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GEOLOGY AND RESOURCES OF SALARS IN THE CENTRAL ANDES

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ABSTRACT

Salars of the central Andes constitute one of the world's major continental evaporite complexes that contain significant portions of the known resources of lithium and boron. At least 100 salars and saline lakes having areas ranging from a few square kilometers to about 9,000 km^2 are found in individual closed basins within a 400,000-km^2 area of internal drainage in northwestern Argentina, western Bolivia, northern Chile, and southern Peru. An arid climate persisted in this region during most of late Tertiary and Quaternary time. Compared to glaciation in the Andes mountains to the north and south, Pleistocene glaciation in this region was scanty. Major Andean uplift took place during the late Tertiary and Quaternary, and this period was a time of intense volcanism. The basins in which the salars and saline lakes are found were formed both by faulting and by volcanic eruptions. The volcanic rocks are the major sources of the saline materials in the salars. Most of the salars formed by desiccation of saline lakes during the Holocene and by subsequent deposition of saline materials from evaporation of spring water, ground water, and annual or intermittent flood water. Some closed basins have had complex histories dating back to the late Tertiary or even to the late Cretaceous.

The salars consist of hard to soft saline crusts that overlie sequences of lacustrine sediments. The saline crusts, generally not more than a few meters thick, contain a variety of saline minerals, of which halite and gypsum are most abundant. Mirabilite, thenardite, and ulexite are found in moderate to minor amounts in nearly all salars. Several other saline minerals are present in minor amounts in many salars and some of these are moderately abundant in a few salars. Five general types of salars can be recognized: (1) zoned salars consisting of an interior halite zone surrounded by a sulfate zone; (2) gypseous salars consisting chiefly of gypsum and lesser amounts of other sulfate minerals, halite, and ulexite; (3) salars having crusts of silty halite that formed chiefly by capillary evaporation of near-surface ground water or brine in lacustrine sediments; (4) salars consisting chiefly of mud flats subject to annual flooding and having thin ephemeral crusts of halite or sulfate minerals during dry seasons; and (5) Salar Grande, in the coastal region of northern Chile, which is a 40-km-long valley filled with coarsely crystalline halite to depths of as much as 160 m.

Although the salars probably have been exploited for rock salt since Pre-Columbian time, systematic exploitation did not start until the 19th century when several salt quarries were opened in Salar Grande, Chile, which prior to the 1880's was in Peruvian territory. Ulexite was mined in several salars before the end of the 19th century. Small amounts of $NaNO_3$ were recovered from salars in the coastal region of northern Chile during the late 19th century and early 20th century. In the early 1940's, several thousand tonnes of KCl and KNO_3 were produced from the K-rich saline crust of Salar de Bellavista, in the coastal region of northern Chile. Since the 1950's, the salars have been exploited as sources of rock salt, borate minerals, and Na_2SO_4. Production of Li_2O_3, using Li-rich brines from Salar de Atacama, Chile, began in 1984.

INTRODUCTION

The central Andean region of northwestern Argentina, western Bolivia, northern Chile, and southern Peru is an area characterized by an arid climate and predominately internal drainage, where many salars (salt-encrusted playas) and saline lakes now exist (Fig. 1, Table 1). The region includes the Andean Highlands, as well as the western Andean front ranges and coastal lowlands of northern Chile. The region of internal drainage, which extends over an area of about 400,000 km^2, is subdivided into about 150 closed basins. At least 100 of the basins contain salars or saline lakes having areas ranging from a few square kilometers to 9,000 km^2. An arid climate has persisted in this region throughout late Tertiary and Quaternary time, and the coastal region of northern Chile may have had an arid climate since early Tertiary (Mortimer, 1973; Mortimer and Sarič, 1972, 1975). At present, the Andean Highlands have a climate that is transitional between that of the Peruvian Andes, which have a summer (December-March) season of rain, and the southern Andes of Chile and Argentina, which have a winter (June-September) season of rain and snow. The central Andean region is an area of sparse Pleistocene glaciation in comparison with the Andean Highlands to the north and south. At altitudes above 3,000 m, present-day annual rainfall is on the order of 100-200 mm but at places is as little as 50 mm or is slightly more than 300 mm. Annual rainfall is greatest in the Altiplano of southern Peru and northern Bolivia, where it exceeds 300 mm, and decreases southward to less than 100 mm in southwestern Bolivia and nearby Argentina and Chile (Montes de Oca, 1982). Rainfall decreases with altitude along the western Andean front to a minimum of only a few millimeters per year in the Atacama Desert of the coastal region of northern Chile.

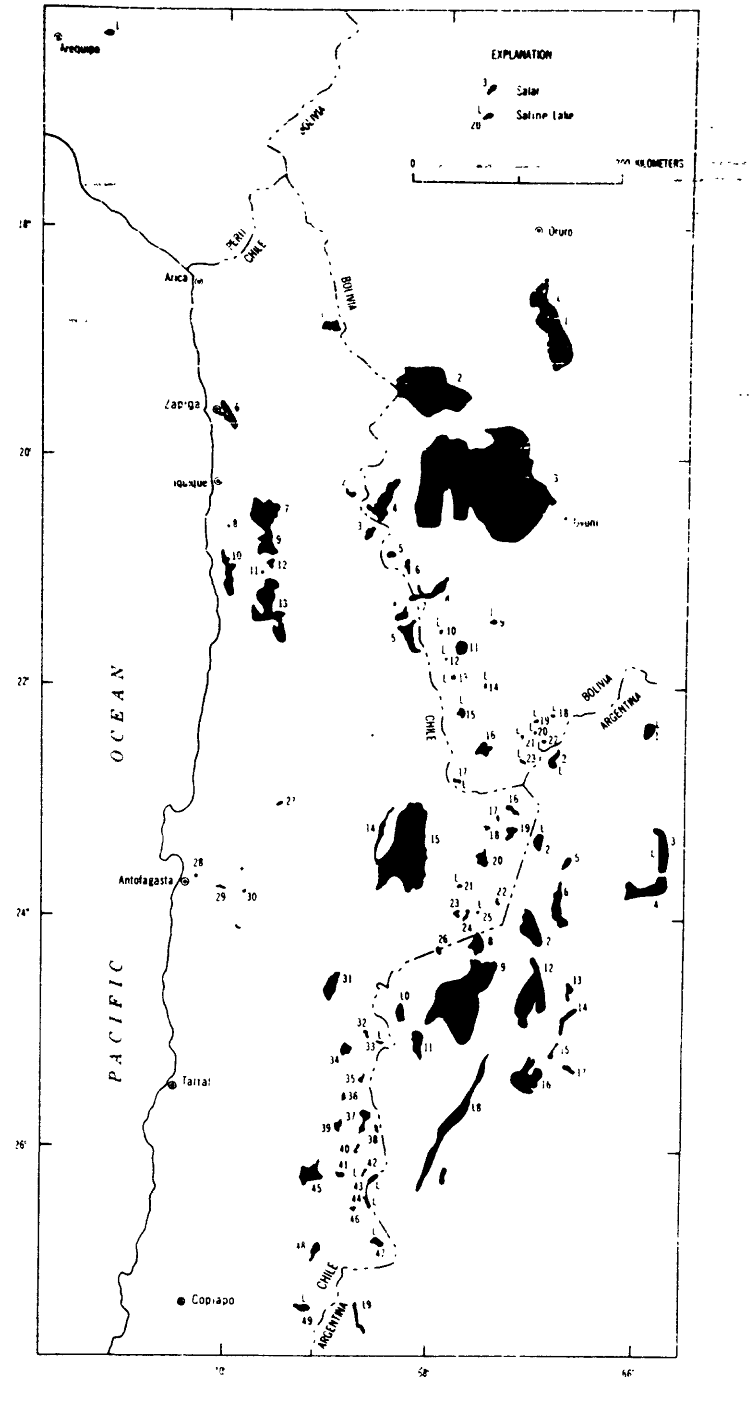

Fig. 1.--Index map of the central Andean region showing the location of principal salars and saline lakes. Numbers refer to Table 1.

Table 1. Principal salars and saline lakes in the central Andean region [Locations shown in figure 1].

ARGENTINA	
1. Laguna Pozuelos	10. Salar de Llullaillaco
2. Laguna Vilama	11. Salar de Rio Grande
3. Laguna Guayatáyoc	12. Salar Pocitos
4. Salinas Grandes	13. Salar de Pastos Grandes
5. Salar Olaroz	14. Salar Centenario
6. Salar de Cauchari	15. Salar Ratones
7. Salar del Rincón	16. Salar del Hombre Muerto
8. Salar de Incahausi	17. Salar Diabillos
9. Salar de Arizaro	18. Salar de Antofalla

BOLIVIA	
1. Lago Poopo	12. Laguna Cachi
2. Salar de Coipasa	13. Laguna Khara
3. Salar de Uyuni	14. Laguna Capiña
4. Salar de Empexa	15. Laguna Colorada
5. Salar de La Laguna	16. Salar de Challviri
6. Salar Laguani	17. Laguna Verde
7. Salar de Ollagüe	18. Laguna Corante
8. Salar de Chiguana	19. Laguna Mama Khumu
9. Laguna Tarija	20. Laguna Chojllas
10. Laguna Cañapa	21. Laguna Loromayu
11. Lagunas Pastos Grandes	22. Laguna Coruto
	23. Laguna Kalina

Table 1 (con't.)

CHILE

1. Salar de Surire
2. Salar de Huasco
3. Salar de Coposa
4. Salar de San Martín
5. Salar de Ascotán
6. Salar de Obispo
7. Salar de Pintados
8. Salar de Soronal
9. Salar de Bellavista
10. Salar Grande
11. Salar de Lagunas
12. Salar de Sur Viejo
13. Salar de Llamara
14. Llano de Paciencia
15. Salar de Atacama
16. Salar de Tara
17. Salar de Aguas Calientes I
18. Salar de Pujsa
19. Salar de Quisquiro
20. Salar de Aguas Calientes II
21. Laguna Miscanti
22. Salar de Laco
23. Salar de Talar
24. Salar de Purisunchi
25. Laguna Tuyacto
26. Salar de Pular
27. Salar de Pampa Blanca
28. Salar del Carmen
29. Salar de Navidad
30. Salar Mar Muerto
31. Salar de Punta Negra
32. Salar de Aguas Calientes III
33. Laguna Azufrera
34. Salar de Pajonales
35. Salar de Gorbea
36. Salar de Agua Amarga
37. Salar de La Isla
38. Salar de Las Pariñas
39. Salar de Aguilar
40. Salar Grande (II)
41. Salar de Piedra Parada
42. Lagunas Bravas
43. Laguna Wheelright
44. Laguna Escondida
45. Salar de Pedernales
46. Salar Wheelright
47. Laguna Verde
48. Salar de Maricunga
49. Laguna Negro Francisco

Table 1 (con'd.)

