

Salt Economy of Great Salt Lake, Utah

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ABSTRACT

The sources of the salt in Great Salt Lake are investigated, the reserves of the individual ions documented, and the natural gains and losses analyzed. Also the effect of commercial extraction on the apparent balances is weighed.

It is concluded that for an average year salt in the amounts listed come from the following sources:

(1) The atmosphere brings to the Great Salt Lake watershed about 15,000 tons of new chloride yearly, which is believed to come from the Pacific Ocean.

(2) The atmosphere also picks up other salts on the desert floor and aerosol particles from the Great Salt Lake surface and deposits 36,000 tons of Cl from these sources over the watershed. The rates of 1 and 2 have probably held over the past 11,000 years. Conclusions 1 and 2 are based on fairly extensive atmospheric fallout data at 5 selected stations.

(3) The desiccation of Lake Bonneville from the Provo level to the present lake which began about 13,000 years ago, resulted in the following accumulations: (a) 130 million tons of Cl by reduction of lake volume and (b) 550 million tons due to inflow over a period of 13,000 years, assuming inflowing streams carried only fallout Cl (15 ppm).

(4) Springs bring saline waters from clay, silt, sand, and gravel beds of the Late Tertiary and Quaternary valley-fills to the surface and contribute about 660,000 tons of Cl annually to the lake.

A much higher concentration of boron and lithium relative to the other ions in Great Salt Lake than in sea water leads to the conclusion that since closed-basin conditions have prevailed there have

been volcanic contributions to the soluble contents.

Losses come from commercial NaCl extraction, about 400,000 tons, and from aerosol formation from the lake, about 74,000 tons annually.

As a result of these gains the lake now has a reserve of about 4.7 billion tons of salt, another 2 billion tons are in the recycling regimen, and 2 billion tons in the salt crusts and underclays. Salt is recycled by the atmosphere, by ground waters, and by lake rises and falls. The present streams and springs are bringing 4.7 million tons of salt to Great Salt Lake each year. Only the 15,000 tons of Cl of fallout is virgin, the rest is recycled. If it is assumed that at the beginning of arid, low lake conditions, about 11,000 years ago, that the amount of salts available for recycling was small and hence the amount in the recycling regimen was negligible; that the amount of recycled salt has risen to a maximum today; and further that the amount of recycled salt has doubled each 1000 years; then the amount of salt that should have accumulated is about 8 billion tons. This is what we measure.

The commercial extraction of the salts of potassium, magnesium, and lithium is related to the natural balances. It is concluded that the half-life of magnesium, viz.; the time consumed to reduce the concentration one half, if Gulf Resources and Chemical Corporation operates solely, is 200 years. If a second company of equal production rate is also active, then the half-life will be about 100 years. For potassium the half-life period will be 150 and 75 years, and for lithium, 75 and 38 years. It is assumed that production will cease to be profitable after the concentration has been reduced one half.

INTRODUCTION

Corporation income tax problems incident to extraction of magnesium, potassium, and lithium from the waters of Great Salt Lake have illicit the study of rates of depletion, if any, of the individual cations. To accomplish this end, an analysis of the total salt economy, including the origin and amount of the salt, was necessary.

Considerable new chemical data of the lake's waters and of the inflowing streams and springs have been obtained in the past six years, and these invite the study. Chloride fallout in the rains and snows of the Great Salt Lake watershed, as an index of salt transportation by the atmosphere, were gathered, and these tell us considerable about the primary and recycled origin of the salts in the lake. It is hoped that these facets of Great Salt Lake's economy can be reduced to a semi-quantitative basis.

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The Utah Geological and Mineralogic Survey performed the chloride analyses under the direction of D.L. Barber. This was greatly appreciated.

PROPOSED THEORIES OF ORIGIN OF SALT IN GREAT SALT LAKE

The following theories of origin of the salt have been proposed:

(1) The salt in Great Salt Lake has been derived from halite beds of Jurassic age from the Arapien Formation of central Utah after internal drainage conditions were established in the Great Salt Lake region.

(2) It has been derived from saline connate waters of marine strata of Paleozoic age, which have been released in the course of erosion. Accumulation could only have occurred since internal drainage conditions have existed.

(3) It has been brought into the Great Salt Lake drainage region by atmospheric transport from the Pacific Ocean and concentrated in the lake by surface runoff.

(4) It is relict salt from former lakes of the basin of internal drainage in late Tertiary and Quaternary time and stored in the deep valley fills but now is being released into the present economy. This salt may have come originally from sources 1, 2, or 3.

(5) It has been derived by weathering of the rocks of the drainage basin.

(6) It has been contributed partly by volcanic emanations, or by juvenile waters which emerge as thermal springs.

DERIVATION FROM JURASSIC STRATA

It was suggested in 1938 that part of the salt was derived from the Jurassic salt beds in Sevier River Valley near Redmond (Eardley, 1938), particularly because Great Salt Lake and the oceans have such similar composition (Table 1). The Sevier River empties into Sevier Lake which is approximately at the Stansbury level and is closed and separated from the lower Bonneville drainage by a shallow alluvial sill. Superficially, at least, Sevier Lake has thus not drained into Great Salt Lake since the climate assumed its present aridity, which started about 11,000 years ago (Broecker and Kaufman, 1965; Morrison, 1965; and Eardley, 1967). That Sevier River and the lake, however, find underground discharge channels into Great Salt Lake basin is most probable. Numerous springs in the Dugway Proving Grounds at the mouth of the "Old Channel" and at Fish Springs Flat into which Whirlwind Valley debouches may indicate the leakage. This spring water flows into the basin of Great Salt Lake Desert, however, and not directly

Table 1. Comparative Composition of Soluble Contents of Sea Water, Great Salt Lake Water, and Average of Streams and Springs Draining into Great Salt Lake.

	Sea Water	Great Salt Lake Water	Waters draining into Great Salt Lake
SO ₄ ⁻⁻	7.7%	6.60 - 8.21%	14.3%
Cl ⁻	55.2	54.63 - 55.88	36.3
Na ⁺	30.4	31.55 - 32.71	22.7
K ⁺	1.1	1.71 - 2.12	1.5
Mg ⁺⁺	3.7	2.91 - 3.49	3.7
Ca ⁺	1.2	.10 - .12	7.1
CO ₃ ⁻⁻	0.4	.06 - .09	12.8
Li ⁺	0.070 ppm	37.00 - 60.00 ppm	

Figures for Great Salt Lake are from 1960-1965 (Handy and Hahl, 1966, Table 1). Data for waters draining into the lake are weighted averages of sampled surficial inflow during the 1960 and 1961 water years (Hahl and Langford, 1964).

into Great Salt Lake, but if Great Salt Lake were about 25 feet higher it would flood the Great Salt Lake Desert and the salt contents would be common to both bodies of water. It is thus possible that the leaching of soluble salts from the Jurassic strata in San Pete Valley has contributed to the salines of Great Salt Lake. The fact, however, that the basins of the Ogden, Weber, and Provo—Jordan rivers each contribute large volumes of soluble salts to the lake where no or little saline Jurassic shale crops out, is adequate proof that the strata of San Pete Valley are not the sole source of the salt in Great Salt Lake.

