

Lithium Resources of North America

By JAMES J. NORTON and DOROTHY MCKENNEY SCHLEGEL

A CONTRIBUTION TO ECONOMIC GEOLOGY

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*A brief summary of the geology,
distribution, production, and
reserves*



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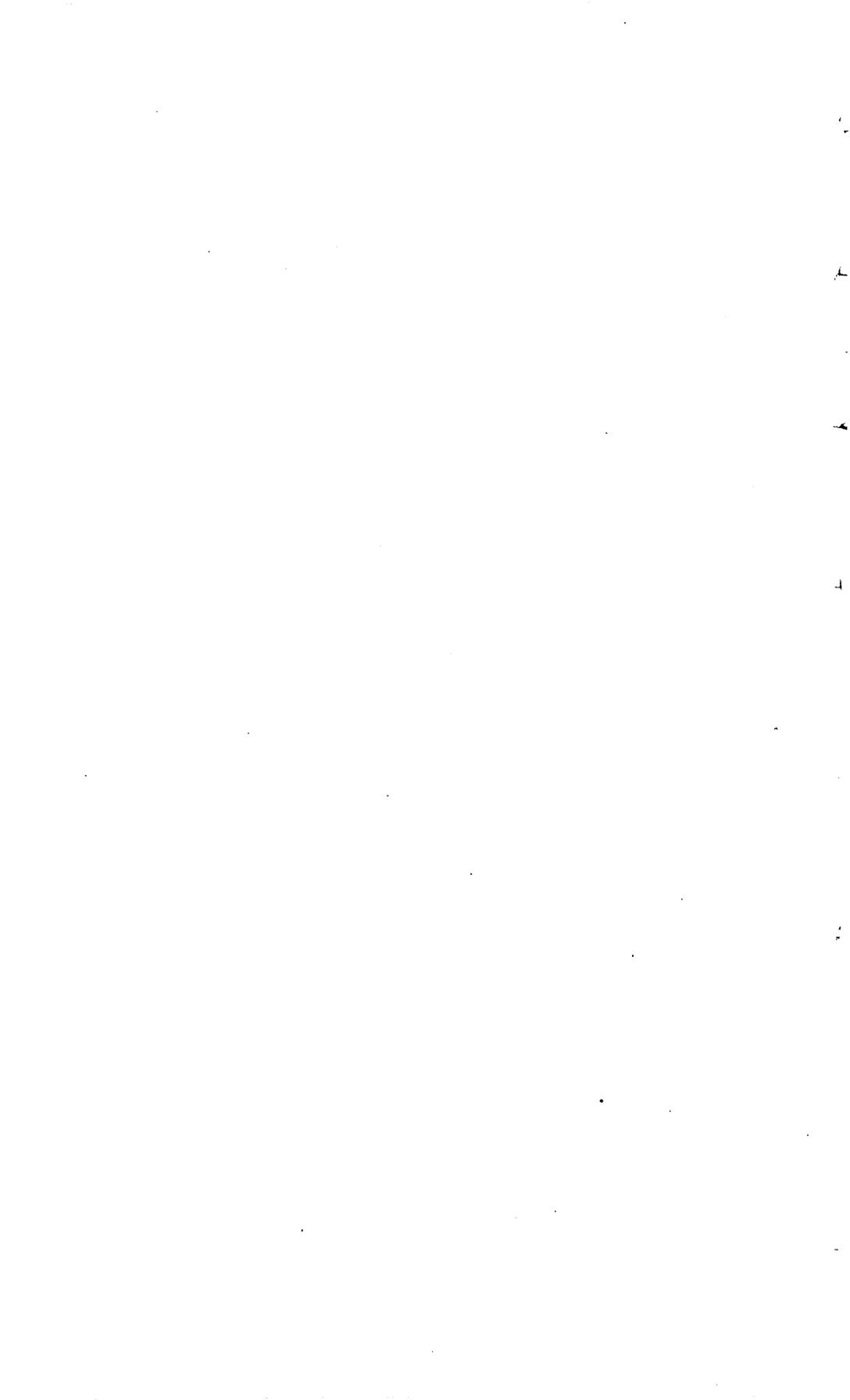
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By JAMES J. NORTON and DOROTHY MCKENNEY SCHLEGEL

ABSTRACT

The United States and Canada have more than ample lithium resources to support the expanding lithium mining industry. The largest reserves are in the tin-spodumene belt of the Carolinas, which was first developed during World War II and is now the largest source of lithium in the world. Prior to World War II, deposits in South Dakota were the chief source of lithium minerals, and these deposits still contain significant reserves. In California lithium has been produced from Searles Lake brines since 1938, and during earlier years lepidolite was mined in the Pala district. Other states containing lithium deposits are New Mexico, Colorado, Wyoming, Connecticut, Maine, and Massachusetts. Canadian resources still are being developed. Significant deposits have not been reported elsewhere in North America.

The earth's crust contains about 0.006 percent lithium, or about 0.013 percent Li_2O . This is close to the grade of the Searles Lake brines, which contain 0.015 percent Li_2O . Pegmatite deposits, on the other hand, must contain 1.0 percent Li_2O in order to be mined profitably.

The most abundant lithium mineral occurring in pegmatites is spodumene. Other minerals include amblygonite, lepidolite, petalite, and triphylite-lithiophilite. These most commonly occur in mineral assemblages that are characteristic of inner zones and replacement bodies of pegmatites.

Indicated reserves in the pegmatites of the United States are 5,000,000 units consisting of 20 pounds of Li_2O . By far the greatest reserves in pegmatites are in the Carolinas. Reserves in Searles Lake, Calif., may amount to 9,000,000 units. Inferred reserves in the United States and Canada are at least 125,000,000 units of Li_2O . In contrast to these figures, domestic consumption in 1953 was about 250,000 units.

INTRODUCTION

Lithium mining has been one of the most rapidly expanding mineral industries in the decade following World War II. In all but a few of the years prior to 1939, the gross value of all lithium minerals produced annually by the United States was less than \$50,000; by 1953, however, the value approached \$2,000,000. This rapid expansion makes a study of our lithium resource position desirable, in order to estimate the level of production that can be sustained by known and readily predictable reserves.

The present report brings together and analyzes all available data on lithium resources. Much of this information was obtained during work by many Survey geologists in the principal domestic pegmatite districts between 1939 and 1953. Additional data have been found in many published and unpublished reports. Information concerning Canadian deposits has been obtained chiefly from the available published reports, but unpublished material was furnished by the Lithium Corporation of America. Significant lithium deposits are not known elsewhere in North America.

This report has been greatly improved by suggestions from various members of the Geological Survey, especially Michael Fleischer, who called attention to published reports and analytical data that would not have been found without his aid.

USES AND PROPERTIES OF LITHIUM

Lithium is the third element of the periodic table. The atomic weight is 6.940, which makes it the lightest of all metals. Its chemical properties place it in the alkali metal group with sodium, potassium, rubidium, and cesium. Lithium is univalent.

Lithium minerals are ordinarily processed to make lithium carbonate and other lithium compounds used in industry, but lepidolite has been extensively used as a direct ingredient in glass making. Before World War I lithium compounds were used chiefly as ingredients in mineral waters and effervescing lithia tablets. The next important use was in alkaline storage batteries; this use probably in large part accounted for the increase in production during World War I. Subsequently the use of lithium compounds in ceramics became important. The hygroscopic nature of lithium chloride is the basis of use in industrial drying and air-conditioning.

Increased demand during World War II was caused largely by the use of lithium hydride as a hydrogen carrier to inflate certain types of naval and air force rescue equipment.