PERU
1. Laguna Salinas

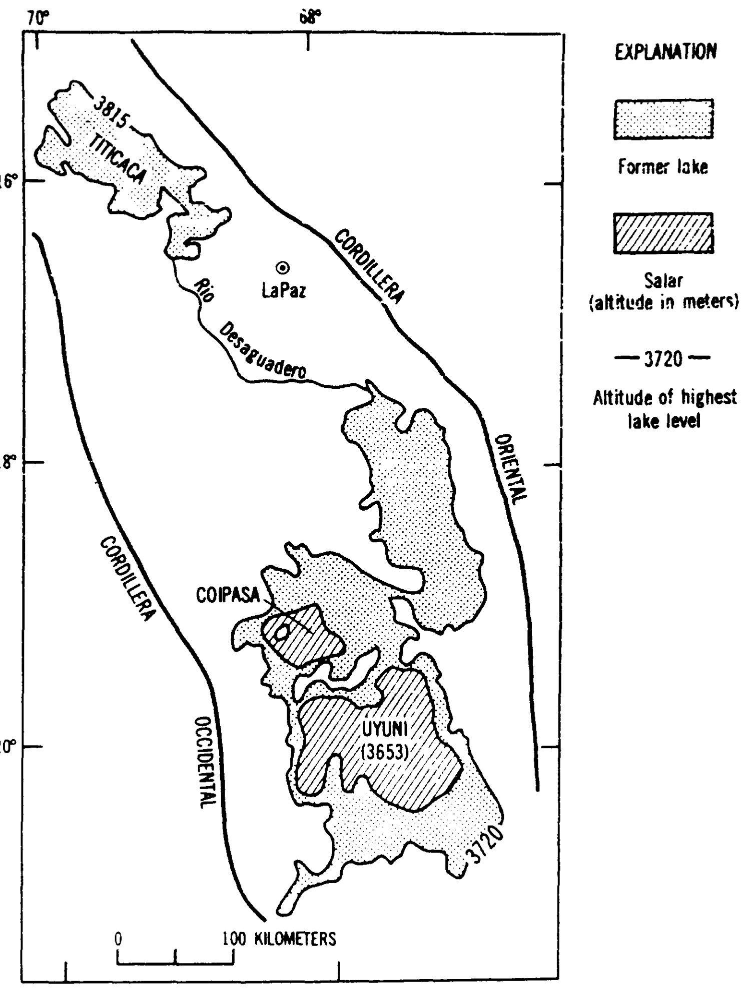

Fig. 2.--Maximum extensions of former large lakes in the Bolivian Altiplano, 12,360±120 to 10,640±280 years B.P., showing the salars Uyuni and Coipasa. These salars are the evaporite remnants of Lago Tauca, the large lake in the southern part of the Altiplano. Modified from Servant and Fontes, 1978. Present-day Lago Titicaca is also a remnant of the larger lake shown here.

Many lakes formed in the central Andes during the Quaternary in response to periods of slightly increased rainfall or of slightly increased temperatures that caused melting of glacial ice and snow. As a result, many of the basins now having salars exhibit multiple shorelines and other features of former lakes (Stoertz and Ericksen, 1974). The largest lakes existed in the Bolivian Altiplano during late Pleistocene (Fig. 2), when they reached a maximum of about 50,000 km^2 (Servant and Fontes, 1978). Lake Titicaca, on the Peru-Bolivian border, is a remnant of a larger lake shown in figure 2, and Lago Poopo and the salars Coipasa, Uyuni, and Empexa are remnants of another, which Servant and Fontes named Lago Tauca.

Systematic study of Andean salars began in the early 1960's. Many reports about them have been published since that time. General features of salars in northern Chile were described by Ericksen (1963), Stoertz and Ericksen (1974), Vila (1974, 1975), and Chong (1984). Moraga and others (1974) made a detailed study of Salar de Atacama, the largest salar in northern Chile, to evaluate the lithium resources. Vila (1976) described salars in the coastal region of northern Chile. Ericksen and others (1976) discussed the lithium resources of Andean salars, and Ericksen and others (1977), Ballivian and Risacher (1981), and Davis and others (1982) described salars in southwestern Bolivia. Risacher (1978) and Rettig and others (1980) discussed the geochemistry of salars in southwestern Bolivia. Muessig (1966) described borate deposits in northwestern Argentina. Nicolli and others (1982a, 1982b) described the salars in northwestern Argentina, including a discussion of the results of systematic exploration for lithium in Salar de Hombre Muerto. Catalano (1964a, 1964b) discussed Salar de Hombre Muerto and thermal-spring deposits of ulexite in northwestern Argentina. Alonso and Viramonte (1985) also discussed thermal-spring borate deposits in northwestern Argentina! Earlier reports about Andean salars are Reichert (1907), Barnabe (1915), and Catalano (1926, 1927, 1930) on borate deposits in northwestern Argentina; Leiding (1942) on borate deposits in northern Chile; and Jochamowitz (1917) on borate deposits in southern Peru. Brüggen (1918) and Gale (1918) discussed potash resources of Salar de Pintados, Chile.

This report is based on our investigations of Andean salars that began in 1961 and on published and unpublished reports of other investigators. Work in Chile was carried out in cooperation with the Instituto de Investigaciones Geológicas, now the Servicio Nacional de Geología y Minería; work in Bolivia was with the Servicio Geológico de Bolivia; and work in Argentina was with the Servicio Minero Nacional and the Dirección General de Fabricaciones Militares.

PHYSIOGRAPHIC AND GEOLOGIC SETTING

The many closed basins within the area of internal drainage in the central Andes owe their existence to intensive block faulting and volcanism during late Tertiary and Quaternary time. The three major longitudinal physiographic units--the Coastal Range and Central Valley of northern Chile and the Andean Highlands to the east--developed during differential uplift that began in the early Miocene (Mortimer and Sarič 1972, 1975). The Central Valley became largely filled with debris from the uplifted Andes by mid-Miocene time. The Coastal Range is a Miocene or even earlier Tertiary landscape (Mortimer and Sarič, 1972) that has since been modified, chiefly by block faulting and by wind erosion. The Andean Highlands of this region consist of a broad longitudinal depression, called the Altiplano, which centers in western Bolivia but which extends from southern Peru to northern Argentina. This depression is filled with continental clastic sediments ranging in age from Cretaceous to Quaternary. It is flanked on the east and west by uplands having discontinuous, longitudinal mountain ranges consisting predominately of lower Paleozoic sedimentary rocks, Mesozoic and Tertiary plutonic rocks, and Mesozoic sedimentary and volcanic rocks. To the west of the Altiplano, the Andean Highlands have an extensive cover of late Tertiary ash-flow tuffs, clastic continental sediments, and hundreds of stratovolcanos.

Base altitude in the Andean Highlands is 3,500-4,000 m, and many mountain peaks and volcanic cones extend to altitudes of 5,000-6,000 m. The highest peaks are volcanic cones of about 6,500-6,800 m. The Altiplano slopes gently southward from southern Peru (Lake Titicaca near the north end of the Altiplano is at an altitude of 3,815 m) to Salar de Uyuni, which at an altitude of 3,653 is the lowest part. The Altiplano again rises southward into Argentina, where it is characterized by many individual closed basins, rather than by the broad basins and open valleys of the Bolivian Altiplano to the north.

The late Tertiary and Quaternary volcanic rocks are of particular importance because they have been the major source of the saline constituents of the lakes and salars of the region. Two distinctly different types of volcanism can be recognized. The earliest volcanic phase, during the Miocene and early Pliocene, was dominated by explosive, caldera-type eruptions of dacitic to rhyolitic ash-flow tuffs that now blanket extensive areas of the Andean Highlands. Superimposed on the ash-flow tuff terrain are hundreds of andesitic stratovolcanos of Pliocene and Quaternary age. Several of the volcanoes now show fumarolic activity, but only a few have had historic eruptions. The ash-flow tuffs contain considerable amounts of water-soluble saline material that has been leached and carried into the lakes and salars by meteoric waters.

In contrast to the Andean Highlands, the geology of the coastal region of northern Chile is dominated by late Tertiary and Quaternary block faulting of pre-Tertiary rocks. In the Coastal Range, salars and former saline lakes formed in basins isolated by late Tertiary and Quaternary faults, whereas those in the Central Valley formed in depressions resulting from differential uplift as well as from faulting and in basins isolated by alluvial fans extending outward from the Andean front. The Central Valley is a structural depression filled largely with continental sediments, of Miocene to Holocene age, to depths of as much as 1,000 m (Mordójovich, 1965). In northernmost Chile, this infilled depression was dissected by deep transverse valleys that formed after mid-Miocene when the fill overtopped the Coastal Range in this area (Mortimer and Sarič, 1972). From Zapiga southward to near Taltal (Fig. 1), only one stream, the Rio Loa, now crosses the Central Valley and cuts through the Coastal Range.

Tectonic movements associated with Andean uplift have affected the closed basins and salars and saline lakes in several ways. Basins have been tilted, causing migration of lakes and salars towards the depressed sides of the basins (Stoertz and Ericksen, 1974). Such salars tend to show an asymmetrical zoning in which the halite crust is crowded against the depressed side and the sulfate zone towards the upraised side (Fig. 3).

This asymmetrical zoning contrasts with symmetrically zoned crusts of salars in basins that have not been tilted, and consequently consist of a central halite zone surrounded by a sulfate zone. Shorelines of former saline lakes and clastic sediments deposited in such lakes in tilted basins may be gently inclined towards the depressed basin sides. Some salars abut active faults whereas others are in sag basins on active faults. Still others have been displaced by faults. The best example of recent fault displacement is at Salar Grande, in the coastal range of northern Chile. This salar is crossed by the Atacama fault (Fig. 3), a longitudinal fault that shows recent displacement throughout its strike length of nearly 700 km. Lacustrine sediments of former lakes in northwestern Argentina have been folded and faulted, and the Tincalayu borate deposit is thought to be a folded remnant of a buried salar crust of late Quaternary or Holocene age (Pratt, 1961).

TYPES OF SALARS AND STRUCTURAL FEATURES OF SALAR CRUSTS

Different types of salars may be distinguished on the basis of the relative abundances of the various saline minerals present and on the physical character of the salar surface. As noted in the previous section, many salars are zoned, having a hard, dense to porous, relatively thick interior halite zone surrounded by a sulfate zone consisting chiefly of gypsum, but having varying amounts of admixed halite, mirabilite, thenardite, and ulexite. Typical zoned salars are Atacama (Fig. 4) and Pedernales in Chile, Empexa in Bolivia, and Hombre Muerto in Argentina (Fig. 1). Salar de Uyuni, Bolivia, is an unusual zoned salar because most of its 9,000 km^2 expanse is covered by a hard halite crust, and because the sulfate zone is confined to narrow muddy or marshy marginal areas. The upper part of the