In addition, the following comparison is informative. Sevier River drainage covers 7,496,000 acres (Mahoney, 1962) and the river contributes about 240,000 tons of Na⁺, K⁺, Mg⁺⁺, Cl⁻, and SO₄⁻⁻ each year to Sevier Lake (Eardley, *et al.*, 1957). The Bear River drainage covers 4,908,000 acres and the river carries annually about 550,000 tons of the same ions into Great Salt Lake (Hahl and Mitchell, 1963). If the comparison of the two drainages is justified, and it seems it is because both contain much Mesozoic and Tertiary sedimentary rocks, then each acre of land produces only about one-fourth as much salt in the Sevier drainage as in the Bear. There may be other factors to consider, but these data by themselves suggest that the Jurassic shales of San Pete Valley are not very large contributors.

DERIVATION FROM SALINE CONNATE WATERS OF PALEOZOIC STRATA

The postulate that the salt has been derived from saline connate waters in the old marine sedimentary rocks is difficult to analyze. Wells drilled in the search for oil in these strata have found both saline and fresh water, and deep mine workings have encountered both chloride and sulfate waters. This may indicate that some saline waters have been or are being flushed out. Existing saline springs may be deriving their salt from the old marine strata, but it seems more probable that the saline springs are bringing to the surface saline waters from the alluvial fill of Tertiary and Quaternary age in the downfaulted valleys west of the Wasatch Range. This point will be taken up later.

WEATHERING AS A SOURCE OF THE SALT

Sources of chlorine in rocks and salt.

Attention has been called by Correns (1956) to fluorine and chlorine in various rocks, and in connection with the ions of these elements in soils as a result of weathering, a few conclusions are appropriate to introduce the subject. Quoting from Correns:

"It appears that fluorine is first of all incorporated into apatite, and any excess entering mica,

hornblende and sphene. Chlorine is mainly incorporated in micas and hornblende. Part of the halogens may be present in aqueous solutions or gases in mineral inclusions, or dissolved in solid rock glasses. . . Evidently, conditions obtaining prior to the consolidation of magmatic rock—e.g., partial degassing—may decisively influence their relative proportions. . . In the weathering processes, halogens are released to the soil and to the hydro- and biospheres. The behavior of fluorine in the soil depends upon the kind of weathering—i.e., upon the breakdown of fluorine-bearing minerals, and perhaps possible combination with phosphoric acid. Chlorine is easily removed, but may return in rain water. —Coarse clastic sediments contain less than average amounts of fluorine and chlorine. —The pelites may contain larger quantities of fluorine but smaller quantities of chlorine. In limestones a substantial proportion of the fluorine is present in admixed clay materials, or combined in phosphate—. Unleachable chlorine is similarly present, generally in small quantity, in part probably in fluid inclusions. Among metamorphic rocks

may be mentioned the fluorine-rich greisen in which topaz and fluorite occur—and in skarn formation where an enrichment of chlorine in amphiboles may be noted. Scapolitization may also give rise to high chlorine contents."

Distribution of cautions in soils of Great Lake Basin.

What do we find by way of chlorine in the soils of the Great Salt Lake drainage? A wealth of data on the soils has been compiled by the U.S. Soil Conservation Service, but unfortunately analyses are made in standard practice only of the cations Ca^{++} , Mg^{++} , Na^+ , and K^+ . Chloride ion data are not obtained. Electrical conductivity is given, however, and this plus the Na^+ , K^+ , and Mg^{++} ions which appear to be combined with chlorine indicate relative abundance of chlorine in the soils of the drainage area of Great Salt Lake (oral communication A.J. Erickson, Soil Correlator, Soil Conservation Service, Salt Lake City). A sample of pertinent data of one of the soils is given in Table 2.

Table 2. Soil on Limestone and Shale
(No. 893, Midway Pass)

Depth in in.	Horizon	Cations extractable in sodium acetate				Cations soluble in water		Conduc- tivity
		Ca	Mg	Na	K	Na	K	
0-5	A ₁₁	10.9	2.2	.27	1.20	.49	.81	.4
5-15	A ₁₂	6.5	1.6	.27	1.05	.39	.46	.2
15-29	A ₁₃	6.3	0.4	.27	.59	.43	.22	.2
29-48	B ₂₁	4.0	2.5	.27	.34	.46	.16	.2
48-56	B ₂₂	4.5	1.6	.27	.31	.58	.15	.3
56-60	B ₂₃	-	-	.13	.22			.3
60+	B ₂₄	-	-	.15	.23			.36

Conductivity is in $\text{EC} \times 10^3$ Millimhos per cm at 25°C. Analyses are made only on particles on 2 mm size or smaller. Larger fragments have been screened out. The figures under cations extractable in sodium acetate are in millequivalents per 100 g. soil and under cations soluble in water in millequivalents per liter.

Some eighteen soils were selected for the study. These were all sampled at elevations of about 7,000 to 8,500 feet and east of Great Salt Lake. Some samples come from Cache Valley, some from the central Wasatch, and some from the western Uinta Mountains. The high elevation soils were chosen with the hope of securing, as much as possible, direct weathering data, with as little as possible of the effects of fallout and a minimum of contamination from irrigation. Significant observations from these soil analyses are summarized as follows:

(1) The top 1-5 inches of the mountain soils are commonly conspicuously richer in the cations than lower soil horizons. This applies to the A_1 and A_{11} horizons.

(2) The above distributions generally hold for both the cations soluble in sodium acetate, and for cations soluble in water, but there are exceptions.

(3) Cations of sodium, potassium, and magnesium commonly are distributed in the same sequence which may be highest at the top and lowest at the bottom or vice versa, or high in some intermediate horizons. However, in some soils the three cations are not in parallel arrangement (Table 3).

(4) The significance of these distributions was sought in the kind of rock from which the soil was derived. Five kinds of parent material are represented in the 18 soils namely; (1) andesite or glacial or alluvial material with abundant andesite fragments, (2) quartz diorite or glacial or alluvial material with diorite fragments abundant, (3) quartzite or sandstone or alluvium derived principally from these rocks, (4) limestone, shale and sandstone from the Oquirrh Formation, and (5) Tertiary conglomerate or alluvium on conglomerate. Little general difference of the soils can be made out by inspection of the analyses, but it is apparent that in the five andesite soils Mg^{++} and K^+ are richer than in the non-andesite soils (Table 4).

Conclusions regarding weathering

The significance of the distribution of cations in the high Wasatch soils is not obvious. It would be desirable to have chloride and sulfate ion analyses in addition to the cations in both sodium acetate extract and water extract, but these are not available. In fact, analyses of the water soluble cations of only a few soils are available. Conclusions that may be reached tentatively from the inadequate data are as follows:

(1) Mg^{++} enrichment in the lower soil horizons may indicate derivation from the bedrock. This is suggested in three of the andesite soils.

(2) The predominance of the cations in the upper inch or two of most of the soils suggest derivation from the atmosphere as fallout. Precipitation moisture at first moves downward, but upon evaporation and drying it is drawn back up and leaves the soluble cations near the surface.

(3) A high concentration of soluble cations in some intermediate soil layer is regarded as a result of a heavy rain or snow with high salt content. Considerable of the water and its contained salt would seep down below the normal depth of penetration. Considerable soil moisture usually would be drawn back up to the surface by capillary attraction during a dry spell. The intermediate salty layer is thus probably a temporary condition.

(4) More work must be done on the sodium acetate extract in order to determine the origin of its ions. The generally parallel arrangement of the ions liberated by sodium acetate solution and by water suggests that those in the acetate solution were also largely contributed by atmospheric fallout, but in time have become fixed in the soil horizons and not immediately available in water solution.

(5) Salt content of the soils is due in small measure to weathering of the underlying rock materials. Neither fallout nor rock weathering, individually or together, on the basis of data considered is adequate to account for the salt increment that the rivers and springs bring to Great Salt Lake.

