UNITED STATES DEPARTMENT OF THE INTERIOR

GEOLOGICAL SURVEY

WHERE ON EARTH IS ALL THE LITHIUM?

By

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WITH A SECTION ON URANIUM ISOTOPE STUDIES

FISH LAKE VALLEY, NEVADA

By

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Open-File Report 80-1234

1980

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INTRODUCTION

A concern for future lithium supplies

Hubbert's (1956) forecast of a decline in United States petroleum production coupled with a shortage of gasoline in 1973 provided an important impetus to the search for alternate energy supplies to replace or conserve our dwindling sources of petroleum. Because of their high energy and their power potential per unit weight, lithium batteries are one choice to replace the internal combustion engine for vehicles whose principal use involves a limited daily range. Researchers at Argonne National Laboratory emphasized the significant savings in petroleum if as many as 18 million vehicles were operated with a lithium-sulfur battery by the year 2,000, (Chilenskas, Bernstein, and Ivins, 1976). An additional benefit to be realized by using electric vehicles in place of gasoline powered vehicles includes the reduction in emissions that could be achieved by producing electric power in a central power plant instead of burning gasoline in numerous automobiles. Because of its large power-storage capacity, the lithium battery is also a principal contender for the storage of off-peak power by power companies. Both of these applications (vehicles and power storage) could place large demands on a relatively small lithium industry. Hence, it was logical to question whether or not there will be enough lithium to supply such a vastly increased demand[2]. Moreover, if the use of lithium in batteries tends to exhaust our resources, the result could have a disastrous effect on the development of thermonuclear (fusion) power for the generation of electricity. The raw material for fusion power consists of deuterium, which occurs naturally in sea water, and tritium, which is produced from lithium by the following reaction: $^{6}\text{Li} + {}^{1}\text{n} \rightarrow {}^{3}\text{T} + {}^{4}\text{He}$. The Lithium Resource Appraisal Group of the U.S. Geological Survey was organized in 1974 in response to these questions

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[2] More recent estimates of the demand have been reduced, in part because other battery couples are expected to be on the market first.

Evolution of the lithium industry

The lithium industry has undergone a series of developmental changes marked by gradual shifts toward less labor-intensive technology. Prior to 1950 most lithium ore consisted of the hand sorted lithium minerals from zoned pegmatites, such as those in the Black Hills of South Dakota, (Page and others, 1953). Increased demand for lithium initiated by new uses during the war years (1941-45) and by a U.S. Atomic Energy Commission purchase program shortly thereafter, were met by the development of beneficiating techniques that made it possible to concentrate spodumene from unzoned pegmatites in which the average crystal size was less than 10 cm across, (Browning, 1958; McVay and Browning, 1962). Beginning in 1951, the Foote Mineral Company developed an unzoned pegmatite ore body near Kings Mountain, North Carolina, that consisted of a cluster of spodumene-bearing pegmatites--each greater than 15 m thick--that could be mined from a single open pit. In the mid-1960's a second ore body of the same type was developed by the Lithium Corporation of American, near Bessemer City, North Carolina, about 6 miles northeast of the Kings Mountain deposit. Meanwhile, a small amount of lithium was produced as a minor byproduct of the extraction of other chemicals from the Searles Lake, California, brine field. This lithium-recovery operation was terminated by Kerr McGee Chemical Company in 1978 after 40 years of production. In the early 1960's, with an increase in demand for lithium, Foote Mineral Company was faced with a need to construct a new facility for extraction of lithium from spodumene or to develop a lithium brine field that had been discovered by the Leprechaun Mining Company at Clayton Valley, near Silverpeak, Nevada. They chose to develop the brine field and produced their first harvest of lithium carbonate in 1967.

The simple technique of using a series of solar evaporating ponds to precipitate sodium chloride and to concentrate the lithium into a residual liquor from which lithium can be precipitated as the carbonate, provided an economic advantage over extraction of lithium from spodumene. The increase in demand for lithium during the 1970's caused another shift in company policy, when in 1978 the Foote Mineral Company placed new facilities into operation at Kings Mountain to extract lithium from spodumene. Among the factors considered, no doubt, were: (1) the brine operation was subject to climatic variations that could adversely influence the yield from one year to the next, and (2) several years' experience with the brine field were required before it became apparent from the hydrologic characteristics of the basin that the reserves were less, and the life of the deposit shorter, than was initially anticipated. Hence, any attempt to expand the capacity of the brine operation would have been unwise.

The Foote Mineral Company also negotiated with the government of Chile to evaluate the commercial potential of a large lithium- and potassium-rich brine field at Salar de Atacama in the desert area of northern Chile (Comer, 1978). This deposit could thus provide a major source for an expansion of lithium supplies. Among the other potential major lithium suppliers in the western world, two are of special importance because they could have an effect on the market in the short term. The large zoned pegmatite at Bikita in Zimbabwe (Rhodesia) was a major source for the mineral petalite prior to the 1965 United Nations sanctions against Rhodesia. The sanctions were removed in early 1980 making possible immediate shipment from the Rhodesian stockpile. Thus, the ore from this source could have an immediate impact on the industry. Similarly, ore from several mines in Canada could reach the market in a relatively short time.

By the close of the decade of the 1970's, the domestic lithium industry included two major companies, the Lithium Corporation of America, a wholly owned subsidiary of Gulf Resources Corporation of Houston, Texas, and the Foote Mineral Company, more than 90-percent owned by Newmont Mining Company of Danbury, Conn. Both are integrated companies, producing a full line of chemicals from their own ores. Major production of lithium ores outside of the United States includes the Bikita mine in Zimbabwe (Rhodesia), the Karibib-Omaruru area in South-West Africa, U.S.S.R., and China (Singleton, 1979). The zoned pegmatite at Bikita is mined by Bikita Minerals, Ltd, a subsidiary of Selection Trust, Ltd. of London, England. Both the American Metal Climax Company (Amax) and Kerr McGee Chemical Company have a partial interest in the Bikita property. Production from the main ore body included five major lithium minerals: petalite, spodumene, lepidolite, eucryptite, and minor amounts of amblygonite (Symons, 1961). Interruption of the petalite production by the U.N. sanctions was of special concern to the Corning Glass Company because of its use in the manufacture of "Corningware", a popular glass-ceramic used in cooking utensils and "glass-top" stoves. In order to provide a substitute for the low-iron petalite, the Foote Mineral Company developed a patented process for removing iron from spodumene.

Although several areas in Canada contain large reserves of lithium ore, most of the mining activity was closed down after termination of the U.S. Atomic Energy Commission lithium purchase contract in the early 1960's. Recently, the Quebec Lithium Division of Sullivan Mines, with pegmatite properties near Barraute in Quebec and the Tantalum Mining Corporation, Ltd., a subsidiary of Chemalloy Minerals, Ltd., affiliated with Kawecki-Berylco Industries, Inc. of Pottsdam, Penna. with pegmatite properties near Bernic Lake, Manitoba, have expressed interest in starting new production. Minor amounts of lithium ores have been produced in recent years from Argentina, Australia, Brazil, Mozambique, Mali, Portugal, and South Africa.

Metallgesellschaft AC of Langelsheim, West Germany, which produced the first commercial lithium chemicals from a lithium mica, zinnwaldite, about 50 years ago, is still a major producer of lithium chemicals, but relies entirely on imported ore. They are the only industrial producer of lithium compounds in Europe. Several Japanese companies, including Honjo Chemical Co. (an affiliate with Lithium Corporation of America), Japan Lithium Company (an affiliate with Foote Mineral Company), Japan Chemical Company, Askai Glass, and Nippon Chemical produce lithium chemicals from imported ores and chemicals.

DISPERSAL OF LITHIUM IN ANCIENT CRYSTALLINE ROCKS

Lithium may be regarded as a rare element because of its low average abundance in the Earth's upper crust, which has been estimated at about 20 ppm (Heier and Billings, 1972, p. 3-E-3). Other more familiar elements including gold and silver are far less abundant than lithium, but they possess physical and chemical properties that enable them to be concentrated by natural processes into readily recognized mineral deposits. The physical and chemical properties of lithium, some of which are listed in table 2, tend to disperse lithium ever more widely with each geologic cycle. As a result, most rocks contain traces of lithium but only rarely is lithium concentrated to the level at which it constitutes more than a few hundredths or tenths of a percent of any sizable body of rock.

The low abundance of lithium is in part, perhaps, more apparent than real when concentration is measured in weight percent because lithium has the lowest atomic weight of any elements except hydrogen and helium. Thus, in comparing lithium and potassium minerals of analogous composition, we find 3.7 weight-percent lithium in spodumene ($LiAlSi_2O_6$) but 17.9 weight-percent potassium in the analogous mineral, leucite ($KAlSi_2O_6$). Thus, a typical ore-grade lithium pegmatite containing 20 percent spodumene contains a maxiumum theoretical concentration of only 0.74 weight-percent lithium.

Table 2.--Physical and chemical properties of lithium

Lithium:	Group 1, the lightest alkali metal
Atomic number:	3
Atomic weight	6.94
Density:	0.534 g/cm^3
Isotope ratios:	^{6}Li 7.4; ^{7}Li 92.6; 1:12.5 = .08
Oxidation potential:	$\mathrm{Li} \rightarrow \mathrm{Li+}$, E = 3.045 volts
Reactivity:	Reacts with water less vigorously than sodium
Melting point:	180.5°C
Electron configuration:	2 (inner orbit), 1 (outer orbit)
Thermonuclear reaction:	$^{6}\mathrm{Li} + {}^{1}\mathrm{n} \rightarrow {}^{3}\mathrm{T} + {}^{4}\mathrm{He}$
Geochemical classification:	Lithophile
Average abundance in common materials (ppm):	Pelagic clay 57, shales 66, sandstones 15, carbonates 5, basalt 17, granite 40, seawater 0.17

Soluble salts of lithium with Cl, Br, and I are hygroscopic to deliquescent and have low vapor pressure.

Compounds of low solubility include the carbonate, phosphate and fluoride.

Lithium metal has high specific heat of 0.8 cal/gr/°C.

Ionic radius of 0.68Å is too small to substitute to any significant extent for Na or K in common rock minerals.

Geochemical behavior dominated by high solubility and resultant concentration in residual magmatic fluids and in residual bitterns during evaporative concentration.

Discrete lithium minerals form only after compositional requirements for common rock minerals such as feldspars, carbonates, sulfates and halides are nearly exhausted.

In exchange reactions, relative bonding force is generally: Cs+ > Rb+ > K+ > Na+ > Li, whereas the exchange capacity is the reverse.

About 40 lithium minerals have been named and described and several of these are intermediate members of an isomorphic series, as shown in table 3. Silicates and phosphates are the most numerous and also the most common, although halides and borates are also known. Most of these minerals have been identified in the very latest stage of crystallization of igneous rocks, especially pegmatites and greisen, which form the residual fluids of a magma after crystallization of nearly all of the common rock minerals such as quartz, feldspar, and mica (Jahns, 1979). Because the lithium ion is too small to substitute to any significant extent for sodium or potassium in these common minerals, the lithium becomes concentrated in the residual fluids to the extent required to form discrete lithium minerals such as spodumene.

Zoned pegmatites typical of the Hill City district in the Black Hills of South Dakota are noteworthy both for their characteristic large crystal size and also for the zonal arrangement of crystal aggregates peripheral to a central core that is typically massive quartz. Most of these pegmatites are small pod-shaped or lenticular bodies that have no continuity at depth although dikelike pagmatites are common in some other districts. Individual pegmatites generally range in size from very small bodies to a few thousand or to a few hundred thousand tons of rock. Lithium-bearing minerals recoverable by hand sorting or beneficiating techniques generally range from a few hundred to a few thousand tons of ore-grade materal in any single pegmatite. Larger bodies are quite rare (Norton, 1975).

Unzoned pegmatites differ from zoned pagmatites not only in being more uniform in mineral composition, but they are more likely to be large dikelike bodies. The North Carolina spodumene belt contains numerous unzoned lithium pegmatites in an area 50 km long and less than 3 km wide (Kesler, 1976). Individual bodies as much as 90 m wide and 1000 m long have been mapped, but there are many small dikes that could not be economically mined. The Foote Mineral Company's ore body at Kings Mountain consists of a cluster of eight nearly vertical pegmatite dikes that can be mined from a single open pit. The only other recognized ore body in the district is the one operated by Lithium Corporation of America, near Bessemer City. If other ore bodies exist in the district they have not been reported as identified or outlined by drilling.

Many of the known lithium pegmatites throughout the world occur in Precambrian "shield" areas, which comprise the core of continental land masses

Table 3.--Lithium-bearing minerals

(Compiled from Roberts, Rapps, and Webber (1974) except as noted.)

	Name and formula	Mineral group or series	Mode of occurrence: Veins	Pegmatite	Altered pegmatite	Greissen	Manganese ore	Igneous (nonpegmatite)	Sedimentary
1	Amblygonite $(Li,Na)AlPO_4(F,OH)$	amblygonite		X					
2	Bertossaite $(Li,Na)_2(Ca,Fe,Mn)Al_4(PO_4)_4(OH,F)_4$	--		X					
3	Bikitaite $LiAlSi_2O_6 \cdot H_2O$	zeolite (?)			X				
4	Bityite $Ca(Al,Li)_2[(Al,Be)_2Si_2(O,OH)_{10}] \cdot H_2O$	margarite		X					
5	Brannockite $KLi_3Sn_2Si_{12}O_{30}$	--			X				
6	Cookeite $(Li,Al_4)Si_3AlO_{10}(OH)_8$	chlorite	X	X					X
7	Cryolithionite $Li_3Na_3Al_2F_{12}$	--		X					
8	Eckermannite $Na_3(Mg,Li)_4(Al,Fe)Si_8O_{22}(OH,F)_2$	amphibole (asbestos)						X	
9	Elbaite $Na(Li,Al)_3Al_6B_3Si_6O_{27}(OH,F)_4$	tourmaline		X					
10	Ephesite $Na(LiAl_2)(Al_2Si_2)O_{10}(OH)_2$	margarite					X		
11	*Eucryptite $LiAlSiO_4$	--		X					
12	Ferghanite $LiH(UO_2/OH)_4(VO_4)_2 \cdot 2H_2O$	--							X
13	Ferri-sicklerite $(Li,Fe^{3+},Mn^{2+})PO_4$	sicklerite			X				
14	Gerstleyite $(Na,Li)_4As_2Sb_8S_{17} \cdot 6H_2O$	--							X
15	*Hectorite $Na_{0.33}(Mg,Li)_3Si_4O_{10}(F,OH)_2$	smectite							X
16	Holmquistite $Li_2(Mg,Fe^{2+})_3(Al,Fe^{3+})_2Si_8O_{22}(OH)_2$	amphibole		X					
17	Hsianghualite $Ca_3Li_2Be_3(SiO_4)_3F_2$	--	X						
18	*Lepidolite $K(Li,Al)_3(Si,Al)_4O_{10}(F,OH)_2$	mica	X	X				X	
19	Liberite Li_2BeSiO_4	--	X						
20	Lithiophilite $Li(Mn^{2+},Fe^{2+})PO_4$	lithiophilite-triphylite		X					
21	Lithiophorite $(Al,Li)MnO_2(OH)_2$	--					X		
22	Lithiophosphate Li_3PO_4	--		X					
23	Manandonite $LiAl_4(AlBSi_2O_{10})(OH)_3$	chlorite		X					
24	Montebrasite $(Li,Na)Al(PO_4)(OH,F)$	amblygonite		X					

Table 3.--Lithium-bearing minerals.--Continued.

			Mode of occurrence						
	Name and formula	Mineral group or series	Veins	Pegmatite	Altered pegmatite	Greissen	Manganese ore	Igneous (nonpegmatite)	Sedimentary
25	Nambulite [5] $LiNaMn_8Si_{10}O_{28}(OH)_2$	--	X						
26	Natromontebrasite $(Na,Li)Al(PO_4)(OH,F)$	amblygonite		X					
27	Palermoite $(Li,Na)_2(Sr,Ca)Al_4(PO_4)_4(OH)_4$			X					
28	*Petalite $LiAlSi_4O_{10}$	--		X					
29	Polylithionite $KLi_2Al(Si_4O_{10})(F,OH)_2$	mica	X						
30	Rankamaite $(Na,K,Pb,Li)_3(Ta,Nb,Al)_{11}(O,OH)_{30}$	--							X [1]
	Regularly interstratified montmorillonite-chlorite	--	X						
31	Sicklerite $Li(Mn^{2+},Fe^{3+})PO_4$	--			X				
32	Sogdianite $(K,Na)_2Li_2(Li,Fe,Al,Ti)_2Zr_2(Si_2O_5)_6$	--	X						
33	*Spodumene $LiAlSi_2O_6$	pyroxene		X					
34	Swinefordite [2]	smectite			X				
35	Taeniolite $KLiMg_2Si_4O_{10}F_2$	mica						X	
36	Tavorite $LiFe^{3+}PO_4OH$	--			X				
37	Tosudite [3]	--			X				
38	Triphylite $Li(Fe^{2+},Mn^{2+})PO_4$	triphylite-lithiophilite		X					
39	Virgilite [4]	--						X	
40	*Zinnwaldite $K(Li,Al,Fe)_3(Al,Si)_4O_{10}(OH,F)_2$	mica	X	X		X			

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*An asterisk preceeding the mineral name indicates a mineral that has been used by industry as a source of lithium or for some special physical or chemical property.

[1] Occurs in the heavy-mineral fraction of alluvial sediment.

[2] As described by Tien, Leavins, and Nelen (1975), the structural formula is $(Si_{7.66}Al_{0.34})(Al_{1.97}Fe^{3+}_{0.15}Fe^{2+}_{0.09}Mg_{1.31}Li_{1.76})O_{20}(F_{0.65})H_{3.35})Ca_{0.23}Mg_{0.05}Na_{0.11}Li_{0.72}K_{0.04}$.

[3] As described by Nishiyama, Shimoda, Shimosaka and Kanaoka (1975), the formula for the interlayer cations $K_{0.16}Na_{0.09}Ca_{0.13}+9.6H_2O$; gibbsite sheet $Li_{1.36}Mg_{0.14}Fe_{0.45}Al_{3.59}(OH)_{12.00}$; silicate layer $Al_{8.00}(Si_{13.60}Al_{2.40})O_{40.00}(OH)_{8.00}$.

[4] As described by French, Jezek, and Appleman (1978), the cell content is $Li_{0.61}(Si_{2.37}Al_{0.60}Fe_{0.02}P_{0.01})O_6$ and is a representative of the solid-solution series between beta-quartz and spodumene with a stuffed beta-quartz structure corresponding to the composition $So_{61}Qz_{39}$.

[5] Yoshii, Aoki, and Maeda (1972).

and are more than 600 million years old. Examples include lithium pegmatities in the Quebec, Manitoba, and Yellowknife areas of Canada, Bikita in Zimbabwe, and others in Zaire, Australia, and Brazil. The pegmatites in the Black Hills of South Dakota occur in rocks of the same age that have been exposed by local uplift. One explanation for the recognition of these lithium pegmatites in ancient rocks is that such pegmatites form only under conditions of high temperature and pressure, thus at great depth, and these are the areas where once deeply buried rocks have been exposed by uplift and erosion. An exception to the ancient age for pegmatites is the North Carolina spodumene belt, which is related in age and origin to the Cherryville Quartz Monzonite, estimated to be of middle or late Paleozoic age, perhaps 260-375 m. y. old (Kesler, 1976), Unlike Canada, the United States has only limited areas of Precambrian rocks at the surface, and this limits significantly the chances for finding more deposits of this type within the United States.