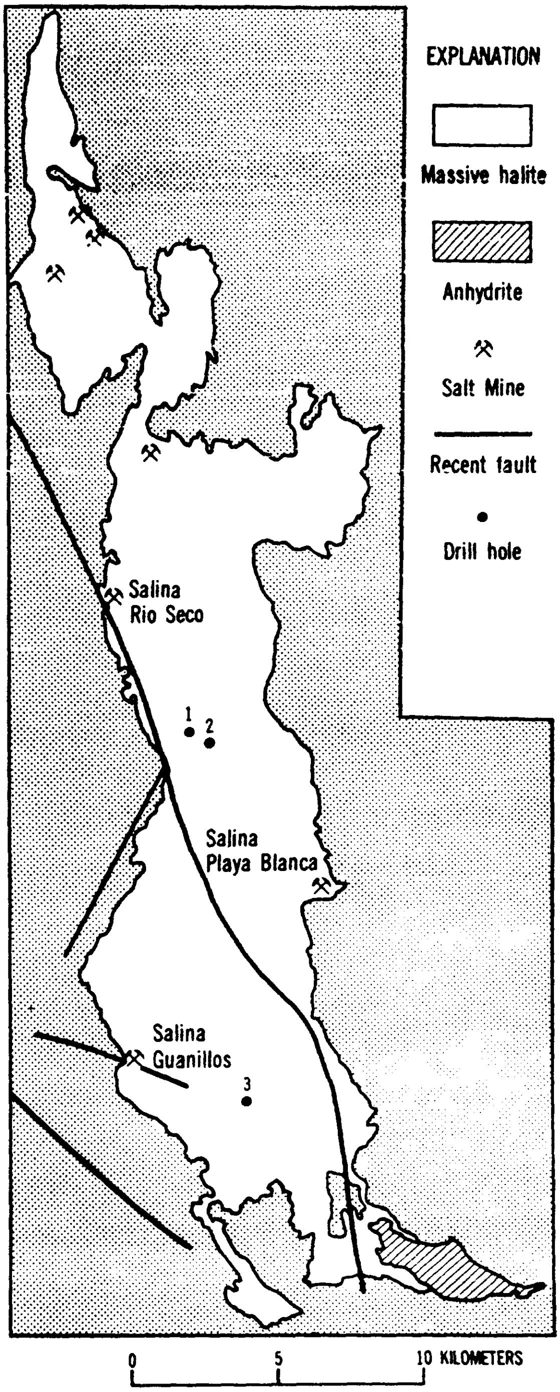

Fig. 3.--Sketch map of Salar Grande, a salt-filled basin near the coast in northern Chile, showing trace of the Atacama fault, which cuts diagonally across the salar. This fault and others shown have had recent movement. From Stoertz and Ericksen (1974).

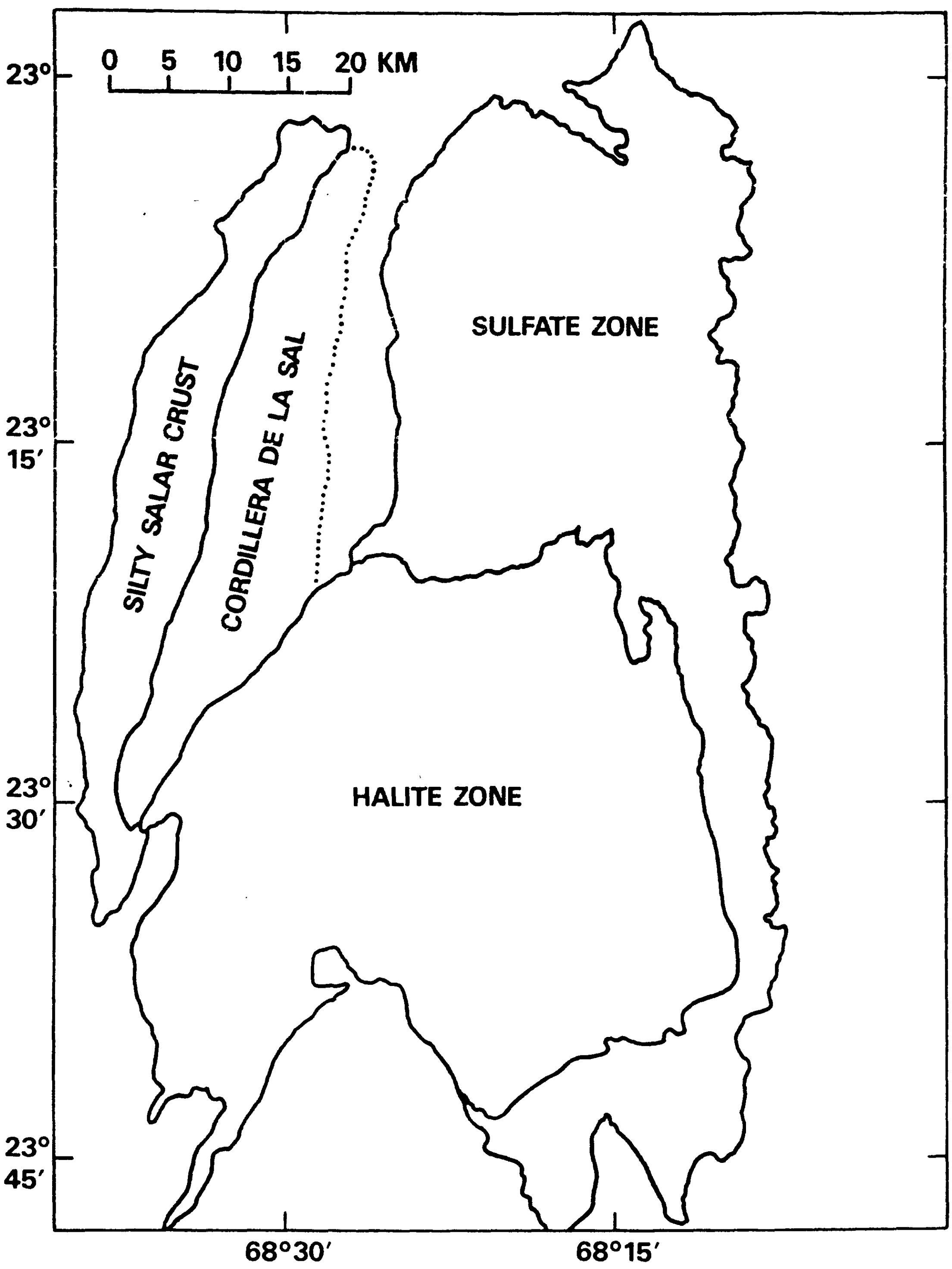

Fig. 4.--Sketch map of Salar de Atacama, Chile, showing asymmetrical zoning in which the halite crust is crowded against the southwestern margin of the salar. The Cordillera de la Sal consists of an intensely folded sequence of continental saline clastic sediments of Tertiary age; several domal structures have cores of coarsely crystalline halite. Modified from Moraga and others (1974).

lacustrine sediments beneath the halite crust of this salar contain gypsum, as probably do the sediments beneath the halite crusts of other zoned salars. Many salar crusts consist chiefly of moist, relatively soft, granular gypsum or crystal meshworks of gypsum, admixed halite and mirabilite, and local layers and nodules of ulexite. Such salars are subject to widespread flooding during the rainy season and have perennial ponds both within the salar and along its margins, as is well shown by Lagunas Pastos Grandes, Bolivia (Fig. 5). Other examples of salars of this type are Ascotan and Surire, Chile (Fig. 1). Some salars or parts of salars consist chiefly of a surface of moist lacustrine sediments that is subject to seasonal flooding; thin ephemeral crusts or scattered crystals of saline minerals form on such surfaces only during the dry season. The near-surface lacustrine sediments may contain layers of gypseous muds and impure to relatively pure ulexite. Lagunas Salinas in southern Peru is a typical salar of this type.

Salars in the coastal region of northern Chile, and some salars in the Andean Highlands, have hard, silty, halite-rich crusts that were formed chiefly by capillary evaporation of near-surface saline ground water in lacustrine sediments. These salar crusts, which generally are not more than a meter thick, are built up by saline material deposited by capillary evaporation of ground-water brine at the base of the otherwise dry crust. Typical salars are Bellavista and Obispo, Chile, and Arizaro, Argentina. Salar del Carmen and Salar de Pampa Blanca in the coastal region of northern Chile have silty crusts that contain considerable amounts of nitratite.

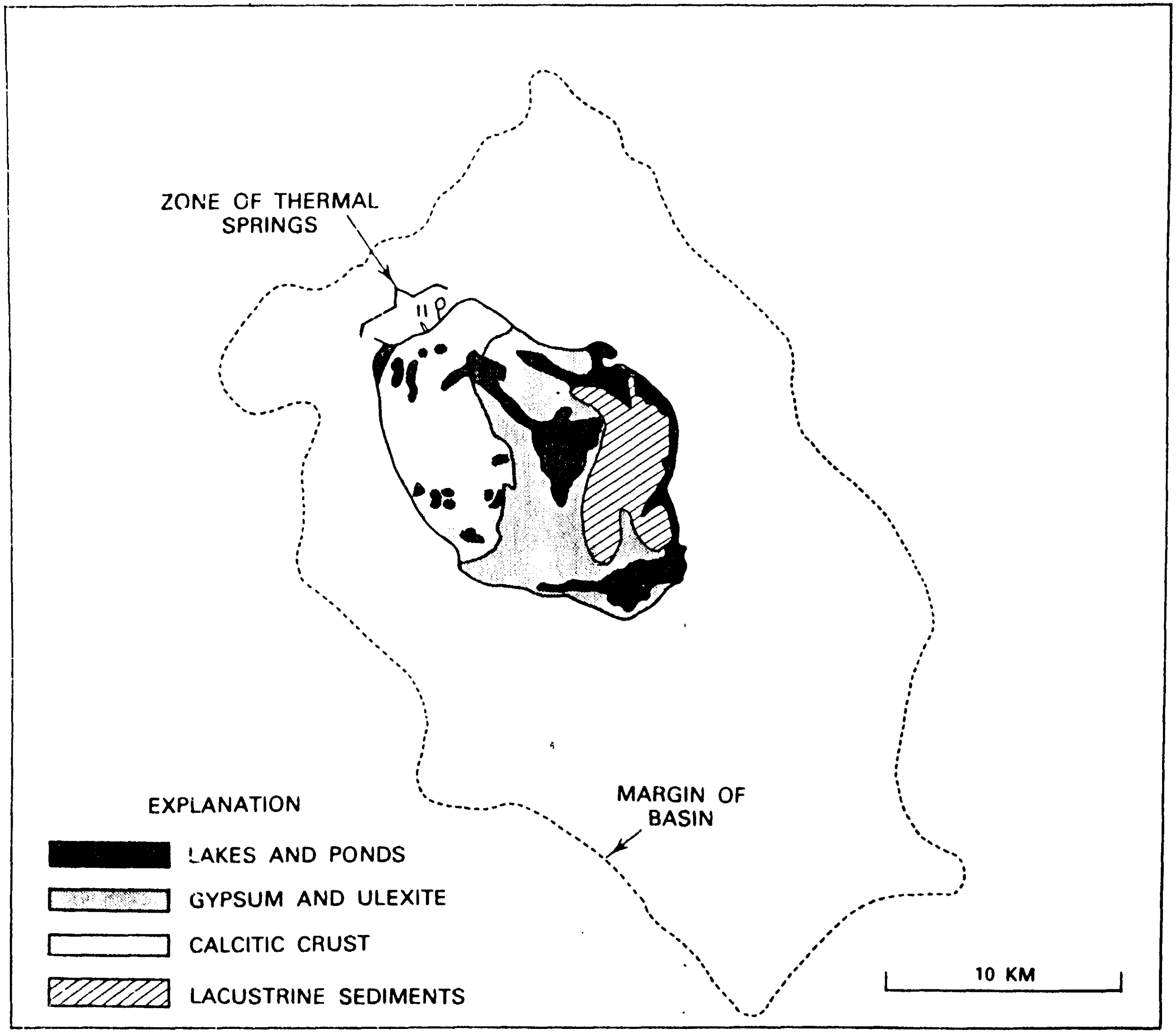

Fig. 5.--Lagunas Pastos Grandes, a salar in southwestern Bolivia, showing an internal gypsum-ulexite crust and abundant lakes and ponds. The calcitic crust in the western part of the salar was deposited by thermal-spring waters. After Ballivian and Risacher (1981).