However, some scientists contend that the weathering and leaching of granular aggregates derived from the highlands but now reposing in the lower basins yield substantial amounts of dissolved solids to percolating ground water. J.W. Hood, personal communication. The writer recognizes that such waters become rich in Cl^- , but regards the Cl^- to be of atmospheric origin primarily.

JUVENILE WATERS AND VOLCANIC EMINATIONS

The warm or hot springs referred to in previous paragraphs in Utah Valley together with those along the Wasatch front and around Great Salt Lake have temperatures above those of normal surface waters. A number of them emit H_2S fumes. The thermal nature and the H_2S gas may lead some to think that they are of juvenile origin. The thermal springs of Utah are discussed in a special study by Milligan and others of the Utah Water and Power Board. They are all listed as chloride waters

Table 3. High Altitude Soils in the Wastach Mountains.

SOIL HORIZON	Soil No. 900			Soil No. 814			Soil No. 893			Soil No. 896			Soil No. 1407		
	Na	K	Mg	Na	K	Mg	Na	K	Mg	Na	K	Mg	Na	K	Mg
A	Water soluble extract														
	.60	-	1.6	-	-	-	.44	.50	.83	.41	.84	.90	-	-	-
B	Sodium acetate extract														
	.29	1.27	3.3	.10	1.0	2.8	.27	.71	1.40	.27	1.84	4.4	.28	1.53	3.55
C	Water soluble extract														
	.67	-	1.0	-	-	-	.54	.15	.30	.38	.37	.57	-	-	-
C	Sodium acetate extract														
	.44	.96	7.9	.25	1.0	4.0	.20	.25	2.00	.28	1.18	5.7	.27	1.90	3.3
C	Water soluble extract														
	1.15	-	.70	-	-	-	-	-	-	.54	.21	.50	-	-	-
C	Sodium acetate extract														
	.65	.73	5.5	.22	.19	-	-	-	-	.26	.59	2.5	.33	.44	3.4

Developed over andesite or andesite-bearing alluvium. Water soluble extract figures are in milliequivalents per liter, and sodium acetate extract figures are in milliequivalents per 100 grams of soil.

Courtesy of the Soil Conservation, Federal Bldg., Salt Lake City.

Table 4. Comparison of K and Mg in Soils Developed in Parent Materials Rich in Andesite or Containing no Andesite.

Soil Horizon	K		Mg	
	Andesite	Non-Andesite	Andesite	Non-Andesite
A	1.27	.90	3.09	2.15
B	1.60	.58	4.60	2.08
C	.49	.45	3.80	1.93

Figures represent sodium acetate extract amounts in milliequivalents per 100 grams of soil.

and according to James Mundorff of the U.S. Geological Survey they are generally similar to the cold spring waters in chemical analyses. The only constituent that possibly comes from within the earth, is H_2S . The thermal nature is not believed to be due to hot ascending waters, but to the fact that the meteoric waters penetrate to depths sufficient to be warmed up before returning to the surface. In the course of this circulating they mingle with saline waters to various degrees. Thus, truly juvenile waters are not believed to have contributed to any measurable degree to the salinity of Great Salt Lake.

Closed-basin lakes in volcanic regions have a characteristic chemistry that identifies themselves as having derived their salts, partly at least, from volcanic liquids and gases. Searles Lake is an example. Great Salt Lake is classed with those of sedimentary terrains and has composition similar to sea water (Clark, 1924). It is, therefore, not believed to have derived any appreciable amount of its salts from volcanic emanations. Under a later heading minor constituents, boron, potassium, and lithium, will be discussed, because they are in excess of the normal marine proportions, and possibly may have come from volcanoes.

SALT FALLOUT FROM THE ATMOSPHERE

Previous Studies.

Although not many fallout or washout data are available for the Great Salt Lake basin, more are

available for other regions, and thus it has been documented that the troposphere transports and deposits sizeable quantities of water-soluble ions as well as solid mineral and organic particles. The fall-out ions with which researchers have generally concerned themselves are Cl^- , SO_4^{--} , Na^+ , K^+ , and Mg^{++} . Rain water carries all these ions, more in one place than another, and all but SO_4^{--} are regarded as predominantly maritime components; that is, they are gathered into the atmosphere from the oceans.* The close resemblance of Great Salt Lake waters to the oceans invites a study of atmospheric transported salts (Table 1).

A map by Junge (1958) of the western United States showing Cl^- concentration in rain water suggests that a good part of the Cl^- is lost along the continental margin and bordering mountains, and that only one-tenth to one-fourth of it is transported as far inland as the Great Salt Lake drainage basin. Junge reviews other examples of transport, and finds that the chloride content reaches the half-value at 600 to 1200 kilometers from the coast.

* SO_4^{--} ions in rain do not prove a reliable guide to an oceanic source. Jensen and Nakai (1961) have demonstrated from sulfur isotope studies that the prime source of SO_4^{--} is atmospherically oxidized H_2S which has been produced by anaerobic bacteria along tidal flats and swampy coast lands. They believe that only a minor part of the SO_4^{--} in aerosols is of oceanic water derivation. The δS^{34} analyses of sea water yield uniformly a figure of +20.7 per mil, whereas those from the atmosphere range from +3.2 to +15.6.

As far as the Great Salt Lake watershed is concerned Junge concludes that here 0.2 parts per million (mmp) of Cl^- is precipitated from the atmosphere. The paucity of data used in the construction of Junge's map lead the writer to embark on a chloride fallout measuring project, which is described in the following paragraphs.

Collection Stations.

Three stations were chosen in the Great Salt Lake watershed for the collecting of rain and snow samples; one at the U.S. Weather Bureau of the Municipal Airport west of Salt Lake City at an elevation of 4,200 feet; one at the writer's home on the east bench of Salt Lake City at an elevation of 5,000 feet; and one at the Avalanche Station of the U.S. Forest Service at Alta at 9,000 feet in the Wasatch Mountains. Systematic collecting of precipitation started on February 12, 1968 and continued until November 1, 1968. Channel samples through the snow pack in a number of places were taken in order to estimate the chloride content of the snows in the mountains of the preceding few months (Table 5). The snow pack data are believed to span the precipitation fallout for the winter snow period in the Great Salt Lake drainage basin, and the collecting period from February to November spanned the rain-fall period. At Alta, however, a number of snow falls were collected individually and analyzed.

Other collecting stations west of Great Salt Lake were established at the U.S. Weather Bureau Stations at Ely and Elko, eastern Nevada. Walter Herrick at Ely and Omar Sinclair at Elko, were very kind to do the collecting and mailing of the samples. Samples from these stations were thought desirable to gain a feeling for the pick up of salt, if any, across the desert floors and Great Salt Lake as the storms sweep from west to east. The period of collecting was the same as for the Salt Lake stations, but road building operations at Elko for a time prevented the collecting there of good samples.

Analytical procedure.

An analytical method for chloride in natural waters that could be carried out on samples as small as 50 cc and which would measure 0.1 part per million was devised by D.L. Barker of the Utah Geological and Mineralogical Survey. It is a colorimetric method and a modification of a procedure by D.M. Zall, D. Fisher, and M.O. Garner, *Analytical Chemistry* 28, 1665 (1956), and L. Skaggs, Technicon Corp.