The transient uses during World War II were succeeded by more permanent uses that created a strong market leading to the great expansion of the industry in the years following 1948. The greatest demand was in greases, ceramics, glass, and air-conditioning. Lithium soaps are used in the manufacture of multi-purpose greases that can withstand extreme temperatures. Lithium is used in dry-cells. Alkaline storage batteries and pharmaceutical uses also continue to be important. Lithium is used as a flux in aluminum welding and brazing. It has important metallurgical uses, especially for degassing and purifying other metals and alloys. Many other uses of lithium have been reported.

TABLE 1.—Lithium mineral production of the United States

[N. A.—figures not available; ?—possibly some production, figures not obtainable; *—figures estimated; **—indicates years in which discrepancies between figures for total United States production and the data for individual States are not readily explainable. Prior to 1943 spodumene-lepidolite concentrates were produced in New Mexico, and small quantities of lithium minerals were mined from pegmatites elsewhere. Total production probably did not exceed 80,000 units. The principal activity was between 1920 and 1930. Lepidolite was produced from 1943 to 1947 in New Mexico and Colorado. Production figures are unavailable. Spodumene was produced in North Carolina in 1943-45 and in 1951-53. Production figures are unavailable.]

Year	South Dakota ¹				California Lepidolite ³		Total production ²		
	Spodumene		Amblygonite		Lepidolite		Tons	Value	Units of lithia ⁴
	Tons	Value	Tons	Value	Tons	Value			
1883									
1880									
1891							*30	*\$450	
1892							*30	*750	
1893									
1894									
1895									
1896									
1897									
1898	30	\$750					*30	*750	
**1899	500	12,500					*210	*3,500	
1900	870	21,750					520	9,500	
1901							1,750	43,200	
1902	200	5,000					1,245	25,750	
**1903	600	12,000					1,155	23,425	*4,000
**1904	250	5,000					577	5,155	
**1905			80	\$3,200			79	1,412	
**1906	200	4,000					383	7,411	
**1907	200	4,000					530	11,000	
**1908	200	4,000		742,200			203	1,550	
**1909	90	1,800		40,800			189	1,890	
**1910							238	2,380	
1911	(?)	(?)	300	12,000			*120	2,000	*3,000

See footnotes at end of table.

TABLE 1.—Lithium mineral production of the United States—Continued

Year	South Dakota 1						California Lepidolite 3		Total production 2		Units of lithia 4
	Spodumene		Amblygonite		Lepidolite		Tons	Value	Tons	Value	
	Tons	Value	Tons	Value	Tons	Value					
**1912.....	(?)	(?)	120	4,800					360	6,800	*11,000
**1913.....	(?)	(?)	780	19,500			30	500	14,900	14,900	
**1914.....			46	1,150					525	8,000	
**1915.....			256	5,120			90	1,400	486	9,867	
1916.....			537	10,740			70	*1,000	619	12,035	
1917.....	1,200	24,000	81	1,620			880	8,800	2,062	42,912	*4,500
1918.....	1,320	72,600	180	9,900			4,110	74,000	5,894	111,600	*11,000
**1919.....	1,000	60,000	203	9,890			800	14,400	6,287	115,000	*22,000
1920.....	625	30,625					10,080	153,500	11,696	173,002	
1921.....	595	25,825					700	10,600	1,833	33,508	
1922.....	570	19,950	16	640	2	\$50	670	10,200	2,192	41,300	
1923.....	1,000	35,000	37	N. A.					2,310	38,800	
1924.....	1,208	48,200	151	N. A.	24	600	110	2,200	2,996	62,391	
1925.....	1,000	40,000	14	840	3	60			3,140	58,500	
1926.....	800	32,000	213	10,520			40	1,000	3,700	53,400	
1927.....			80	3,520			500	12,500	4,173	59,656	
1928.....			100	4,400			400	16,000	4,600	94,750	
1929.....	40	N. A.							N. A.	N. A.	
1930.....									1,797	56,327	*1,000
1931.....									N. A.	N. A.	
1932.....									N. A.	N. A.	
1933.....			56	2,224					504	12,997	*3,000
1934.....	26	N. A.	\$20	\$22,788	15	300			719	20,980	*5,000
1935.....			134	5,520					1,154	26,834	*7,000
1936.....			500	20,560	2	40			1,241	34,273	*8,000
1937.....	640	N. A.							1,357	36,206	*8,000
1938.....	779	N. A.	131	5,240	162	3,164				47,088	*6,000
1939.....	18	N. A.	\$377	\$15,960	557	11,051	(9)	(9)	892	97,000	*13,000
1940.....	680	17,000	160	6,400	898	17,507			1,990	80,679	11,300
1940.....	635	19,050	80	3,200	1,127	21,966			2,011		

1941.....	2, 192	76, 245	132	4, 752	1, 374	30, 920	115, 718	3, 832	20, 900
1942.....	11 3, 162	11 98, 130	336	N. A.	1, 292	29, 079	243, 516	5, 405	29, 900
1943.....	4, 303	N. A.	814	N. A.	1, 580	71, 084	314, 660	8, 155	46, 300
1944.....	5 3, 606	5 131, 926	N. A.	N. A.	810	40, 495	552, 977	13, 319	84, 800
1945.....	12 749	12 28, 325					285, 520	2, 446	27, 400
1946.....	5 1, 190	5 35, 655	N. A.	N. A.			303, 892	3, 065	32, 300
1947.....	1, 707	*50, 000	11	N. A.			151, 113	2, 441	19, 900
1948.....	2, 633	*70, 000	80	N. A.	16	N. A.	210, 792	3, 881	29, 100
1949.....	12 6, 349	12 141, 670					345, 970	4, 838	47, 500
1950.....	5 5, 821	5 142, 949					579, 922	9, 306	74, 700
1951.....	12 8, 568	12 274, 701	N. A.	N. A.			896, 000	12, 897	95, 600
1952.....	*8, 000	*400, 000					13 1, 052, 000	13 15, 611	13 108, 800
1953.....	*10, 000	*500, 000					*13 28, 000	*13 28, 000	*196, 000
Total.....	14 73, 556	2, 444, 651	8, 655	265, 984	7, 862	226, 316	432, 800	185, 933	1, 122, 000

¹ Figures for years through 1944 were published in Page, and others, 1953, p. 3, table 1. Part of the data on spodumene for 1939-44 and all figures for 1945-51 are based on the annual reports of the South Dakota Inspector of Mines.

² From U. S. Geological Survey, Mineral Resources of the United States, for 1900-23; and U. S. Bureau of Mines, Mineral Resources of the United States, for 1924-31, and Minerals Yearbook, for 1932-51.

³ From Jahns and Wright, 1951, p. 51, table 5.

⁴ Most of the estimates of the number of units of lithia produced probably have errors of less than ±20 percent. A unit is 1 percent per ton, or 20 pounds of contained Li₂O.

⁵ Includes some amblygonite.

⁶ Production of only 21 tons from this district reported in Mineral Resources of the United States, 1905.

⁷ Includes 100 tons of triphylite valued at \$3,000.

⁸ Includes production of Beecher Lode for 1933-34.

⁹ Includes production of High Climb for 1934-38.

¹⁰ Lithium was obtained from brine at Searles Lake, San Bernardino County, starting in 1938. Production figures are unavailable.

¹¹ Includes production of Dyke Lode for 1936-42.

¹² May include a small quantity of amblygonite.

¹³ From J. C. Arundale, U. S. Bureau of Mines.

¹⁴ One operator may have produced as much as 8,000 tons not included in this total.