Salar Grande, also in the coastal region of northern Chile (Fig. 1), is unique in that it consists of a longitudinal basin, about 40 km long and 5-8 km wide, filled with dry, coarsely crystalline, high-purity rock salt (Fig. 3) to depths of as much as 160 m. Although its origin is somewhat uncertain, we believe that the halite was deposited from residual chloride-rich brines draining from a huge Pliocene-Pleistocene saline lake in the Central Valley to the east. This lake, of which Salar de Llamara (Fig. 1, Table 1) is a desiccation remnant, was named Lago Soledad by Brüggen (1950). Marginal areas of this salar have remnants of a thick (5 m or more), eroded anhydrite crust that evidently was deposited as the Lago Soledad brines became progressively enriched in NaCl. Lago Soledad either periodically overflowed a low divide between the two basins or flowed into the Salar Grande through fault channelways.

Salar crusts exhibit diverse structures that formed during primary deposition and desiccation and during subsequent modification by rain- and spring-water, fog, wind, regional tectonic deformation and local faulting, and diurnal temperature changes (Table 2). Most of these features have been described by Stoertz and Ericksen (1974) and are discussed only briefly here. Of the primary structures, zoning of crusts of Andean salars results chiefly from progressive concentration of brines in saline lakes and deposition of the saline minerals according to their solubilities. Such crusts, however, may be modified by subsequent deposition of saline minerals from annual flood waters or by capillary evaporation of ground water. The typical zoned salar consists of an interior halite crust underlain by gypsum-rich lacustrine sediments and surrounded by a zone of gypsum admixed with other sulfate minerals and halite, and, at places, layers and nodules of ulexite. Depositional

Table 2. Structural features of Andean salars
[From Stoertz and Ericksen (1974)]

PRIMARY STRUCTURES

Mineral zoning

Depositional layering

Desiccation polygons

Salt blisters and pressure ridges

SECONDARY STRUCTURES

Surface-water flooding

Salt cusps and crenulate margins

Smooth rock-salt crusts

Salt channels

Springs

Salt channels

Brine pools

Rainwater and fog

Rugged rock-salt crusts

Salt pinnacles

Salt nodules

Salt saucers

Salt stalactites

Wind

Gypsum dunes

Gypseous ramparts

Diurnal temperature changes

Chaotic blocks and pressure ridges in silty halite crusts

Salt-solution tubes

Salt cones

Salt veins

Salt sheet

Tectonic deformation

Asymmetric mineral zoning

Giant oriented polygons

Faults

Fault sag basins

layering, best displayed by thick rock-salt crusts in the Andean Highlands, is the result of sporadic flooding and desiccation of surface brines. In Salar de Uyuni, distinct layers of brine-saturated salt, ranging from a centimeter or two to 10-20 cm thick, are separated by laminae of organic-rich mud. Such muds accumulated during annual floods. Desiccation polygons are characteristic of halite crusts and generally are about a meter in diameter. However, some thick halite crusts also have giant desiccation polygons, as much as 100 m in diameter, which evidently formed subsequently to the normal-size polygons. Salt blisters and pressure ridges formed by desiccation and expansion of thin (not more than a few centimeters thick), newly deposited halite crusts. Such crusts do not show desiccation polygons and evidently formed by rapid drying of shallow surface brines on muddy flats. In addition to these primary features, most salars in the Andean Highlands have marginal ponds and marshes that are fed by local springs and streams. Others consist chiefly of a perennial saline lake having marginal, perennial or ephemeral saline crusts.

Massive rock-salt crusts have been extensively modified subsequent to their formation. Where not subject to annual flooding, they tend to have extremely rugged, blocky, pinnacled surfaces due to rainwater leaching. In contrast, rock-salt crusts subject to annual flooding tend to be smooth. Such flooding is local at many salars, and the transition between the smooth zones and the blocky zones above flood level may be gradational, as for example around brine pools in Salar de Pedernales, or abrupt, with the unflooded crust marked by a cuspate or crenulate margins, as in the northeastern part of Salar de Atacama. Salar de Uyuni, Bolivia (Fig. 1), which is flooded annually, consists of a smooth, flat, hard, rock-salt crust surrounded by a narrow zone of perennial marshes. The rock-salt crust of this salar, which extends over an area of nearly 9,000 km^2, is probably the most extensive hard, flat surface on Earth. The average relief is less than a centimeter, which is the average size of scattered halite crystals and upraised or depressed margins of desiccation polygons. This salar also has local mounds of dried salt froth, as much as 10 m in diameter and 20 cm high, that consist of wind-blown salty foam accumulated on the wet salar surface as the surface dried after annual flooding.

At some salars, wind-blown water from fresh-water springs on the windward sides has etched multiple, narrow channels extending for hundreds of meters out onto halite crusts. Similar channels occur in upraised halite crusts at the margins of zones subject to annual flooding. Renewed spring activity in lacustrine sediments beneath thick rock-salt crusts dissolve the salt, forming steep-sided "brine pools" in the crust, which stabilize at a size commensurate with the rate of spring-water flow. These pools range from irregular tube-like openings along margins of desiccation polygons, as is well displayed in the north-central part of Salar de Uyuni, to circular pools many meters in diameter, as in Salar de Pedernales and Salar de Atacama.

Fog, rain, and wind cause additional modification of salar crusts. Slow leaching of blocky, silty salar crusts in the coastal region of northern Chile by fog has reduced irregular blocky fragments to rounded "salt nodules" and has changed surfaces of flat polygonal slabs to shallow, concave "salt saucers." Undersides of loose, upraised slabs of halite crusts in the Andes have "salt stalactites" formed by dripping rainwater solutions.

Gypseous ramparts, consisting of 50-cm- to 1-m-high walls of nodular gypsum, have been formed by wind-blown spray along the lee sides of spring-fed ponds at the western side of Salar de San Martín. Gypsum dunes are found on the lee sides of several salars in the Andean Highlands. They consist of wind-blown gypsum sand, eroded from newly deposited saline material on the salar surfaces, from which the more soluble saline minerals have been leached by rainwater.

Several features of salar crusts are attributed to expansion and contraction of the crusts due to diurnal temperature changes. The effects are the greatest in the silty crusts of salars of coastal Chile where the crusts are dry and diurnal temperature changes are great. On a quiet day, a person standing in a salar can hear an almost continuous sound of popping and cracking as the crust adjusts to temperature changes. Addition of new salt (by capillary rise and evaporation of saline ground water) in cracks formed by this movement, as well as new saline crust deposited beneath the older crust, causes heaving and expansion to form sharp pressure ridges 50-75 cm high and rugged surfaces of loose polygonal slabs. "Salt veins" are deposited in expansion cracks within polygonal blocks of hard rock-salt crusts of salars in the Andean Highlands. Where rock-salt crusts are relatively thin, and brine levels at depths of not more than a few tens of centimeters, lacy "salt sheets" may be extruded at margins of desiccation polygons.

One of the most unusual effects of diurnal temperature changes is the formation of "salt-solution tubes" along fractures in hard rock-salt crusts where brine levels are at depths of not more than a meter. These tubes, which are as much as 10 cm in diameter and a meter long (extending from brine level to the salar surface), evidently form by diurnal pumping of moist air out of the crust and concomitant capillary rise of brine to form a "salt cone" over the tube at the salar surface. Such cones form more rarely on dry salt crusts where moisture is furnished by rain and fog.

Tectonic deformation, as discussed in the section Physiographic and Geologic Setting, has affected the symmetry of closed basins and of salars within them, and recent faults define the margins of some salars and have displaced the crusts of others. In addition, stresses related to faulting have caused development of giant oriented polygons as much as 150 m across, which are outlined by intersecting sets of fractures. Recent fault movement has initiated spring activity within several salars, of which one manifestation is formation of "brine pools" in halite crusts. Sag basins several meters deep and many tens of meters in diameter are found along the recently active Atacama Fault where it cuts across Salar Grande (Fig. 3).

MINERALOGY

The minerals listed in Table 3 include those for which we have positive identification, chiefly by X-ray diffraction techniques, and minerals reported by others but not identified in our studies. We believe that some of the latter minerals, as noted in the table, may have been misidentified and that additional study is needed to confirm their presence.

Table 3. Saline minerals in salars of the central Andean region
[Underlined minerals are believed to need additional study to confirm their presence. Numbers in parentheses after mineral name refer to publications in which occurrence is reported; other minerals have been identified by authors of present report]

HALIDES	
Halite, NaCl	Bischofite (3), $MgCl_2 \cdot 6H_2O$
Sylvite (1, 2), KCl	Carnallite (3), $KMgCl_3 \cdot 6H_2O$
Tachyhydrite, $CaMg_2Cl_6 \cdot 12H_2O$	
SULFATES	
Gypsum, $CaSO_4 \cdot 2H_2O$	Aphthitalite (glaserite) (1, 4, 5), $K_3Na(SO_4)_2$
Anhydrite, $CaSO_4$	Syngenite (5), $K_2Ca(SO_4)_2 \cdot H_2O$
Mirabilite, $Na_2SO_4 \cdot 10H_2O$	Polyhalite (5), $K_2Ca_2Mg(SO_4)_4 \cdot 2H_2O$
Thenardite, Na_2SO_4	
Glauberite (4, 5), $Na_2Ca(SO_4)_2$	
Hydroglauberite, $Na_4Ca(SO_4)_3 \cdot 2H_2O$	
Leonite, $K_2Mg(SO_4)_2 \cdot 4H_2O$	
Bloedite (5), $Na_2Mg(SO_4)_2 \cdot 4H_2O$	
BORATES	
Ulexite, $NaCaB_5O_6(OH)_6 \cdot 5H_2O$	Gowerite (9), $CaB_6O_{10} \cdot 5H_2O$
Borax (2, 6, 7), $Na_2B_4O_5(OH)_4 \cdot 8H_2O$	Probertite (2), $NaCaB_5O_7(OH)_4 \cdot 3H_2O$
Inyoite (7, 8), $Ca_2B_6O_6(OH)_{10} \cdot 8H_2O$	Colemanite (10), $Ca_2B_6O_{11} \cdot 5H_2O$
Tincalconite (6), $Na_2B_4O_5(OH)_4 \cdot 3H_2O$	Hydroboracite (11), $CaMgB_6O_8(OH)_6 \cdot 3H_2O$
Kernite (6), $Na_2B_4O_6(OH)_2 \cdot 3H_2O$	
Inderite (6), $MgB_3O_3(OH)_5 \cdot 5H_2O$	
Escurrite (6), $Na_4B_{10}O_{17} \cdot 7H_2O$	

Table 3.--(cont'd.)

CARBONATES
Calcite, $CaCO_3$
Dolomite (12), $CaMg(CO_3)_2$
Natron (2), $Na_2CO_3 \cdot 10H_2O$
Thermonatrite (2), $Na_2CO_3 \cdot H_2O$
NITRATES
Nitratite, $NaNO_3$

(1) Ericksen (1963).

(2) Ballivian and Risacher (1981).

(3) Runge and others (unpublished data, Instituto de Investigaciones Geológicas, 1974).

(4) Gale (1918).

(5) Vila (1976).

