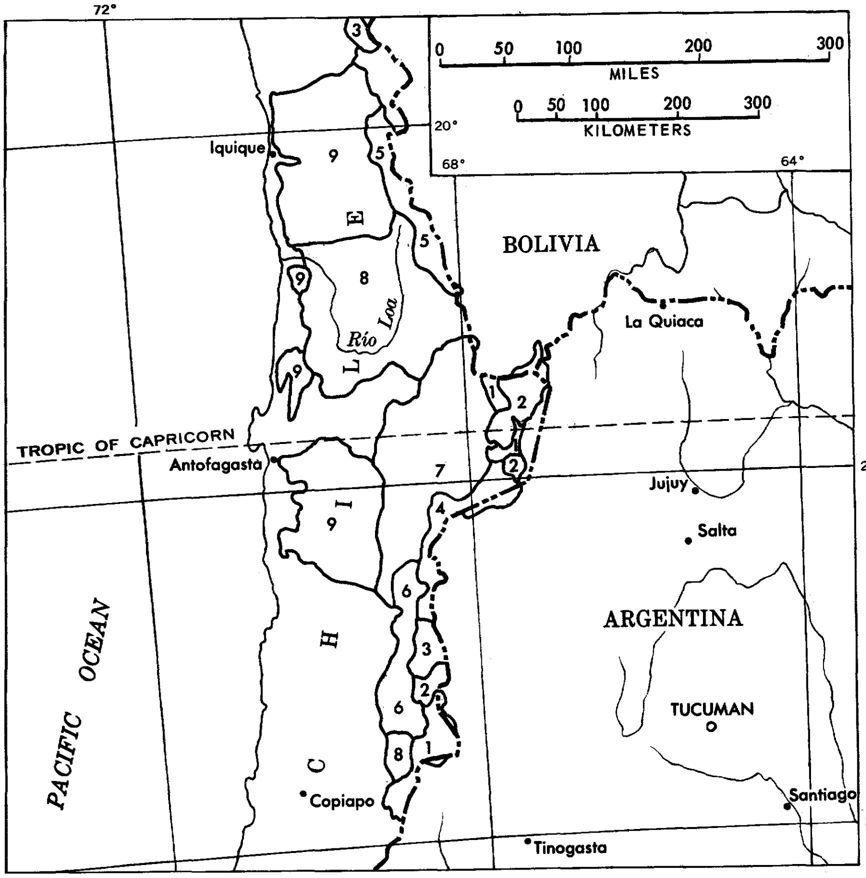


FIGURE 46.—Topographic and climatic factors favoring occurrence of perennial lakes in closed drainage basins of northern Chile.



Number	Required increase in mean annual precipitation only (in.)	Required decrease in mean annual temperature only (°F)	Region
1	None	None	Region presently favorable for lakes in Andean Highlands south of lat 26°30′S.; also small regions in eastern Antofagasta Province
2	1–2	2–3°	Andean Highlands, chiefly in east-central part of Antofagasta Province
3	4–5	5–7°	Andean Highlands, chiefly in northeastern part of Atacoma Province
4	5–7	7–9°	Crest of Andean Highlands between lat. 24°S. and 25°30′S.
5	9–11	12–14°	Andean Highlands east of Iquique between lat 20°S. and 22°S.
6	11–15	16–18°	Western ranges of the Andean Highlands between lat 25°S. and 27°S.
7	Over 20	Over 20°	Atacoma Basin and vicinity; also adjoining basins in lower parts of the Andean Highlands in eastern Antofagasta Province
8	Large increase	Large decrease	Río Loa drainage basin; probably a former closed basin draining into Salar de Llamara
9	Extraordinarily large increase	Extraordinarily large decrease	Closed drainage basins of salars in Coast Range and Central Valley, lat 19°S. to 25°S.

Figure 47.—Estimated climatic changes necessary to produce lakes in closed drainage basins in northern Chile.

Basin and vicinity, as well as in the Río Loa basin. Extraordinarily large changes in one or both factors appear to be required in the remainder of the Central Valley and Coastal Range areas.