Table 5. Chloride in Composite Snow Samples

Winter snow pack 1967-68 in parts per million	
Sierra Nevada	
West side Donner's Summit (7200')	0.13
East side, Rose Mountain (8900')	2.00
Central Nevada	
Austin Summit	1.4
Eastern Nevada	
Schell Creek Range	4.2
Schell Creek Range	6.52
Schell Creek Range	2.75
Saxton Peak	1.2
Egan Range	0.46
Dorsey Basin	1.82
Green Mountain	0.51
Lehman Cave	4.9
Central Utah	
Cedar Breaks	0.6
Parley's Summit	3.9
Uinta Mts., west end at Howells Gate	0.86

Analyses by David L. Barber, Utah Geological and Mineralogical Survey. Eastern Nevada snow samples through the assist of Walter Herrick, U.S. Weather Bureau at Ely and Omar Sinclair, U.S. Weather Bureau at Elko.

Basic fallout data.

The number of samples collected and analyzed from the Great Salt Lake watershed is as follows: Municipal Airport, 38; Home, 42; and Alta, 24. From Ely 25 samples were obtained, and from Elko, 12. They are the basis from which the various calculations that follow were made.

Feth (1967) and Whitehead and Feth (1964) have been concerned with the dry fallout that is dropped by the atmosphere between rains and snows, and conclude that the water-soluble parts of the dry fallout must be included with the wet when amounts and effects of precipitated salts are being computed. For this combined fallout they use the term "bulk precipitation." It is believed that the samples collected for the present study represent the bulk precipitation for the following

reasons. The standard Weather Bureau rain gauges used were first washed out with distilled water, and left in place thereafter under open atmospheric conditions, during the period of investigation. What dry fallout occurred was washed into the collecting basin with each rain or melted snow, and thus its soluble content became part of the rain or snow sample. As far as the snow pack samples of the total winter snows are concerned, it is evident that the dry fallout would be included. However, the possibility does exist with the snow pack samples that water from short episodes of thawing might have leached the salts from the upper layers and carried them to lower layers or even to the underlying soils. Since the samples were collected in mid-February, no melting had probably occurred. Also a perusal of the snow pack Cl^- analyses does not lead to a suspicion of irregularities resulting from leaching.

Observations on chloride fallout.

Observations concerning chloride fallout are summarized as follows:

(1) Snow contains less chloride than rain. At Alta the snows had a weighted average of 0.35 ppm Cl^- . The weighted average of the rains at Alta was 1.2 ppm. At Cedar Breaks and the west end of the Uinta Mountains the average was 0.73 ppm. Eleven snow profiles from eastern California and central and western Nevada averaged 2.3 ppm Cl^- . This is higher than in Utah, and may be due to dry dust falls in times between snow falls. The samples collected at Alta were taken immediately after each fall.

(2) Weighted average of annual Cl^- precipitation was least at Alta, intermediate at Home, and highest at the Airport.

Alta (9,000 ft)—0.51 ppm Cl^-

Home (5,000 ft)—1.91 ppm Cl^-

Airport (4,200 ft)—3.75 ppm Cl^-

(3) Small rainfalls have highest Cl^- content, and large rainfalls have lowest content. Smallest rainfall at Home was 0.03 in with 54.0 ppm Cl^- . Largest rainfall at Home was 0.80 in with 0.08 ppm Cl^- .

(4) Can't recognize the progressive sweep of storms from Nevada to the Great Salt Lake watershed, but certain rains within the watershed had fairly uniform quality. Study Table 4. From this table it will be seen that:

- a. The rain of April 4 had uniform quality at Airport and Home.
- b. The rain of July 22 had uniform quality at Home and Alta.

c. The rains of August 13, 14, and 17 had uniform quality at Airport and Home.

(5) It is concluded that the rains of small amounts and with high Cl^- content were very spotty, and that spring, summer, and early fall rains are associated with very turbulent atmosphere with frequent pick-ups of salt from the desert floor and from Great Salt Lake, and with erratic fallout patterns of the resulting rains.

(6) The main problem in this study is to determine the amount of Cl^- (salt) that comes from the Pacific Ocean, which would be considered *new* salt in the Great Salt Lake watershed, and how much of the salt that falls out is locally recirculated or recycled.

Virgin salt from the Pacific Ocean.

By perusal of the fallout data it will become evident that the bulk of the Cl^- analyses show less than 2 ppm Cl^- , and that those higher than 3 ppm spread out over a wide range. From this and the foregoing observations, it seems to the writer that the rains with the low Cl^- content comes from the atmosphere uncontaminated with local ground dust and lake spray, and that their storms bring the salt from the Pacific. Further, it would seem that the erratic, high-chloride rains have had considerable salt added to that of the Pacific aerosols by local pick-up. In order to get a better picture of the Cl^- fallout data in this regard, the analyses were plotted by frequency of occurrence and by amount of Cl^- (Fig. 1). It is fairly evident that the low-chloride rains and snows form a singular and regular group, but that the high Cl^- rains form an irregular group in numbers, content of Cl^- , and also, it may be added, in distribution. This seems satisfying evidence that the Cl^- fallout in amounts below about 2 ppm is mostly virgin and has come from the Pacific Ocean. Amounts beyond 3 ppm must contain considerable recycled salt already in the drainage region of the Great Salt Lake or in desert areas surrounding or west of the basin, perhaps in the Great Salt Lake Desert. It is on the basis of this conclusion that the volumes of new salt brought in by the atmosphere each year are calculated.

But the chloride content of the rains indicated as coming from the Pacific (Fig. 1) is less than 3 ppm, and a weighted average of these is 0.674 ppm. It is thus concluded that the average precipitation in the Great Salt Lake watershed brings 0.674 ppm of new chloride into the drainage which will be washed into the lake. Also in order to calculate the volume of recycled salt each year, 0.674