(6) Muessig and Allen (1957).

(7) Muessig (1966).

(8) Muessig (1958).

(9) Salas (1975).

(10) Cadima and Lafuente, (unpublished data, Servicio Geológico de Bolivia, 1967).

(11) Catalano (1926).

(12) Muessig (1958).

Relatively few of the minerals shown in Table 3 are abundant and widespread. Others are found in minor amounts in most salars but are abundant in only a few, and still others are found in only minor amounts in any salar. Halite and gypsum are by far the most abundant saline minerals, occurring in all salars. The typical halite crust is hard and white, has a sugary texture, and is highly porous. The unique, coarsely crystalline halite in Salar Grande has an average grain size of 1-2 cm, and local coarsely crystalline zones contain anhedral crystals as much as 75 cm in diameter. Gypseous salar crusts consist of medium-grained gypsum and coherent meshworks of gypsum crystals. Nodules and lenticular layers of feathery, white ulexite are found in gypseous crusts, in lacustrine sediments having ephemeral crusts, and in perennial marshes at salar margins. Nodules of ulexite are generally less than 10 cm in diameter, and ulexite layers generally have maximum thicknesses of 30-40 cm, but layers as much as a meter thick have been found in some salars.

Borate minerals other than ulexite are found in only a few of the salars. Small amounts of borax are associated with ulexite in several salars and have been found in a borate-rich thermal-spring tufa in northwestern Argentina (Muessig, 1966). Borax is the dominant mineral in the Tincalayu borate deposit, Argentina, which also contains minor amounts of tincalconite (the desiccation product of borax), kernite, inderite, and escurrite (Muessig and Allen, 1957). This is only known occurrence of these minerals in the Andes. Small amounts of inyoite have been found in a thermal-spring deposit at the east side of Laguna Salinas, Peru (Muessig, 1958). Other reported borate minerals (Table 3) require confirmation.

Mirabilite and its desiccation product, thenardite, are widespread and moderately abundant in the salars. Mirabilite is found as prismatic crystals, as ice-like crystalline masses, and as impregnating material in marginal sulfate zones of zoned salars, in gypseous crusts, and on exposed surfaces of brine-saturated lacustrine sediments in the Andean Highlands. Mirabilite is stable in these areas because maximum surface temperatures are below the mirabilite-thenardite transition temperature of 32.4° C. However, mirabilite does slowly desiccate in the dry air of this region, and consequently, salars in the Andean Highlands also contain powdery, secondary thenardite. Thenardite also is moderately abundant and widespread in salars of the coastal region of northern Chile, occurring both as powdery material resulting from desiccation of mirabilite and as large prismatic and bipyramidal crystals. Lenticular layers of ice-like mirabilite, as much as 30 cm thick, occur at the base of a 50-cm- to 1-m-thick silty halite crust in the northeastern part of Salar de Pintados (Ericksen and others, 1970). This mirabilite contains nodular masses of tan hydroglauberite, the only known occurrence of this mineral in the central Andes. This area also has local zones in which the salar crust consists chiefly of a dry, coherent meshwork of sand-size thenardite grains and scattered prismatic crystals of translucent, white thenardite as much as 20 cm long. Clusters of tan, bipyramidal crystals of thenardite, 2-8 cm long, are found locally in the coarsely crystalline rock salt of Salar Grande.

Of the other sulfate minerals listed in Table 3, only anhydrite is abundant; others are either widespread minor constituents, local minor constituents, or mineralogical rarities in Andean salars. Anhydrite is widespread in salars and soils in the Atacama Desert of northern Chile, where it is principally a desiccation product of gypsum and is stable because of the extreme dryness of this desert. It is the dominant mineral in the northern part of Salar de Llamara, in a zone that stretches across the northern side of this salar to the southern part of Salar Grande (Fig. 3). This anhydrite is as much as 10 m thick in places and has a rugged surface showing a relief of several meters, which is characterized by solution and collapse structures. Bloedite and glauberite have been identified only in Salar de Pintados, Chile, but these minerals probably occur in minor amounts in most salars in the central Andes. We have found leonite in newly deposited K-rich salt from experimental evaporation pits in the southern part of Salar de Bellavista. Aphthitalite reportedly was found in this same locality (Ericksen, 1963), but we have been unable to confirm its presence here or in other salars of the region.

Halides, other than halite, have been found in a few salars. Small amounts of sylvite have been found in the rock-salt crust of salar de Uyuni (Ballivian and Risacher, 1981) and has been reported to occur in the K-rich crust in the southern part of Salar de Bellavista (Ericksen, 1963). We have been unable to confirm the prsence of sylvite in either of these salars. We found efflorescences of feathery, white tachyhydrite at the site of abandoned borate workings in the southwestern part of Salar de Pedernales, Chile. This mineral is stable only at low temperatures and probably forms here and in sulfate zones of other salars in the Andean

Highlands only during winter months, when average temperatures approach 0°C. Bischofite and carnallite, reported to occur in Salar de Bellarista, need confirmation.

Except for calcite, carbonate minerals have been found in only a few salars of the central Andes. Calcitic marles and ostracod-rich beds occur in lacustrine sediments of several salars. Algal limestones, which were deposited in former Lago Tauca, are widespread in the southern part of the Bolivian Altiplano. Calcareous tufa is a characteristic thermal-spring deposit of the region, and $CaCO_3$-rich crusts were deposited by thermal-spring waters at Lagunas Pastos Grandes (Fig. 5) and Salar de Empexa (Ballivian and Risacher, 1981). Dolomite has been identified in lacustrine sediments of one salar in Argentina (Muessig, 1958) and may occur in such sediments in others. Natron and thermonatrite, the only sodium carbonate minerals identified, have been found in saline evaporites at Laguna Collpa and nearby saline lakes in southern Bolivia.

Nitratite occurs in several salars in the coastal region of northern Chile, where it is associated with halite and sulfate minerals in silty halite crusts. Nitratite is not a normal mineral of saline complexes, and its presence in this region reflects formation (probably by microbial activity in moist soils of the salars) and slow accumulation under conditions of the long-term, nearly rainless climate of the Atacama Desert. This climate also has been a major factor in the accumulation of the well-known nitrate caliche deposits of this region. Some salars have been contaminated with waste waters from nearby nitrate beneficiation plants, and, in addition to nitratite, contain concentrations of iodate and perchlorate, both of which are constituents of nitrate ore.

BRINE CHEMISTRY

The brines of the central Andean salars are chiefly NaCl types in which the relative abundances of the constituents are $Na^{+}>>K^{+}>Mg^{2+}>Li^{+}>Ca^{2+}$ and $Cl^{-}>>SO_4^{2-}>>B_2O_3>HCO_3^{-}$ (Table 4). Typical saturated brines have about 350,000 mg/L dissolved solids, of which 80 percent or more is NaCl. Sulfate concentrations are variable but generally show a range from about 5,000 mg/L to 20,000 mg/L. Chloride-rich brines of a few salars have SO_4^{2-} concentrations ranging from about 25,000 mg/L to nearly 90,000 mg/L. These brines would be classed as chloride-sulfate brines. A few saline lakes in southwestern Bolivia have relatively high concentrations of Na_2CO_3. Concentrations of K^+, Li^+, and B_2O_3 are relatively high (Table 4) in most of the brines.

The brines of Andean salars formed by evaporative concentration of meteoric waters in which the relative amounts of Cl^-, SO_4^{2-}, and HCO_3^- are variable, but which have relative cation abundances of $Na^{+}>Ca^{2+}>K^{+}>Mg^{2+}>Li^{+}$. These waters generally contain several hundred to several thousand mg/L dissolved solids and have relatively high concentrations of Li and B (Fig. 6). Thermal springs tend to be more saline and have higher values for Li and B than do streams and ground water, and they show concentrations of these elements that vary somewhat independently from total dissolved solids (Fig. 6).

Evolution of the NaCl-rich brines in the central Andes involves major depletion of Ca^{2+}, HCO_3^-, SO_4^{2-}, SiO_2, and B_2O_3 during evaporative concentration of the meteoric waters and enrichment of K^+, Mg^{2+}, and Li^+. Ca^{2+} and HCO_3^- are removed from the solutions as thermal-spring tufa, as algal limestone such as that deposited in Lago Tauca in the

Table 4. Chemical analyses (in mg/L; n.d. = not determined; do=ditto) of selected brines from salars in the central Andes

Salar	Cl	SO_4	HCO_3	Na	K	Ca	Mg	Li	B_2O_3	Dissolved solids
Argentina 1/										
Hombre Muerto	194,800	11,100	n.d.	121,900	9,340	1,000	268	914	1,455	340,920
Rincon	190,500	15,990	n.d.	122,200	6,570	280	2,120	350	1,609	338,510
Pocitos	190,600	7,440	n.d.	123,100	3,400	600	1,290	97	708	326,747
Pastos Grandes	178,700	26,080	n.d.	118,200	4,730	740	2,980	440	2,220	332,560
Centenario	192,700	19,980	n.d.	112,300	8,170	320	7,550	1,020	3,765	343,210
Rio Grande	148,900	10,610	n.d.	92,400	3,710	800	2,600	420	1,673	259,960
Arizaro	190,700	8,260	n.d.	119,500	160	760	1,840	160	138	321,423
Bolivia										
Uyuni 2/	191,800	13,200	592	94,900	13,500	461	11,800	700	1,136	351,000
Empexa 2/	120,000	34,100	430	67,200	3,400	259	8,480	213	702	239,000
Coipasa 2/	186,000	25,300	785	100,400	9,080	253	12,120	338	2,208	368,000
Pastos Grandes 3/	194,000	2,460	n.d.	101,000	14,200	3,100	3,480	1,640	3,041	320,825
Cañapa 3/	126,000	17,900	n.d.	68,900	12,000	600	1,670	712	2,011	228,407

Table 4. (cont.)

Salar	Cl	SO_4	HCO_3	Na	K	Ca	Mg	Li	B_2O_3	Dissolved solids
Chile										
Atacama 4/	183,100	16,140	560	103,000	12,900	520	6,130	760	1,705	370,000
- do -	182,800	25,500	220	98,000	19,500	300	8,500	1,200	1,673	385,000
- do -	189,500	15,900	230	91,100	23,600	450	9,650	1,570	1,416	370,000
Surire 5/	131,380	11,430	n.d.	73,200	13,200	890	3,830	540	3,700	235,620
Azufrera 6/	172,130	87,990	0	60,000	14,960	88	48,640	86	740	400,000
Laco 6/	109,630	15,360	620	62,200	4,800	820	6,251	101	1,078	210,000
Huasco 7/	112,980	26,700	n.d.	65,000	13,500	610	5,880	480	2,333	277,270
San Martín 8/	68,000	1,570	415	30,100	2,410	8,469	1,646	170	985	112,960
Ascotán 9/	70,000	25,000	2,900	45,000	3,530	920	5,125	186	2,520	153,600

1/ All analyses from Nicolli and others (1982b).

2/ Analyses by Shirley L. Rettig, (unpublished data, U.S. Geological Survey, 1976).

3/ Ballivian and Risacher (1981).

4/ Moraga and others (1974).

5/ Salas (unpublished data, Instituto de Investigaciones Geológicas, 1975).

6/ Vila (1975).

7/ Corporación de Fomento de la Producción (unpublished data, 1981).