Very little has been published about glacial deposits in northern Chile. Moraines have been described near the eastern edge of the Río Loa drainage basin (Brüggen, 1950; Hollingworth and Guest, 1967). No glacial deposits were observed on aerial photographs or in the field during the present study. The general lack of glacial deposits, cirques, or other evidences of glaciation, even at elevations of 15,000 feet and above in the Andean Highlands, suggests that the climate during glacial stages of the Pleistocene was not much different from that of today.

Inasmuch as deep perennial lakes have left their evidence in at least half the basins in the Andean Highlands, the lakes being widely distributed throughout the region, there is little doubt that the climate of this region was formerly somewhat more humid. A circle graph (fig. 48) similar to figure 46 has been prepared to show the estimated effects of a small to moderate increase in precipitation on probability of lake formation. This graph is based on an estimate of climatic conditions that would be favorable for simultaneous formation of perennial lakes in nearly every topographically closed basin in the northern Chilean Andes whose hydrologic closure is sufficient to hold water. It is estimated that these climatic conditions are reflected by the hypothetical curve of elevation vs. precipitation[2] shown in the lower left corner of figure 48. This graph shows that at all elevations the hypothetical precipitation would need to be about twice that which now falls in the region, although at elevations below 10,000 feet the increase would need to be less than 2 inches annually. Above 10,000 feet, the hypothetical increase in precipitation required to produce a pluvial age is estimated to be equivalent to present precipitation at elevations no more than 2,000–2,500 feet higher. When one considers the great relief of the Chilean Andes, in which at least 60 closed basins have divides averaging over 14,000 feet in elevation, this required increase in humidity does not seem extraordinarily large. The estimated average increase in annual precipitation required for such a pluvial age ranges from about 5 inches at 12,000 feet to 10 inches at 15,000 feet.

Although a uniform decrease in mean annual temperature of 2°F was arbitrarily assumed for all basins in northern Chile, to permit preparation of figure 48, a larger temperature decrease would favor lake formation with less change in precipitation. On the average, each additional decrease of 2°F in mean annual temperature was estimated to be roughly equivalent to an increase of 1 inch in mean annual precipitation. It is concluded that if the above hypothetical climatic conditions persisted for several years over northern Chile, perennial lakes would tend to form in basins having mean elevations approximately 2,000 feet lower, or drainage divides roughly 2,500 feet lower, than the basins in which perennial lakes now occur in northern Chile.

During such a hypothetical climate, perennial lake formation would be favored in the following basins: those having mean elevations of drainage divides higher than 14,000 feet; those whose mean overall elevations were higher than 13,000 feet; those receiving 15 or more inches of annual precipitation averaged over the basin; and those in which the potential rate of evaporation was an index of 16 or less. When all the 100 principal closed basins in northern Chile are considered in terms of these factors, 58 basins in the Andean Highlands (those clustered in the center of fig. 48) would be highly favorable for lake formation and three more would be moderately favorable during such a period of more humid climate. These 61 basins constitute 90 percent of the 67 closed basins in the northern Chilean Andes.

The hypothetical former precipitation pattern indicated in figure 48 would probably be insufficient to produce perennial lakes in the Atacama Basin and vicinity, although it undoubtedly would result in higher ground-water tables and the formation of lakes in some of these lower basins. A somewhat higher regional precipitation or lower temperature would be required to form numerous perennial lakes in this lower region. Nevertheless, it seems evident that a climate sufficiently humid to produce extensive perennial lakes in most of the Andean basins would