HISTORY OF LITHIUM MINING AND PRODUCTION

The first recorded production of lithium in the United States consisted of an estimated 30 tons of lithium minerals mined in 1889 (table 1), but the source of this material is not recorded. Lepidolite was mined as early as 1892 at the Stewart mine, Pala, Calif. (Jahns and Wright, 1951, p. 59). Spodumene was first obtained in 1898 at the Etta mine, Keystone, S. Dak. (Connolly and O'Harra, 1929, p. 240). The year 1898 is ordinarily regarded as marking the start of lithium mining in the United States (Schaller, 1919, p. 7).

Amblygonite was first obtained as a by-product of lepidolite mining at the Stewart mine in 1902 (Jahns and Wright, 1951, p. 51, table 5), and it was produced at the Tin Queen mine, Hill City, S. Dak., about 1905 (Hess, 1911, p. 652). Amblygonite production from South Dakota deposits rapidly became dominant in the industry, and remained so until 1917.

Lithium production figures for the years prior to 1917 are inadequate (see table 1), but 1901-1903 was probably the only period in which annual production exceeded 1,000 tons of lithium minerals or had a gross value of more than \$20,000.

Production increased during World War I, and reached a maximum of 11,696 tons in 1920. This was the period of greatest activity at the Stewart mine, Pala, Calif.; it was also one of the more productive periods in the history of the Etta mine, Keystone, S. Dak.

Production dropped to 1,833 tons in 1921, and then gradually increased during the 1920's until it reached 4,600 tons in 1928. During these years the chief source was the Harding mine, Taos County, N. Mex., where spodumene-lepidolite concentrates were produced; but spodumene from the Etta mine and lepidolite from the Stewart mine were also important.

Lithium mines were inactive in the early 1930's, but production was resumed in South Dakota during the latter half of the decade. As in the past, the Maywood Chemical Co. mined spodumene at the Etta mine. Lepidolite production first became significant in the Black Hills in 1937, when it was mined from the Bob Ingersoll No. 1 pegmatite, near Keystone. The American Potash and Chemical Corporation began the production of dilithium sodium phosphate at Searles Lake, Calif., in 1938.

Lithium mining increased greatly during World War II, and reached a peak production of 84,800 units¹ of lithia in 1944. This increase in production was possible largely because of the introduction of modern mineral dressing techniques, which permitted exploitation of deposits of fine-grained lithium minerals that could not be concentrated by *hand-cobbing* methods used previously. The Solvay

¹ A unit consists of 1 percent Li₂O per ton of concentrate, or 20 pounds of contained Li₂O.

Process Co. built the largest mill at Kings Mountain, N. Car. Spodumene was also milled at Tinton, S. Dak. Lepidolite was milled in South Dakota and Colorado.

Annual production from 1945 through 1948 averaged about 27,000 units. In succeeding years production increased until in 1952 it exceeded 100,000 units, and at the present rate of development should soon reach 200,000 units. A major producer has been the Foote Mineral Co., which purchased the Solvay properties in North Carolina in 1951 and began mining and milling spodumene soon thereafter. Searles Lake has continued to be a major source. Canadian lithium districts were actively explored, and by 1954 at least one major mine was being developed (Anonymous, 1954, p. 1).

From 1948 to 1950 the Lithium Corporation of America used a sink-float process to concentrate spodumene from the Edison mine near Keystone, S. Dak. In 1952 this company completed a spodumene flotation plant at Hill City, S. Dak., to process ore from the nearby Mateen pegmatite and from the Beecher No. 2 pegmatite, about 15 miles to the south. The Black Hills Tin Co. resumed mining at Tinton, but work came to a halt when the mill burned in November 1953. The Etta mine and several smaller operations also contributed to the Black Hills production.

Recorded production figures for South Dakota, California, other states, and the entire United States through 1953 are shown on table 1. The national totals for many of these years are not consistent with the figures for the various states and sufficient data to resolve the discrepancies were not obtainable. For example, the figures for early production in South Dakota may have significant errors. Schaller (1937, p. 430) reported that before 1935 South Dakota had produced 26,000 tons of lithium minerals; table 1, however, shows only 18,600 tons.

IMPORTS AND EXPORTS

Import and export figures for lithium minerals are not reported separately, and complete data are not available. Prior to World War II the United States was a net exporter, chiefly to Germany. Since World War II, there have been large imports of lepidolite from Southwest Africa and petalite from Southern Rhodesia. Other countries have significant lithium deposits, and in the future these deposits may increase the supply of lithium minerals on the world market.

PRICES

The preprint on lithium from the U. S. Bureau of Mines Minerals Yearbook for 1952 (Arundale and Mentch, 1954, p. 4) quotes the following prices for spodumene and dilithium sodium phosphate at the mine:

Spodumene, \$10 to \$12.50 per unit consisting of 1 percent Li_2O per short ton of ore.

Dilithium sodium phosphate, about \$183 per short ton.

The Minerals Yearbook for 1951 (Arundale and others, 1954, p. 1372) quotes the following prices for lepidolite and amblygonite at the mine:

Lepidolite, 4 percent Li_2O , \$80 per short ton.

Amblygonite, \$110 per short ton.

Concentrates from domestic sources are ordinarily processed by the companies that do the mining, and the lithium is sold in the form of lithium compounds or lithium metal. Lepidolite used in glass making may be sold directly to the consumer. Imported lithium minerals have been sold as raw concentrates.

GEOLOGY OF LITHIUM

DISTRIBUTION OF LITHIUM

Available data indicate that the earth's crust contains about 0.006 percent lithium (Fleischer, 1953, p. 4, table 2). Rankama and Sahama (1950, p. 422-428) show that igneous rocks contain an average of about 0.0065 percent lithium, and sedimentary rocks contain somewhat less.

The lithium content of sea water has been reported as 0.1 part per million (Thomas and Thompson, 1933, p. 548). Rankama and Sahama (1950, p. 295, 428) show that only 0.3 percent of the lithium supplied to sea water remains in solution; they presume that the remaining 99.7 percent goes chiefly into clays. There may be unrecognized lithium concentrations in sedimentary rocks.

Known lithium minerals, however, occur almost entirely in pegmatites. The only other source of lithium is at Searles Lake, Calif., where the lithium is in solution in brine extracted from evaporite beds. Lithium minerals are virtually unknown in sedimentary rocks; the clay mineral hectorite, however, contains enough lithium to be of possible commercial interest.

The small amount of lithium in igneous and metamorphic rocks is distributed among several minerals, especially biotite, pyroxene, and amphibole. Possibly lithium is more common than available analyses indicate, but it is very rare for any of these minerals to have as much as 1 percent Li_2O , or for rocks containing these minerals to have as much as 0.1 percent Li_2O . These occurrences have no commercial significance.

Lithium is not known to be associated with metalliferous veins, but ultimately it may be found in such deposits. Some pegmatites contain replacement units that evidently were formed by hydrothermal or pneumatolytic activity during a late stage in crystallization.

Lithium mica is the predominant mineral of some of these replacement units, and it may be related, though perhaps remotely, to the mica and clay minerals that occur in alteration zones around many metalliferous veins.

MINERALOGY OF LITHIUM ORES AND CONCENTRATES

PEGMATITE LITHIUM MINERALS

The chief lithium minerals mined from pegmatites of North America are spodumene, amblygonite, and lepidolite. Zinnwaldite, other lithium micas, and triphylite-lithiophilite have been used in only small quantities, but may become more important (table 2). Petalite is an important product of foreign deposits.

Spodumene is a monoclinic member of the pyroxene group of minerals. The simplified formula for spodumene is $\text{LiAlSi}_2\text{O}_6$, indicating a theoretical content of 8.03 percent Li_2O . Many analyses show Na and K (which presumably substitute for Li) and also Fe, Mg, and Ca (for examples, see Dana, 1892, p. 367). Spodumene containing more than 7.5 percent Li_2O is rare.