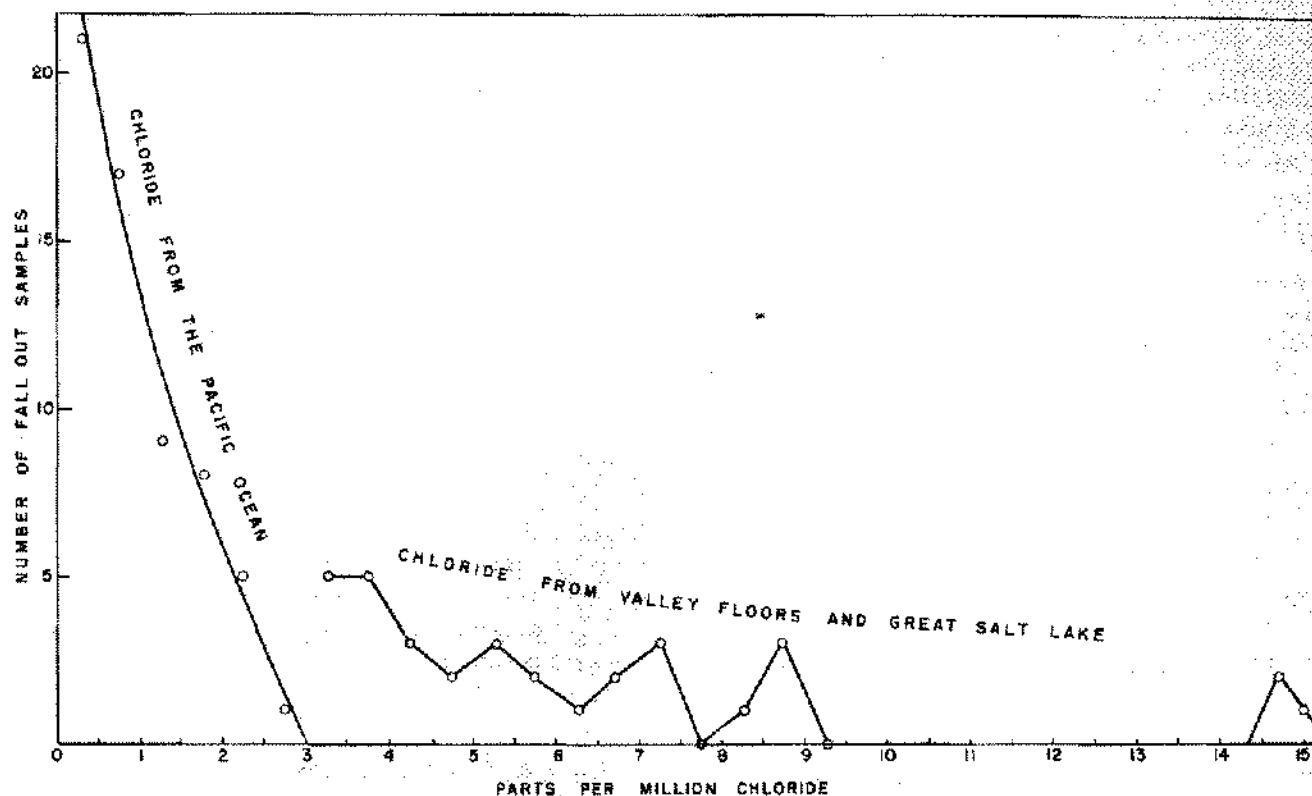


Figure 1. Frequency plot of chloride fallout analyses. The number of analyses in each 1/2 ppm division is plotted as the vertical coordinate.

ppm must be subtracted from the weighted average of total precipitation.

Volume of virgin salt brought to the Great Salt Lake watershed annually.

Using the figure of 0.674 ppm of chloride in the precipitation that falls over the Great Salt Lake watershed, and the volume of precipitation that comes each year, we can compute the volume (tonnage) of new salt that comes to the basin, and thus to Great Salt Lake. Other salt in the rains and snows must be considered to be recycled if the amount in the precipitation is more than 0.674 ppm.

The precipitation data by Mahoney (1962) for the Great Salt Lake watershed are as follows:

	acre-feet
Bear River drainage	7,399,684
Brigham City drainage	160,145
Weber River drainage	2,564,418
Farmington drainage	173,187
Jordan River drainage	879,725
Provo River drainage	1,246,004

Spanish Fork River drainage	1,172,105
Utah Lake	771,634
Great Salt Lake	1,055,951
Skull Valley	672,091
Tooele-Rush Valley	952,636
Total precipitation	16,903,508
Rounded to	16,900,000

Therefore:

$$\begin{aligned}
 &16.9 \times 10^6 \text{ acre feet of precipitation} \times 0.674 \\
 &\text{ppm Cl} \\
 &\times 0.00136 \text{ (factor to convert ppm to tons/acre} \\
 &\text{ft.)} \\
 &= 15,490 \text{ new tons Cl per year added to Great} \\
 &\text{Salt Lake's salt economy.}
 \end{aligned}$$

The total amount of Cl^- dropped by precipitation in the Great Salt Lake watershed can be calculated if a weighted average of the total Cl^- content is obtained. It will be assumed that the area of the basin represented by the Airport station at 4,200 feet will have a factor of 1; the area represented by the Home station at 5,000 feet will have a factor of 1; and the area represented by the Alta station will

have a factor of 0.5. It will be assumed also that the precipitation of the Airport area will be 1; that of the Home station 2; and that of Alta 3. Thus, the importance of the three areas as far as volume of precipitation is concerned is

Airport area $1 \times 1 = 1$

Home area, $1 \times 2 = 2$

Alta area, $0.5 \times 3 = 1.5$

Thus

Airport weighted average of recycled Cl^- will be 3.81 ppm minus 0.674 ppm (virgin Cl^-) = 3.136 ppm.

This times a factor of 1 = 3.136 ppm.

Home weighted average of recycled Cl^- will be 2.00 ppm minus 0.674 ppm = 1.626 ppm.

This times a factor of 2 = 3.252 ppm.

Alta weighted average of recycled Cl^- will be 0.536 ppm.

This is below the general average of the uncontaminated precipitation. This times a factor of 1.5 = 0.704 ppm.

Now, if 3.136, 3.252, and 0.740 ppm are added and divided by 4.5, the result will be 1.575 ppm Cl^- , which is the weighted average of the Cl^- fallout of local derivation.

Thus, the total annual amount of recycled Cl^- , in addition to the virgin Cl^- from the Pacific, is

16.9×10^6 acre feet $\times 1.575$ ppm $\text{Cl}^- \times 0.00136$ (factor = 36,200 tons of Cl^- already in the Great Salt Lake economy but which is being recycled by the atmosphere annually).

It has been calculated on theoretic grounds (Langbein, 1961) that Great Salt Lake stands to lose annually by aerosol formation about 40,000 tons of Cl^- which is carried away in the track of the storms. Presumably not all of the aerosol particles are precipitated in rain drops or snow flakes—some evaporate and the resulting salt crystals become atmospheric dust. Thus, two consequences may be postulated: (1) only part of the aerosol loss from Great Salt Lake is dropped over the watershed whereas part is carried beyond, and (2) the part of aerosol that settles to the surface of the watershed falls both as dust and as precipitation fallout. Thus only a small part of the aerosol loss from Great Salt Lake needs to be precipitated as rain or snow in the watershed.

In any event, one year's Cl^- fallout is a small fraction of the annual inflow in Great Salt Lake. The average annual inflow of soluble salts is about

3.75 million tons which is composed of 36.3 percent Cl^- (Hahl and Langford, 1966). Thus there is an average annual addition by inflow of 1.36 million tons of Cl^- . Assuming 51,700 tons of Cl^- fallout annually, (15,500 + 36,200) the Great Salt Lake inflow is 26 times as much. Other factors must prevail in the salt economy of Great Salt Lake!

If the rate of 15,500 tons of new Cl^- fallout per year is assumed, it would take 170,000 years to accumulate the salt in Great Salt Lake (about 4.7 billion tons of total salt or 2.5 billion tons of Cl^-). It appears that only about 13,000–15,000 years are available or possible for the accumulation. Even if the entire Bonneville basin is considered as the fallout catchment area, which is about twice as large as the Great Salt Lake watershed, and if the rate or precipitation were at first somewhat greater, the time of accumulation is still longer than expected. But there are other factors that must be considered.

SALT ACCUMULATION BY DESICCATION FROM PROVO LEVEL

In calculating the amount of Cl^- that concentrated in the lowering of Lake Bonneville from the Provo level to Great Salt Lake (from 4800 feet to 4200 feet), the amount of Cl^- that existed in the lake at the Provo level, the amount that the streams brought in during the decline must be determined.

The amount of Cl^- that accumulated during the desiccation of the lake below 4800 feet (simply by reduction of a static lake volume) may be found approximately as follows:

Chloride content of lake waters at Provo level assumed to be about 25 ppm

Volume in acre feet at Provo level— $3,800 \times 10^6$

$3800 \times 10^6 \times 0.00136$ (factor) $\times 25$ ppm Cl^- = 130,000,000 tons of Cl^- , approximately.