DISPERSAL OF LITHIUM IN SEDIMENTARY ROCKS, SEDIMENTS, AND WATERS

Although the distribution of lithium and lithium-bearing minerals in ancient rocks is mostly a function of geochemical processes that take place at elevated temperatures and pressures, the distribution of lithium in younger rocks and sediments is commonly a function of low-temperature geochemistry associated with weathering, sedimentation, and diagenesis. During weathering and deposition of normal marine, brackish water, and freshwater sediments, lithium tends to become widely dispersed in the clay-mineral fraction of the rocks (Horstmann, 1957; Tardy, Krempp, and Trauth, 1972). Lithium concentrations of 20-100 ppm are relatively common in shaly rocks and these contrast markedly with lithium values of less than 20 ppm in most limestones and sandstones unless they are also shaly.

Evaporite sequences in hypersaline basins would appear to provide the best opportunity for finding abnormally high concentrations of lithium. However, because lithium chloride is so hygroscopic and even more soluble than sodium or potassium, and because the lithium ion is too small to substitute to any significant extent for these other alkali elements in carbonate, sulfate and halide minerals, most evaporites are extremely low in lithium. In this respect lithium does not follow bromine, which shows a pronounced substitution in halite crystals as the potassium chloride (sylvite) stage of precipitation is approached. Moreover, the average lithium content of seawater is only about 0.17 ppm and the ratios Li:Na and Li:K are quite low so that the concentration of lithium in the residual bittern after precipitation of KCl is only about 27 ppm, according to Collins (1975, p. 134). Thus, the occurrence of some oil-field formation waters associated with marine evaporites that contain as much as 50-500 ppm Li (Collins, 1976) requires a special explanation to account for the evolution of chemical changes in the brine over a long period of time.

Although the lithium content of freshwaters may be only a few tens of parts per billion, the ratio Li:Cl is generally higher than that for seawater (Li:Cl = 0.00001), and so nonmarine evaporites commonly have higher concentrations of lithium than do marine evaporites. The highest ratios of Li:Cl tend to occur in neutral or slightly alkaline hot-spring waters associated with silicic volcanic rocks typified by the geyser fields in Yellowstone National Park where ratios of Li:Cl may reach as much as 0.01 (White, Thompson, and Fournier, 1976). If waters from such a source were concentrated by evaporation to the stage at which sodium chloride was precipitated, the residual brines could contain high concentrations of lithium. Thus, closed desert basins or playa deposits in volcanic terrain should provide the most favorable setting in which to find lithium-rich brines or lithium-bearing sediments. Terminal lakes such as Great Salt Lake, Pyramid Lake, Mono Lake, and Abert Lake, and the numerous dry lakes or playas that occur throughout the Great Basin provide natural geochemical laboratories in which to study the processes by which lithium is concentrated and partitioned between aqueous and solid phases. Ancient lake sediments such as the Green River Formation of Eocene age and the numerous smaller and less well known lake deposits of Tertiary age throughout many basins in the Rocky Mountain and Great Basin states are also logical places to search for lithium.

Areas of immediate special interest include the Clayton Valley, Nevada, the lithium brine field described by Kunasz (1970), the type locality for hectorite in the Mojave Desert of California as described by Ames, Sand, and Goldich (1958), another lithium-clay deposit in central Arizona described by Norton (1965), the Spor Mountain lithium-clay deposit in western Utah described by Shawe, Mountjoy, and Duke (1964), the lithium-bearing smectites of the Amargosa drainage described by Sheppard and Gude (1968) and by Starkey and Blackmon (1979), and the lithium-bearing magnesite from southern Nevada described by Hewitt and others (1936, p. 124). One additional area was revealed by a search of the U.S. Geological Survey's computerized analytical data files. This was an area of Tertiary lake beds near Jackson, Wyoming, that had been examined and sampled by J. D. Love (written communication, 1974).

DEFINING THE PROBLEM

In the summer of 1974, the U. S. Geological Survey began to examine numerous areas of ancient and modern lake deposits with emphasis on those known to contain evaporites in an effort to locate and define areas of anomalous lithium concentration worthy of more detailed investigations. This broad approach was required if we were to learn how to distinguish normal from anomalous concentrations of lithium and to gain some appreciation for the distribution and extent of anomalous concentrations of lithium and of the sedimentary environments favorable for their occurrence.

The results of some of these reconnaissance investigations are summarized in a series of U.S. Geological Survey Open-file reports: Bohannon and Meier (1976a), California; (1976b), Nevada; Brenner-Tourtelot, Meier, and Curtis (1978), Montana; Brenner-Tourtelot and Machette (1979), New Mexico; Davis and Meier (1976a), Arizona; Davis and Meier (1976b), Oregon; Glanzman and Meier (1979), Utah and Idaho; Smith, Meier, and Downey (1977), Nevada; and E. B. Tourtelot and Meier (1976a), Rocky Mountain states. Studies of specific areas or topics were published on more formal maps and reports: Bohannon (1976b), Muddy Mountain area, Nevada; (1977a) Valley of Fire, Nevada; (1977b) White Basin, Nevada; Brenner-Tourtelot and Glanzman (1978) Horse Spring Formation; Brenner-Tourtelot (1979) Frenchman Mountain and Henderson Quadrangles; Davis (1976) Basin and Range drainage areas; Davis and Vine (1979), Clayton Valley; Ericksen, Chong, and Vila, (1976) Andean salars; Ericksen, Vine, and Ballon (1978) Salar de Uyuni, Bolivia; Glanzman and Meier (1976), brine in Utah; C. L. Smith (1976), geochemical exploration; G. I. Smith (1976), Searles Lake chemistry; E. B. Tourtelot, and Meier (1976b), Gila Conglomerate, N. Mex.; H. A. Tourtelot and Meier (1976), Pennsylvanian age shales; Tourtelot, and Brenner-Tourtelot (1978) flint clays; Vine, (1976b) potential resources; Vine, and Brenner-Tourtelot (1977), progress of Li investigations. Among the above-mentioned contributors are several U.S. Geological Survey colleagues (G. E. Ericksen, H. A. Tourtelot, and G. I. Smith) not assigned to the lithium program but interested in its progress.

A symposium entitled: "Lithium resources and requirements by the year 2000" held in January, 1976, and a second one in October, 1977, helped to focus discussion on the lithium industry, and to the uses, geologic occurrence, and resources of lithium. Papers from the first symposium were published in U.S. Geological Survey Professional Paper 1005 and those from the second symposium were published in a special volume of Energy (Pergamon Press) v. 3, no. 3, 1978. Some of the references in the previous paragraph are to articles in these two volumes.

The results of lithium analyses of playa-surface sediments in the southwestern United States were generally inconclusive. In his study of the influence of drainage area on the distribution of lithium in playa sediments, Davis (1976) defined an anomalous concentration as approximately 300 ppm or more lithium, ($\mu + 2\sigma$). Using this definition, only four valleys (Amargosa River, Death Valley, Fish Lake Valley, and Long Valley) of the 41 included in the study yielded samples that could be classed as anomalous. Although problems of access could have limited the opportunity to collect the best samples in some instances, it is also probably true that many playas simply do not have anomalous concentrations of lithium at the surface. Even some of the playas such as Searles Lake and Great Salt Lake Desert that are known to have anomalous concentrations of lithium in subsurface brines might not be identified as anomalous by analysis of a few surface-sediment samples. Sediments at the surface of Clayton Valley playa were anomalous locally prior to the construction of roads, evaporating ponds and related mining facilities but sediments along the margins and in the southern part of the valley are not anomalous even today in spite of the chances for contamination by windblown dust.

In the course of evaporation of a lake to dryness, and the subsequent lowering of the water table below the sediment surface, any concentration of lithium in the waters is apparently leached from the surface sediment without leaving a significant trace. Common surface clays, carbonates, sulfates and chlorides do not necessarily retain enough lithium to show an anomaly. Stable lithium clays or other lithium minerals probably form only under special conditions not generally found at the surface of the playa.

Playa sediments tend to be highly variable in texture and mineral composition from one basin to the next but most basins show a decrease in the size of clasts in the detrital fraction from basin margin toward the depositional center of the basin. Although sand dunes and other eolian material may disrupt this pattern, the finer fraction of the playa sediments form a series of sediment zones ranging from silts at the margin to clays, carbonates, sulfates and chlorides at the center. The evaporite minerals are of greatest interest in searching for lithium anomalies because this zone is where the most concentrated brines are generated. Where the playa surface is moist, access to some of these zones may be difficult or even impossible. The clay and sulfate zones are especially difficult to cross in a vehicle or on foot as the surface can remain soft and puffy even during prolonged dry periods. The chloride zone tends to be more firm but can range from a smooth, flat surface typical of Salar de Uyuni in Bolivia to rough, broken salt crusts and uptilted edges of salt polygons exemplified by the Devils Golf Course in Death Valley.

The limitations of access largely dictated how and where surface samples were collected on nearly all but the few playas that are characterized by hard dry silt. Rogers Dry Lake in the western Mojave Desert of California is of value to the Edwards Air Force Base as a flight test center precisely because it has a characteristic hard dry surface. In a general way, however, the playas that have the most difficult problems of access are the ones of greatest interest for lithium because they do provide the most variety of sediment zones suitable for sampling. A large dry surface playa such as Rogers Dry Lake offers little or no indication of what underlies the surface and no way of defining a target suitable for drilling. In these areas, geophysical data such as seismic, gravity, or resistivity may be of great help in locating suitable drilling targets (Smith and Mabey, 1976).

THE SEARCH FOR LITHIUM IN UNCONVENTIONAL DEPOSITS

Focus on Cenozoic basins, volcanic activity, and thermal systems in the western United States

Although the reconnaissance search for lithium anomalies in surficial materials, including weathered rocks and sediments, was disappointing it provided the much-needed basis to narrow the search to specific geographic and geologic environments. Clearly, lithium is a mobile element in the geochemical sense. Lithium alumino-silicate minerals such as spodumene, although stable below the zone of weathering, break down in weathering and are readily altered to kaolin with an accompanying loss of lithium to solution. Similarly, in common rocks the lithium that is dispersed in the 1-100 ppm range is also lost during weathering and is carried by streams out to sea to be dispersed once more in marine clays and related fine-grained rocks. Unlike potassium, which may become fixed on illite during burial metamorphism of marine strata, lithium may be remobilized at the elevated temperatures of deeply buried sediments. Thus, the quartz-cookeite veins of Arkansas (Stone and Milton, 1976) may be the product of this kind of burial metamorphism, but there is no evidence that they form bodies of sufficient size to be of any economic significance as lithium ore. Hence, with the exceptions of certain brines associated with marine evaporites, and of rare high-alumina clays in Missouri, there is little reason to search for significant concentrations of lithium in the predominantly marine and near-marine sedimentary rock sequences that occur throughout most of the central and eastern United States. Moreover, this same area characteristically receives sufficient rain and snow to maintain through-flowing streams so that any lithium released by weathering or brought to the surface by hot springs will be carried out to sea with little chance for concentration, precipitation, or entrapment.

The climate and the geology of the western United States combine to provide optimal conditions for lithium concentration, precipitation, and entrapment. Evaporation exceeds rainfall throughout large parts of the inland West and this situation has apparently persisted for long periods of time. Tectonic forces have repeatedly broken the western landscape into mountain ranges and basins, and many of these basins have accumulated thick sequences of nonmarine sediments, including lacustrine and evaporite facies in which lithium could be concentrated, precipitated, or entrapped. Furthermore, the breaking up of the landscape into mountains and basins was accompanied by outpouring of volcanic material and establishment of geothermal areas. The volcanic material is important because it provides vast quantities of chemically reactive glassy material, whose alteration to secondary minerals profoundly influenced the chemistry of the waters and sediments that accumulated in the basins. The geothermal areas are important because lithium is remobilized in the geothermal environment (Dibble and Dickson, 1976) and may be recycled into the streams and playas by hydrothermal activity, including hot springs and geysers such as in the Yellowstone National Park area (White, Thompson, and Fournier, 1976).

Drilling for geochemical background data in Clayton Valley, Nevada

The only clearly satisfactory way to search for and to identify lithium deposits in sedimentary rocks or in the brines that might accompany buried evaporite sequences is by drilling. However, because the funds appropriated to the U.S. Geological Survey are heavily committed to regular program activities, there is virtually no opportunity to include contract drilling in the normal budgetary process. Funding for drilling was sought from the U.S. Department of Energy or DOE (formerly U.S. Energy Research and Development Administration). The DOE Division of Electrochemical Storage and Division of Uranium Resources and Enrichment jointly supported the lithium-exploration drilling program of the U.S. Geological Survey for the fiscal years 1977, 1978, and 1979. Drilling sites were selected, first to obtain background information about the known lithium brine field at Clayton Valley, Nevada; second, to test nearby valleys; third, to test similar geologic settings elsewhere; and fourth, to test hypotheses for the occurrence of lithium brines.

Clayton Valley was drilled first to gain experience with the reverse-circulation rotary drilling technique and to learn what to expect in the way of sediment mineralogy and geochemistry that might be different in a lithium brine field than in nonlithium-bearing playa sediments. A series of drill sites were selected in Clayton Valley that were peripheral to the area of known lithium brine. The exact locations were chosen with the permission and assistance of Foote Mineral Company personnel under an agreement by which Foote Mineral Company would have access to data for about 2 years prior to publication. A brief description of the drill sites is included in a more general discussion of the origin of the lithium brines of Clayton Valley in Davis and Vine (1979), and additional descriptive material was provided by J. R. Davis (written communication 1980).

Although the brine-saturated sediments of Clayton Valley are thought to be less than 2 million years old (Davis and Vine, 1979), a significant amount of mineralogical alteration has taken place, especially in the finer grained sediments, which are derived chiefly from volcanic glass or pumice. The alteration consists chiefly of devitrification of glassy shards and formation of such authigenic minerals as opal, cristobalite, phillipsite, nontronite, and hectorite. The lithium clay is, thus, just one of several authigenic minerals formed by rock-water interaction and this process is regarded as an important clue as to its origin. Elsewhere, near Jackson, Wyoming, on the Oregon side of the McDermitt caldera, and in parts of the Lake Mead, Nevada, area, lithium clays related to hectorite have been recognized that are interbedded with unaltered pumice, or that are interlaminated with such evaporite minerals as dolomite, celestite, and halite so as to suggest that they formed by direct chemical precipitation from brine.

It may be noted here that Kunasz (1974) suggested a detrital origin for the hectorite at Clayton Valley because of the occurrence of older hectorite-bearing rocks in nearby outcrops of the Esmeralda Formation of Miocene and Pliocene age. Although this possibility may account for some of the hectorite in the valley sediment, the property of hectorite to form a colloidal suspension in water makes hectorite an unlikely candidate for its later concentration as a detrital mineral. Hectorite more likely would be uniformly dispersed throughout the sediments rather than being concentrated in individual beds containing as much as 1,700 ppm Li such as were encountered in drilling.

Although lithium-rich brines and hectorite-bearing altered sediments occur together at Clayton Valley, such brines could easily be separated from the altered sediment in older basins where there has been uplilft and removal of the original connate brines. Alternatively, the rock-water interaction could eventually deplete the mineralizing solution of most of its lithium. Thus, the occurrence of a lithium-rich brine in association with lithium-bearing sediment may be attributed in part to the fact that the deposit is young and in part to some unknown factor that has limited the degree of rock-water interaction. This limit could be an insufficient supply of one of the other constituents required to form hectorite. An example could be the amount of fluorine, as the formation of hectorite requires nearly 10 times as much fluorine as lithium, whereas the brine contains more lithium than fluorine.

Playa deposits of Southwestern Nevada

The Nevada portion of the Great Basin is characterized by north-south trending mountain blocks separated by deep basins that are partly filled with alluvial sediments. Many of these basins include a dry lake or playa at the lowest part of the modern valley. Pyramid Lake and Walker Lake are modern terminal lakes, which are remnants of formerly much larger lakes whose high strand lines can be readily observed at elevations as much as 100 m above the present lake levels. These high strand lines have been correlated with the last glacial stage of the Pleistocene (Meinzer, 1917), roughly 11,000 to 25,000 years ago. Because the lithium at Clayton Valley occurs in a subsurface brine, which is the remnant of a former lake, the subsurface brines, waters, and clays of adjacent valleys that have had a similar geologic history should be tested to see if they are also rich in lithium. (See figure 1 and table 4). Alternatively, these adjacent valleys, which are topographically higher than Clayton Valley (elevation 4,270 feet, or 1,301 m) may contribute ground water to Clayton Valley through subsurface flow (Rush, 1968). Former surface flow has been ruled out because the high strand lines are always below the present-day surface divide.

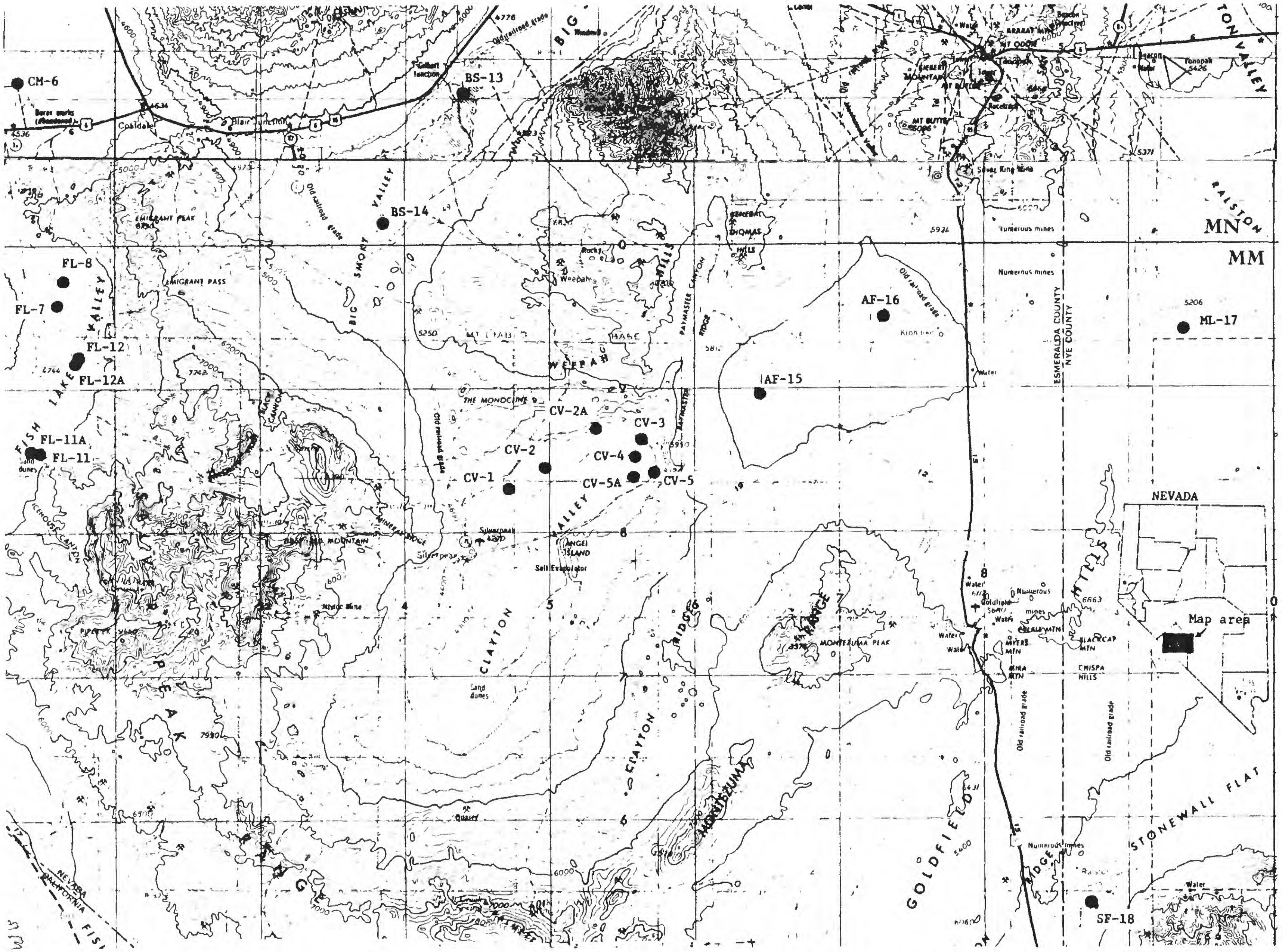


Figure 1.--Index map of a part of Esmeralda and Nye Counties, Nevada, showing location of drill sites. Base reduced about 30 percent from U.S. Geological Survey Goldfield (1954) and Tonopah (1956) quadrangles, 1:250,000.