8/ Instituto de Investigaciones Geológicas (unpublished data, 1967).

9/ Analysis by Shirley L. Rettig, (unpublished data, U.S. Geological Survey, 1978).

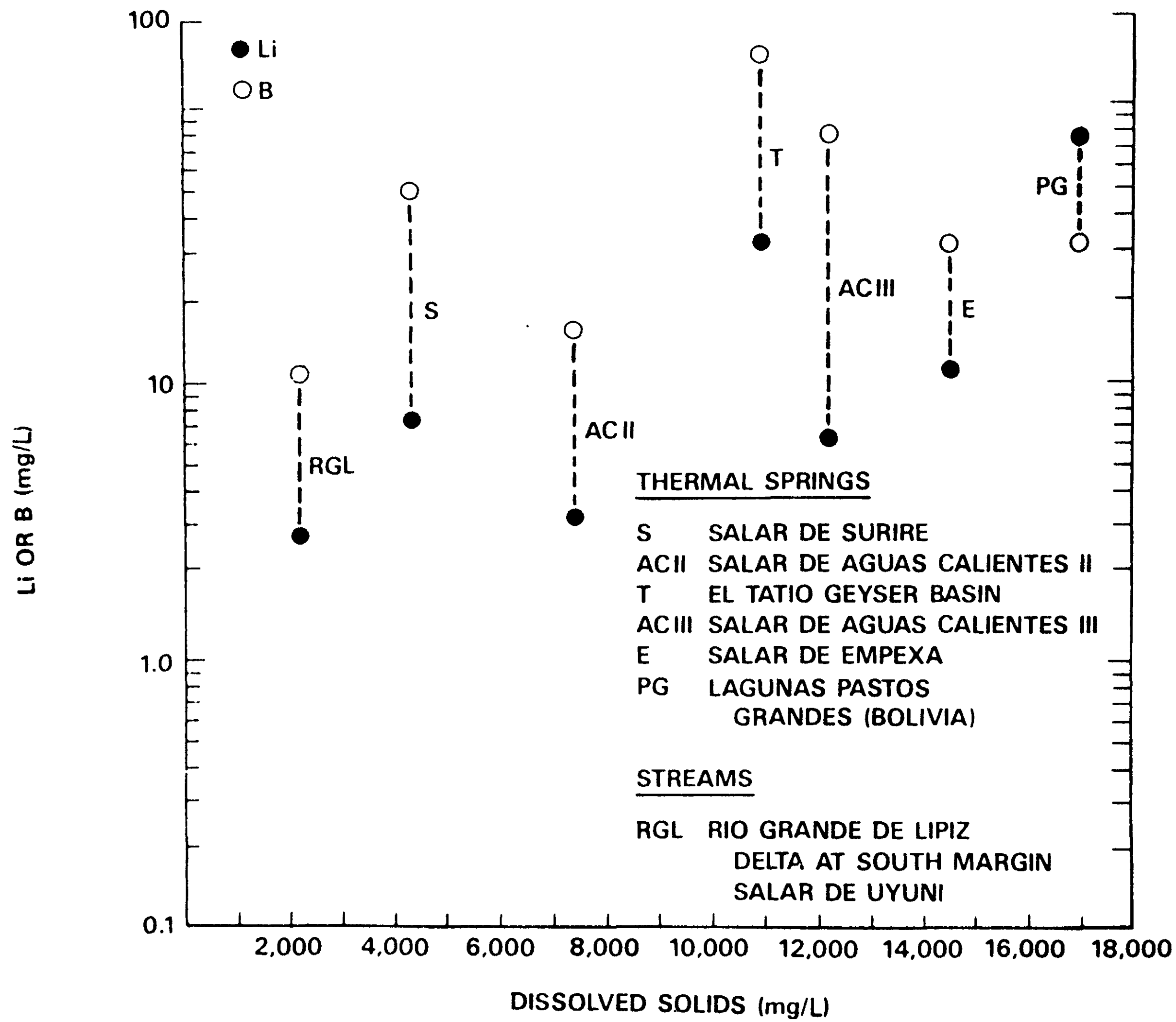

Fig. 6.--Li and B concentrations plotted against total dissolved solids for selected thermal springs and streams in the central Andes. Based on analyses from Vila (1975), Salas (unpublished data, 1975), Rettig and others (1980), Cusicanqui and others (1975), and Ballivian and Risacher (1981).

southern Bolivian Altiplano, and as $CaCO_3$-rich marls and ostracod-rich lacustrine sediments. SiO_2 is removed chiefly by diatoms to form the widespread diatomaceous lacustrine sediments. SO_4^{2-} is removed from the solutions chiefly as gypsum, but small amounts of SO_4^{2-} are reduced to H_2S by bacteria in organic-rich muds in some halite crusts and in lacustrine sediments. Rettig and others (1980) have shown that major depletion of HCO_3^- and SO_4^{2-} takes place in saline waters having less than 35,000 mg/l dissolved solids. B_2O_3 is removed as ulexite, also at relatively low concentrations of dissolved solids.

Up to the point of NaCl saturation, the amounts of K^+ and Li^+ are more or less those that would be expected from evaporative concentration of the meteoric waters of this region, as shown by the Li and K curves (Fig. 7) for the average concentrations in several salars in the Chilean Andes. These curves are approximately parallel to the curve for normal evaporative concentration. Mg^{2+} behaves similarly. In contrast, the concentrations of Li and K relative to Cl for Salar de Uyuni (Fig. 7) are less than expected from the curve for simple or straightforward evaporative concentration; the lower concentrations indicate progressive loss of these ions. This loss of Li and K in Salar de Uyuni may be due to adsorption of these ions by montmorillonitic clays in the lacustrine sediments (Rettig and others, 1980). Salar de Atacama (Fig. 7) differs in showing an increase of Li content relative to Cl but normal evaporative concentration of K. Mg, which is not shown in figure 7, also shows normal evaporative concentration in Salar de Atacama. The apparent enrichment of Li relative to K and Mg in Salar de Atacama is not easily explained. Perhaps K^+ has been depleted

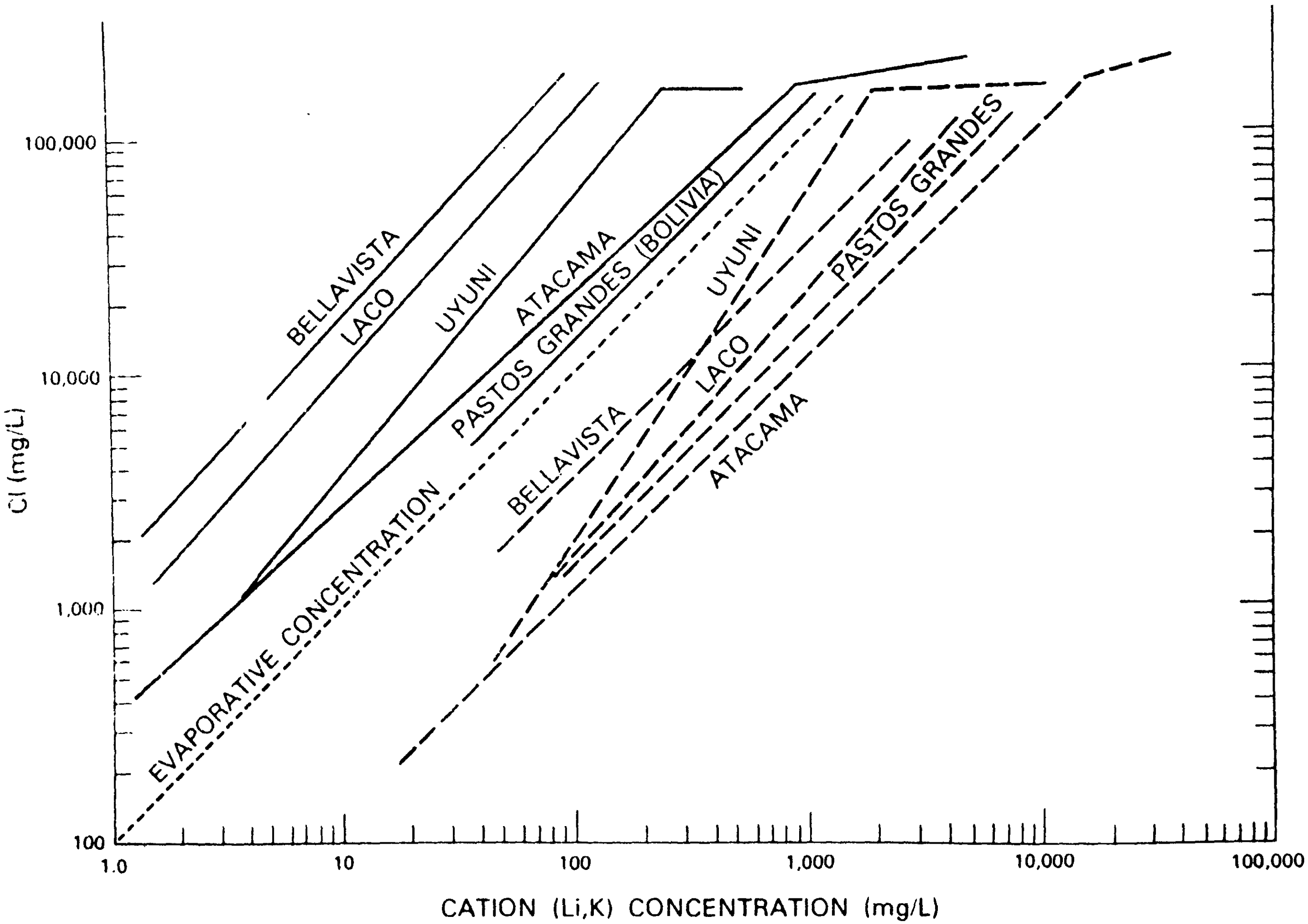

Fig. 7.--Li (solid lines) and K (dashed lines) concentrations plotted against Cl concentrations for brines from selected Andean salars, compared with curve for normal evaporative concentrations below NaCl saturation. Deflected upper parts of curves indicate evaporative concentrations at Cl saturation. Based on chemical analyses in Chong (1984), Moraga and others (1974), and Rettig and others (1980).

in the brines by formation of K-bearing saline minerals that have not yet been recognized in this salar. In addition, this is the oldest basin in the Andes, having been in existence since late Cretaceous or early Tertiary time, and has had many cyclic changes in climate, tectonic deformation, and volcanism, all of which might have affected the sources of the saline constituents and, consequently, the composition of the brines.

Although the relative concentrations of Li^{+}, K^{+}, and Mg^{2+} tend to be relatively constant in individual salars, concentrations may differ considerably from one salar to another (Figs. 8 and 9). The ratios for Li:K indicated by the curves in figure 8 range from about 1:9 to 1:24, which is probably near the maximum range for salars in the central Andes, and those for Mg:K are 1:1.2 to 1:8, also near the maximum range.