Spodumene is ordinarily white to light gray, but gem varieties are green (hiddenite) or lilac-colored (kunzite). The luster is vitreous on fractured surfaces and pearly to silky on cleavages. Crystals characteristically are elongate, flat blades, but crystals with rounded and square cross-sections are also common. Anhedronal spodumene is rare. A spodumene crystal as much as 47 feet long has been reported (Schaller, 1916, p. 138), but deposits are known in which nearly all grains are less than a quarter of an inch long (Page and others, 1953, p. 204). Crystals break readily along cleavage surfaces to form splintery laths.

TABLE 2.—Composition of the principal lithium minerals of pegmatites

Mineral	Formula	Theoretical Li_2O content (percent)	Li_2O content of marketed concentrates (percent)
Spodumene.....	$\text{LiAlSi}_2\text{O}_6$	8.03	4-7.5
Amblygonite-montebrazite-natromontebrazite series.	$(\text{Li,Na})\text{Al}(\text{PO}_4)(\text{F,OH})$ End member montebrazite with maximum lithium content is $\text{LiAl}(\text{PO}_4)(\text{OH})$.	¹ 0-10.24	8-9
Lepidolite, lithium muscovite, zinnwaldite, and other lithium micas.	$\text{K}(\text{Li,Al,Fe})_3\text{Si}_3\text{-}_4\text{O}_{10}(\text{OH,F})_2$ End member polyolithionite or lepidolite with maximum lithium content is $\text{KLi}_2\text{AlSi}_4\text{O}_{10}(\text{OH})_2$.	0-7.74	2.5-5
Petalite.....	$\text{LiAlSi}_4\text{O}_{10}$	4.88	3-4
Triphylite-lithiophilite series.....	$\text{Li}(\text{Fe,Mn})\text{PO}_4$	9.47-9.53	(²)

¹ Palache and others (1951, p. 825) record only one analysis in which the Li_2O content is less than 6 percent. This is natromontebrazite or fremontite containing 3.21 percent Li_2O , reported by Schaller, 1911, p. 48.

² Rarely marketed.

A distinctive characteristic of spodumene is pseudomorphic replacement by many other minerals. Spodumene may be so thoroughly replaced by micaceous and clay minerals that the lithia content is less than 0.1 percent, yet the cleavage of spodumene may still be preserved (Schwartz and Leonard, 1926, p. 257-264; M. H. Staatz, written communication). The so-called "altered", "soft," or "rotten" spodumene is gray, green, or pink. Many standard mineralogic texts (for example, Dana, 1932, p. 564) describe the alteration of spodumene first to a sodium-rich product consisting of eucryptite (LiAlSiO_4) and albite, and subsequently to potassium-rich products in which muscovite takes the place of eucryptite. These statements, however, are based almost entirely on studies of the Branchville, Conn., pegmatite; they may have wider application, but knowledge on this point is incomplete.

Pseudomorphic replacement of spodumene by coarser pegmatite minerals has been recognized by Norton and Page² in the Hugo pegmatite and may also have occurred in the Peerless pegmatite near Keystone, S. Dak. The spodumene parentage can be recognized by the characteristic bladed shape of the aggregates and by cleavelandite sheaths that surround both the pseudomorphs and unreplaced spodumene crystals. The minerals replacing spodumene are quartz, albite, perthite, muscovite, beryl, amblygonite, apatite, and tourmaline.

A thorough study of the alteration products of spodumene, using modern mineralogic techniques, has not been made. An investigation of this sort might reveal information useful in research on spodumene beneficiation.

Amblygonite (Li, Na) $\text{Al}(\text{PO}_4)$ (F, OH) is the common name of a phosphate series in which hydroxyl-rich material is sometimes called montebasite and the fluorine end of the series is amblygonite in the strict sense. Sodid montebasite containing little lithia has been called natromontebasite (Palache and others, 1951, p. 823-825), natramblygonite (Schaller, 1911, p. 48), and fremontite (Schaller, 1914, p. 356, and 1916, p. 141). Schaller (1911, p. 48) reported that the type specimen of this material contained 3.21 percent Li_2O and 11.23 percent Na_2O . Actually, however, material of this sort is so exceedingly rare that for all practical purposes the amblygonite series ranges from 6.7 to 9.65 percent Li_2O (Palache and others, 1951, p. 825).

Amblygonite is ordinarily milky white to gray in color. The luster is pearly on the principal cleavage, but otherwise vitreous. Ambly-

² Norton, J. J., and Page, L. R., *Geology of the Hugo Pegmatite, Keystone, S. Dak.* (In preparation.)

gonite generally occurs as rounded or ellipsoidal masses that commonly exceed 5 feet in diameter. The outer surface of many amblygonite masses is coated with a characteristic chalky covering that consists of micaceous and clay minerals.

The name lepidolite is applied in the lithium mining industry to a widely varied group of lithium micas. Marketable lepidolite ordinarily must contain 3 to 4 percent Li_2O . Nearly all such lepidolite is pink, lilac, or violet-gray. Gray and rose-colored micas containing less lithia are sometimes called lepidolite. All varieties occur most commonly as fine-grained aggregates associated with albite and other pegmatite minerals.

Knowledge of the mineralogy of lepidolite and its relatives has been greatly increased in recent years as a result of work by Levinson (1953), Winchell (1942), Hendricks and Jefferson (1939), and Stevens (1938). These authors show that the lithium micas belong to a complex series with various structures that fit in the hexagonal, monoclinic, and triclinic systems. The many members include: muscovite, lithium muscovite, polyolithionite (lithium-rich mica), protolithionite and zinnwaldite (iron-rich micas), biotite, and taeniolite (magnesium-lithium mica). The simplest general formula for this series is $\text{K}(\text{Li},\text{Al},\text{Fe})_3\text{Si}_{3-4}\text{O}_{10}(\text{OH},\text{F})_2$.

Levinson (1953) found a continuous gradation in composition between muscovite and lepidolite. Micas containing less than about 3.3 percent Li_2O have the structure of muscovite. Micas containing 3.4-4.0 percent Li_2O belong to three different structural varieties of lepidolite. The richest sample contained 7.26 percent Li_2O , and the theoretical maximum is 7.74 percent Li_2O (Stevens, 1938, p. 619-620).

These studies indicate that the lepidolite of commerce has a significant range of composition and structure. At the present time these differences have no practical importance, but in the future a knowledge of them may be of value in developing specialized uses of the various lithium-bearing micas.

Petalite ($\text{LiAlSi}_4\text{O}_{10}$) occurs as white to gray masses. For many years petalite has been described in the literature as a source of lithium, but actually it was rarely used for this purpose until recently. Significant petalite deposits are unknown in North America, but petalite deposits elsewhere are economically important (Clark, 1950, p. 1068).

Pegmatites have a wide variety of phosphate minerals that contain lithium, iron, manganese, calcium, and other constituents. The principal minerals are in the triphylite-lithiophilite series, which has the formula $\text{Li}(\text{Fe},\text{Mn})\text{PO}_4$. Lithium can be replaced by sodium and calcium to form the less common hühnerkobelite series, and thus gradations from 0 to 9.55 percent lithia may occur (Palache and others, 1951, p. 664-670).

Triphylite-lithiophilite is bluish gray to brown, but ordinarily it is intimately associated with many alteration products that make it grayish brown to nearly black. Triphylite-lithiophilite is also intergrown with other primary pegmatite minerals. Phosphate-rich aggregates form rounded masses ranging from a few inches to several feet in diameter. The mineralogy of such aggregates is difficult; these aggregates may contain many undescribed species of phosphate minerals.