It will be assumed for the present that desiccation below the Provo level started about 13,000 years ago. Within 2,000 years it had reached the present Great Salt Lake level. Thus for the past 11,000 years the regimen of stream flow and introduction of Cl^- would have been approximately what it is now. But for the first 2,000 years the introduction of Cl^- would have been greater. Precipitation would have been about 19,000,000 acre

feet per year at the start of the decline, as shown below:

15,000 sq. miles (area of lake) \times 640 acres/mile \times 2.0 feet of evaporation per year) = 19,000,000 acre feet per year which is the measure of the water increment necessary to sustain the lake. This is made up of precipitation on the lake and stream inflow.

The relative amounts contributed by inflowing streams and direct precipitation on the lake may be estimated as follows. The lake at the Provo level occupied about 35 percent of the drainage basin, as judged from Gilbert's maps, and thus approximately 35 percent of the 19,000,000 acre feet would come as direct precipitation on the lake.

Table 6. Fallout Samples from Municipal Airport

Date of collection	Inches of precipitation (A)	Parts per million Cl^- (B)	A \times B
2/12/68	0.13	15.0	1.95
2/13/68	0.49	1.5	0.735
2/13/68	0.22	6.0	1.320
2/17/68	0.18	7.1	1.278
2/19 & 20/68	0.24	4.3	1.032
2/21/68	0.07	3.43	0.240
2/27/68	0.38	3.5	1.130
3/7/68	0.48	1.8	0.864
3/8/68	0.54	1.42	0.825
3/9/68	0.02	2.46	0.049
3/13/68	0.10	5.26	0.526
3/17/68	0.18	3.5	0.630
3/17/68	0.08	4.46	0.357
3/17/68	0.35	1.52	0.532
3/19/68	0.11	1.4	0.154
4/2/68	0.38	0.75	0.285
4/3/68	0.41	0.30	0.123
4/5/68	0.05	0.60	0.030
4/5/68	0.48	1.42	0.682
4/16/68	0.11	17.0	1.870
4/21/68	0.39	0.65	0.234
4/22/68	0.13	0.33	0.043
5/14/68	0.04	35.0	1.400
5/15/68	0.06	15.0	0.900
5/16/68	0.17	8.7	1.479
5/22/68	0.46	5.17	2.378
5/25/68	0.25	8.4	2.100
6/5/68	0.29	3.52	1.028
6/8/68	0.94	4.90	4.606
6/10/68	0.51	2.28	1.163
6/13 & 14/68	0.56	6.65	3.724
6/17/68	0.41	7.06	2.895
6/22/68	0.65	0.83	0.539
9/13/68	0.05	14.67	0.733
9/20/68	0.35	8.88	3.108
10/14/68	0.24	1.00	0.240
10/30/68	0.29	0.33	0.097
10/30/68	0.14	5.01	0.701
Total	10.93		41.780

$$\frac{41.780}{10.93} = 3.82 \text{ ppm } \text{Cl}^-, \text{ weighted average of all Airport samples}$$

Assuming the precipitation contained 1.57 ppm Cl^- (see p. 88), then the amount of Cl^- that would fall in one year would be

$$1.57 \text{ ppm} \times 0.35 \times 19,000,000 \times 0.00136 \text{ (factor)} = 116,300 \text{ tons } \text{Cl}^-.$$

In the cooler and more humid climate of Lake Bonneville time the entering streams probably would have contained less Cl^- than they now do at the 4500 foot elevation, which is 25 ppm. As an approximation it will be assumed that they contained 15 ppm, and further, that the Cl^- derived from the soils is partly an accumulation of many years of previous fallout.

Thus

$$15 \text{ ppm} \times 0.65 \text{ (area of watershed)} \times 19,000,000 \times 0.00136 \text{ (factor)} = \text{about } 0.25 \text{ million tons } \text{Cl}^- \text{ per year.}$$

Thus, each year at the Provo level, 13,000 years ago, the lake received approximately 0.26 million tons of Cl^- . It is assumed, further, that saline springs were not important contributors, as they are at present. In any event, saline springs are believed to be bringing in recycled salt of older lakes now in storage underground, and for the present purpose only fallout salt of the present regimen is considered.

Now, if it is assumed that the yearly increment of Cl^- gradually changed to what it is now in the desiccation of the lake from the Provo level to the level of Great Salt Lake (13,000 years to 11,000), then the average of the two multiplied by 2000 would give the total increment during this period. In arriving at the annual increment at the end of the period it will be assumed again that springs were not important contributors of Cl^- , and that the rivers were adding water with 25 ppm Cl^- . The volume of Cl^- contributed annually by the rivers would be about 50,000 tons (see p. 91) and the amount of Cl^- in the precipitation that falls on the Great Salt Lake would be

$$1,000,000 \text{ acres} \times 1.57 \text{ ppm } \text{Cl}^- \times 0.00136 \text{ (factor)} = 2,200 \text{ tons.}$$

The total annual increment would thus have been about 52,000 tons of Cl^- 11,000 years ago. Thus the total increment for the 2000 year period would be approximately

$$0.26 \text{ million} + 52,000 \times 0.5 \times 2000 = 265 \text{ billion tons } \text{Cl}^-.$$

It is believed as the lake fell below 4500 feet the spring contributions became important, for they

now bring to the lake over 600,000 tons of Cl^- annually. Also the surface recycling processes became more pronounced at lower lake levels, increasing the salinity of the entering streams greatly. But aside from the recycled salt, the amount of new salt brought into the basin between 11,000 years ago to the present is computed as follows:

$$1,280,000 \text{ acre feet average present runoff} \times 25 \text{ ppm} \times 0.00136 \text{ (factor)} \times 11,000 \text{ years} = 480,000,000 \text{ tons of } \text{Cl}^-, \text{ approximately.}$$

Then, the total chloride content that would have accumulated from the start of desiccation below the Provo level to the present, aside from the spring input, would be:

130 million tons of Cl^- by reduction of lake volume

265 million tons of Cl^- by stream inflow and precipitation on lake 13,000–11,000 years b.p.

480 million tons of Cl^- by inflow, 11,000–present

875 million tons of Cl^- total.

This is the amount that should exist in the Great Salt Lake assuming that the Cl^- is mostly of atmospheric origin. Considering the assumptions and variables the calculated amount must be considered very approximate. If the spring input 11,000 years ago was one third of what it is now, and if it has gradually increased to its present rate (660,000 tons Cl^- annually) then the springs would have contributed approximately 4.4 billion tons in the 11,000 year period. Thus 0.875 billion and 4.40 billion tons add up to 5.275 billion tons of Cl^- which is approximately twice the assessable inventory today.

RELICT SALT FROM PAST LAKES

Buried salt beds.

Unfortunately the drill has yet failed to discover any bedded salt other than one of Glauber's salt west of Promontory Point. The age of Glauber's salt is presumably about 11,000 years (Eardley, 1962) and its accumulation would thus be related to the post-Bonneville history. Now that the top of the bed has been trenched below about 25 feet of fine plastic sediments in the building of the Southern Pacific Railroad causeway, some of the salt of the buried bed has undoubtedly gone into solution in Great Salt Lake, but until the trenching it

apparently was well-sheltered from the lake waters and did not contribute to the lake's present salt economy. The continuity of the interstratified salt and clay layers as interpreted from core records, suggests that much of the salt has been left undisturbed to the present.

Connate waters in sediments of valley fill.