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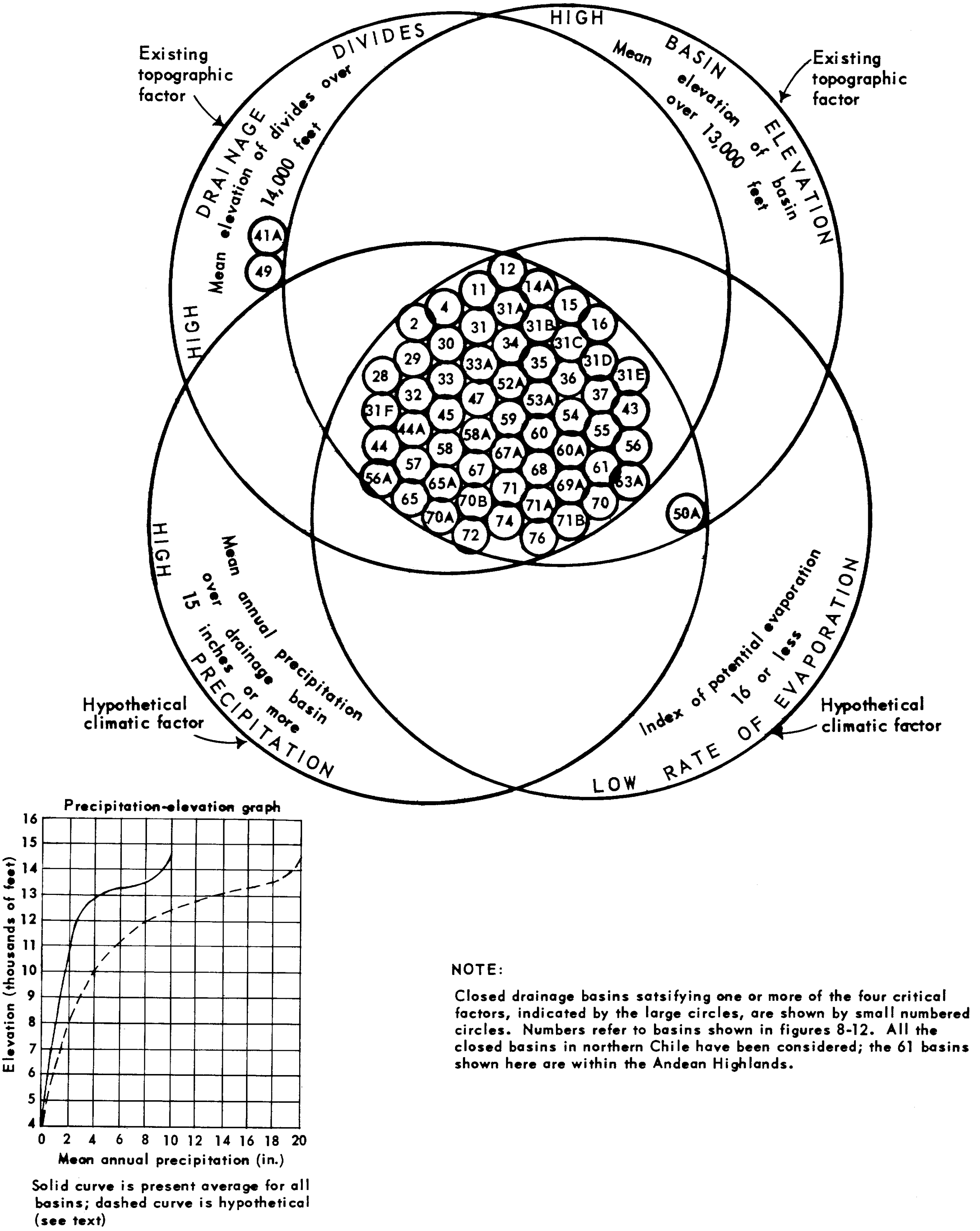
[2] The hypothetical elevation versus precipitation curve in figure 48 was constructed as follows: (1) the driest part of the Andean Highlands in which lakes formerly occurred (region no. 6, fig. 47) was compared with the more humid adjoining parts in which lakes now occur; (2) the amount of increased precipitation and decreased temperature necessary to produce conditions in region 6 similar to those now found in region 1 was estimated; (3) an arbitrary overall decrease in mean annual temperature of 2° F. was assumed, and the required change in rainfall was estimated from the curve of precipitation vs. elevation based on present climatic conditions; (4) it was assumed that the former mean annual precipitation was constant throughout the Andean Highlands at given elevations and that the elevations of drainage basins were the same as at present.

Because of normal fluctuations in climate, both in space and time, the curve in figure 48 is intended as a rough estimate of the character of former climates likely to have been associated with lake formation during some exceptionally humid period in specific regions, subregions, or even in specific lake basins, and not necessarily the long-term climate of the region as a whole.



Solid curve is present average for all basins; dashed curve is hypothetical (see text)

NOTE:

Closed drainage basins satsifying one or more of the four critical factors, indicated by the large circles, are shown by small numbered circles. Numbers refer to basins shown in figures 8-12. All the closed basins in northern Chile have been considered; the 61 basins shown here are within the Andean Highlands.