Table 4.--Drilling sites, total depths, and maximum lithium content of samples from wells drilled

Well number	Latitude	Longitude	Elevation at surface		Total depth penetrated		Maximum lithium content (ppm)		Comments
			(ft)	(m)	(ft)	(m)	Water	Sediment	
Clayton Valley, Esmeralda County, Nevada									
CV-1	37°47'N.	117°35'W.	4,273	1,302.4	395	120.4	60	310	Gravel below 300 feet.
CV-2	37°48'N.	117°34'W.	4,275	1,303.0	395	120.4	55	930	
CV-2A	37°50'N.	117°31'W.	4,280	1,304.5	275	83.8	100	390	Gravel below 235 feet; bottom hole temp. 44°C.
CV-3	37°49'N.	117°30'W.	4,279	1,304.2	615	187.5	160	640	Maximum 33°C at 415 feet.
CV-4	37°49'N.	117°30'W.	4,270	1,301.5	795	242.3	190	1,700	
CV-5	37°48'N.	117°29'W.	4,270	1,301.5	480	146.3	110	770	Mostly in gravels.
CV-5A	37°48'N.	117°30'W.	4,270	1,301.5	735	224.0	640	960	Penetrated thick sequence of salt beds.
Columbus Marsh, Esmeralda County, Nevada									
CM-6	38°02'N.	117°59'W.	4,521	1,378.0	475	144.8	4	500	Mostly loose sand.
Fish Lake Playa, Esmeralda County, Nevada									
FL-7	37°54'N.	117°57'W.	4,705	1,434.1	455	138.7	7	360	Tuff altered to cristobalite and clinoptilolite; bottom-hole temp. 93°C.
FL-8	37°55'N.	117°57'W.	4,690	1,429.5	375	114.3	13	140	Tuff, altered as in FL-7.

Table 4.--Drilling sites, total depths, and maximum lithium content of samples from wells drilled.--Continued

Well number	Latitude	Longitude	Elevation at surface (ft)	Elevation at surface (m)	Total depth penetrated (ft)	Total depth penetrated (m)	Maximum lithium content (ppm) Water	Maximum lithium content (ppm) Sediment	Comments
				Wilcox Playa, Cochise County, Arizona					
WP-9	32°10'N.	109°53'W.	4,136	1,250.7	1,035	315.5	0.88	650	Maximum lithium in greenish clays, upper third of hole.
				Red Lake Playa, Mohave County, Arizona					
RL-10	35°41'N.	114°01'W.	2,758	840.6	1,510	460.2	13.8	170	Bottomed in freshwater-bearing gravel.
				Fish Lake Valley, Esmeralda County, Nevada					
FL-11	37°49'N.	117°58'W.	4,712	1,436.2	355	108.2	0.03	92	
FL-11A	37°49'N.	117°58'W.	4,710	1,435.6	475	144.8	21	115	Anomalous uranium and lithium in water.
FL-12	37°52'N.	117°56'W.	4,700	1,432.6	155	47.2	5.7	240	Terminated because of difficult drilling.
FL-12A	37°52'N.	117°56'W.	4,702	1,433.2	320	97.5	0.89	409	Do.
				Big Smoky Valley, Esmeralda County, Nevada					
BS-13	38°02'N.	117°37'W.	4,735	1,443.2	675	205.7	1.7	364	Penetrated alluvial fill and 20 feet into underlying older rock.

Table 4.--Drilling sites, total depths, and maximum lithium content of samples from wells drilled.--Continued

Well number	Latitude	Longitude	Elevation at surface (ft)	Elevation at surface (m)	Total depth penetrated (ft)	Total depth penetrated (m)	Maximum lithium content (ppm) Water	Maximum lithium content (ppm) Sediment	Comments
Big Smoky Valley, Esmeralda County, Nevada									
BS-14	37°57'N.	117°42'W.	4,760	1,450.8	215	65.5	1.3	287	Terminated because of difficult drilling.
Alkali Valley, Esmeralda County, Nevada									
AF-15	37°51'N.	117°24'W.	4,805	1,464.6	675	205.7	0.38	727	Penetrated alluvial fill and into volcanic ash.
AF-16	37°54'N.	117°18'W.	4,845	1,476.8	515	157.0	.49	240	Penetrated mostly gravels.
Mud Lake, Nye County, Nevada									
ML-17	37°54'N.	117°04'W.	5,195	1,583.4	275	83.8	No Sample	75	Terminated because of difficult drilling.
Stonewall Flat, Nye County, Nevada									
SF-18	37°32'N.	117°08'W.	4,720	1,438.7	475	114.3	0.16	121	Penetrated alluvial fill and into altered tuff.

Fish Lake Valley

Fish Lake Valley is a north-south elongate valley located some 25 miles (40 km) to the west of Clayton Valley from which it is separated by the Silver Peak Range. Fish Lake Valley includes a wet playa whose geologic setting (Robinson and others, 1976) is comparable in many respects to that of Clayton Valley. Both valleys have been influenced by the late Tertiary history of volcanic activity in the intervening Silver Peak Range. A shallow, surface brine pool at the northern outlet of Fish Lake Valley Playa where it empties into Columbus Salt Marsh was reported by Smith, Meier, and Downey (1977) to contain as much as 350 mg/L Li at the time of their examination in the autumn of 1976.

Two sites near the north end of Fish Lake Valley Playa were selected and drilled in the summer of 1977, as shown on figure 1. Drill site FL-7 on the northwest edge of the playa was located on a resistivity anomaly reported by Bruce Smith (oral commun., Sept., 1977). Drill site FL-8 near the north outlet of the playa was selected as near as practical to the site of the anomalous lithium concentration at the surface brine pool. Both sites were located as near to the edge of the moist lake sediments as possible without incurring undue risk of foundering the drilling equipment. Both holes penetrated volcanic ash, tuff, and reworked volcanic sandstone similar to the rocks exposed in the surrounding mountain ranges. No playa deposits or saline minerals such as those that underlie Clayton Valley were found. Clearly, this northern end of the valley is not underlain by playa sediments beyond the present playa margin. Because of the evidence for subsurface drainage northward from Fish Lake Valley toward Columbus Salt Marsh (Rush and others, 1971) water samples from these two holes probably are similar to those in the playa sediments. Thus, the average 6 mg/L Li that was found in the water samples from these holes may be close to that in the playa subsurface. Sediment samples averaged 89 ppm Li in FL-7 and 57 ppm Li in FL-8 with high values of 360 ppm Li and 170 ppm Li, respectively.

A high geothermal gradient was found at drill site FL-7, which reached a maximum bottom-hole temperature of 93°C at a depth of about 455 feet (139 m). The elevated temperature rather than a high concentration of soluble ions apparently accounts for the anomalous resistivity at this site.

Two additional sites were drilled in Fish Lake Valley during the summer of 1979. Site FL-11, located about 3 miles south of the playa and site FL-12, located near the south edge of the playa were chosen in an attempt to penetrate the alluvial valley sediments. The original site FL-11 was abandoned after drilling 215 feet because of a drilling problem and an alternate site FL-11A half a mile farther west was completed to a depth of 455 feet. Water samples from FL-11A are of special interest because of high values for both uranium and lithium (Asher-Bolinder, Vine, Glanzman, and Davis, 1980). Water samples collected at 55, 115, 335, and 435 feet (17, 35, 102, and 133 m) contained 0.336, 0.380, 0.150, and 0.186 ppm U and 21, 4.5, 0.94, and 0.16 ppm Li, respectively. The uranium values compare with an average of about 0.025 ppm for other playa samples collected during this same drilling program. The maximum value of 0.380 ppm U is thus about 15 times the average, suggesting that this may be an area worthy of further search for uranium.

Site FL-12 was abandoned at a depth of 155 feet (47 m) and alternate site FL-12A, 30 feet (10 m) away completed to a depth of 320 feet (98 m) in gravel and loose sand before terminating because of difficulty in drilling.

The maximum lithium value of 21 ppm in a water sample from Fish Lake Valley is of academic interest, but when combined with the Li-Cl ratio of 0.0027, it indicates an anomalous water that could evolve into a potentially economic lithium brine similar to that in Clayton Valley through evaporative concentration to the saturation point for sodium chloride. These water samples are of further interest, however, because the occurrence of high lithium is stratigraphically above the occurrence of high uranium. This is a relationship observed in ore deposits of uranium and lithium in the McDermitt area of Nevada and the Date Creek area of Arizona (Glanzman, Rytuba and Otton, 1979). The Fish Lake Valley water samples thus confirm a general principal of mineral zonation with respect to uranium and lithium occurrences in volcaniclastic sediments of lacustrine origin. The association of these two elements in a consistent pattern can be of considerable significance in geochemical prospecting for either element.

Fish Lake Valley uranium isotopic data

By J. R. Dooley, Jr.

Because of the anomalously high uranium values reported south of Fish Lake Playa from drill site 11A, uranium isotopic values were determined in a further effort to evaluate the significance of the anomaly. Four water-sample splits from drill site 11A were analyzed; one sample split from site 12A was analyzed as a comparison. The resulting concentration values for ^{238}U and the $^{234}U/^{238}U$ activity are shown in table 5. The activity ratios indicate the degree of isotopic fractionation of ^{234}U from radioactive equilibrium (activity ratio = 1.00) with its radiogenic parent ^{238}U. The sample from the greatest depth, 435 feet (133 m), is approximately in equilibrium, whereas those from the upper part of the hole are not. This equilibrium pattern compares with patterns found in ore at the Ambrosia Lake uranium deposits in New Mexico (Dooley, Granger, and Rosholt, 1966). Near-equilibrium $^{234}U/^{238}U$ values are found at Ambrosia Lake near uranium ore-zone boundaries and at impermeable zones throughout the ore. By analogy, one might hope to find uranium deposition in progress at the 435-foot-(133-m) depth zone at Fish Lake Valley.

Table 5.--Uranium isotopic water sample analyses

Drill hole No.	Depth, in feet (meters)	^{238}U Concentration (ppm)[1]	$^{234}U/^{238}U$ activity ratio[2]
11A	55 (17)	0.351	1.14
11A	115 (35)	0.418	1.22
11A	335 (102)	0.135	1.10
11A	435 (133)	0.175	0.99
12A	135 (41)	0.011	1.48

[1] The concentration values were obtained by the isotope dilution method using ^{236}U.

[2] The activity ratio is the integrated alpha-energy radioactivity spectrum of ^{234}U (4.75 MeV) count rate divided by the ^{234}U (4.19 MeV) count rate.

Columbus Salt Marsh

The large wet playa known as Columbus Salt Marsh is located 12 miles (20 km) north of and is 14 feet (45 m) lower than the playa in Fish Lake Valley. At times of heavy runoff, surface drainage from Fish Lake Valley flows directly into Columbus Salt Marsh through a narrow gap, and subsurface drainage continues even in the dry season, as indicated by springs in the gap and in the southern part of Columbus Salt Marsh (Smith, Meier, and Downey, 1977). Drill site CM-6 was located on an old road that provides access onto the playa for a distance of about 2 miles (3 km) north of U.S. highway 6. Drilling in 1977 penetrated playa sediments consisting of unconsolidated sand, pebbly gravel, and thin units of clay and altered volcanic ash. No saline minerals or lithium-rich brines were found. Loose sand filled the drill stem each time the air pressure was released to add another length of drill pipe and eventually limited the depth of penetration to 475 feet (145 m).

Water samples from CM-6 contained an average of 1 ppm Li. Sediment samples contained an average of 190 ppm Li and had a high value of 500 ppm Li, which is enough to be regarded as anomalous. Columbus Salt Marsh is still regarded as having a significant potential for finding lithium brine or clay of economic value even though the drill site was about 2 miles (3 km) south of the center of the playa, and drilling did not penetrate the full thickness of playa sediments, but did indicate anomalous lithium.

Big Smoky Valley

Big Smoky Valley is one of the large intermontane valleys in Nevada and was occupied by two large lakes during the Pleistocene (Meinzer, 1917). The southern lake was 22 miles (35 km) long by 5.5 miles (9 km) wide and covered an area estimated to be 85 square miles (211 km^2) to a maximum depth of about 70 feet (21 m). A series of gravelly beach ridges encircles the southwestern part of the ancient lake, enclosing a playa characterized by soft, puffy, unconsolidated, silty and clayey lake sediments. For this reason, drill site 13 was located on a power line right-of-way road, and drill site 14 was located on a beach ridge on the southwestern edge of the playa.

Bore-hole 13 was completed to a depth of 675 feet (206 m), of which 655 feet (199 m) was in alluvial valley fill and the last 20 feet (7 m) was in the more consolidated sedimentary rocks of the Esmeralda Formation of Miocene age. This complete penetration of the valley fill is helpful in the interpretation of the results of water analyses. A maximum value of 1.7 ppm Li was found in a water sample with a Li-Cl ratio of 0.0027 at a depth of 395 feet (120 m).

Bore-hole 14 was abandoned after drilling 215 feet (66 m) into unconsolidated sand and gravel. A maximum of 1.3 ppm Li was found in a water sample with a Li-Cl ratio of 0.0031 at a depth of 135 feet (41 m). The relatively low salinity and high Li-Cl ratios of water samples from Big Smoky Valley indicate that this area is not likely to contain a lithium brine but it may have contributed lithium to the deposit in Clayton Valley through subsurface flow of ground water, which eventually was evaporated and concentrated in Clayton Valley.

Alkali Valley

Alkali Valley depression lies to the northeast of Clayton Valley and receives surface drainage from much of the area between Tonopah and Goldfield. Like Big Smoky Valley, it is thought to be a source of ground-water flow into Clayton Valley (Rush and others, 1971). Drill-site 15 was located in the southwestern part of the barren Alkali Valley playa surface to test the composition of the supposed ground-water source into Clayton Valley. Drill-site 16 was located on a pediment slope about 6 miles (10 km) farther to the northeast, in an area thought to be the former basin center, where it might be used to test the composition of ground waters derived from the Tonopah and Goldfield mineralized districts. Bore-hole 15 was completed to a depth of 675 feet (206 m) and may have penetrated a complete section of valley fill and several hundred feet into the underlying volcanic ash, which may represent part of the Esmeralda Formation. A water sample from 515 feet (157 m) had only 0.38 ppm Li and a Li-Cl ratio of 0.0012. Bore-hole 16 was completed to a depth of 515 feet (157 m) after penetrating a large thickness of gravel. The maximum lithium content of the water at a depth of 515 feet was only 0.49 ppm Li, but this sample had the high Li-Cl ratio of 0.0075. Thus, this area may be another source for the lithium that is now found in Clayton Valley.

Mud Lake

Mud Lake is a circular playa nearly 6 miles (10 km) in diameter, about 23 miles (37 km) east of Alkali Valley. It occupies the lowest point in Ralston Valley, east of Tonopah. When dry, the surface is hard and flat enough for use in vehicle speed tests. Bore-hole 17 was located near the northern margin of the playa in order to be outside the Nellis Air Force Bombing Range and to take advantage of drainage from a small gravelly beach bar. The drilling was terminated at a depth of 275 feet (84 m) because of difficulty in penetrating dry gravel.

Stonewall Flat

Stonewall Flat is a small playa about 3 miles (5 km) northeast of Lida Junction and 25 miles (40 km) south of Mud Lake. The playa lies on the northwest perimeter of the Stonewall Mountain volcanic caldera (Cornwall, 1972, p. 29). Thus, the composition of ground water in the area might be influenced by contributions from a volcanic source. Bore-hole 18 was drilled to a depth of 475 feet (114 m) through the alluvial fill and perhaps as much as 100 feet (30 m) into altered and mineralized volcanic ash. A water sample from the bottom of the hole contained 0.16 ppm Li and had a Li-Cl ratio of 0.0032.

Concluding remarks

Previous reports of shallow-water wells in several of the valleys near Clayton Valley led us to believe we might find highly saline waters. Thus, the relatively low content of total dissolved solids recovered from many of our drilling sites was not anticipated. In fact, the chloride concentrations are so low in some samples that even with lithium concentrations of only a few tenths of a part per million, the Li-Cl ratio is comparable to that in the lithium brine at Clayton Valley. Almost any of these waters could have contributed lithium to the concentrated brine at Clayton Valley. Sites selected for many of the drill sites were not our first choices because of our agreement with the Bureau of Land Management not to dig mud pits. Nevertheless, better sites would probably not alter the results significantly. Thus, with the possible exception of Fish Lake Valley and Columbus Salt Marsh, there is little chance of locating another lithium brine field in the vicinity of Clayton Valley.

Playa deposits of the California Desert

A program to evaluate the leasable mineral potential of the desert playas of California was initiated by the U.S. Geological Survey in 1978. This work was done in cooperation with the U.S. Bureau of Land Management, who requested the data for use in land classification and land-use decisions in the

California Desert Planning Area. The entire area is of special interest to the lithium resource-appraisal program because of the potential economic importance of the known lithium deposits and occurrences, and because of the possibility that there may be more deposits. For example, this area (1) includes the type locality for the lithium clay, hectorite, at the Hector clay pit where the clay is mined for its physical properties by N L Industries, (2) includes the Searles Lake brine field from which lithium was produced as a byproduct of extraction of various other salts from 1936 to 1978, (3) includes the Kramer borate deposits, in which hectorite is a potential byproduct from the waste dumps (Morgan and Erd, 1969), (4) includes the Imperial Valley geothermal brine, which contains as much as 200 ppm Li (White, 1968) that may be recoverable some day as a byproduct of geothermal energy production, and (5) includes Bristol, Cadiz, and Danby dry lakes which are sources or potential sources of various salts including NaCl, $CaCl_2$, gypsum, and celestite and contain as much as 100 ppm Li in the brines at Bristol Lake. Other lithium anomalies have been reported in the area, for example at Lake Tecopa, and Ash Meadows (Starkey and Blackmon, 1979) so the area should receive thorough study before restrictions are placed on access and exploration.