It has been said many times that salt accumulation in the Bonneville basin could only have commenced after the last outflow, because it is assumed that the lake became completely fresh during an outflow stage. Much uncertainty exists concerning overflow. It is not clear how the lake held fairly stationary during the establishment of the pronounced Bonneville beach, and then rose just a few feet to overflow, as Gilbert postulated. This seems somewhat artificial. A second uncertainty is the time of overflow. One great flood through the outflow channel is recorded which Morrison (1965a and b) and Broecker and Kaufman (1965) believe occurred about 13,000 years ago, Malde (1960) about 30,000 years ago, and Bright and Rubin (1965) about 18,000 years ago. A third uncertainty comes from the possibility that more than one overflow occurred. Morrison (1966) suggests this as a bare possibility, based on detailed stratigraphic studies. He thinks if the lake did have an early overflow, that it happened at the time of the last maximum of Alpine age, not less than 27,000 years ago. In order for the outflow river to cut a 300 foot channelway twice, there must have been an intermediate filling of the channel, but as yet no one has published evidence for such an occurrence. Goode (personal communication) has mentioned that there may be evidence of a landslide at Red Rock Pass, the place where the overflow started.

Considering the rate of maritime airborne salt fallout, a much longer time even than from an early Alpine stage to the present is indicated. Thus one is justified in exploring the possibility of salt retention from one saline lake to another in spite of the overflow at Red Rock Pass.

A 650-foot-deep core on the east shore of Great Salt Lake (Eardley and Gvosdetsky, 1960) indicated a succession of several fresh-water lakes alternating with saline lakes which at times completely disappeared. This record correlates fairly well with the exposed stratigraphic record (Morrison, 1966, and Eardley, 1966). Equally deep cores were also taken in the Great Salt Lake Desert, one 7 miles east of Wendover and one about 40 miles east, near

Knolls. The sediments in both cores were saline water deposits. At the time of coring, a relationship with the alternating fresh and saline lake on the east side of the Bonneville basin was not evident. However, now that an apparent need occurs for 100,000 years of salt accumulation rather than 13,000, the recognition of these saline water deposits becomes significant.

A primary, fairly continuing source of salt is visualized in the down-faulted, and deeply sediment-filled valleys of the Bonneville basin. The salt is presumed trapped both in the calcareous clays and silts and in pervious aquifers. Both can yield their salty waters along joints and faults to the surface. A good lead in the search for such evidence was discovered in the chloride-ion profiles of the several rivers emptying into Great Salt Lake, particularly the Provo River—Utah Lake—Jordan River profile.

RIVER CHLORIDE PROFILES

Profile data.

If the chloride content of the rivers is charted from high elevations down to Great Salt Lake it will be seen that chloride is first detected in small amounts in the headwaters (3-5 ppm) and gradually increases to about 25 ppm at 4,500 feet above sea level. Then it conspicuously increases many times before the rivers reach the lake (Fig. 2). The increase at about 4,500 feet is taken to mean that recycling of the salt becomes abrupt at 4,500 feet and that most of the rivers' chloride is due to this effect. On the other hand, above 4,500 feet the rivers' chloride is believed due mostly to fallout and in very small part to weathering. The recycling below 4,500 feet probably involves several processes in addition to atmospheric fallout, such as the distribution of dry dust particles by the wind over the lower elevations and addition by saline springs. It also includes salt that has been spread over extensive basin areas as the lake rose and fell, and which now is being returned to the lake by run off. The assumption that about 25 ppm of Cl^- would be the normal concentration of inflowing waters, if it were not for recycling, is interesting because it permits the following calculations and conclusions:

1,280,000 acre ft (average total run-off of all rivers into lake during 1960, 1961, and 1963) \times 0.00136 (factor to convert ppm to ton/acre ft) \times 25 ppm Cl^- = 43,500 tons Cl^- gained per year by Great Salt Lake through surface stream inflow.

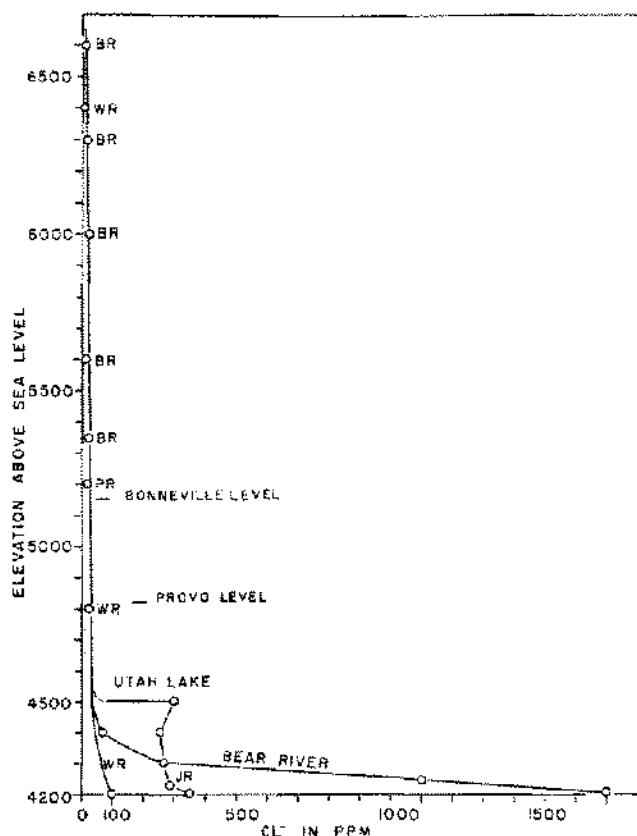


Figure 2. Profiles of Cl^- in Bear River, Weber River, and Provo-Jordan River. Water samples taken in summer months. BR, Bear River, PR, Provo River, WR, Weber River. For Utah Lake an average of 11 samples are used.

This result does not take into account the water and Cl^- that seeps into the underground and which finds its way into Great Salt Lake as unmeasured ground water and bordering springs. Handy and Hahl (1966) estimate that this unmeasured inflow amounts to 0.2 million acre feet which, if the ground water did not pick up additional amounts of salt and carried only fallout salt at the rate of 25 ppm of Cl^- , would add about 6,800 tons. Thus 43,500 plus 6,800 equals about 50,300 tons of Cl^- total gain from surface and ground water flow, which is equal to the gain from rain and snow fallout. This equality suggests that a balance has been established between fallout and stream removal to the lake above the 4,500 foot elevation. Considerable salt is added below the 4,500 elevation, most of which must be recycled salt.

Gain in chloride in Utah Lake and the saline springs.

The chloride ion curve of Provo River, Utah Lake and Jordan River is instructive because it undoubtedly indicates that Utah Lake is gaining much salt from the underground, which it feeds into the Jordan River and thence into Great Salt Lake. The concentration of chloride in Utah Lake is about 300 ppm whereas the entering streams average less than 25 ppm. (Provo River/11 ppm, American Fork/3.2 ppm, Spanish Fork/15-87 ppm, Hobbie Creek/7-19 ppm, Spring Creek/25-35 ppm. [Connor, *et al.*, 1958, and Hahl and Mitchell, 1963]). However, about 400,000 acre feet of water evaporates each year, and this concentrates the chlorine considerably.

The highway departments of Provo City and Utah County use together about 200 tons of salt (NaCl) each year for melting snow and ice on the streets and highways. This contributes noticeably to the chloride content of the flood drain waters, according to Professor Grant Borg of the Civil Engineering Department, University of Utah. In the case of Salt Lake City and Salt Lake County most of the 9,000 tons of salt which the city and county use each year probably drains back into the Jordan River within a year. Sewage effluent generally runs about 50 ppm of Cl^- which is about twice as much as the original water used.