Once the brines in the salars reach NaCl saturation, further changes in relative concentrations of the solute constituents take place during crystallization of halite. The principal result is a progressive increase in the concentrations of Li^{+}, K^{+}, and Mg^{2+} and a decrease in Na^{+}, relative to Cl^{-}. As a consequence, salars having extensive halite crusts tend to show the greatest concentrations of Li, K, and Mg, and the amounts of these ions may be much greater than would be expected from evaporative concentration. This is shown in figure 7 by the sharp deflections of the curves for salars Uyuni and Atacama at or near chloride saturation of 115,000 to 120,000 mg/L. Salar de Hombre Muerto, Argentina, shows Li-K-Mg:Cl ratios in saturated brines similar to those of Salar de Uyuni (Nicolli and others, 1982b). As indicated by the slopes of the deflected parts of the curves, rates of increase in the concentration ratios of Li:Cl and K:Cl at Cl saturation may differ from one salar to another. Rettig and others (1980) compared Li and K concentrations in saturated brines of

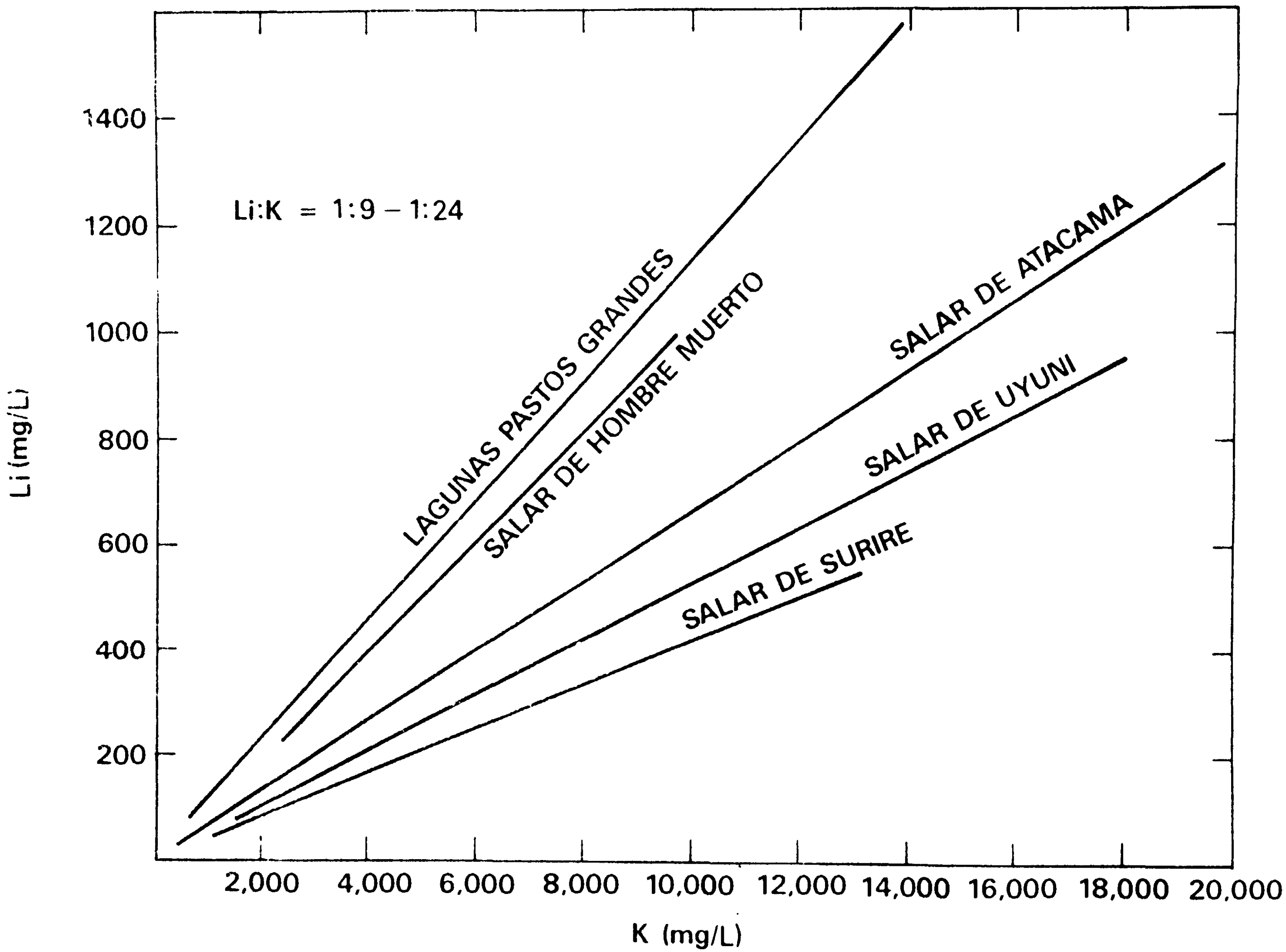

Fig. 8.--Li/K ratios of brines from selected Andean salars. Plotted from analyses by Nicolli and others (1982a), Ballivian and Risacher (1981), Ericksen and others (1977), Moraga and others (1974), and Salas (unpublished data, 1975).

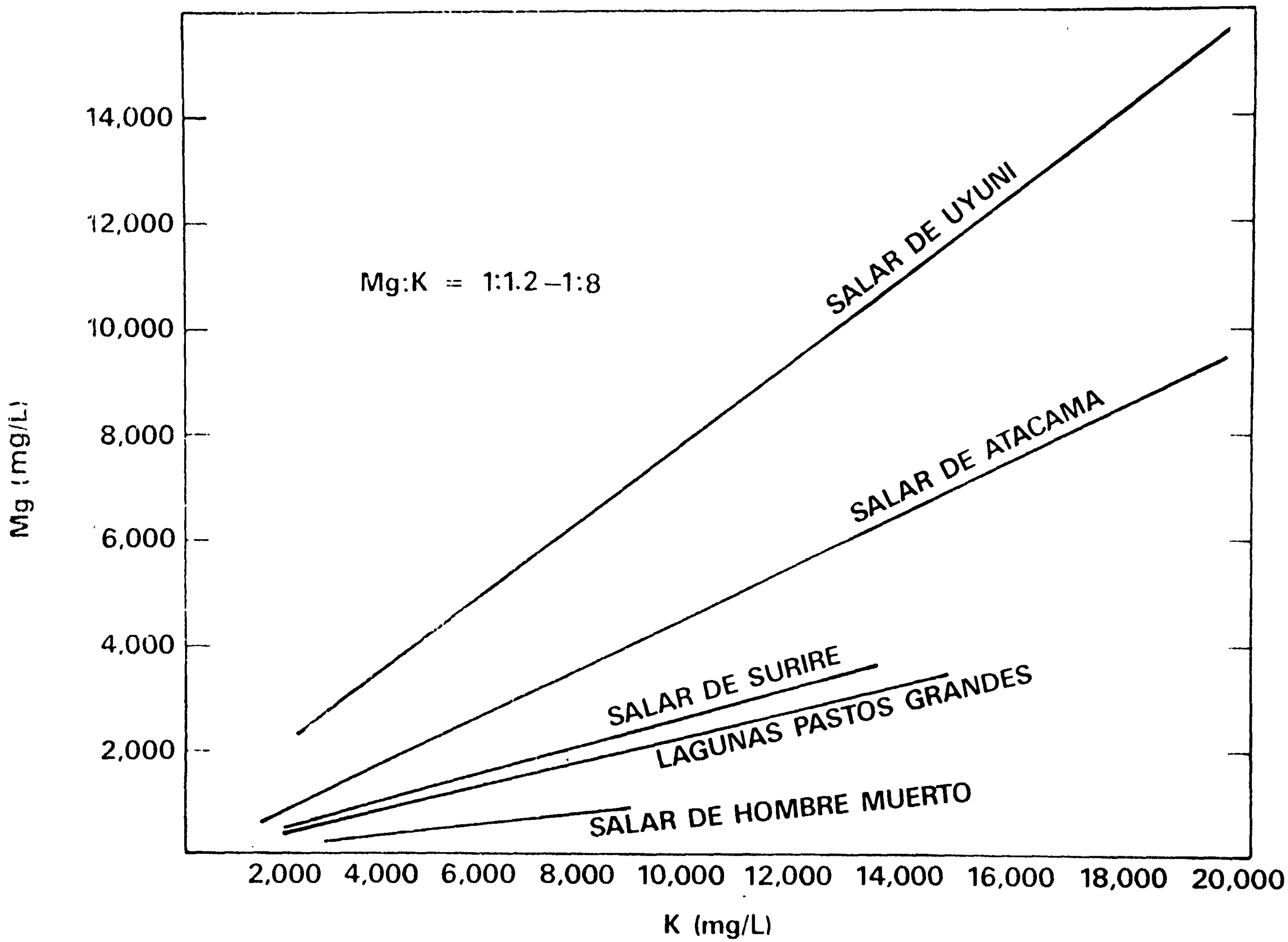

Fig. 9.--Mg/K ratios of brines from selected Andean salars. See Figure 8 for sources.

Salar de Uyuni with bromine concentrations (which presumably are affected only by evaporative concentration) to show that the relative amounts of Li and K were less than would be expected from evaporative concentration. These authors suggested that the brines, as well as the saline waters from which they formed, lost Li, K, and Mg by adsorption on montmorillonitic clay in the lacustrine sediments beneath the salar crusts. The curves for Salar de Atacama (Fig. 7) show greater rates of increase for Li^+ and K^+ at Cl saturation than do those for Salar de Uyuni. Unfortunately, Br was not analyzed for the Atacama brines (Moraga and others, 1974), so that comparison of Li-K:Br ratios of the two salars cannot be made.

SOURCES OF THE SALINE CONSTITUENTS

The distribution of the salars and of accumulations of saline materials along present-day streams and marshes clearly shows that late Tertiary and Quaternary volcanic rocks have been the principal sources of the saline materials in Andean salars. Additional, probably small amounts of saline material were leached from older rocks or transported by wind from distant sources. Saline material in the volcanic rocks include water-soluble salts that were incorporated at the time of eruption and saline constituents in volcanic glass, which are readily leached during hydration of the glass. Widespread saline encrustations along streams and in marshes in areas of abundant volcanic rocks attest to the presence of readily leachable saline material in these rocks. Furthermore, many salars are in basins where volcanic rocks and atmospheric fallout are the only possible sources of the saline materials. Thermal springs in the region tend to be saline, commonly containing several thousand mg/L dissolved solids, and have relatively high concentrations of Li and B, both of which are characteristic of meteoric waters draining rhyolitic volcanic terrains. For example, thermal springs in the Tatio Geyser Basin, near the Chile-Bolivia border about 60 km north of Salar de Atacama (Fig. 1, Table 1), have 10,000-15,000 mg/L NaCl and as much as 47 mg/L Li and 183 mg/L B (Cusicanqui and others, 1975). Another NaCl-rich thermal spring at Salar de Surire (Fig. 6) has 4,200 mg/L dissolved solids and 8.3 mg/L Li and 47 mg/L B. Among the most unusual thermal springs are those in northwestern Argentina that have aprons of ulexite-rich tufa (Muessig, 1966; Alonso and Viramonte, 1985). Catalano (1964b) cites three analyses of thermal-spring waters from one area (Antuco) that show 14.9-16.4 percent NaCl, about 1 percent SO_4, and traces of CaO and MgO. B was found to be present, but the amount was not determined.