The difficulty of using hand-cobbing methods to obtain a lithium-rich concentrate of consistent composition from aggregates of this sort doubtless is one of the main reasons why these minerals have rarely been mined. Triphylite-lithiophilite and its associated minerals have been found in and near minable deposits of other lithium minerals, and now that milling is widely used in the lithium mining industry, the triphylite-lithiophilite may also be produced. More mineralogical study of these minerals and their possible economic applications is needed.

Eucryptite (LiAlSiO_4) has generally been considered a very rare mineral. For three-quarters of a century it was known only from Branchville, Conn., but recently it was found in Arizona (J. W. Adams, oral communication), New Mexico, and New Hampshire (Mrose, 1952, p. 1283). Still more recently it was found in a large petalite deposit at Bikita, Southern Rhodesia (Michael Fleischer, oral communication, 1953). No data are available concerning the abundance of eucryptite in this deposit. Possibly eucryptite is more abundant in this and other pegmatites than has been supposed.

Cryolithionite ($\text{Na}_3\text{Li}_3\text{Al}_2\text{F}_{12}$) has been described in cryolite deposits (Palache and others, 1951, p. 99-100). It is not known to occur in significant quantities anywhere in the world.

NONPEGMATITE LITHIUM MINERALS

One of the principal sources of lithium is Searles Lake, Calif., where the lithium is in solution in brines. No lithium minerals, however, have been described in saline deposits. The lithium in saline deposits may be a minor constituent of the major minerals, where it could occupy alkali positions in the lattices.

Hectorite is a lithium-bearing mineral of sedimentary rocks that is potentially important as a source of lithium, but it has been reported only at Hector, Calif. Hectorite is an end member of the montmorillonite group that is rich in magnesium, lacks aluminum, and contains about 1 percent lithia (Ross and Hendricks, 1945, p. 27, 35, 47). The formula is $16 \text{MgO} \cdot \text{Li}_2\text{O} \cdot 24\text{SiO}_2 \cdot 6(\text{F}, \text{H}_2\text{O}) \cdot (\text{Na}_2\text{O})$. Lithium is an essential part of the crystal lattice, and cannot be replaced by simple base exchange (Ross and Hendricks, 1945, p. 38).

Ephesite, a soda-rich margarite, contains as much as 3.80 percent Li_2O (Schaller and Carron, 1952, p. 301). The possible commercial value of this mineral is unknown.

TYPES OF LITHIUM DEPOSITS

Pegmatite deposit containing spodumene, amblygonite, and lepidolite are the chief sources of lithium, and were the only sources prior to 1938, when production of lithium was begun at Searles Lake, Calif. (Mumford, 1949, p. 513). No North American deposits have been mined for petalite and no deposits anywhere have been mined for lithium mica containing less than 2.5 percent Li_2O . Small quantities of triphylite-lithiophilite have been used as a lithium source, presumably only in experimental work. Searles Lake is the only other commercial source of lithium. Lithium has also been detected, however, in saline deposits, clays, and other sedimentary rocks, and also in hot springs.

LITHIUM DEPOSITS IN PEGMATITES

Nearly all lithium pegmatites mined in the United States and Canada are intrusive into metamorphic rocks. Lithium pegmatites large enough to be of commercial interest intrude igneous rocks in Quebec (Derry, 1950; Rowe, 1953b).

Most pegmatites from which lithium minerals have been profitably extracted can be classified as well-segregated zoned or heterogeneous pegmatites. Many spodumene pegmatites, however, consist of essentially the same rock from wall to wall. Such pegmatites may have a fine-grained border zone or wall zone, and slight changes in composition and texture may be recognizable within the pegmatite. Clear distinctions between pegmatite units may be difficult to find.

Lithium deposits occur with mineral assemblages that Cameron and others (1949, p. 59-70, tables 1-5) show are characteristic of inner units of pegmatites. Table 3 shows the principal lithium minerals and nonlithium minerals in the sequence of 11 assemblages described by Cameron and others. No pegmatite contains all of these assemblages, but those in any one pegmatite occur from the wall inward in the sequence given in the table. This sequence probably is also the order in which the units formed. Nearly all lithium deposits are in assemblages 5 through 8.

Table 3 shows that the types of lithium minerals change from one part of a pegmatite to another. The lithium phosphates, especially triphylite-lithiophilite, are most abundant in the first part of the sequence (in the outer parts of pegmatites) where perthite and muscovite are common minerals. Amblygonite tends to be nearer the montebrazite or hydroxyl end of the series in outer units and nearer the fluorine end of the series in inner units of some pegmatites of the

TABLE 3.—*Distribution of the principal lithium minerals of pegmatites*

Assemblage	Principal non-lithium minerals ¹	Principal lithium minerals
1.....	Plagioclase, quartz, muscovite.....	Amblygonite (especially montebrasite?).
2.....	Plagioclase, quartz.....	None.
3.....	Quartz, perthite, plagioclase, muscovite.....	Triphylite-lithiophilite.
4.....	Perthite, quartz.....	Triphylite-lithiophilite.
5.....	Perthite, quartz, plagioclase.....	Amblygonite, spodumene.
6.....	Plagioclase, quartz.....	Spodumene, petalite(?).
7.....	Quartz.....	Spodumene.
8.....	Plagioclase, quartz.....	Lepidolite.
9.....	Quartz, microcline.....	None.
10.....	Microcline, plagioclase, quartz.....	Lithium muscovite.
11.....	Quartz.....	None.

¹ After Cameron and others, 1949, p. 68.

Black Hills, S. Dak. (Norton and Page ³). This relation has not been demonstrated elsewhere.

The richest spodumene-bearing units tend to be inside amblygonite-bearing units. The distribution of petalite is not so well known but, like spodumene, it is a lithium-aluminum silicate and presumably it forms in the same part of the sequence. Lepidolite and other lithium micas tend to form in the centers of pegmatites.

Spodumene deposits.—Spodumene deposits of greatest commercial importance are in units containing assemblages 5–7 (table 3). In some pegmatites the spodumene-bearing units are surrounded by barren wall and intermediate zones many feet in thickness. However, most commercial spodumene has been produced from a common and rather characteristic type of pegmatite in which the spodumene-bearing units extend to within a few inches or feet of the pegmatite contact.

Many deposits in the Black Hills, S. Dak., are in multiple intrusives. In places the individual pegmatite bodies in these intrusives are separated by a schist parting; elsewhere, outer zones of adjacent pegmatites are in contact with each other. As a result, the entire deposit consists of successive spodumene-rich units separated by barren units (for example, see Page and others, 1953, pls. 14 and 15). L. R. Page (oral communication) has observed similar relationships in the tin-spodumene belt of the Carolinas.

The spodumene deposit in the Giant-Volney pegmatite, Tinton, S. Dak., is a large replacement unit (Page and others, 1953, p. 204). Elsewhere, however, known replacement and fracture-filling deposits are small and commercially unimportant.

Spodumene-bearing units large enough to be mined contain a maximum of about 30 percent of spodumene or 2.0 percent Li_2O , but 20 percent of spodumene is more general. If the spodumene contains 7.5

³ Norton, J. J., and Page, L. R., Geology of the Hugo pegmatite, Keystone, S. Dak. (In preparation.)

percent Li_2O , the grade of such a deposit is 1.5 percent Li_2O . In places, however, alteration of the spodumene reduced the grade to as low as 0.1 percent Li_2O .