Drilling results

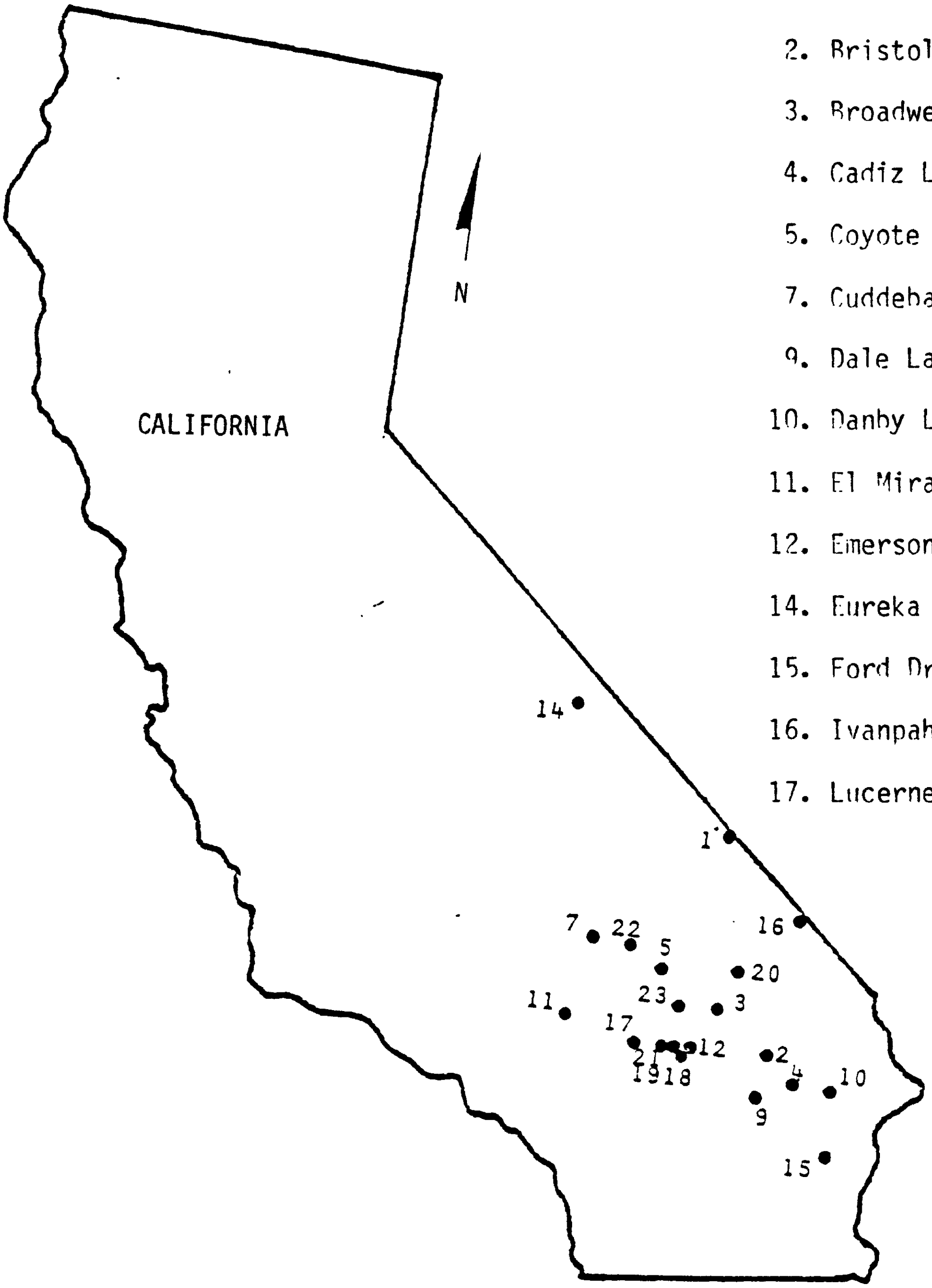
The lithium content of sediment samples collected at approximately 5-foot (1.5-meter) intervals from the 23 holes drilled by the reverse circulation technique is summarized in table 6 and their localities are shown on figure 2. If the definition of an anomalous concentration of lithium in a playa sediment of 300 ppm Li, as calculated by Davis (1976) is accepted, then 82 samples of a total of 1,441 samples (5.7 percent) qualify as anomalous. Of these, 79 are from two borings, Alkali Flat and Eureka Valley (Morgan, 1979, Pantea, 1980). The other three samples include two from Means Lake Playa and one from Lucerne Lake Playa. Of the samples from Alkali Flat, 45 of 68 samples (66 percent) are anomalous, as compared with 34 of 64 (53 percent) from Eureka Valley Playa, 2 of 34 (5.9 percent) from Means Lake Playa, and 1 of 46 (2 percent) from Lucerne Lake Playa. None of the samples contained more than 1,000 ppm Li, although 7 from Alkali Flat and 9 from Eureka Valley contain more than 600 ppm Li, and 3 from Eureka Valley contain more than 900 ppm Li.

Table 6.--Lithium content of bore-hole samples from the California Desert playa-evaluation project

Name of area and total depth of boring, in feet (meters)	Number of samples each group having range of Li values in ppm				Total samples
	300-999	100-299	30-99	0-29	
Alkali Flat (Franklin Lake Playa), 335 (102.1)	45	22	1	0	68
Bristol Lake Playa (central), 815 (248.4)	0	137	21	3	161
Broadwell Lake Playa, 504 (153.6)	0	89	13	0	102
Cadiz Lake Playa, 415 (126.5)	0	38	43	1	82
Coyote Lake Playa (central), 455 (138.7)	0	3	49	12	64
Coyote Lake Playa (southwest), 255 (77.7)	0	7	44	1	52
Cuddeback Lake Playa (fan), 405 (123.4)	0	1	28	24	53
Cuddeback Lake Playa (north), 236 (71.9)	0	8	35	1	44
Dale Lake Playa, 435 (132.6)	0	4	54	29	87
Danby Lake Playa (south), 503 (153.3)	0	16	38	32	86
El Mirage Playa, 255 (77.7)	0	0	14	38	52
Emerson Lake Playa (west), 335 (102.1)	0	9	20	21	50
Eureka Valley Playa, 335 (102.1)	34	15	15	0	64
Ford Dry Lake Playa, 317 (96.6)	0	2	36	24	62

Table 6.--Lithium content of bore-hole samples from
California Desert playa-evaluation project.--Continued

Name of area and total depth of boring, in feet and (meters)	Number of samples each group having range of Li values in ppm				Total samples
	300-999	100-299	30-99	0-29	
Ivanpah Valley, 335 (102.1)	0	0	53	15	68
Lucerne Lake Playa, 335 (102.1)	1	13	8	24	46
Means Lake Playa, 335 (102.1)	2	9	5	18	34
Melville Lake Playa, 335 (102.1)	0	10	5	16	31
Soda Lake Playa, 415 (126.5)	0	4	66	14	84
Soggy Lake Playa, 162 (49.4)	0	0	16	18	34
Superior Playa, 365 (111.3)	0	0	11	37	48
Troy Lake Playa, 95 (29.0)	0	1	16	3	20
Total--	82	391	612	356	1,441



Locality names

1. Alkali Flat
2. Bristol Lake Playa
3. Broadwell Lake Playa
4. Cadiz Lake Playa
5. Coyote Lake Playa
7. Cuddeback Lake Playa
9. Dale Lake Playa
10. Danby Lake Playa
11. El Mirage Playa
12. Emerson Lake Playa
14. Eureka Valley Playa
15. Ford Dry Lake Playa
16. Ivanpah Valley
17. Lucerne Lake Playa
18. Means Lake Playa
19. Melville Lake Playa
20. Soda Lake Playa
21. Soggy Lake Playa
22. Superior Playa
23. Troy Lake Playa

Figure 2.--Index map showing location of bore holes in the California Desert planning area.

Samples from Broadwell Lake include 89 of 102 samples (87 percent) that fall in the range of 100 to 299 ppm Li, and those from Bristol Lake include 137 of 161 (85 percent) that fall in this same range. Considering that the 50-th percentile for this set of 1,441 samples falls somewhere near the middle of the 30-99 ppm Li group, the Broadwell and Bristol Lake samples might well be considered as unusually high, even if not anomalous by the above definition. In fact, the Broadwell Lake and Bristol Lake samples have a larger percentage of samples that contain more than 100 ppm Li than does any other locality except for Alkali Flat, where the percentage is 98.5. An explanation for the large percentage of high values that do not exceed 300 ppm Li may be related to the chemistry of the sediments in which the available lithium is inclined to be dispersed throughout rather than concentrated in individual anomalous beds.

Samples of the formation fluids, either water or brine, were collected from most bore holes at convenient intervals if the drill operator could produce clear fluid by circulating air through the drill stem. Analyses of recovered samples are shown in table 7. The highest content of lithium in a fluid sample came from Bristol Lake Playa, where several values were reported in excess of 100 ppm Li from highly concentrated brine. The next highest values came from Cadiz Lake, where the analyses ranged from 20 to 67 ppm Li in brine. Other noteworthy analyses came from Danby Lake with 6-7 ppm Li, from Cuddeback (north) with 4.4 ppm Li, and from Ford Dry Lake with 3 ppm Li.

Table 7.--Lithium analyses of bore-hole water samples from the California desert playa-evaluation project

Name of area	Depth sampled ft	Depth sampled m	Lithium, in ppm	Chloride, in ppm	Conductivity	Li/Cl
Alkali Flat (Franklin Lake)--	135	41.4	.07	1,500	--	0.000046
	235	71.6	.12	1,000	--	.00012
	335	102.1	.12	1,100	--	.00011
Bristol Lake (northwest)-----	95	29.0	101	216,000	200,000	.00047
	275	83.8	70	216,000	200,000	.00032
	504	153.6	68	216,000	200,000	.00031
Bristol Lake (central)-------	215	65.5	108	180,000	180,000	.0006
	415	126.5	30	56,000	120,000	.0005
	495	150.9	102	204,000	190,000	.0005
	695	211.8	13	21,000	56,000	.0006
Broadwell-------------------	135	41.1	.17	2,200	--	.00008
	235	71.6	5.52	26,000	--	.00021
	355	108.2	.66	3,000	--	.0002
	504	153.6	1.54	3,000	--	.0005
Cadiz Lake------------------	171	52.1	67	180,000	200,000	.00037
Cadiz Lake well #1-----------	200	61.0	55	170,000	200,000	.00032
Cadiz Lake well #2-----------	217	66.1	20	90,000	170,000	.00022
Cadiz well B-2--------------	190	57.9	60	180,000	200,000	.00033
Cadiz well H-2--------------	250	76.2	20	80,000	150,000	.00025
Cadiz well D-2--------------	180	54.9	49	216,000	2,000	.00022
Coyote, central-------------	235	71.6	.02	2,320	--	.000009
	375	114.3	.05	1,700	--	.00003
	455	138.7	.08	2,000	--	.00004

Table 7.--Lithium analyses of bore-hole water samples from the California Desert playa-evaluation project.--Continued

Name of area	Depth sampled		Lithium, in ppm	Chloride, in ppm	Conductivity	Li/Cl
	ft	m				
Coyote Lake (southwest)------	255	77.7	0.04	1,800	--	.000022
Coyote Lake, spring #1-------	--	--	.05	100	--	.0005
Coyote Lake, spring #2-------	--	--	.29	60	--	.0048
Coyote Lake, spring #3-------	--	--	.05	280	--	.00018
Cuddeback Lake (fan)---------	75	22.9	.36	450	--	.0008
	175	53.3	.30	750	--	.0004
	275	83.8	.38	800	--	.0005
	375	114.3	.62	1,500	--	.0004
	405	123.4	.56	1,700	--	.00033
Cuddeback Lake (north)-------	75	22.9	4.40	8,000	--	.00055
	215	65.5	.51	1,600	--	.0003
Dale Lake-------------------	155	47.2	.24	14,760	45,000	.000016
	195	59.4	.17	7,200	23,000	.000024
	395	120.4	.19	12,000	36,000	.000016
Danby Lake (north)----------	135	41.1	5	100,000	170,000	.00005
	503	153.3	6	80,000	170,000	.000075
El Mirage-------------------	115	35.1	.1	60	--	.00167
	175	53.3	.05	225	--	.0002
Emerson Lake (west)---------	115	35.1	.19	25,200	65,000	.000008
	215	65.5	.07	5,100	17,000	.000014
	335	102.1	.09	750	2,700	.00012

Table 7.--Lithium analyses of bore-hole water samples from California desert playa-evaluation project.--Continued

Name of area	Depth sampled ft	Depth sampled m	Lithium, in ppm	Chloride, in ppm	Conductivity	Li/Cl
Emerson (central)------------	95	29.0	1	68,000	120,000	0.000015
	155	47.2	.03	26,000	62,000	.000001
	355	108.2	.10	1,500	6,000	.000066
Eureka-----------------------	155	35.1	.04	280	--	.00014
	335	102.1	.02	180	--	.00011
Ford Dry Lake----------------	315	96.0	3	--	--	--
Ivanpah----------------------	175	53.3	.07	210	--	.00033
	335	102.1	.01	50	--	.0002
Lucerne Lake-----------------	115	35.1	1.25	40,000	69,900	.000031
	215	65.5	.12	1,500	6,580	.00008
	335	102.1	.14	2,400	8,740	.000058
Means Lake-------------------	95	29.0	.46	4,800	15,000	.000096
	215	65.5	.40	2,000	9,000	.00023
	335	102.1	.71	1,600	5,800	.00044
Melville Lake----------------	95	29.0	.15	1,000	5,900	.00015
	215	65.5	.02	160	1,300	.00013
	308	93.9	.05	1,000	6,600	.00005
Soda Lake--------------------	75	22.9	.32	4,400	--	.000073
	195	59.4	.43	1,700	--	.00025
	315	96.0	.20	650	--	.00030
	415	126.5	.06	150	--	.0004

Table 7.--Lithium analyses of bore-hole water samples from the California desert playa-evaluation project.--Continued

Name of area	Depth sampled ft	Depth sampled m	Lithium, in ppm	Chloride, in ppm	Conductivity	Li/Cl
Soggy	115	35.1	0.03	220	--	0.00014
	162	49.4	.01	190	--	.000053
Superior	95	29.0	.04	100	--	.0004
	155	47.2	.01	90	--	.00011
	255	77.7	.01	850	--	.000012
	355	108.2	.01	1,200	--	.000008
Troy	75	22.9	.38	12,000	--	.000032

Although the absolute lithium content of fluid is useful in making an appraisal of the potential for commercial development of a brine field, the study of ratios with other constituents is even more useful in understanding the origin and evolution of the chemical constituents in solution, as suggested by White, Thompson, and Fournier (1976). Among the more useful of the ratios is Li-Cl because chloride is a highly soluble common constituent of water that does not enter into chemical reactions with clays or other rock-forming minerals until the concentration of both sodium and chloride are sufficient to precipitate halite. A plot of the Li-Cl ratio against the absolute chloride concentration has been shown by Smith (1976) to be a useful means of judging the likelihood that any given water could be a source for a lithium-rich brine. The highest ratios of Li:Cl (greater than 0.001) found in the California Desert playa-evaluation program are the dilute spring water at Coyote Lake, spring #2, and a dilute subsurface water at El Mirage Playa. Other high ratios greater than 0.0005 are associated with the brine from Bristol and Cadiz Lakes and the moderately mineralized water from Cuddeback Lake. Ratios of 0.0001 or more occur at Alkali Flat, Broadwell, Emerson (west), Eureka, Ivanpah, Means, Melville, Soda, Soggy, and Superior playas. Ratios of Li:Cl less than 0.0001 are characteristic of Coyote, Dale, Danby (north), Emerson (central), Lucerne, and Troy playas.

From the data in table 7 and the preceeding discussion there appears to be little or no correlation between a high ratio of Li:Cl and a high lithium or high chloride content. High ratios of Li:Cl were found in both dilute and briny waters and in waters with low lithium and others with high lithium. This indicates a wide diversity in origin and evolution of the various waters, even in adjacent playas where a common geologic history might be expected . Bristol, Cadiz, and Danby Lakes, for example, form a chain of playas with Bristol the highest and Danby the lowest elevation, yet the waters are quite different and the chemistry at Bristol suggests an even more highly evolved history than at Cadiz or Danby, contrary to what might be expected if they had ground-water movement from the highest to the lowest. Moreover, the relation, if any, between water data and sediment data is also obscure. Among the playas where anomalous lithium was found in sediment, Alkali and Eureka playa waters have neither an unusually high content of lithium nor a high ratio of Li:Cl in the waters.

Buried salt bodies of Arizona

Two sites in Arizona were selected for drilling in 1978 to test the possible association of lithium-rich brines with salt deposits of Tertiary age and of probable nonmarine origin. Rock salt is known to be exposed along the shore of Lake Mead, near Overton Beach, Nevada, and other exposures of salt along the Virgin River Valley in the area now covered by the waters of Lake Mead were described by Longwell (1928, p. 93) and by Ransome (1950, p. 218). Moreover, a series of subsurface salt bodies are known from drill data to occur along the west and south margin of the Colorado Plateau from northwestern Arizona to southeastern Arizona (Peirce, 1974). These include salt at 420-600 feet (128-183 m) depth in Detrital Wash, 1,200-1,600 feet (366-488 m) depth at Red Lake Playa in Hualapai Valley and at similarly shallow depths at Luke Air Force Base, near Picacho Reservoir, and near Safford, Arizona. A probable nonmarine origin for these salt bodies has been proposed by Peirce (1974). Although some of these salt bodies show little or no surface geomorphic expression, Red Lake Playa lies in a basin having about 50 feet (15 m) of topographic closure, suggestive of surface subsidence through subsurface solution over the body of salt. Other playas, such as Willcox Playa in the southeastern corner of Arizona, may be the surface expression of subsurface salt bodies yet to be penetrated by drilling.

The salt exposed near Overton Beach on the shore of Lake Mead was described by Longwell (1928) as part of the Muddy Creek Formation of Pliocene age. However, this exposure can also be interpreted as a salt dome or piercement structure in which the salt is older than the Muddy Creek Formation with which it is now in contact. Underlying the Muddy Creek Formation is the Horse Spring Formation of Miocene age which in nearby areas includes exposures of gypsum, borate deposits, lithium-bearing clays and volcanic rocks. Thus, the body of salt probably is also of Horse Spring age and there may be genetic relation among the salt, the lithium-rich clays, the gypsum, and the borate deposits.

The rationale for the selection of drilling sites in Arizona is as follows:

1. If the anomalous concentrations of lithium in the Horse Spring Formation are related to a major episode of nonmarine salt deposition, and
2. If the salt bodies in Arizona along the margin of the Colorado Plateau are

related in age and manner of origin, then

3. The subsurface salt known to occur at Detrital Wash, Red Lake, Luke, and Picacho may represent a closely related series of nonmarine salt basins in which there may have been enough connection that the more soluble constituents such as potassium and lithium would tend to be concentrated at the distal end of the basin chain.

4. Provided these foregoing assumptions are true, then drilling designed to penetrate the margin of the saline sequence at or near both ends of this chain of evaporite basins could yield samples of sufficiently diagnostic chemical characteristics to indicate which end of the chain of basins was the distal end, and hence possessed the best chance for the discovery of economically valuable deposits of saline minerals and brines, including those rich in lithium.

Red Lake Playa and Willcox Playa were chosen to test the lithium potential of Arizona salt deposits and a drilling contract prepared that would allow for penetration to depths greater than 1,000 feet (305 m) but not more than 2,000 feet (610 m). The results of the drilling at Willcox Playa are described in an open-file report (Vine, Asher-Bolinder, Morgan, and Higgins, 1979) and the results of the drilling at Red Lake Playa are described in a companion report (Asher-Bolinder, Vine, and Morgan, 1979). At both sites the object was to penetrate permeable sediments near the margin of a salt body where it might be possible to find residual brines pressed out of the salt when it recrystallized to form a solid dry mass. The desired objective was not achieved at either site.

Although a shallow aquifer or water-bearing sand was penetrated from about 35 to 85 feet (11-26 m) at Willcox Playa there were no significant aquifers in the deeper portions of the boring, only dry gypsiferous mudstone, and hence there was no opportunity to learn the chemistry of ground water that might be in chemical equilibrium with the deeper sediments. Moreover, the data failed to rule out the possibility that a salt body underlies the center of the playa, even though drilling failed to penetrate salt or brine. At Red Lake Playa, the lower part of the boring penetrated about 600 feet (183 m) of water-bearing alluvial-fan gravels that contained relatively fresh water under hydrostatic head at depths equivalent to the top of the salt body in wells a few miles distant. At both localities, the exact drilling site was about as near as we dared approach the soft playa muds without placing the drilling equipment in jeopardy of foundering in the event of a heavy rain. Hence, although a more favorable site for prospecting for lithium brines and clays might now be chosen toward the center of each playa, safe drilling practice would require construction of gravel roads and drilling pads at significantly greater expense.

Lithium clays in the Lake Mead and McDermitt areas, Nevada

Because lithium clays are soft and offer little resistance to weathering processes, they tend to be covered by soil or colluvial material from adjacent more resistant units. Moreover, the hectorite-type clays[4] reported from the western United States occur without exception in relatively young (Cenozoic) sequences, many of which remain buried or are only partly exhumed by uplift and erosion. Thus, the occurrence of excellent exposures of hectorite(?) in the Miocene and Pliocene rocks of the Lake Mead area provide a unique opportunity to learn more about the distribution of lithium in an ancient playa environment. Exposures in this area are enhanced in part by the arid climate, but the rocks have also been subjected to intense structural deformation and subsequent erosion so that even the least resistant units can generally be observed at favorable locations.