The distribution of Li in brines of Salar de Uyuni (Fig. 10) indicates that Rio Grande de Lipiz is the major source of Li. The brines show similar concentration patterns for K and Mg. The rocks in the Rio Grande de Lipiz drainage system are largely quartz-latite ash-flow tuffs and dacite to andesite flows of late Miocene and Pliocene age. In the Rio Grande de Lipiz delta (Fig. 10), the stream waters, which have been slightly concentrated by evaporation, average about 3 mg/L Li and 10 mg/L B (Fig. 6). The brines formed from these waters are superimposed on the residual brines in the salar crust, which formed during final desiccation of Lago Tauca (Fig. 2) in early Holocene time. To judge from the present distribution of Li in Salar de Uyuni (Fig. 10), the residual Lago Tauca brines contained less than 250 mg/L Li.

Leaching tests of pulverized samples of rhyolitic ash-flow tuffs and obsidian from northern Chile have shown these rocks to contain water-soluble saline material (Ericksen, 1963). Cold-water leachates were found to

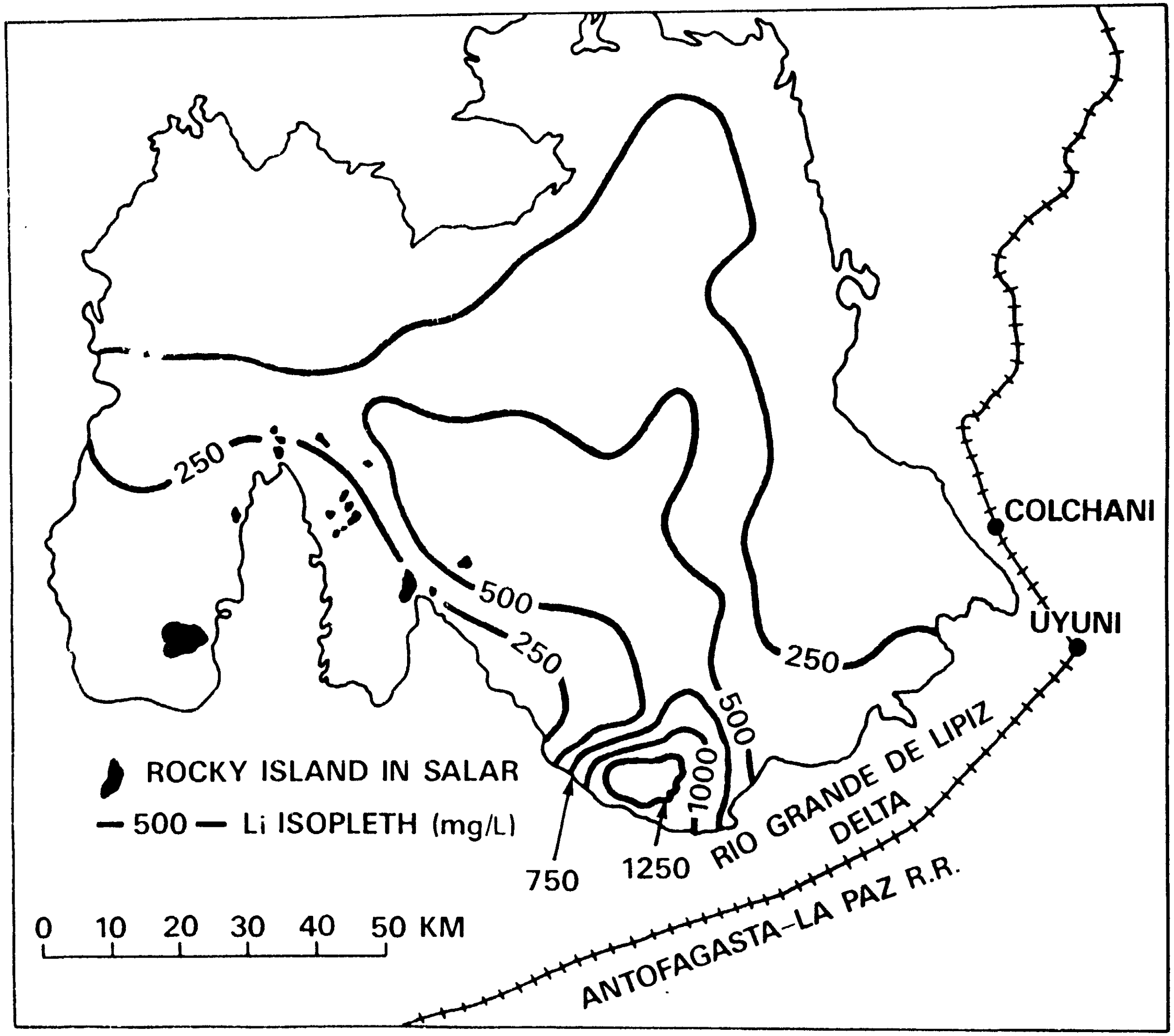

Fig. 10.--Distribution of Li in near-surface interstitial brines of the porous halite crust of Salar de Uyuni. Modified from Davis and others (1982).

contain from about 500 mg/L to 3,500 mg/L dissolved solids, consisting chiefly of Cl^-, SO_4^{2-}, Na^+, and Ca^{2+}. We believe that this saline material includes both contaminants, perhaps from wind-blown saline dust, and primary water-soluble constituents of the magma that were trapped at the time of eruption.

PRODUCTION AND RESOURCES

In terms of world consumption, Andean salars contain large resources of rock salt, lithium, and boron, and moderate to small resources of gypsum, sodium sulfate, potassium, and magnesium. With the exception of gypsum and magnesium, all these commodities have been produced. The greatest production, by far, has been of rock salt and borate minerals, both of which have been exploited since the mid- to late 19th century. In addition, rock salt probably has been exploited for local use since pre-Columbian times. Data about rock-salt production are scanty, but to judge from existing production records, annual production during the 1980's has been on the order of 800,000 t. Most has been high-purity rock salt quarried from Salar Grande, in the Coastal Range of northern Chile, with smaller amounts recovered as newly recrystallized salt from brines in Salar de Lagunas, in the Coastal Range east of Salar Grande, in Salar de Uyuni, Bolivia, and in Salar de Pocitos, Argentina. Additional large amounts of salt are obtained from brines in saline lakes and salars in Argentina that are outside the area discussed in this report. Production of borate minerals in 1984 was 166,889 t, which included 142,880 t of borax from the Tincalayu deposit and 13,000 t of ulexite from an unspecified salar, both in northwestern Argentina (Milka Brodtkorb, written commun., 1986), and 10,000 t of ulexite from Laguna Salinas, Peru, and 1,000 t of ulexite from Salar de Ascotán, Chile (U.S. Bureau of Mines, 1986; Ericksen, unpublished data, 1986). Production of lithium carbonate from Li-rich brines at Salar de Atacama, Chile, began in 1984, in an operation designed for an annual production of 7,500 t of lithium carbonate (Ihor Kunasz, oral commun., 1986).

Production of the other saline commodities has been small. Since the 1950's, sodium sulfate as been recovered sporadically from deposits of mirabilite and thenardite in the northeastern part of Salar de Pintados, Chile. During the early 1940's, several thousand tons of potassium chloride and potassium nitrate were produced from the K-rich salt crust in the southern part of Salar de Bellavista, Chile. Efflorescences of natron and thermonatrite reportedly are harvested periodically at Laguna Collpa, Bolivia, by local inhabitants (Ballivian and Risacher, 1981). During the latter part of the 19th century and early part of the 20th century, two salars in northern Chile, Salar del Carmen and Salar de Pampa Blanca, were exploited for nitrate ore.

Although potentially exploitable materials are found in many salars, the largest resources are in relatively few. Li-rich brines, for example, are found in many salars, but by far the largest quantities and highest grades of Li-rich brines are in Salar de Atacama, Salar de Uyuni, and Salar de Hombre Muerto. The brines of these salars also contain large amounts of potentially recoverable K and B. The central halite body of Salar de Atacama has the greatest amount of Li- and K-rich brines, which average about 1.800 mg/L Li and nearly 28,000 mg/L K. Ihor Kunatz (oral commun., 1985) reported that this salt crust extends over an area of about 1,400 km^2 and to depths of as much as 426 m. He also reported that the brines are concentrated in the uppermost highly porous and permeable 10 m of this salt body, whereas the underlying more dense and less permeable salt contains relatively little recoverable brine. In contrast, Li-rich brines (500 mg/L Li and 10,000 mg/L K) are found in an area of about 2,000 km^2 in the central part of Salar de Uyuni (Fig. 10). We estimate the average thickness of the porous salt crust in this zone, which contains most of the recoverable brine, to be at least 5 m. A recent drill hole in Salar de Uyuni, by the Office de la Recherche Scientifique et Technique Outre-Mar, penetrated alternating layers of porous rock salt, and clastic lacustrine sediments to a depth of 43 m (F. Risacher, Oral Commun., 1986). Brines in Salar de Hombre Muerto average 700-800 mg/L Li and 7,000-8,000 mg/L K over an area of 100-150 km^2 (Nicolli and others, 1982b). The salt body of this salar is known to extend to depths of at least 15 m, but neither the average nor maximum thickness is known.

Potentially exploitable ulexite deposits also are known in many salars, and the largest deposits, many of which have been exploited, are in salars Surire, San Martín, Ascotán, Pedernales, and Pintados in Chile; Uyuni, Laguani, Pastos Grandes, and Capiña in Bolivia; and Salinas Grandes, Cauchari, Pastos Grandes, Rincon, and Pocitos in Argentina.

Salar Grande, in the coastal region of northern Chile, is by far the most valuable deposit of rock salt in the central Andes. Not only does it contain huge amounts of high-purity salt (averaging 99 percent NaCl), but it also lacks interstitial brine, so that the salt can be mined easily and cheaply. The salar is near the deep-water port of Iquique. As a result, the salt can be shipped at a competitive price on the world market. Since the 1960's, large amounts have been exported, chiefly to Japan.

The other potentially recoverable saline constituents of Andean salars, gypsum and anhydrite in salar crusts, Na_2SO_4 and Na_2CO_3 as minerals in salar crusts and dissolved in brine, and Mg and B in brine, may be exploited for internal markets, but for the foreseeable future probably will not be competitive in the world market, either because of small potential production or because of high costs of beneficiation and transport.

CONCLUSIONS AND RECOMMENDATIONS

Future production from Andean salars probably will include recovery of rock salt, lithium, borate minerals, and, perhaps, potassium for the manufacture of fertilizer. Production of rock salt and lithium may increase slowly in the near future, but major increases probably will come about only in response to major increases in world demand and prices. Of the borate minerals, only borax from the Tincalayu deposit is now highly competitive in the world market, and this deposit should continue to be a dominant source of borate minerals in the central Andes. Ulexite, which is virtually the only borate mineral in present-day salars, is relatively costly to beneficiate. It is now produced largely for internal consumption. Because world resources of borate minerals such as borax, kernite, and colemanite, which can be processed relatively cheaply, are very large, ulexite from Andean salars is not likely to become a significant export commodity within the foreseeable future. Potassium and magnesium are potential biproducts of Li-rich brines. Recovery of potassium is planned for Salar de Atacama.

Investigations during the past two decades have shown the nature, distribution, and resource potential of the saline constituents of Andean salars. The principal near-future problem is one of development of these resources. Future exploration for saline materials in the central Andes, other than exploration required for development of known resources, should emphasize the search for buried deposits of borate minerals in late Tertiary and Quaternary playa sediments. Such deposits, of which Tincalayu, Argentina, is an example, may contain borax or other borate minerals that are more competitive on the world market than the ulexite of the present-day salars.

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