Altered spodumene has been observed in four structural positions in Black Hills pegmatites: in the deeper and narrower parts of the spodumene-bearing zones, in the outer parts of spodumene-bearing pegmatite in zones rich in feldspar, in the ends of spodumene crystals extending into a quartz core, and along fractures in the pegmatite (Page and others, 1953, p. 56). The lithium content of spodumene-bearing pegmatites may decrease with depth in other districts.

Prior to World War II the only spodumene mining was in deposits containing spodumene crystals large enough for hand-sorting. Ordinarily crystals at least 1 foot in length were required. The development of milling processes, however, has eliminated the requirement for coarse grain size.

Amblygonite deposits.—Amblygonite has been mined chiefly from quartz-perthite-amblygonite or quartz-perthite-amblygonite-spodumene pegmatite in assemblage 5 of the general sequence, but amblygonite has also been obtained from quartz-plagioclase-muscovite pegmatite of assemblage 1 (table 3). In Southwest Africa amblygonite occurs in perthite-bearing units of zone 3 (Cameron, E. N., oral communication). Few deposits contain as much as 10 percent of amblygonite, but many deposits contain other marketable minerals that allow the amblygonite to be obtained as a byproduct. Amblygonite deposits, in general, are smaller and of lower grade than spodumene deposits.

Amblygonite crystals range from grains weighing a fraction of an ounce to masses weighing several hundred tons. The large size of crystals in some deposits make it possible to produce a very pure concentrate by hand-sorting.

Deposits of lepidolite and other lithium micas.—Lepidolite containing more than 2.5 percent Li_2O has been mined chiefly from lepidolite-albite-quartz pegmatite of zone 8 (table 3); lepidolite also occurs in the spodumene and amblygonite units of some pegmatites. A part of the lepidolite deposit in the Pidlite pegmatite, Mora County, N. Mex., is a replacement unit (Jahns, 1953, p. 1087-1089). Gray lithium micas, containing less than the 2.5 percent Li_2O , occur with microcline, albite, and quartz in zone 11 of the general sequence and also in replacement bodies of the same mineral composition at the Hugo pegmatite, Keystone, S. Dak. (Norton and Page⁴). Lepidolite deposits are relatively rare; there are only five pegmatites in North America that have a recorded production of more than 100 tons of lepidolite.

Deposits of other lithium minerals of pegmatites.—Triphylite-lithiophilite and associated iron-manganese phosphates are significant

⁴ Norton, J. J., and Page, L. R., Geology of the Hugo pegmatite, Keystone, S. Dak. (In preparation.)

constituents of perthite-bearing units of assemblages 3 and 4, and possibly assemblage 5, of the general sequence (table 3). Triphylite-lithiophilite has never been commercially important as a lithium source, and consequently virtually no information regarding grade of typical deposits is available. These minerals are intimately intergrown with nonlithium minerals, and the aggregates are stained with phosphates and oxides. Consequently, estimates of the content of lithium minerals cannot be made readily. Assay data are needed.

The only other important lithium mineral is petalite, but no significant deposit has been found in North America.

LITHIUM IN BRINES AND SALINE DEPOSITS

The brines at Searles Lake, Calif., are the only commercially important non-pegmatite deposits of lithium. Even in these brines the content of lithium is only about 70 parts per million, corresponding to about 0.015 percent Li_2O . Thus, the grade of this deposit is very nearly the same as the average content of the earth's crust. Other saline deposits in the Mohave desert may also contain lithium, but there are no published data.

A few U. S. Geological Survey analyses have shown that other brines and saline deposits contain small amounts of lithium, but their commercial potentialities have been virtually unexplored. The lithium of evaporites may be largely in associated clay minerals. J. J. Fahey (oral communication) found that parts of the Green River formation of Wyoming contain about 0.01 percent Li_2O . Analyses of two potassium-rich parts of a core from the Carlsbad area, New Mexico, by K. J. Murata show the lithium content to be approximately 0.003 percent. Six other samples of potash ore from this area analyzed by R. S. Harner had 0.0001 to 0.0017 percent Li_2O . Old analyses of waters from closed basins, mineral springs, and wells contain lithium (Clarke, 1924, p. 157-162, 185-200). Possibly some lithium-bearing waters are partly of juvenile origin. At Manitou Springs and Steamboat Springs, Colo., 19 analyses by P. R. Barnett of waters collected by E. P. Beroni indicate an average content of 2 parts per million Li_2O . One sample from the Steamboat Springs area had 6.5 parts per million Li_2O , and the solids had 0.11 percent Li_2O .

Lindgren (1933, p. 44-45) has pointed out that salts in many of the chloride ground waters may have been derived from saline deposits. Clarke (1924, p. 187-188) gives two analyses of chloride waters from Saratoga Springs which contain 0.08 and 0.16 percent of lithium and an analysis of water from a deep well at Conneautville, Pa., which contains 0.04 percent of lithium. These are old analyses and may be inaccurate. Nevertheless, it is clear that saline deposits may contain significant quantities of lithium.

LITHIUM IN SEDIMENTARY ROCKS

No lithium has been mined from sedimentary deposits, and only hectorite clay is known to contain enough lithium to compare with pegmatites. Nevertheless, other deposits in sedimentary rocks may be found.

The only recorded hectorite deposit is in the Mohave desert near Hector, San Bernardino County, Calif. The hectorite forms bentonite beds in an intensely folded and sheared sequence of Tertiary ash, clay, and limestone (Kerr and Kulp, 1949, p. 74-76). A basalt flow overlies these rocks unconformably. Analyses of the mineral hectorite have shown a content of 1 percent Li_2O (Ross and Hendricks, 1945, p. 27, 35), but no information on the average grade of the deposit is available.

Clay of Tertiary age, 16 miles northeast of Amboy, Calif., has been found to have 0.50 percent Li_2O (Foshag and Woodford, 1936, table 1, p. 241). It is possible that other clays have an appreciable lithium content that has previously been overlooked.

LITHIUM RESERVES AND RESOURCES

DETERMINATION OF GRADE AND RESERVES

The grade and reserves of deposits of lithium minerals and of other minerals in pegmatites can be estimated with reasonable accuracy (Norton and Page⁵). Large samples must be used to determine the grade of coarse-grained lithium-bearing units in pegmatites, but otherwise there are no special sampling problems in collecting material for analysis.

Difficulties have been experienced in obtaining accurate analyses with the gravimetric and volumetric techniques used by commercial analysts. Table 4 shows the wide range of results on three samples analyzed by seven reputable laboratories in 1944.

TABLE 4.—Comparative analyses of three spodumene samples, Edison mine, Keystone, S. Dak.

[After Clarke, and others, 1948, p. 22, table 7.]

Supposed lithia content	Lithia content, in percent, according to analyst indicated						
	U. S. Bureau of Mines	A	B	C	D	E	F
Low.....	0.79	0.94	(¹)	1.10	1.24	1.38	1.48
Medium.....	2.80	3.12	{ 2.88 3.10 }	3.50	3.50	3.52	3.55
High.....	4.63	5.54	{ 5.54 5.50 }	6.05	6.00	5.41	5.74

¹ Trace.

⁵ Norton, J. J., and Page, L. M., Methods used to determine grade and reserves of pegmatites. (In preparation.)

More recently the flame photometer has been widely used for lithium analyses. The Lithium Corporation of America has found that results from analyses of spodumene-bearing samples by flame photometer are consistently higher than results from a routine chemical technique also used by this company. One explanation is that the chemical method extracts all the lithium in spodumene, but not all the lithium in associated minerals (F. F. Clarke, oral communication).