FIGURE 48.—Topographic and climatic factors that would have favored formation of perennial lakes in closed basins in the Andean Highlands of northern Chile.

strongly favor the occasional formation of perennial lakes in most of the bordering basins to the west.

At the time of high lake levels in the Andean Highlands, perennial lakes may have formed in basins in the Central Valley that are supplied by Andean drainage. The basin of Río Loa is particularly well situated to receive runoff from the high Andes. It can be shown that flooding in the Atacama Basin, unless of a very local nature, would probably also have been accompanied by flooding of Salar de Llamara, prior to its dissection by the Río Loa, and that the same climate required to produce a lake 20 feet deep in the Atacama Basin could produce a lake 250 feet deep in the Río Loa basin. In our study we believe there is good evidence that former lakes attained at least these depths in the two basins.

The climate, at least in some of the less arid basins, appears to have been slightly drier at some former time. For example, Laguna del Negro Francisco (fig. 12) appears once to have been shallower. A prominent island within the lake, about 2 miles long and 100–1,000 feet wide, is apparently covered by shorelines, some extending below present water level. The shorelines extend across the lake floor, being visible beneath the shallow water. Evidently the lake formerly occupied only the northwestern part of its present area and maintained that size long enough to build fairly prominent shorelines.

CONCLUSIONS

Our purpose was to study the total environment of existing salar crusts in the Atacama Desert and Andean Highlands of northern Chile to gain a better understanding of processes that modify them and to help interpret past climates of the region. Salars offer an unusually good opportunity for such a study because they receive the drainage from large closed basins and are responsive to a wide range of environmental factors, including geology, hydrology, topography, and climate.

The study was aided by excellent aerial-photograph coverage of all of northern Chile, which permitted photointerpretation of 75 salars and the preparation of photogeologic maps of 35 salars. This study was followed by field examination of 20 salars that show a wide variety of morphological and structural features.

Northern Chile offers a unique opportunity for the study of salars, which are exceptionally numerous and diversified in size, morphology, and mineralogy. Within the large area of interior drainage, covering more than 38,000 square miles, there are approximately 100 salars that together occupy about 2,800 square miles. Hard evaporite crusts alone cover more than 1,500 square miles, whereas such crusts are comparatively uncommon in the United States. Two-thirds of the Chilean salars are high in the Andes at elevations of 10,500–16,000 feet, a semiarid setting that contrasts sharply with the extremely arid coastal desert. Comparison of salars in these two areas of distinctly different climates—precipitation, relative humidity, and temperature—gave new information about climatic influence on salt crust morphology.

Of two major crustal types recognized in Chilean salars, the most prevalent is a hard perennial evaporite crust that is roughly equivalent to the zone of chlorides (chiefly halite). Soft salar crusts in Chile are commonly the rough equivalent of the zone of sulfates, including chiefly gypsum, mirabilite (or thenardite), and ulexite. A unique type of salar crust found in the Atacama Desert is a silty nitrate-bearing crust; five salars in northern Chile were mined for nitrate during the 19th century.

Evaporation of both ground water and surface water has been important in the formation of salars, but crusts resulting from these two sources could not be differentiated on aerial photographs. Field study, however, revealed morphological and structural features indicative of a surface- or ground-water source and of a variety of climatic and geologic processes. Several features of Chilean salars are thought to be better formed there than in other desert regions, and a few may be unique to Chile.

Northern Chile also offers an unusual opportunity for study of former climates. Aerial photographs clearly reveal evidence of former deep perennial lakes in at least 35 basins in the northern Chilean Andes where no lakes now exist. The largest and deepest of these lakes was probably an arm of Lago Minchin, which was chiefly in Bolivia and which is estimated to have attained at its greatest extent a depth of more than 400 feet, an area of about 10,000 square miles, and a length of about 300 miles.

A study of the environment of perennial lakes that presently exist in five basins in the Chilean Andes provides clues to probable environments of the past, when lakes were more numerous. It is concluded from this study that perennial lakes could form in nearly all the 67 Andean basins if the mean annual rainfall of the region above 10,000 feet increased to 15 inches from its present average of about 8 inches, and if the mean annual temperature were about 2°F lower than it is at present.

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