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[4] Note that the positive identification of hectorite as a clay mineral species requires a combination of structural and chemical tests conducted on a clay-size fraction of the sample to distinguish hectorite from other trioctahedral smectites such as stevensite that do not contain as much lithium or fluorine. Because routine sample procedure involved only a lithium analysis and an X-ray diffraction pattern of the whole-rock sample, positive identification of hectorite is not possible. Hence, throughout the remainder of this report, lithium-bearing samples known only to contain a trioctahedral smectite are described as hectorite(?) rather than by the more awkward expression "hectorite-type clay," or "hectorite-like clay."

In the Lake Mead area, lithium enrichment is most pronounced in rocks of Lovell Wash (informal name) assigned to the Horse Spring Formation of Miocene age. The rocks of Lovell Wash crop out in a number of discontinuous exposures separated by intervals in which only older or younger rocks are exposed as a result of major strike-slip faulting, some of which was contemporaneous with sedimentation and some of which was post-depositional. Typically, the rocks of Lovell Wash of the Horse Spring Formation can be recognized as a conspicuously light-colored sequence of beds in which some units are white. The light color is attributed to a large proportion of altered volcanic ash. Alteration minerals especially responsible for the light colors include a clay mineral comparable to hectorite, cristobalite, clinoptilolite, dolomite, gypsum, celestite, halite, and magnesite. As many as four of these minerals are present in the same rock. The sequence of beds varies along strike so that individual beds cannot be correlated from one area to another even though there is sufficient uniformity in overall appearance to make the stratigraphic sequence readily recognized.

In the Frenchman Mountain area, near Henderson, Nevada, excellent exposures of the rocks of Lovell Wash occur on the east flank of Lava Butte. The upper 656 feet (200 m) of a 1,640-foot (500-m) section there contains an average 800 ppm Li and a 131-foot (40-m) part of this high-lithium section contains an average of 1,000 ppm Li according to Brenner-Tourtelot (1979). Of special interest in this Lava Butte area is the occurrence of primary sedimentary structural features that have been interpreted as fossil spring orifices constructed of limestone imbedded in altered volcanic ash. These features are commonly 1-3 feet (0.3-1 m) high funnel-shaped "spring pots" or "pools" that open upward and measure as much as 10 feet (3 m) across at the top. Near the middle of the high-lithium section they are so closely spaced as to form a nearly continuous limestone bed that can be traced more than half a mile (1 km). Parts of the limestone are replaced by dark-brown- to black-weathering chalcedony, that makes a striking color contrast with the adjacent light colored beds. Locally, saucer-shaped spring pools as much as 10 feet (3 m) across can be observed stacked in a step-wise fashion, one on top of another, through a stratigraphic interval of as much as 20 feet (6 m) indicating continuous spring activity at nearly the same location for an extended period of time. In this instance, the lamination of the adjacent altered volcanic ash can be observed to terminate abruptly against the crosscutting massive limestone and tufa of the spring pool.

The occurrence of hectorite(?) associated with abundant evidence of spring activity suggests that spring waters probably introduced some of the chemical constituents, including the lithium required to form hectorite(?), whereas other constituents were probably provided as a result of the alteration of the volcanic ash.

The Lovell Wash area is located 12-15 miles (19-24 km) northeast of the Lava Butte area and includes typical exposures of the rocks of Lovell Wash in an area of outcrop that is separated from Lava Butte by faulting of unknown but possibly large displacement. A comparison of the sedimentary features of the two areas is striking, for the Lovell Wash area also includes excellent examples of spring pots similar to those at Lava Butte. Near the top of the exposed Lovell Wash sequence along the axis of the West End Wash Syncline, a zone of abundant spring pots occur within larger algal bioherms or mounds as much as 20-30 feet (6-10 m) thick and 50-100 feet (15-30 m) long composed of massive brown limestone. As in the Lava Butte area, the laminations of the adjacent altered volcanic ash unit terminate abruptly against the massive limestone. The algal mounds and spring pots lie within a sequence of light-gray- to white-weathering altered volcanic ash beds that contain anomalous concentrations of lithium. Individual samples representing 6-12 inches (0.15-0.3 m) of laminated hectorite(?) contain as much as 3,000 ppm Li.

This area is also noteworthy for the occurrence of several isolated individual spring pots that grew within a single 1.5-foot (0.5-m) bed of massive volcanic ash. The volcanic ash has been altered largely to clinoptilolite and cristobalite, whereas the spring pots are composed of limestone, partly replaced by chalcedony. One spring pot is irregularly lobate in plan as though it had difficulty maintaining its normally circular pattern of growth against the enroaching volcanic ash. Some spring pots were seemingly restricted in size and then snuffed out by the ash, whereas others apparently survived the ashfall and spread out over the top of it.

Algal stromatolites composed of laminated dolomite and hectorite(?) are also found in the same sequence as the spring pots in the vicinity of Callville Wash, the main drainage for which Lovell Wash is a tributary. Typical examples are 4-6 inches (0.10-.15 m) high and 2-3 inches (0.05-.08 m) across with only 1-2 inches (0.02-.05 m) between them. In these features, the laminations appear draped between individual stromatolites and to continue through them. They weather out locally because of a greater content of carbonate in the stromatolite than between them but they are highly friable and difficult to collect intact. By comparison with modern stromatolites these probably formed in a shallow-water or nearshore environment, possibly within the zone of wave action in a body of water that was too saline for grazing mollusks to be sufficiently abundant to cause their destruction prior to burial. Although stromatolites are fairly abundant in parts of the lithium-rich zone they serve primarily to indicate the environment of deposition and have no recognized relationship to the occurrence of lithium clays.

The Lovell Wash area also includes the West End Wash borate district, which is a separate zone of lithium and borate mineralization in the limestone of Bitter Ridge of the Horse Spring Formation, directly under the rocks of Lovell Wash (Bohannon, written communication, 1980). The mineralized zone contains borate minerals (chiefly colemanite) within a larger zone of hectorite(?) and interbedded carbonates more than 100 feet (30 m) thick. The limestone beds are characterized in part by the occurrence of abundant carbonate-rich stromatolites that form columns as much as 1 foot (0.3 m) high and 6 inches (0.15 m) across. On bedding surfaces these stromatolites weather out as hemispherical oval forms that resemble broken egg shells and were referred to as eggshell carbonate by the miners who found them a useful guide in their search for borate minerals. As mentioned in the previous paragraph, these stromatolites probably indicate a shallow-water environment with high salinity and perhaps a relatively high pH, but are not known to have any genetic relation to the occurrence of hectorite(?) or colemanite. A genetic relation, however, may exist between the mineralized zone and the occurrence of some of the most outstanding examples of spring pools, as much as 50 feet in diameter that are exposed on the upper surface of a conspicuous dip slope on the limestone of Bitter Ridge about 700 feet (240 m) stratigraphically below the borate zone. These spring pools are suggestive of a local source for perhaps both the borate and the lithium, which later became concentrated enough through continued evaporation to form a mineralized zone more or less contemporaneous with the formation of the stromatolites.

Good exposures of the rocks of Lovell Wash of the Horse Spring Formation are in the White Basin area, some 8-12 miles (13-19 km) to the north and northeast of Lovell Wash. The lithium-rich strata in this area form a continuous belt of outcrop that is nearly 6 miles (10 km) long on the north and northwest side of Bitter Ridge. Of special interest in this area is a regular sequence of strata that includes altered volcanic ash, hectorite(?) and algal limestone (from bottom to top) in repetitive series, to as many as 3 or 4 times. The volcanic ash is generally altered in part to clinoptilolite and cristobalite and becomes more clay-rich going up section until locally it is almost completely altered to a hectorite(?). The clay is overlain, in turn, by a ledge-forming limestone bed with algal mounds and spring pots similar to those from the Lovell Wash area, but with perhaps a greater proportion that simply resembles limestone tufa. Many of the units are partly replaced by variously colored opal or chalcedony, which weathers out in fragments as much as 1-2 feet (0.3-.7 m) across with characteristic forms and colors for different stratigraphic intervals.

In the McDermitt area of northern Nevada and southern Oregon, the lithium-bearing strata differ from those in the Lake Mead area in several important respects. The volcaniclastic sedimentary rocks in the McDermitt area were deposited in a caldera moat, which is a ring-shaped depression within the area of subsidence, but peripheral to the resurgent dome at the center of the caldera. In the McDermitt area, the moat sediments are mostly lacustrine volcanic ash, with minor amounts of airfall ash, pumicite, and fluvial deposits. Clastic deposition was sufficiently rapid that there was little opportunity for deposition of discrete beds of carbonate or evaporite minerals, and hence little or no chance to accumulate the same kind of evidence for spring activity that was found at Lake Mead. There is evidence, however, for several kinds of thermal activity, part of which can be regarded as presumptive evidence for spring activity. On a regional scale, there is a zonal arrangement of alteration minerals in the form of authigenic zeolites and clay minerals that has been interpreted as a regional pattern of varying intensity of alteration (Glanzman and Rytuba, 1978). The more intense alteration is probably the result of higher temperature, greater salinity of the environment of deposition, or a combination of the two factors. Superimposed on the regional pattern are several local point sources of more intense alteration and associated mineralization. These probably represent local sources of higher temperature, mineralizing solutions, or both. Hence, these may be regarded as source areas for thermal springs.

Another noteworthy aspect of the McDermitt lithium clay deposits is their association with other mineral deposits, including uranium and mercury (Rytuba and Glanzman, 1979). The zone of hectorite(?) generally lies stratigraphically above a zone of uranium mineralization that occurs near the base of the moat sequence of sedimentary volcaniclastic rocks (Glanzman, McCarthy, and Rytuba, 1978). Mercury mineralization, on the other hand is localized by the point sources of mineralization, such as at the Opalite area in southern Oregon and the Cordero Mine near McDermitt (Rytuba and Glanzman, 1979).

Unusual and speculative lithium deposits

Although much of the U. S. Geological Survey's effort has been directed at the search for lithium in smectite clays and brines associated with Cenozoic basins, volcanic activity, and thermal systems in the western United States, other types of lithium deposits and other regions should not be overlooked. Unusual deposits that may provide clues for further search include: (1) cookeite in quartz veins where they cut the Jackfork Sandstone in central Arkansas (Stone and Milton, 1976), (2) the occurrence of lithiophorite in manganese deposits of Arkansas, also reported by Stone and Milton (1976), and (3) the occurrence of lithium with high-alumina clays and bauxite, reported by H. A. Tourtelot and Meier (1976) and by Tourtelot and Brenner-Tourtelot (1978).

Any explanation for the occurrence of cookeite in quartz veins in Arkansas should account for the fact that all the known occurrences are in the Jackfork Sandstone of Late Mississippian and Early Pennsylvanian age, although numerous quartz veins and commercial quartz crystal mines occur throughout the lower Paleozoic rocks in many parts of the Ouachita Mountains. In general, such quartz mineralization probably forms from aqueous solutions expelled from the thick eugeosynclinal sedimentary sequence in response to the elevated temperature and pressure associated with deep burial and subsequent uplift and folding that occurred at the close of the Paleozoic Era. Because of the relatively small quantity of lithium involved, an outside source need not be invoked for the constituent minerals of the veins. The minerals were probably derived from the dissolved constituents of the pore waters buried with the original sediment and were precipitated as a result of decreasing temperature and pressure as the fluids were expelled upward. In order to account for the lithium in the mineral cookeite where these veins cross the Jackfork Sandstone, pore waters in the Jackfork may have to be assumed to have been enriched in lithium relative to the underlying units. This, in turn, could indicate a hypersaline environment of deposition for the Jackfork Sandstone, or the subsequent introduction of lithium-bearing ground water.

A more convincing argument for the occurrence of cookeite in the Permian (Weissliegende) sandstone of Germany may be possible because the mineralized unit lies only a few meters below the Zechstein salt deposits which could have supplied lithium-rich brines to the sandstone during burial of the salt sequence. This explanation differs from that of Flehmig and Menschel (1972) who proposed that the cookeite is an authigenic alteration of lithium-rich biotite similar to zinnwaldite, but who failed to identify a source area for such a mineral. Although these various occurrences have no known economic value, an understanding of their origin might aid in the search for larger deposits. It would be of interest to know, for example, if cookeite occurs in other areas where quartz veins are associated with eugeosynclinal sequences, burial metamorphism, or evaporite deposits. For example, does cookeite occur in the gold-quartz veins of the Mother Lode district in California, or in the eugeosynclinal rocks of Nevada or Vermont? Perhaps a worthwhile search for cookeite would be in the vicinity of salt bodies, especially those associated with lithium-rich oil field formation waters or potash deposits, such as the Luann Salt of the Gulf Coast, the Permian basin of southweastern New Mexico, the Paradox Basin of Utah, or the Williston Basin of Montana and North Dakota.

The origin of the lithium-rich manganese oxide mineral, lithiophorite, is not known because the source of lithium for the mineral is obscure. Fleischer and Faust (1963) reported that lithiophorite is a common mineral associated with weathering of ultramafic rocks, and noted that it is generally of supergene origin. They also noted that lithophorite has been reported from the weathered zone at a number of localities in the southeastern United States where it commonly occurs as encrustations and fracture fillings in sandstone, quartzite, and chert, and as black stains on the weathered surfaces of quartz, as previously described by Pierce (1944). Attempts to identify lithiophorite in the manganese deposits of Arkansas were somewhat less successful than expected (Stone and Milton, 1976). Moreover, lithiophorite was not recognized in lithium-rich samples from the 3-Kids manganese mine near Henderson, Nevada (E.F. Brenner-Tourtelot, oral communication, 1977). Samples of manganese nodules from the ocean floor have also been analyzed for lithium and tested for lithiophorite with negative results. Although most of these observations tend to support a supergene origin for the mineral they fail to offer an expanation for the source of the lithium. Hypogene deposits have also been described. For example, the lithiophorite associated with gibbsite in veins that replace limestone in the southern Quinn Canyon Range, Nye County, Nevada (Hewett, Cornwall, and Erd, 1968). Perhaps these deposits are exceptional because the mineral forms from acid solutions that are neutralized, a situation more common to supergene than hypogene deposits. However, until a satisfactory explanation for the occurrence of lithiophorite is verified, there is little reason to suggest whether or not it could occur in sufficient quantity to constitute a lithium resource.

The occurrence of lithium with high-alumina clays is another association that requires an unusual explanation to account for the source of the lithium. Studies by H. A. Tourtelot (oral communication, 1979) suggest two different types of occurrence of these clays. The first is typified by the bedded deposits of Pennsylvanian-age underclay associated with coal beds in Pennsylvania. These clays are probably fossil soil zones on which the vegetation was rooted that later became beds of coal. The environment in which the vegetation grew was probably a coastal swamp, which was supplied by fresh water from adjacent land areas but which may have experienced occasional flooding from the sea. Neither water source is adequate by itself to explain the enrichment of lithium in these deposits.

The second type of occurrence of lithium in high-alumina clay is typified by the clay pits of central Missouri that have been described by Keller (1975, p. 69), as "clay fillings in sink hole deposits...locally more than 100 feet thick." The occurrence of these deposits in limestone depressions as much as 650 feet (200 m) across into which is draped the Pennsylvanian Warner Formation, probably contributes to the concept that the depressions formed on a subaerial karst topography. However, the depressions are not joint-controlled galleries of interconnecting solution cavities typical of karst landscapes. Rather, the clay deposits occupy vertical pipelike cavities that do not appear to be connected with each other even where closely spaced. Similar features in soluble rock are thought to form by rising ground water (Vine, 1976a). This distinction between pipes and sink holes is important to the interpretation of the source of the lithium. If the clay deposits were formed from the cave-entrapped insoluble residue of Paleozoic limestones, how did this residual clay get altered to flint clay, diaspore, and lithium clay? The enrichment to as much as 5,000 ppm Li requires either an unusually effective mechanism for its concentration or a localized source. If the clay deposits accumulated in pipes formed by rising spring waters then the spring waters could be the source of lithium derived from subsurface leaching of older rocks. The spring water could come from ground-water circulation through Cambrian or Ordovician sandstones dipping off the north flank of the

Ozark uplift during Early Pennsylvanian time. Perhaps there was an even deeper source for mineralized water related to the uplift itself. If the principal occurrence of lithium is in a mineral comparable to cookeite, $(LiAl_4)Si_3AlO_{10}(OH)_8$, as suggested by Tourtelot and Brenner-Tourtelot (1978), then it probably formed by interaction of lithium-rich ground water with residual alumina and silica not organized into kaolinite, which is the dominant mineral of flint clay.

If this explanation is reasonably accurate, then it might be profitable to search for cooketite-bearing clays elsewhere on the flanks of the Ozark uplift or comparable uplifts such as the Nashville Dome in Tennessee or the Llano Uplift in central Texas. In general, cookeite might be expected to occur wherever lithium-bearing waters come in contact with aluminous sediments, especially where the pH is low.

Risk-reduction in lithium exploration

Exploration activity has long been regarded as a high-risk business but one in which the rewards can be great. Reduction of the risk can best be accomplished by making use of all available information in the selection of a drilling site, including an analysis of past results. In searching for lithium, prudently keep in mind that it can occur in the liquid phase, the solid phase, or both depending up on the chemical reactions between the sediments and their contained pore waters. In this respect, searching for lithium differs from most other commodities and any interpretation of results must be judged accordingly.

In general, the discovery or lack of discovery of a lithium deposit as determined from the water and sediment samples from a single drill hole can lead to several alternate conclusions as suggested by figure 3. In a simple closed system such as a basin from which there is no surface or subsurface outflow except by evaporation, the interpretation is relatively simple. At Clayton Valley, for example, interpretation 3 probably represents the most general case, in which a lithium anomaly occurs both in the sediment and in the brine. Interpretations 2 and 4, in which anomalous lithium is found only in the water or the sediment, but not in both, can be viewed as end-member extremes for a closed system. When dealing with an open system, such as a basin with restricted subsurface drainage into the next lower basin, the interpretation is less certain. If the basin has been tilted so that the mineralizing solution has been separated from the altered sediment, one drill

		Drill-hole data indicates				
		No lithium anomaly	Lithium anomaly in water only	Lithium anomaly in both water and sediment	Lithium anomaly in sediment only	
No source of lithium in solution		Interpretation No. 1				Closed System
Source of lithium in solution	No reaction with sediment		Interpretation No. 2			
	Incomplete reaction with sediment			Interpretation No. 3		
	Complete reaction with sediment				Interpretation No. 4	
	Sediment flushed with fresh water before reaction could be completed		Interpretation No. 5-B		Interpretation No. 5-A	Open System
	Mineralizing fluid escaped directly to surface runoff without any chance to react with sediments	Interpretation No. 6				

Figure 3.--Some possible interpretations of data from a lithium exploration program.

site might penetrate only altered sediment, interpretation 5A, and another drill site offset to a deeper part of the basin might penetrate only lithium-rich water or brine, interpretation 5B. Moreover, when thermal springs bring lithium-bearing waters directly to the surface where they can mix with surface runoff having a direct outlet to the sea, the lithium may be lost without a trace, interpretation 6.

From this analysis of some possible interpretations possible from drill hole data, the absence of a lithium anomaly does not prove that an area has no potential for lithium resources. This is probably especially true in areas where there has been a long or complicated history of deposition interrupted by periods of tilting, uplift, faulting, or other styles of deformation that have shifted the center of deposition. Moreover, any area where anomalous lithium is recognized either in water or in sediments is probably worthy of continued search for more information. Realizing this should also make clear the need to examine both the sediments and the pore waters that occur in the sediments in order to understand the distribution of lithium and the probability of locating a deposit of commercial significance. In order to obtain uncontaminated samples of both waters and unconsolidated sediments special drilling procedures are required.