Many deposits have more than one mineral containing lithium. Usually, however, lithium is extracted from only one of these minerals, and the others are waste products. Consequently, chemical analyses are not completely adequate for grade determinations unless the deposit contains only one lithium mineral, or the proportions of the various lithium minerals in the deposit are known. To correct for errors that may be introduced in this way, grade has sometimes been determined by measuring the intercepts of lithium minerals on equally spaced lines along exposed surfaces. Grain counts under the microscope have also been used (Gries, 1950, p. 6). The most accurate results can be obtained by screening the samples, making grain counts for each sieve size, and computing weighted averages. Such an elaborate procedure may not always be necessary. At least one investigation of the spodumene content of analyzed samples appears to have been successful without sieving the samples (Gries, 1950, p. 6). Nevertheless, spodumene has such a great tendency to break to small sizes that grain counts used alone may give erroneously high results.

Spodumene and amblygonite have a greater specific gravity than the other essential minerals of most deposits. Consequently, heavy liquid separations can be used for approximate determinations of grade. Heavy accessory minerals may, however, cause significant inaccuracies.

Reserves in zones or other pegmatite units can be determined by projections along strike, dip, and plunge. The techniques used for this purpose in pegmatites are essentially the same as for other mineral deposits. Detailed discussion of these methods is being presented elsewhere (Norton and Page⁶).

UNITED STATES

Lithium reserve data compiled in table 5 show that pegmatites in the United States contain indicated reserves of 5,000,000 units and inferred reserves of about 124,000,000 units of lithia. Searles Lake, Calif., may contain 9,000,000 units of lithia that can be extracted by the methods now in use. In the mining and concentrating techniques now used at lithium mines, a significant proportion of all lithium minerals—perhaps as much as one-third—are not recovered. Even

⁶ Norton, J. J., and Page, L. R., Methods used to determine grade and reserves of pegmatites. (In preparation.)

TABLE 5.—*Lithium reserves of the United States*[Minimum grade used in calculating reserves in pegmatite deposits is 1.0 percent Li_2O .]

Localities	Principal lithium mineral	Other lithium minerals	Indicated reserves			Inferred reserves			Total units Li_2O
			Average depth in feet	Average grade percent Li_2O	Units Li_2O	Average depth in feet	Average grade percent Li_2O	Units Li_2O	
Tin-spodumene belt, North and South Carolina.	Spodumene.	Amblygonite.	400	1.7	4,000,000	450	1.3	124,000,000	128,000,000
Black Hills, S. Dak.	Spodumene.	Amblygonite, lepidolite.	100	1.2	1,200,000	100	1.2	400,000	1,600,000
Pegmatite districts of New England, Colorado, Arizona, New Mexico, California, and Wyoming.	Spodumene.	Amblygonite, lepidolite.	-----	1.2	200,000	-----	-----	-----	200,000
Upper deposit at Searles Lake, California.	Brine.	-----	90	.015	9,000,000	-----	-----	-----	9,000,000
Totals	-----	-----	-----	-----	14,400,000	-----	-----	124,400,000	138,800,000

with such losses, however, this reserve would last many hundreds of years at the estimated 1953 domestic consumption rate of about 250,000 units annually (J. C. Arundale, U. S. Bureau of Mines, oral communication.)

Nearly all of the lithium reserves of pegmatites are in spodumene. The Black Hills district, South Dakota, has significant amblygonite reserves, but these contain not more than a few hundred thousand units of Li_2O . Lepidolite reserves are trivial in comparison with spodumene and amblygonite.

The minimum grade used in calculating reserves in pegmatite deposits in table 5 is 1.0 percent Li_2O . If deposits containing 0.4–1.0 percent lithia were also included, the reserves in all districts would be increased somewhat, but the change in the Carolina reserves would be small. Inasmuch as the Carolina reserves constitute a very large part of the national total, the overall effect of including deposits containing 0.4 percent Li_2O would be slight.

Most of the reserves shown in table 5 are within 300 feet of the surface, but calculations for a few of the larger deposits have been extended to depths as great as 800 feet.

Doubtless lithium deposits could be found at much greater depths, but reserves near the surface are so great that with few exceptions any deposits below 300 feet must be considered submarginal at the present time.

No saline deposits have been included except the upper salt body at Searles Lake, Calif.

Additional lithium resources are in types of deposits not being worked at present, and are not included as reserves in table 5. The lithium clay at Hector, Calif., is an example.

NORTH AND SOUTH CAROLINA

A very large share of the known spodumene reserves of the United States are in the tin-spodumene belt at the border of North and South Carolina near Kings Mountain, N. C. (fig. 49). This district has recently been studied in detail by W. R. Griffiths of the U. S. Geological Survey and he has supplied the reserve data used in this report (written communication, 1954). An earlier study was made by T. L. Kesler (1942).

The tin-spodumene belt contains many hundreds of lenticular, tabular, and irregularly shaped pegmatites intrusive into gneiss and schist, and more rarely into quartz monzonite. Spodumene is a major constituent of many of these pegmatites, and amblygonite has been recognized as an accessory mineral. Lithium deposits extend from wall to wall of many of the pegmatites. Some of these deposits are very large: one is 3,200 feet long, and another is 225 feet thick. How-

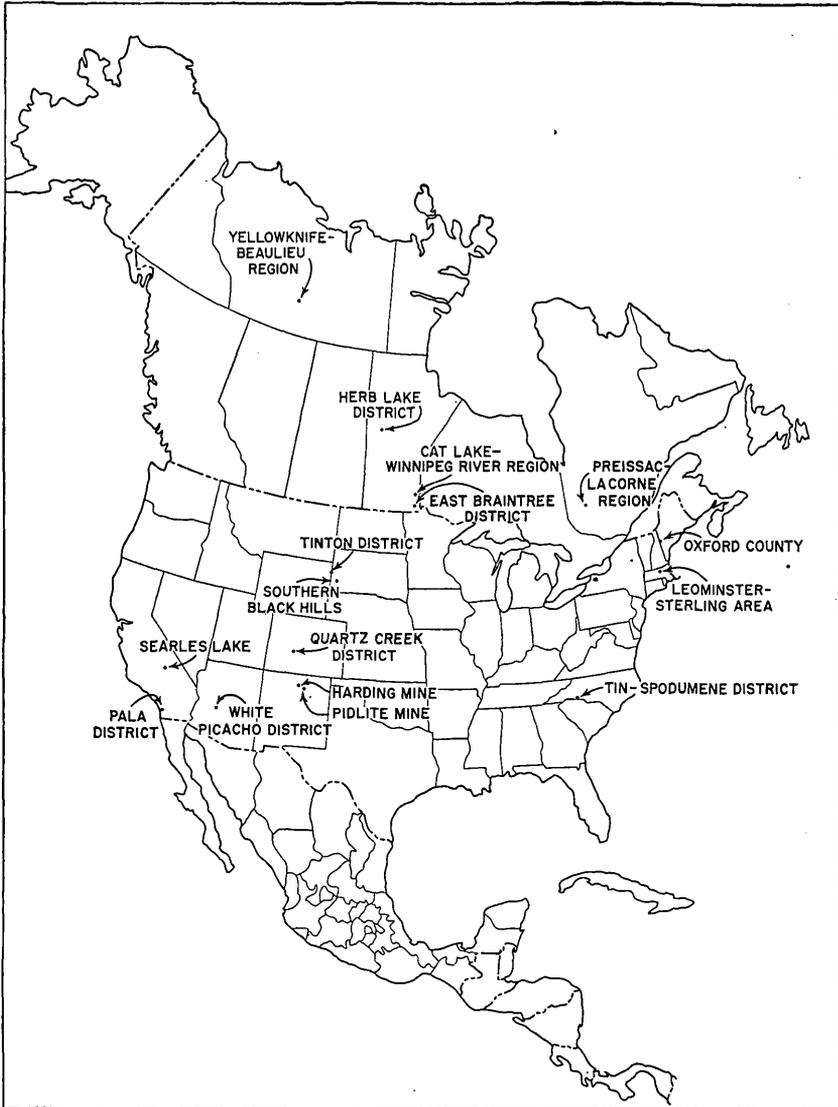


FIGURE 49.—The principal lithium localities of North America.

ever, many other deposits are so small that only very small scale mining operations would be feasible.