Applicable drilling technology for unconsolidated playa sediments

Conventional rotary drilling technology is of little or no value in the exploration for lithium in unconsolidated playa sediments. Normally, such drilling practice requires use of a heavy drilling mud to cool and lubricate the bit and to carry the cuttings up the outside of the drill pipe to the surface. In the process of penetration, soft sediments become disaggregated and mixed with the slurry of mud so that only sand and gravel fragments can be separated from the mud at the surface. Moreover, the walls of the hole tend to erode rapidly, further contaminating the mud with material already penetrated. Hence, recovery is impossible of sediment samples that are representative of the strata penetrated. Equally impossible is to recover samples of formation water or even to recognize a water-bearing zone unless there is sufficient flow to significantly reduce the density and viscosity of the drilling mud. Even then, there is no way to recover a water sample that is not seriously contaminated with drilling mud and clay penetrated in drilling.

Reverse-circulation rotary drilling using dual-wall drilling pipe can eliminate most of the problems just described and can provide a means for recovering relatively uncontaminated samples of both the sediments and the formation waters. For best sample recovery, drilling should be done with a mixture of air and water, using a fixed face bit with tungsten carbide facing inserts and a bit diameter only slightly larger than the drill stem. A mixture of air and water is forced down the outer annulus and returned through the inner opening of the drill stem. If the bit has a large central opening, it will permit corelike pieces of sediment to be recovered at the surface with virtually no contamination. Furthermore, the technique facilitates the recovery of uncontaminated samples of formation water at any time. The driller stops drilling and shuts off the water supply while continuing to blow air through the drill stem. If there is formation water flowing into the bottom of the hole it will be recovered at the surface with a minimum of contamination.

Limitations to the reverse-circulation drilling technique as described above include the following: (1) Loose gravel is difficult to penetrate and there is a chance that a piece of gravel will become wedged in the opening of the bit, thereby preventing circulation. (2) Loose sand under a hydrostatic head will tend to flow into the drill stem whenever the air pressure is reduced to add another section of drill pipe. With increasing depth and pressure clearing the drill stem and restoring circulation may become impossible. (3) Plastic clay can be of a consistency so thick as to plug the drill stem and prevent circulation. (4) Siliceous layers may be encountered that are too hard to penetrate with an open face bit, but may require use of an air hammer or tri-cone bit. Although these limitations can seriously hinder a drilling program or delay its progress, they are a small inconvenience compared to the frustration of conventional drilling techniques when used in soft-sediment exploration.

ANALYSIS OF THE LITHIUM RESOURCE PROBLEM

Introduction

Like the other alkali metals, lithium occurs in different forms in nature, and each form has advantages and disadvantages with respect to selecting the most economic method of recovery. The most abundant alkali metal, sodium, is readily obtained from bedded deposits of halite, NaCl, and trona, $Na_3H(CO_3).2H_2O$, or nahcolite, $NaHCO_3$, or from seawater. Although sodium is also a common constituent of silicate rock minerals, including certain feldspars, zeolites, and clays, even the courts have ruled against the classification of sodium bentonites and sodium zeolites as a resource for sodium because it is so much more abundant and more readily available in other forms. The next most abundant alkali metal, potassium, is currently also recovered from domestic bedded salt deposits, but these were unknown at the time of the First World War so that a great effort was made to recover potassium from potassium-rich brines and igneous rocks when imports from Germany were cut off. The proportions of Li:K:Na, which range from about 1:2,200:62,000 for seawater to about 1:10:100 for some geothermal hot springs (White and others, 1976), are an indication of how difficult it is to isolate lithium in nature to the extent required to form discrete lithium minerals. This difficulty also means that lithium must be extracted from deposits that are much lower in tonnage and grade than analogous deposits of sodium or potassium. It does not mean that the resource picture is hopeless, but simply that the effort required to find and process lithium resources will be greater than for sodium or potassium, and, hence, that the final product will necessarily be more costly.

Types of lithium deposits having potential economic value

Overview

Although lithium minerals in pegmatites and lithium-bearing brines comprise the only commercial sources for lithium at the present time, lithium-bearing clays comprise a third type of deposit that may be commercially exploitable at some time in the near future. Other occurrences of lithium minerals, as previously discussed, including cookeite in quartz veins, lithium micas in greisen, lithium micas in granite, cookeite alteration of sandstones, lithiophorite coatings on sand grains, lithium-rich volcanic glass, and lithium-rich borates and other salines generally tend to be too small or too dispersed (low grade) to be regarded as having any commercial potential at the present time. Some studies have even suggested seawater as a potential source for lithium.

Seawater

The identification of lithium in seawater at an average concentration of less than 0.2 ppm has given rise to the hope that seawater may become the ultimate source for lithium. The tonnage of seawater is so large that even at this very low concentration Steinberg and Dang (1976) have estimated that seawater contains about 2.5×10^{11} tonnes of lithium. But even if price were no consideration there is no likelihood that a recovery method can be devised that will be effective in isolating the lithium. Evidence from the geochemical behavior of lithium and commercial experience in handling lithium brines on a large scale suggest that lithium is dispersed and lost in a variety of ways (adsorption on clays, inclusions in salt, entrainment with other cations) long before any significant concentration could be achieved. Thus, seawater should not be regarded as a potential future resource for lithium, at least not until all the numerous other possibilities have been exhausted. Further discussion of potential lithium resources, therefore is limited to the three principal types of deposits: pegmatites, brines, and clays.

Pegmatites

The geologic occurrence and probable origin of lithium-bearing pegmatites has been discussed by so many workers that no more than a brief summary of their findings need be repeated here. The following references are recommended for anyone interested in further reading:

Reference	Topic
Norton (1975)	Black Hills, South Dakota, pegmatite district.
Jahns (1979)	Pocket pegmatites of the San Diego, Calif., region.
Mulligan (1965)	Canadian pegmatite deposits.
Stewart (1978)	Origin of pegmatites in light of experimental data.
Kesler (1976)	North Carolina spodumene belt.
Cerny and Trueman (1978)	Western Canadian shield pegmatite district.
Lasmanis (1978)	Yellowknife district, Northwest Territories.
Steiger and von Knorring (1974)	Lithium pegmatites in Ireland.
Cooper (1964)	Lithium pegmatite at Bikita, Rhodesia.
Flanagan (1978)	Lithium pegmatites of Quebec and eastern Canada.

Many pegmatites contain no lithium minerals--in fact lithium-bearing pegmatites are relatively rare. One study of the numerous pegmatites in New England by Cameron and others (1954), makes only brief mention of lithium minerals. Of those pegmatites that contain lithium minerals, some contain predominantly lepidolite, others spodumene, and only rarely does petalite occur in commercial quantities. Such lithium minerals as amblygonite, eucryptite, and cookeite occur chiefly as minor accessory minerals in most lithium pegmatites.

Two major structural subtypes of lithium pegmatites have particular significance in mining and milling operations as well as in studies of deposit origin. These are: (1) zoned pegmatites, typical of the Black Hills region of South Dakota, and (2) unzoned pegmatites, typical of the North Carolina spodumene belt. Heinrich (1976) has compared the zoned pegmatites from Bernic Lake, Manitoba; Bikita, Rhodesia; and Verutrask, Sweden, and described layers or zones rich in lithium minerals. A typical spodumene zone may contain 10 to 30 percent spodumene with quartz and feldspar as the principal gangue minerals. The unzoned pegmatites from the North Carolina spodumene belt contain an average 20 percent spodumene throughout the width and length of the pegmatite dike or pod-shaped ore body. Although zoned pegmatites commonly contain individual spodumene crystals more than 3 feet (1 m) long, and this large average crystal size facilitates the hand sorting of ore minerals, the uniform grade of unzoned pegmatites is more conducive to mechanized mining and milling methods. Ore from unzoned pegmatites also requires a beneficiating technique, usually flotation of the ground rock, to concentrate the ore minerals and to separate them from the gangue minerals. Unzoned pegmatites are less common than zoned pegmatites. Major unzoned lithium pegmatites in addition to those in North Carolina are known to occur primarily at Manono, Zaire (Geomines company report, 1967), and locally in the Yellowknife area of the Canadian Northwest Territories (Lasmanis, 1978).

Brines

Until recent years very little research was done on the geologic occurrence and geochemsitry of lithium-bearing brines as an alternate source for lithium competitive with lithium pegmatites. The first byproduct recovery of lithium from a subsurface brine at Searles Lake, California, (70 ppm Li) was a result of the need to eliminate a problem that lithium caused in the recovery of the major products (borates, potash, soda ash, and salt cake). The answer described by Rykken (1976) was to remove the lithium as Li_2NaPO_4, beginning in 1936. By 1951 a plant was built to convert the product to lithium carbonate. Lithium-carbonate recovery was terminated in 1978 when a new refinery was put into operation in which lithium no longer interfered with the recovery of other products. Meanwhile, the subsurface brine at Clayton Valley, Nevada, (300 ppm Li) became a primary source for lithium about 1967, with lithium carbonate as the final product. To date, these are the only brines that have actually been used commercially as a source of lithium. Two different brine-recovery operations at Great Salt Lake, Utah, (40-60 ppm Li) have included lithium recovery in their plans but ended up rejecting the plans for economic reasons. Tentative plans for the recovery of lithium from concentrated brines at Salar de Atacama (1,500 ppm Li) in northern Chile were announced in the January 18, 1980, Mining Journal, but no date given when the operation is expected to begin. The liquid extraction of lithium from oilfield brines of the Smackover type (100-500 ppm Li) has been accomplished by Dow Chemical Company at the mini pilot-plant stage (Dennys Miller of Dow Chemical Co., oral commun., 1980), but no date for commercial operation has yet been announced. The extraction of lithium from geothermal brines in the Imperial Valley area of California (as much as 200 ppm Li) has been discussed (Berthold and Baker, 1976), but again no commercial plans announced to date, probably because of waste-disposal problems if saltwater is not pumped back into the ground. The Dead Sea provides Israel with a number of important mineral commodities, including magnesium, potash and bromine (Gradus, 1977), but has yet to be developed for the production of lithium. The British Mining Journal announced in March of 1979 that the New China News Agency has reported lithium accumulations believed to be the largest in the world in salt lakes on the Tibetan plateau, but gave no details of the occurrence or plans for its utilization.

Other closed-basin evaporite sequences that may be worthy of further exploration for lithium brines include additional salars or playas in the South American Andes of Chile, Bolivia, Peru, and Argentina, the Rift Valley closed-basin lakes in Africa, the salt deposits and sabkhas along the Red Sea and Persian Gulf coasts, the salt body in the Danakil depression of Ethiopia, the Turkish (Anatolian) plate boundary zone, the central Asian closed-basin lakes and salt deserts, and the Cenozoic evaporite basins of the Mediterranean region. (The evaporite basins in Australia have been examined for the occurrence of potash and incidentally for lithium without notable success).

Other marine evaporite basins that may be worthy of further exploration for lithium brines include all those where the sequence of evaporites is known to include potash minerals, such as the Permian and Paradox Basins of the United States, the Williston Basin of the United States and Canada, the Khorat Plateau of Laos and Thailand, the Cretaceous basins of Brazil and west Africa, and the Zechstein Basin of central Europe.

Other geothermal areas worthy of further exploration for lithium brines are not readily forecast. Most active geothermal areas yield waters that are relatively dilute compared with those of the Imperial Valley, California. Even the geothermal waste waters from the Cerro Prieto geothermal powerplant in Baja, California, Mexico, about 25 km south of the U.S. border, are relatively dilute when compared with those from the nearby Salton Sea field in the Imperial Valley. However, because of the very large quantity of waste water (reported by the Commission Federal de Electricidad, 1979, as 3,540 tons/hour even the relatively low concentration of lithium, (estimated to be about 20 ppm) produces about 600 tons of lithium per year that is concentrated by solar evaporation in a waste pond to nearly 2,000 ppm Li (oral commun., Antonio Lopez, November, 1979). Thus, other geothermal areas may also have the potential for being a source of lithium if they produce a sufficiently large quantity of waste water and occur in a setting where evaporative concentration is equally effective.

Clays

Investigations by the U.S. Geological Survey since 1974 have demonstated that lithium clays can be found in several different geologic settings. Hectorite(?) or similar lithium-bearing stevensites are probably a relatively common constituent of lacustrine sequences in alkaline closed basins. Among the probable requirements are a high concentration of dissolved magnesium and silica. Under these circumstances, thermal springs capable of introducing lithium and fluorine could result in the direct precipitation of hectorite from the aqueous phase that would accumulate as a layer of clay on the lake bottom. The occurrence of hectorite(?) in laminated evaporite sequences in the Lake Mead area, Nevada, suggestive of seasonal variations in lake temperature or chemistry, and also in sequences near Jackson, Wyoming, and McDermitt, Nevada where hectorite(?) is interbedded with relatively little-altered pumice further emphasizes its formation as an evaporite mineral. In the Montana Mountains area, Humboldt County, Nevada, lithium-bearing smectite occurs which has a significant amount of aluminum as well as magnesium in the mineral and which is associated with altered volcanic sediment containing zeolites and other authigenic minerals that testify to the diagenetic or epigenetic alteration and formation of minerals not present in the original sediment (Glanzman and Rytuba, 1978). The lithium in these deposits is probably introduced post-depositionally by hydrothermal solutions or by connate lake brines. Some of these clays in the McDermitt area of Nevada, actually contain as much as 0.7 percent lithium, which is more than occurs in typical hectorite. Most hectorite(?) and lithium-bearing smectites occur in relatively young Cenozoic sediments associated with closed basins, or volcanic activity, or both.

A third type of lithium clay is associated with high-alumina or refractory clays of near-shore or marine origin and of much greater antiquity than the previously described types. Most of the deposits noted to date are of late Paleozoic age and occur in the mid-continent or Appalachian region. They tend to be either low grade or small and hence of little or no value as a resource of lithium, but larger and higher grade deposits might be discovered if their origin possibly could be related to recognized geologic processes. In Missouri, some of these deposits fill cylindrical openings in limestone that could be variously interpreted as sink holes or pipes. The term pipe is preferred because no particular process of formation is implied. Because lithium is much more likely to be found in significant concentrations in ground water than in surface water, these lithium clays probably are related to lithium-bearing ground water derived from some deep-seated source such as a geothermal area, a tectonic feature, or to a source of brine. The principal clay mineral is generally kaolinite, sometimes in association with diaspore, but the lithium-rich clays studied by H. A. Tourtelot (oral commun., 1979) also generally contain a 14Å clay mineral. Because cookeite is a 14Å lithium-aluminum chlorite it could account for the 14Å clay peak as well as the high lithium content, which is as high as 0.5 percent. Positive identification of the lithium-bearing mineral is hampered, however, by the generally fine texture of the rock minerals. Further search for high-alumina clay deposits of sufficient size and grade to constitute a resource for lithium could be facilitated by additional studies designed to understand their origin and distribution, and, hence, lead to the formulation of prospecting guides. Until then, any discoveries will be largely happenstance.

The differing physical and chemical properties among various lithium-bearing clay minerals will have an important bearing on the selection of metallurgical extraction techniques. Table 8 lists some of the types of deposits that might be distinguished on the basis of a preliminary and incomplete understanding of their properties. A more thorough study of lithium clay types, making use of modern techniques with supporting chemical data to characterize each species, would be of considerable value in devising suitable extraction techniques as well as in understanding the origin and distribution of each.

Table. 8--Physical and chemical properties of some lithium clays

Mineral name	Li	Al	Mg	F	Relative dispersion of clay in water	Relative Li solubility in water
	(percent or relative amount)					
Hectorite[1]--------	0.5	Trace	Major	5.0	Very high	Low.
Li-stevensite[2]----	0.4	Low	Major	5.0	Variable	High.
Li-smectite[3]------	0.7	Medium	Low	Low	Poor	Low.
Li-bearing high--- alumina clay[4]	0.5	High	None	None	Very poor	Very low.

[1] Type material from Hector clay pit, San Bernardino County, California.

[2] Representative material from Kirkland area, Yavapai County, Arizona.

[3] Representative material from Montana Mountains, Humboldt County, Nevada.

[4] Representative material from Missouri fire-clay district, Mint Hill area, Osage County, Missouri. Probably a mixture of kaolinite, cookeite, and possible diaspore.

Hectorite, $Na_{0.33}(Mg, Li)_3Si_4O_{10}(F, OH)_2$, from the type locality in the Mojave Desert of California is a magnesium smectite that is readily dispersed in water to a gel-like consistency. The gel can be flocculated by treatment with an acid or in an electrolyte. Hectorite is a trioctahedral smectite with a characteristic X-ray pattern, including the 001 peak at about 15 angstroms (Å), and the 060 peak at about 1.519Å (61° 2-theta, using Cu K-alpha radiation). Ames and others (1958) proposed that it was formed by hydrothermal alteration of volcanic ash, but field evidence indicates that hectorite may also form as a chemical precipitate in a saline lake environment. Lithium-stevensite is chemically intermediate between hectorite and stevensite, $Mg_3Si_4O_{10}(OH)_2$, but contains less lithium and fluorine than hectorite. Note that Starkey and Blackmon (1979, p. 23) defined similar material as lithium saponite. This is apparently a less-stable structure than hectorite as the lithium in some samples is more readily soluble in water[5]. Moreover, some samples do not form a good dispersion in water. Lithium-stevensite is probably the hectorite-like mineral most frequently found in saline lake sediments, sometimes in association with pumice or unaltered volcanic ash, but it may also be associated with zeolitic alteration of volcanic ash. The X-ray pattern for lithium-stevensite is indistinguishable from that for hectorite. Another lithium-smectite with as much as 4 percent Al in the structure differs significantly from hectorite and lithium-stevensite (May and others, 1980, p. 5). Some samples from the Montana Mountains area of the McDermitt caldera, Humboldt County, Nevada, have been reported by R. K. Glanzman (oral commun., 1979) to contain nearly 0.7 percent lithium. Some samples show 060 peaks at both 61° and 62° 2-theta, indicating a possible mixture of dioctahedral and trioctahedral clay minerals. The lithium-bearing high-alumina clay deposits from the Missouri refractory-clay district are quite different from any of the previously mentioned clay-mineral species. Preliminary studies by H. A. Tourtelot (oral communication, 1980) suggest that these samples consist of a mixture of at least two minerals, probably kaolinite, $Al_2Si_2O_5(OH)_4$, and cookeite, $(Li, Al_4)Si_3AlO_{10}(OH)$. The conditions under which this mixture formed are not understood.

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[5] During lithium analyses of numerous samples, Allen L. Meier found that much of the lithium could be removed from some samples by a simple water leach.

A preliminary classification of lithium anomalies and deposits

Mineral resources are subject to precise measurement only under specified economic and technologic conditions. Just as the value of a field of wheat is not determined until after the harvest and the farmer makes a sale, so the value of an ore deposit in the ground is not determined until after it is mined, milled, and the product sold. Similarly, as the value of the wheat crop may vary with the quality of the harvested grain, the value of a mineral deposit is subject to many variables. The definition of legally and economically extractable ore can be a function of commodity prices, labor market, technology, land-use decisions, and geologic bias.

1. Price changes mean that lower grade material is included in ore estimates when the price goes up and that only higher grade material is economically recoverable when the price goes down. For those types of deposits that have a broad and gradual transitional zone between ore and barren rock, any price change can make a significant difference in resource calculations. For orebodies that have uniform grade but sharp boundaries with barren rock a price change can mean all or none of it is ore.

2. Labor-market changes, especially unresolved disputes, are a common cause for the failure of mining ventures, and are perhaps nearly as important as price changes.

3. Technologic improvements can significantly increase the mineral-resource base by making new types of deposits competetive with more conventional deposits.

4. Land-use decisions that designate lands for nonmineral purposes limit exploration, and hence reduce resources because the decision-makers necessarily assume that lands worth setting aside for mineral development have previously been identified. Although this assumption may be largely true for such bedded deposits as coal that are easily recognized and have predictable continuity, the identification of lithium brines and lithium clays is largely unknown and unpredictable. Once land is designated for any nonmineral use, exploration will cease because there is no reasonable expectation of recovering the expense of exploration. Time has nearly run out when public lands can be viewed as having vast mineral potential. Most land not already set aside for nonmineral uses are effectively withdrawn pending final designation for special uses. Potential resources of lithium in these areas

will remain unevaluated for the foreseeable future even though the public lands of the United States amount to nearly one-third of the total.

5. Exploration geologists tend to prejudice their search for new deposits by their understanding of previously exploited deposits. Thus, unusual or unfamiliar deposits may go unrecognized for years. This is especially true when the resource sought is not readily distinguishable by color, density, texture, or radioactivity. Nonpegmatite lithium minerals tend to fall into this category because they resemble common rock minerals. Chemical analysis is generally required for their identification. Thus, hectorite has generally been regarded as an uncommon mineral and thus of little significance as a resource for lithium. Recent discoveries of large hectorite(?) deposits suggest they may indeed have resource potential. Eventual discoveries of large deposits of cookeite, bikitaite, lilthiophorite, and sedimentary lithium phosphates and carbonates may have to await an increase in demand and price.

In evaluating anomalous localities for a commodity such as lithium, common practice is to collect samples for analysis even though it is not known whether the sample is representative of a significant tonnage of rock. A typical channel sample or drill-hole sample may be representative of a specified bed thickness, but the continuity along strike and down dip can be only roughly inferred from geologic evidence. Thus, a scheme for preliminary classification of anomalies has been devised, figure 4, that uses only the lithium content and thickness data to provide a basis for deciding whether the locality is sufficiently anomalous to be worthy of further study. Additional samples are always required to demonstrate continuity of tonnage and grade or to assign an anomalous locality to a resource category. A resource classification can then be devised that parallels the preliminary classification using tonnage and grade to replace thickness and grade to classify the ore.

A preliminary classification of anomalous lithium-bearing brines and waters requires consideration of both the lithium content and the chemical characteristics of the water, as shown on figure 4. For most water or brine samples an estimate of the quantity of water represented by the sample is not practical as this would require a measure of reservoir-capacity data not generally available except by expensive engineering tests. Exceptions include

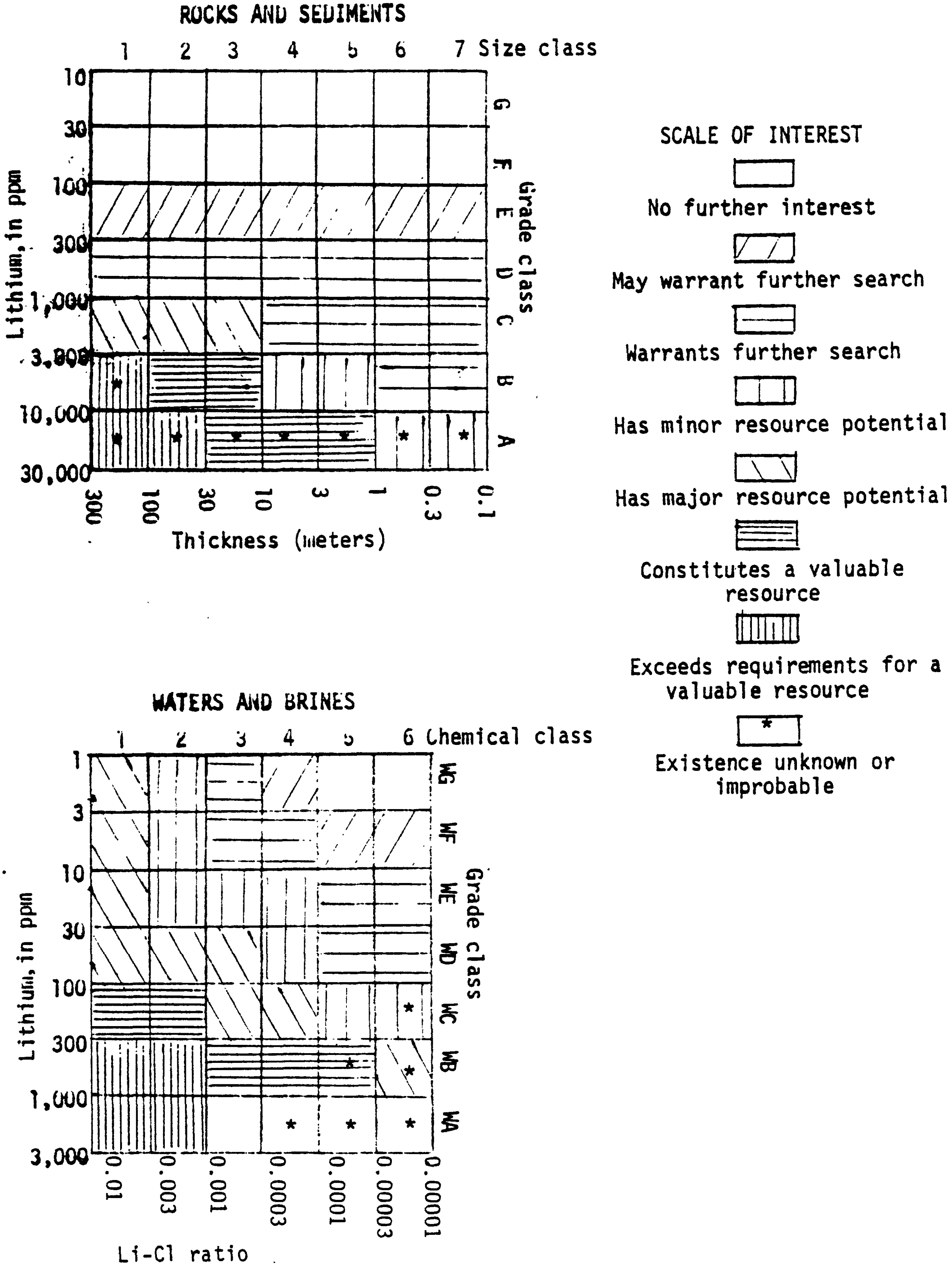

Figure 4.--Classification guide for lithium deposits and anomalies.

standing bodies of water such as Great Salt Lake whose area and depth are known, or samples from subsurface aquifers such as at Searles Lake where accumulated pumping data permit an interpretation of reservior capacity. The preliminary calssification of anomalous lithium-bearing brines and waters used in figure 4 is based on lithium content and the ratio of lithium to chloride. This ratio, Li:Cl, is a useful means of recognizing both brines and relatively dilute waters that could evolve by evaporative concentration into an economically valuable source of lithium. It does not take into account other chemical characteristics such as a high ratio of Mg:Li, or of Ca:Li that could seriously complicate the economics of lithium recovery.

For both preliminary classification guides, figure 4, the scales chosen approximate a logarithmic scale with each order of magnitude divided into two nearly equal intervals, whose boundaries are multiples of the numbers 1 and 3. Because further interest in any anomaly is a function of size or chemical characteristics as well as of grade, a scale of interest is shown as an overlay on the data matrix. Note also that both preliminary classification guides cover a range of sample from worthless to occurrences whose size and grade exceed anything presently known to exist in nature.

Lithium anomalies and deposits in the United States

Although lithium is a rare element in the sense that it is widely dispersed at extremely low levels of concentration throughout many kinds of geologic environments, it is also recognized in anomalous concentrations at a number of localities. A tabulation of this locality data, organized into the three principal kinds of deposits previously described is presented here. Lithium-bearing pegmatites, veins, and greisen are listed in table 9. Lithium-bearing brines and waters are listed in table 10. Lithium deposits and occurrences in rocks of sedimentary and volcanogenic origin are listed in table 11. The localities listed in these tables are keyed to the map of the United States, figure 5. Only a few of these localities are known to have a sufficient accumulation of lithium to warrant inclusion in a list of lithium resources.

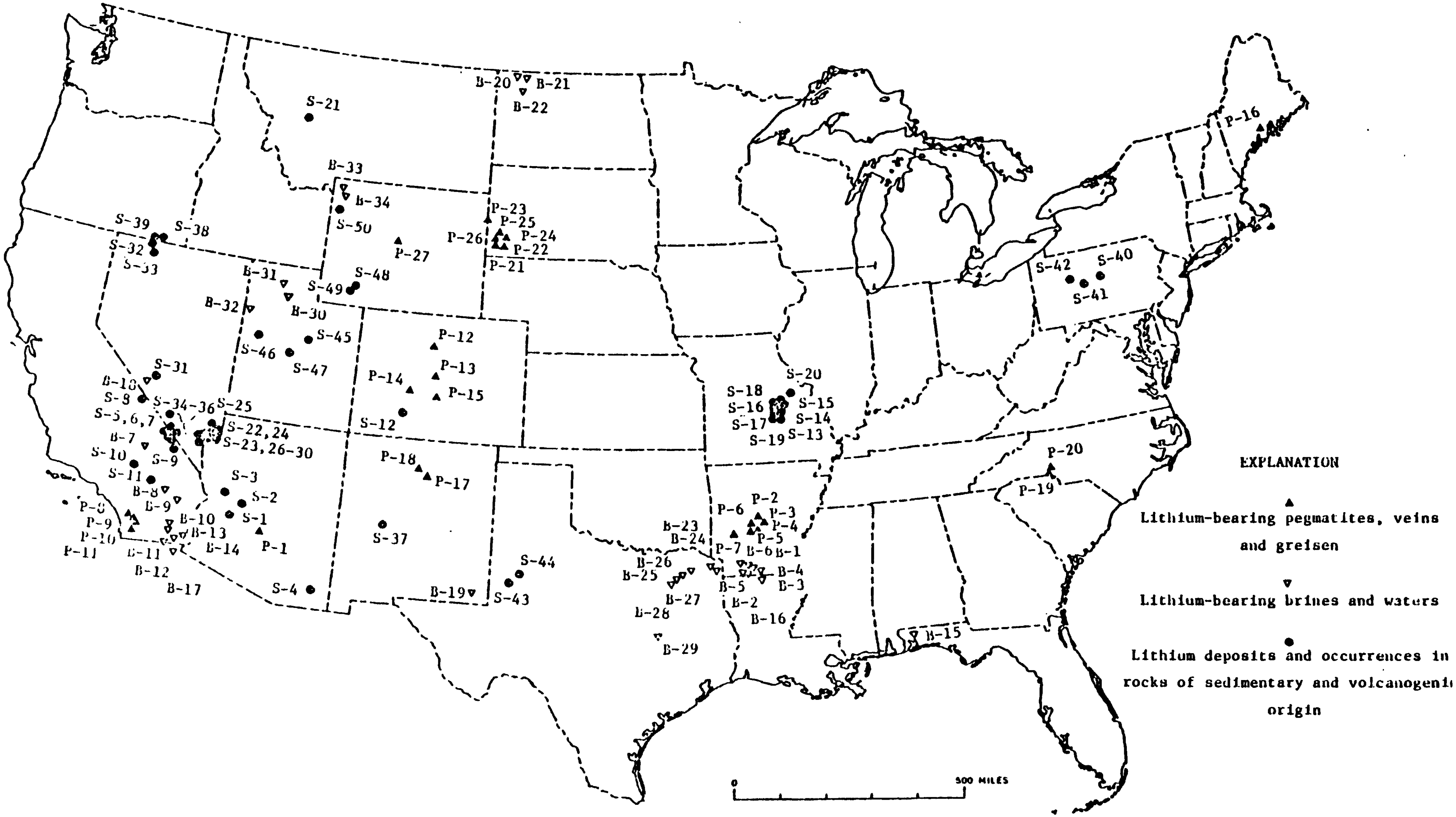

Figure 5.--Map showing lithium deposits and occurrences of anomalous lithium in the United States.

Table 9.--Lithium-bearing pegmatites, veins, and greisen in the United States

Locality number (see fig. 5)	Locality name	State and County	Type 1/ of deposit	Reference
		ARIZONA		
		Yavapai and Maricopa Counties		
P1	White Picacho		zPgl	Jahns (1952).
		ARKANSAS		
		Pulaski County and Perry County		
P2	Lake Sylvia area		Vc	Stone and Milton (1976).
P3	Little Rock-Ouachita frontal area		Vcx	Do.
		Hot Springs County		
P4	Magnet Cove		Vm	Do.
		Garland County		
P5	"V" intrusive		Vm	Do.
P6	Coleman-Teal crystal quartz veins		Vx	Do.
		Montgomery and Polk Counties		
P7	West-central manganese district		Vx	Do.

Table 9.--Lithium-bearing pegmatites, veins, and greisen in the United States--Continued

Locality number (see fig. 5)	Locality name	State and County	Type 1/ of deposit	Reference
		CALIFORNIA		
		San Diego County		
P8	Pala		zPgl	Jahns (1954).
P9	Mesa Grande		zPg	Do.
P10	Rincon		zPg	Do.
P11	Ramon		zPg	Do.
		COLORADO		
		Boulder County		
P12	Camp Albion		Ve	Wahlstrom (1940).
		Fremont County		
P13	Eight-mile Park area		zPl	Hanley and others (1950).
		Gunnison County		
P14	Quartz Creek area		zPsl	Do.
		Park County		
P15	Badger Flats area		VG	Hawley (1969).

Table 9.--Lithium-bearing pegmatites, veins, and greisen in the United States--Continued

Locality number (see fig. 5)	Locality name	State and County	Type 1/ of deposit	Reference
		MAINE		
		Knox County		
P16	Knox County district		zp	Kesler (1960, p. 525).
		NEW MEXICO		
		Mora County		
P17	Pidlite mine		zPl	Jahns (1953, p. 1181).
		Taos County		
P18	Harding mine		zPlsg	Jahns (1951).
		NORTH CAROLINA		
		Cleveland County		
P19	Kings Mountain		uPs	Kesler (1976).
		Gaston County		
P20	Bessemer City		uPs	Do.

Table 9.--Lithium-bearing pegmatites, veins, and greisen in the United States--Continued

Locality number (see fig. 5)	Locality name	State and County	Type 1/ of deposit	Reference
		SOUTH DAKOTA		
		Custer County		
P21	Tin Mountain mine		zPs	Norton (1975, p. 132-149).
P22	Beecher mines		zPg	Do.
		Lawrence County		
P23	Tinton district		zPs	Do.
		Pennington County		
P24	Keystone district		zPsl	Do.
P25	Hill City district		zPs	Do.
P26	High Climb mine		zPs	Do.

Table 9.--Lithium-bearing pegmatites, veins, and greisen in the United States--Continued

Locality number (see fig. 5)	Locality name	State and County	Type 1/ of deposit	Reference
		WYOMING Fremont County		
P27	Copper Mountain--		zP1	Zen Merritt (written commun. 1975).

1/ Type of deposits: P, Pegmatite; V, vein; G, Greisen; z, zoned; u, unzoned, 1, lepidolite; s, spodumene; g, gem minerals; e, eckermanite (lithium asbestos); m, lithium mica; c, cookeite; x, lithiophorite (Mn-oxide).

Table 10.--Lithium-bearing brines and waters

Locality number	Locality name	State and County (or Country and State)	Type1/	Reference
		ARKANSAS		
		Columbia County		
B1	Kerlin field		0	Collins (1974, 1976).
B2	Walker Creek field		0	Do.
B3	Pine Tree field		0	Do.
B4	Brister field		0	Do.
		Lafayette County		
B5	Dooley Creek field		0	Do.
B6	Midway field		0	Do.
		CALIFORNIA		
		Imperial county		
B7	Salton Sea geothermal area		G	Elders and others (1972); Elders (1979).
B8	Brawley geothermal area		G	Do.
B9	Heber geothermal area		G	Do.
B10	Holtville geothermal area		G	Do.
B11	East Mesa geothermal area		G	Do.

Table 10.--Lithium-bearing brines and waters--Continued

Locality number	Locality name	State and County (or Country and State)	Type[1]	Reference
		CALIFORNIA San Bernardino County		
B12	Searles Lake		E	Smith, G. I. (1976).
B13	Bristol Lake		E	J. D., Vine (unpub. data).
B14	Danby Lake		E	Do.
		FLORIDA Santa Rosa		
B15	Unidentified		0	Collins (1974, 1976).
		LOUISIANA Clairborne County		
B16	Unidentified		0	Collins (1974, 1976).

Table 10.--Lithium-bearing brines and waters--Continued

Locality number (see fig. 5)	Locality name	State and County (or Country and State)	Type[1]	Reference
		MEXICO Baja California		
B17	Cerro Prieto geothermal plant		G	Elders (1979).
		NEVADA Esmeralda County		
B18	Clayton Valley		E	Kunasz (1974).
		NEW MEXICO Eddy County		
B19	Waste Isolation Pilot Plant		E	Lambert (1978).

Table 10.--Lithium-bearing brines and waters--Continued

Locality number (see fig. 5)	Locality name	State and County (or Country and State)	Type1/	Reference
		NORTH DAKOTA		
		Divide County		
B20	Noonan field		0	Collins (1976).
		Burke County		
B21	Lignite field		0	Do.
		Williams County		
B22	Beaver Lodge field		0	Do.
		TEXAS		
		Cass County		
B23	Byron Mills field		0	Collins (1974, 1976).
B24	Frost field		0	Do.
		Wood County		
B25	Yantis		0	Do.
		Franklin County		
B26	Putoff		0	Do.

Table 10.--Lithium-bearing brines and waters--Continued

Locality number (see fig. 5)	Locality name	State and County (or Country and State)	Type1/	Reference
		TEXAS		
		Raines County		
B27	Deosinia		0	Collins (1974, 1976).
		Van Zandt County		
B28	Edgewood field		0	Do.
		Robertson County		
B29	Unidentified		0	Do.
		UTAH		
		Weber, Davis, Salt Lake, Tooele and Box Elder Counties		
B30	Great Salt Lake (south arm)		E	Whelan and Petersen (1976)
B31	Great Salt Lake (north arm)		E	Do.
B32	Great Salt Lake Desert		E	Do.

Table 10.--Lithium-bearing brines and waters--Continued

Locality number (see fig. 5)	Locality name	State and County (or Country and State)	Type1/	Reference
		WYOMING Park County		
B33	Norris Geyser Basin, Yellowstone National Park		G	White, Thompson and Fournier (1976)
B34	Heart Lake Geyser basin		G	Do

1/ Type of brine: 0, oil-field formation water; G, geothermal; E, evaporite basin.

Table 11.--Classification of lithium deposits and occurrences in rocks of sedimentary and volcanogenic origin in the United States

Locality number (see fig. 5)	Locality name	State and County	Deposit class (see fig. 4)	Reference1/
		ARIZONA		
		Cochise County		
S4	Willcox Playa		D3	Vine and others (1979).
		Mohave County		
S3	Wikieup area		C7	Sheppard and Gude (1973).
		Yavapai County		
S1	Date Creek uranium district		C6	Glanzman, Rytuba and Otton (1979); (Sherborne and others 1979).
S2	Kirkland area		B5	Norton (1965).

Table 11.--Classification of lithium deposits and occurrences in rocks of sedimentary and volcanogenic origin in the United States--Continued

Locality number (see fig. 5)	Locality name	State and County	Deposit class (see fig. 4)	Reference1/
		CALIFORNIA		
		Inyo County		
S5	Alkali Flat subsurface clays		D3	J.D. Vine (unpub. data).
S6	Amargosa desert borate pits		D6	(Denny and Drewes, 1965).
S7	Death Valley borate mine		C7	J. D. Vine (unpub. data).
S8	Eureka Valley subsurface clays		D3	Morgan (1979).
S9	Lake Tecopa		D3	Starkey and Blackmon (1979).
		Kern County		
S10	Kramer borate mine		C3	Morgan and Erd (1969).
		San Bernardino County		
S11	Hector clay pit		B5	Ames and others (1958).

Table 11.--Classification of lithium deposits and occurrences in rocks of sedimentary and volcanogenic origin in the United States--Continued

Locality number (see fig. 5)	Locality name	State and County	Deposit class (see fig. 4)	Reference1/
		MISSOURI		
		Gasconade County		
S13	Canaan pit		C6	H.A. Tourtelot (written commun., 1979); Tourtelot and Brenner-Tourtelot (1978)
S14	Rosebud Edel Toppmeier area		C6	Do.
S15	Drake area		C6	Do.
		Maries County		
S16	Lanes Prairie		C6	Do.
S17	Light area (south)		C6	Do.
		Osage County		
S18	Hope-Mint Hill-Crook area		C5	Do.
		Phelps County		
S19	Royal area		C6	Do.
		Warren County		
S20	Pinckney Ridge area		C6	Do.
		MONTANA		
		Powell, Lewis and Clark Counties		
S21	Beaver Creek (NW of Lincoln)		C6	Brenner-Tourtelot, Meier and Curtis (1978).