Analyses and estimates of the spodumene content of many exposures have been used to determine grade of these deposits. The average grade of spodumene-bearing pegmatite (table 5) is 1.7 percent Li_2O .

Reserves of some deposits have been determined by drilling. Reserves of others have been estimated by projections from the surface to a depth of 300 feet. Of course, many exposed deposits do not ex-

tend very far downward; but deposits that do not reach the surface should compensate for them.

Lepidolite has been recognized in Franklin County, N. C., but reserves are not known to be significant (Griffitts, 1953, p. 284).

SOUTH DAKOTA

Lithium deposits have been found in the Tinton district of the northern Black Hills and in three districts in the southern Black Hills, S. Dak.: the Keystone district, northeast of Harney Peak; the Hill City district, northwest of Harney Peak; and the Custer district, southwest of Harney Peak. The principal known deposits are as follows: Tinton district—Giant-Volney; Keystone district—Etta, Edison, Hugo, Bob Ingersoll Nos. 1 and 2, and Dyke Lode; Hill City district—Mateen; and Custer district—Beecher Lode, Beecher No. 2, and Tin Mountain. Only five of these deposits are known to contain more than 100,000 units of Li_2O . Lithium minerals have been found in about 40 additional pegmatites.

Spodumene is the dominant lithium mineral in nearly all deposits, and constitutes 85 percent of the known reserves. Amblygonite is the chief lithium mineral at the Hugo mine, and ranks close to spodumene in the Beecher Lode. Lepidolite is the only lithium product of the Bob Ingersoll No. 1 pegmatite. Known lepidolite reserves in the Black Hills are small, but potentialities have by no means been exhausted.

A significant proportion of the lithium reserves at the Etta, Tin Mountain, Beecher Lode, and Hugo can be recovered by handcobbing. Milling is necessary for most of the rest of the Black Hills lithium deposits.

CALIFORNIA

Searles Lake-Mohave area.—The principal source of the sodium and potassium salts and also of by-product lithium at Searles Lake, San Bernardino County, Calif., has been brine that fills interstices in a body of salt that reaches a maximum depth of about 90 feet. A second salt body occurs at greater depth. The Searles Lake deposits have been described in various reports (Gale, 1945; Dyer, 1950; Ryan, 1951).

Available published data are adequate for making only a tentative estimate of reserves of lithium obtainable by present methods at Searles Lake. The brine containing lithium probably can be pumped from an area of at least 20 square miles. The average thickness of the upper salt body is probably between 40 and 70 feet. The brine occupies a volume of between 25 and 50 percent of the salt body. Data from Mumford (1949, p. 513) and Gale (1945, p. 442-446) indicate that the grade is about 0.01 percent Li_2O ; more recently Ryan (1951, table 1, p. 449) has given the grade as 0.015 percent Li_2O . The specific gravity

of the brine is 1.30 (Dyer, 1950, p. 41). Calculations based on these figures indicate that the brine contains between 2,000,000 and 12,000,000 units of lithia. These calculations do not allow for transfers of lithium during reactions between the crystalline salts and the brine.

Another approach to the problem of estimating reserves may be made by use of Dyer's estimate (1950, p. 44) that 35,000,000 tons of sodium and potassium salts can be recovered by methods now in use. Data presented by Ryan (1951, p. 452) indicate a recovery of approximately 1 part of lithia for every 400 parts of sodium and potassium salts obtained. By applying this ratio to Dyer's figures, the reserves of lithia are estimated to be 9,000,000 units. This is the figure used in table 5.

Ryan (1951, p. 449) states that brine in the lower salt body has 0.006 percent Li_2O . Presumably, the evaporite beds also contain lithium. If lithium is ever recoverable from these sources, the reserves may be increased by tens of millions of units.

Clay at Hector, Calif., and possibly clays, saline deposits, and other deposits elsewhere in the Mohave area contain lithium, but no quantitative data are available.

Pala pegmatite district.—California also has lithium pegmatites in the Pala district, San Diego County. The Stewart pegmatite was at one time a significant source of lepidolite, and amblygonite was also produced. Production since 1928 has been meager, and evidently no substantial reserves are known (Jahns and Wright, 1951, p. 52-55).

ARIZONA, NEW MEXICO, COLORADO, WYOMING, AND NEW ENGLAND

Small lithium reserves in pegmatites are known in Arizona and New Mexico, and a few deposits are in Colorado, Wyoming, and New England.

Jahns (1952, p. 77) estimates reserves of at least 8,000 tons of spodumene and amblygonite in the White-Picacho district near Wickenburg, Ariz.

In New Mexico, the Harding mine in Taos County has long been known for lepidolite and spodumene, and the Pidlite mine in Mora County has been a source of lepidolite. Another important lepidolite source has been the Brown Derby mine in the Quartz Creek district, Gunnison County, Colo. (Staatz and Trites, 1955). Amblygonite and spodumene also occur in Colorado, but no substantial reserves of lithium are known in the state (Hanley and others, 1950, p. 14). Wyoming has pegmatites containing petalite, lepidolite, spodumene, and probably amblygonite, but no significant deposits have been reported.

Lithium minerals have been recognized in Maine, Massachusetts, and Connecticut (Cameron and others, 1954; Billings and Wolfe, 1944). Reserves are small.

CANADA

Canada has large reserves of spodumene and small reserves of other lithium minerals. R. B. Rowe, of the Geological Survey of Canada, has compiled data on Canadian deposits, and part of the results have been published (Rowe, 1953a, b).

The Cat Lake-Winnipeg River region of southeastern Manitoba probably has at least 2,000,000 units of lithia (L. R. Page, oral communication).

Three lithium-bearing pegmatities in the Preissac-LaCorne region, north of Val d'Or, Quebec, have been described by Derry (1950) and Rowe (1953b). These deposits contain reserves of at least a few hundred thousand units of lithia. More recently this district has been intensively explored, and reserves of several million units have been found (Anonymous, 1954, p. 1, 7, and 8).

Spodumene and other lithium minerals are also known in the East Braintree and Herb Lake districts of Manitoba and in the Yellowknife-Beaulieu region of the Northwest Territories (Rowe, 1953a, and Jolliffe, 1944).

FUTURE OF THE LITHIUM MINING INDUSTRY

The lithium mining industry has expanded about eight-fold in the period from 1947 through 1953. It is generally anticipated that the demand for lithium will continue to expand, perhaps even to 50 or 100 percent above the 1953 level within a few years. Reserve figures indicate that even greater expansion is possible without significant change in mining and milling methods or costs.

Spodumene is so much more abundant than the other lithium minerals that it will continue to be the chief raw material. Lepidolite mining in North America is not likely to be important unless new deposits are discovered, but lepidolite will doubtless be imported. Searles Lake, Calif., will continue to be a significant source of lithium. Possibly at some future time other saline deposits, sedimentary rocks, or other types of rocks may also become lithium sources.

Flotation milling for spodumene, as at Kings Mountain, N. C., and in the Black Hills, S. Dak., is firmly established in the industry. Nevertheless, a few deposits containing cobbable spodumene and amblygonite, notably in the Black Hills, will continue to furnish a part of the lithium supply.

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