Table 11.--Classification of lithium deposits and occurrences in rocks of sedimentary and volcanogenic origin in the United States--Continued

Locality number (see fig. 5)	Locality name	State and County	Deposit class (see fig. 4)	Reference[1]
		NEVADA		
		Clark County		
S22	Devils Throat area		C5	R.K., Glanzman (written commun., 1977).
S23	Gale Hills area		D4	E.B., Tourtelot (written commun., 1976).
S24	Horse Spring area		D4	R.K., Glanzman (written commun., 1977).
S25	Overton Ridge magnesite prospects		D4	Bohannon (1976a).
S26	Lava Butte area		C2	Brenner-Tourtelot (1979).
S27	3-Kids manganese mine		C5	Do.
S28	West End Wash borate district		C4	J.D. Vine (unpub. data).
S29	West End Wash upper unit		C3	Do.
S30	White Basin borate district		C3	Bohannon (1977b).
		Esmeralda County		
S31	Clayton Valley playa		C4	J. D. Vine (unpub. data).

Table 11.--Classification of lithium deposits and occurrences in rocks of sedimentary and volcanogenic origin in the United States--Continued

Locality number (see fig. 5)	Locality name	State and County	Deposit class (see fig. 4)	Reference1/
		Humboldt County		
S32	Bull Basin (McDermitt caldera)		B6	Glanzman and others (1978). Rytuba and Glanzman (1979).
S33	Montana Mountains (McDermitt caldera)		B3, C2	Do. Do.
		Nye County		
S34	Amargosa Desert marl		D5	J.R. Davis (written commun., 1977).
S35	Beatty area volcanic ash		C6	J.D. Vine (unpub. data).
S36	Ash Meadows clay pits		D6	Do.
		NEW MEXICO		
		Socorro County		
S37	Rio Salado area		C7	Brenner-Tourtelot and Machette (1979).

Table 11.--Classification of lithium deposits and occurrences in rocks of sedimentary and volcanogenic origin in the United States--Continued

Locality number (see fig. 5)	Locality name	State and County	Deposit class (see fig. 4)	Reference[1]
		OREGON Malheur County		
S38	Cottonwood Creek-Bretz area		C3	Glanzman, McCarthy, and Rytuba (1978); Rytuba and Glanzman (1979); Rytuba (1976).
S39	Opalite		C4	Do.
		PENNSYLVANIA Clinton County		
S40	Beech Creek area		C6	H.A. Tourtelot (written commun., 1979); Tourtelot and Brenner-Tourtelot (1978).
		Clearfield County		
S41	Deemer pit		C6	Do.
		Jefferson County		
S42	Brookville area		C6	Do.

Table 11.--Classification of lithium deposits and occurrences in rocks of sedimentary and volcanogenic origin in the United States--Continued

Locality number (see fig. 5)	Locality name	State and County	Deposit class (see fig. 4)	Reference1/
		TEXAS Gaines County		
S43	Cedar Lake area		C6	Goolsby, Reeves, and Lee (1977).
		Lynn County		
S44	Wilson Lake area		C7	Goolsby (1975).
		UTAH Duchesne County		
S45	Indian Canyon area		E2	Dyni (1976).
		Juab County		
S46	Spor Mountain beryllium deposits		B6	Lindsey, Ganow, and Mountjoy (1973).
		Sanpete County		
S47	Ephraim area		C7	Tettenhorst and Moore (1978).

Table 11.--Classification of lithium deposits and occurrences in rocks of sedimentary and volcanogenic origin in the United States--Continued

Locality number (see fig. 5)	Locality name	State and County	Deposit class (see fig. 4)	Reference1/
		WYOMING		
		Sweetwater County		
S48	Green River area		D6	Fahey (1962, p. 15).
S49	Rock Springs area		D7	Bradley and Fahey (1962).
		Teton County		
S50	Shadow Mountain area (north of Jackson)		C6	Love (written commun., 1973).

1/ Principal reference to the occurrence of lithium and /(or) a more general reference (in parentheses) to the geology of the area. Where only a reference to the areal geology is given it is because no published account of the lithium occurrence is available.

Lithium reserves and resources

The U.S. Geological Survey (USGS) and U.S. Bureau of Mines (USBM) have combined efforts to develop a uniform method of reporting reserves and resources of the various mineral commodities for which each agency has a specific responsibility. In general, the USBM has responsibility for compiling and reporting reserve data that they obtain from industry, whereas the USGS has the broader responsibility of evaluating potential future resources of these same commodities based on an understanding of the mineral occurrence and an extrapolation of available geologic data.

Definitions for the terms "reserves" and "resources", as jointly agreed upon by the two Federal agencies, was based on the concept of economic recoverability (McKelvey, 1972). The tonnage and grade of material in the ground could be measured as precisely as needed by analyses of drilled sample or by surface-sampling techniques, but this data was reduced by a factor assigned for recoverability--for example, 50 percent for coal, or 30 percent for petroleum. The resulting combination of data was no more precise than the least precise figure used to derive the data. Commonly the least precise figure was the recoverability factor. In order to avoid this pitfall and adhere to the data for which the geologist is primarily trained and qualified to judge, there has been a growing tendency to report only the tonnage and grade data, and to leave the estimate of recoverability to the mining engineers and economists who are trained to make these estimates. Thus, the latest annual volume of the USBM volume, entitled: "Mineral Commodity Summaries, 1980" uses a heading "Reserve Base", which is intended to refer to the new definition of material in the ground, or "in place." The 1980 revision of the resource classification system is set forth along with definitions of the new terms in U.S. Geological Survey Circular 831.

Most previous estimators of lithium reserves and resources have generally adhered to the older definitions of these terms, or they devised their own set of definitions. For example, the report of the Lithium Subpanel[6] of the

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[6] The Lithium Subpanel consisted of Thomas L. Kesler, chairman, Ihor A. Kunasz of the Foote Mineral Company, R. Keith Evans of the Lithium Corporation of America, and James D. Vine of the U.S. Geological Survey. The original data were quoted by Evans (1978).

Committee on Nuclear and Alternative Energy Sources (CONAES) of the National Research Council estimate of lithium resources prepared as of August, 1976, uses their own definitions to distinguish four classes of reserves and resources. This data is here reinterpreted and in a few instances updated to fit the new USGS-USBM definitions for reserve base (tables 12A, 12B, 12C, and 12D). However, because there is a significant loss in going from the reserve base which represents resources in the ground to the quantity of lithium that eventually reaches the market place, probable-yield figures are also given. Because probable yield is a function of recoverability plus imperfect forecasts of economic, political, and sociological trends, this figure is only intended to provide the reader with a point of departure from which he can make his own forecast of the amount of lithium that will reach the market place. The object in showing probable yield is to provide the reader with a reasonable figure for the bottom line rather than only a resource figure, which is too easily misinterpreted as the quantity of lithium available to industry at any time.

Table 12A.--Lithium reserve base and probable yield

Locality name	Lithium ore and brine (x 10^6 tonnes)		Grade (percent Li)		Reserve base (x 10^6 tonnes)[1]		Percent ultimately recoverable		Probable yield (x10^6 tonnes)	
									Ultimate	By year 2000
Pegmatites										
North Carolina spodumene-belt	65.4		0.69		0.45					
Barraute, Quebec	13.6		0.58		.079					
Bernic Lake, Manitoba	4.5		1.38		.062					
Canada, Yellowknife, N.W.T.[1]	20		.65		.13					
Canada (other localities)	26.4		.57		.151					
Bikita, Zimbabwe	5.1		1.4		.071					
Manono, Zaire[2]	30		.6		.18					
Karibib, South West Africa	.45		1.4		.006					
Australia	4.3		.69		.03					
Brazil	2.5		.7		.017					
Argentina	.14		.7		.001					
Total (pegmatites)[3]	175	x	0.69	=	1.2	x	65	=	0.8	0.5
Brines										
Silver Peak, Nevada	200		0.02		0.04					
South America[4]	1000		.1		1.00					
Totals (brines)[3]	1200	x	0.086	=	1.04	x	33	=	0.3	0.1
GRAND totals[3]	1400				2.3				1.1	0.6

Table 12B.--Lithium inferred reserve base and probable yield

Locality name	Lithium ore and brine (x 10^6 tonnes)		Grade (percent Li)		Inferred reserve base (x 10^6 tonnes)		Percent ultimately recoverable		Probable yield (x 10^6 tonnes)	
									Ultimate	By year 2000
					Pegmatites					
North Carolina spodumene-belt-	42		0.69		0.29					
Maine-------------------------	.5		.58		.003					
Barraute, Quebec--------------	10		.58		.058					
Canada, Yellowknife, N.W.T.[1]--	30[4]		.65		.19					
Canada (other)----------------	11.4		.53		.06					
Bikita, Zimbabwe--------------	5.4		1.4		.076					
Manono, Zaire[2]----------------	30		.6		.18					
Karibib, South West Africa----	.65		1.4		.009					
Australia---------------------	3.2		.69		.022					
Brazil------------------------	2.6		.7		.018					
Total (pegmatites)[3]-----	135	x	0.68	=	0.9	x	65	=	0.6	0.08
					Brines					
Silver Peak, Nevada---------	385		0.02		0.08					
South America[4]--------------	2000		.1		2.					
Total (brines)[3]--------	2400	x	0.087	=	2.1	x	33	=	0.7	0.07
GRAND totals[3]----------	2510				3.				1.3	0.15

Table 12C.--Subeconomic and undiscovered in-place resources of lithium and probable yield

Locality name	Lithium ore and brine (x 10^6 tonnes)	Grade (percent Li)	In-place resource (x 10^6 tonnes)	Percent ultimately recoverable	Probable yield (x 10^6 tonnes) Ultimate	Probable yield (x 10^6 tonnes) By year 2000
Pegmatites						
North Carolina spodumene-belt-	750	0.69	5.2			
Canada------------------------	10	.5	.05			
Manono, Zaire-----------------	460	.6	2.75			
Totals (pegmatites)[3]---	1,200		8.0	33	3.6	0
Brines						
Great Salt Lake, Utah[4,5]----	3,000	.003	.1			
South American salars[4]------	4,000	.05	2.			
Geothermal brines[4]----------	5,000	.02	1.			
Oilfield brines[4]------------	5,000	.01	.5			
Total (brines)[3]-------	17,000		4.0	33		0.04
Clays[6]						
Nevada----------------------	1,000	.3	3			
Totals (clays)[3]--------	1,000		3	33	1	0.03
GRAND totals[3]---------	20,000		15		5	0.1

Table 12D.--Summary of in place reserves and resources of lithium and probable yield

Class of resource	Lithium ore and brine (x 10^6 tonnes)	Geologic resource (x 10^6 tonnes)[1]	Probable yield (x 10^6 tonnes)	
			Ultimate	By year 2000
		Pegmatites		
Demonstrated reserves--------	175	1.2	0.8	0.5
Inferred reserves------------	135	.9	.6	.08
Identified marginal and speculative resources------	1,200	8.0	3.0	0.0
		Brines		
Demonstrated reserves--------	1,200	1.0	0.3	0.1
Inferred reserves------------	2,400	2.1	.7	.07
Identified marginal and speculative resources-----	17,000	4.0	1.0	0.04
		Clays[6]		
Identified marginal and speculative resources------	1,000	3.0	1.0	0.03
TOTALS[3]---------------	23,000	20	7	0.8

Footnotes to tables 12A, 12B, 12C, 12D

[1] Lasmanis (1978) lists 49 million tons, which is here arbitrarily divided between demonstrated and inferred categories, and the numbers rounded.

[2] At Monono and nearby Kitotolo, Zaire, a pair of pegmatite bodies, each 5 km long and averaging nearly 400 m wide are estimated to contain the world's largest resource of spodumene ore. The CONAES report lists three categories of resources--Class A, 35 million tonnes, Class B, 85 million tonnes , and Class C, 400 million tonnes--here divided arbitrarily into 30 million tonnes reserve base, 30 inferred million tonnes reserve base, and 460 million tonnes subeconomic and undiscovered in-place resources, respectively. The pegmatite was exposed in the course of stripping the overlying weathered zone to recover tin and tantalum. Lithium recovery has been postponed, pending improvement in transportation problems (Eugene Claeys, Director, Geomines, oral communication, 1979).

[3] Figures have been rounded to avoid impression of unwarranted accuracy.

[4] Recovery of lithium as a coproduct or byproduct and hence the rate of production is highly dependent on the rate of production of other commodities.

[5] Great Salt Lake, Utah, actually contains about 7,500 million tonnes of brine. The figure of 3,000 million tonnes is arbitrarily used here, as it is unreasonable to assume that as much as half the volume could be used, or if the volume is to remain constant it is unreasonable to assume that as much as half of the lithium could be extracted.

[6] The CONAES report did not include any figures for the potential resources of lithium in clays. The figures given here are based on recent investigations of the U.S. Geological Survey in the western United States and represents a cautiously low preliminary estimate. Further field studies should vastly increase the subeconomic and undiscovered resources of lithium in clays.

For convenience, tables 12A, 12B, and 12C are arranged so that the product of lithium ore, column 1, and grade, column 2, gives the reserve base (or in-place resource), column 3. In turn, the product of column 3 and the percent ultimately recoverable, column 4, gives the ultimate probable yield, column 5. The figure in column 6 is conjectural and is not supported by a defensible precentage factor, hence none is given.

Most of the individual locality figures are taken from the report of the lithium subpanel of the Committee on Nuclear and Alternative Energy Systems (CONAES) National Research Council, dated August 10, 1976, with several exceptions recorded in the footnotes. The original two classes of resources for which geologic data are most complete, A-proved reserves, and B-indicated reserves, are here generally combined under the heading "lithium reserve base," table 12A. The original class C-inferred resources is here shown, with some exceptions under the heading "inferred reserve base," table 12B. The original class D-resources, whose extraction is dependent on major coproducts, has been combined with certain subeconomic and undiscovered resources under the heading: "subeconomic and undiscovered in-place resources," table 12C. Resources that are not expected to be recovered except as a coproduct or byproduct are identified by footnotes to the tables. These cannot be counted on during periods of rapid market expansion.

Most of the original figures for individual localities are shown with the same number of significant digits as in the original CONAES report, but the totals are generally rounded to reduce the apparent accuracy implied by too many significant digits. Further rounding is incorporated, where deemed desirable, in the products of column 1 and 2 to give column 3, and in the product of column 3 and 4 to give column 5. Because column 6 is conjectural, it is generally limited to 1 significant digit.

In estimating probable yield by the year 2,000, consideration is given to the gradual increase in demand and in price that is likely to occur as a result of the predicted new uses for lithium in batteries for electric vehicles and for storage of off-peak power. Unforeseen economic and political changes could alter these figures by a factor of 2, or more. Most of the probable yield by the year 2,000 will come from the reserve base, but a small amount may also come from the inferred reserve base and from subeconomic and undiscovered in-place resources. To avoid any implied production or lack of production from specific localities, probable yield is given only for the total resources for various categories of ore.

Figures for the percent ultimately recoverable are estimates based on highly variable industry averages and thus are not representative of any specific operation. Openpit mines commonly obtain higher recoverability than underground mines because there is no need to leave ore as roof support, and both types of mining operations tend to be more efficient than brine precipitation of the chemicals involved.

The reader should be aware that the resource data presented herein is limited to the western trading countries. Although both the USSR and China are known to have appreciable lithium resources (Singleton, 1979, p. 5) and the USSR has been an exporter of lithium chemicals in times past, there are no reliable statistics available to the writer comparable to those from the western trading countries.

Looking ahead to a bright future for the lithium industry

When compared with various major commodities, the lithium industry seems relatively small. Nonetheless, at a production rate of nearly 5,000 tonnes of lithium per year, estimated to be worth more than 60 million dollars wholesale, it is large enough to attract attention from various investors, mining companies, and chemical companies. Moreover, its potential for growth is indeed of interest to those considering entry into the industry. Because the lithium industry is small and has been subjected to sudden demand shifts resulting from government policy changes, it is especially wary of government suggestions of a future demand surge resulting from new energy-related uses for lithium. Most industry representatives are confident of their ability to meet any rapid demand increase by rapid expansion of capacity (Comer, 1978).

As of early 1980, any rapid increase in demand for lithium could most easily be met by imports from pegmatite deposits in Canada or Africa, or from brine deposits in Chile, because they are available and can be quickly produced using present technology. Thus is seen the probability that another United States mineral industry will become increasingly dependent upon foreign supplies. In all likelihood this trend will continue as long as government regulations in this country tend to discourage the exploration and development of domestic mining properties. A modest expansion of mining and refining capacity at the two existing domestic pegmatite mines is also a good possibility, but technical problems probably limit the prospects for expanding the capacity of the Clayton Valley lithium brine field near Silverpeak, Nevada. Further production increases from the United States will probably require the development of new mining and refining capacity. The choice could be either pegmatite, brine, or clay deposit. The best chance for locating a new spodumene-bearing pegmatite would be somewhere along the known North Carolina lithium-belt. The chances of finding a sizable lithium pegmatite elsewhere in the United States are poor. The second possibility would be to identify a new commercial lithium brine field, preferably in an arid part of the country where it would be possible to use solar energy to evaporate and concentrate the brine. Preliminary test holes by the U.S. Geological Survey on several playas have produced negative results but a number of good prospects remain to be tested by drilling. Known lithium-bearing oil-field formation waters are mostly rather deep and are located in areas that are poorly suited for evaporative concentration. Although the geothermal waters of the Imperial Valley are deep they do not require pumping. The first 10-megawatt plant using geothermal brines to power its turbines began operating in July, 1980, according to the Brawley News, Brawley, California, July 7, 1980. The waste brine is pumped back into the ground in order to avoid waste-disposal problems in a high-value agricultural area. The Dow Chemical Company is currently working to develop a liquid-extraction technology to recover lithium as a byproduct of bromine recovery from some of the brines from the Smackover Formation, and this may become a viable source for lithium in the near future (Dennys Miller, oral commun., 1980). The U.S. Bureau of Mines has studied the problem of liquid extraction of lithium and other products from geothermal brines (Berthold, 1976), but the problems are technically complex and the answer may not be economically feasible. Thus, it may be less expensive to recover lithium from clays such as those in the McDermitt area of Nevada and Oregon where lithium clays occur as part of the overburden that will have to be removed to get at underlying uranium deposits. This could have an advantage to both industries. A similar situation is reported by Sherborne and others (1979) to occur in the Date Creek area, Arizona.

The lithium industry is in the enviable position of having adequate reserves to meet the steady growth of conventional uses for lithium and of having a number of attractive options available for expansion should the anticipated new energy-related uses for lithium cause a rapid increase in demand. It would appear to be in the best interest of the people and government of the United States for the U.S. Geological Survey to continue to provide geologic data and prospecting guidelines so that industry can more efficiently locate and develop domestic lithium resources of various kinds in preference to developing deposits overseas.

It is appropriate here to attempt an answer to the question: Will there be enough lithium to supply the anticipated demands of the battery industry and still have enough for fusion power in the next century? The answer is a qualified yes--an adequate resource of lithium has been identified in the ground worldwide. A qualified answer is required, however, because there is no assurance that these resources will become available to the people of the United States. Much of the identified resource occurs in remote areas of the world and in countries whose political and economic future are uncertain. Such a valuable resource as lithium can be sold or withheld from the market, depending up on the political and economic advantage to those who control the resource. In the long run, for the United States will be best served by locating new resources of lithium in domestic clays, brines, and other kinds of deposits through application of geochemical, geophysical and physical exploration techniques. There is every reason to believe that industry can and will develop such deposits provided they are encouraged to do so through appropriate economic and political policies.

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