The U.S. Bureau of Reclamation has been studying Utah Lake rather thoroughly in planning for its more efficient use, and supplies the following pertinent data: about 45 percent (21,100 tons) of the chloride comes from the entering streams and 55 percent (25,600 tons) from thermal springs in Goshen Bay, off Lincoln Point and Bird Island, and at Saratoga Resort.

Thus, it must be concluded that about 25,600 tons of chlorine are gained by Utah Lake, and subsequently by Great Salt Lake by underground flow each year. This chloride is not part of the lake's current recycling regimen as far as the surface waters and the atmosphere are concerned. With this, we realize that a steady flow of salty water comes from springs, which here in Utah Valley may be coming from the down-faulted Quaternary and Late Tertiary sediments in the valleys of the Great Salt Lake drainage. Cook and Berg (1961) have shown that a buried graben filled with 6,000-9,000 feet of light density rocks exists under Utah Valley, and the sediments from ancient

lakes probably hold salt which is now being slowly released.

A measure of the Cl^- that is being released by spring flow into Great Salt Lake is revealed in the survey of Handy and Hahl (1966). They estimate that in an average water year the springs contribute about 660,000 tons of Cl^- to the lake. Of this, we have just concluded, a minor amount, 6800 tons, is of surface fallout origin. But the rest must come from the saline waters in the sediments of the valleys.

Therefore, the problem of origin seems to be in hand, and we have a reasonable answer to the question: where did the salt in Great Salt Lake come from?

CONCLUSIONS ON THE SOURCES OF SALT IN GREAT SALT LAKE

(1) The atmosphere brings to the Great Salt Lake watershed approximately 15,500 tons of new chloride annually. This comes from the Pacific Ocean, the source of the storms.

(2) The atmosphere picks up from desert floors to the west and from Great Salt Lake considerable amounts of chloride, and deposits 36,000 tons with rain and snow in the drainage basin. The total amount of atmospheric Cl^- fallout annually is about 51,500 tons.

(3) The 36,000 tons of chloride is considered Cl^- already in the surface regimen of the basin, and is the amount recycled by the atmosphere annually.

(4) At the rate of addition of 15,500 tons of new Cl^- annually it would take about 170,000 years to build up the salt that exists now in Great Salt Lake, and 300,000 years to build up the total assessable amount in the basin.

(5) Due to the desiccation of Lake Bonneville from the Provo level to the present salt lake there has accumulated about 3,260 million tons of Cl^- . This is made up of two components: (a) 130 million tons by reduction of lake volume and (b) 3,130 million tons due to inflow over a period of 13,000 years assuming the inflowing streams carried only fallout Cl^- (25 ppm).

(6) Closed drainage basins have been in existence in the Bonneville Lake region possibly since mid-Tertiary time, and the study of saline springs whose waters drain into Great Salt Lake suggest that the sediments of these closed basins have trapped and retained some of the salts of past saline lakes. As a result of Basin and Range faulting the trapped saline waters are being released. Any of these saline waters released before the overflow

stage would not have been retained in the post-Provo regimen, but all those released since the last overflow have accumulated, except for an unknown amount that may have been blown beyond the drainage rim. A measure of the Cl^- brought by spring flow at present lake levels is 660,000 tons per year. Only 6,800 tons of the total comes from fallout that seeps into the underground water circulation system. The rest comes from saline waters of the basin sediments.

(7) Salt, recycled either by the atmosphere or by spring release from trapped saline waters of older lakes, occurs mainly below elevations of 4,500 feet. Chloride profiles of streams of the drainage basin from their headwaters to 4,500 feet show a gradual pick-up of Cl^- from a few ppm to 25 ppm, and the amount thus represented equals the fallout at these elevations. Thus, it is concluded that the stream removal of Cl^- down to 4,500 feet is in balance with the fallout supply. This leads to the suggestion that the contributions from weathering of the rocks of the terrain are very small.

(8) The total amount of Cl^- that should have accumulated in the post-Provo regimen, on the basis of calculations and assumptions of the previous seven points is 5.275 billion tons, which is about twice the total amount that the writer can assess in the modern regimen.

SALT GAINS AND LOSSES MEASURED DIRECTLY

Salt accretion.

The author calculated from limited data in 1957 that the rivers and springs draining into Great Salt Lake added 1.5 million tons of salts annually. The salts are made up principally of the ions given in Table 1. In view of the commercial value of the salts in solution in the lake and the inadequacy of the existing data, the Utah Geological and Mineralogical Survey and the U.S. Geological Survey initiated a more thorough study of the chemistry of the lake's waters and the run-off into the lake, and the result of three years survey are now available. The results of the water years of 1960 and 1961 were published by Hahl and Mitchell (1963) and Hahl and Langford (1964), and of 1964 by Handy and Hahl (1966). The years 1960 and 1961 were relatively dry whereas 1964 was about average. The authors of these reports conclude that in each of the two dry years the streams, drains, and springs carried into the lake about 2.2 million tons of salt, and the underground flow about 0.5 million tons. For the average year the streams, drains,

and springs added about 3.5 million tons and the underground flow about 1.2 million tons, which is believed by the authors is close to the average contribution of dissolved mineral matter by surface run-off.

Salt loss.

It would thus appear that Great Salt Lake is gaining about 4.7 millions of tons of salt each year ($3.5 + 1.2$), but now, if we look at the lake's salt economy another way we may conclude that it is losing in natural ways about as much as it gains. The lake sank below its overflow level about 13,000 years ago (Morrison, 1963a and b) and the salts began to accumulate. At the rate of 4.7 million tons per year over 50 billions of tons would have accumulated in 13,000 years. But only about 8 billion tons of salt seem to exist in the lake's present economy. It would appear that a great amount of salt has been lost by natural causes, and that the losses may equal the gains by now. Furthermore, the lake has gained salt equilibrium in the range of historical level fluctuations, viz.; 4,191-4,212 feet.

If the amount of Cl⁻ that the entering streams carry at the 4,500 foot level is considered, it would take at the present rate of 51,000 tons per year about 50,000 years to build up the salt that is present. On the other hand, if the amount of Cl⁻ that the streams carry as they enter the lake is considered, it is strikingly in excess of the amount necessary. At the present rate for instance it would take only 1,600 years to build up the concentration. All these conflicting figures need careful review, because the conclusions drawn are probably not correct or, at least, misleading.

Variations in salt content with changing levels.

Calculations by the writer in 1935 and Cohenour in 1960 showed that at high levels of Great Salt Lake there was much more salt in the lake than at low levels. The reduction was not due to salt precipitation, and moreover the percentage composition remained constant, as far as analyses permit interpretation. The conditions are well summarized by Handy and Hahl (1966).

"The concentration of dissolved solids in percentage (by weight) in the lake brine has ranged from about 14 percent during the high lake stage of 1877 to as much as 29 percent during the low lake stages of the early 1960's. . . .

"Although the dissolved-solids concentration of the brine changes with lake stage and volume, the

percentage composition of the dissolved solids has remained constant during the past hundred years. . . .

"The amount of mineral matter dissolved in the brine also fluctuates with lake volume. In 1873, when the lake was at its highest recorded stage, the lake volume was about 30 million acre-feet and the brine contained about 6 billion tons of dissolved solids. In contrast, at the low stage of November 1963, the volume was about 8.7 million acre-feet and the brine contained about 4 billion tons of dissolved solids."

Table 7 shows the writer's computations of the dissolved solids in Great Salt Lake at various lake levels. Figure 3 presents these data graphically. The areas at different levels are probably in error by 5 percent. The concentration figures were taken

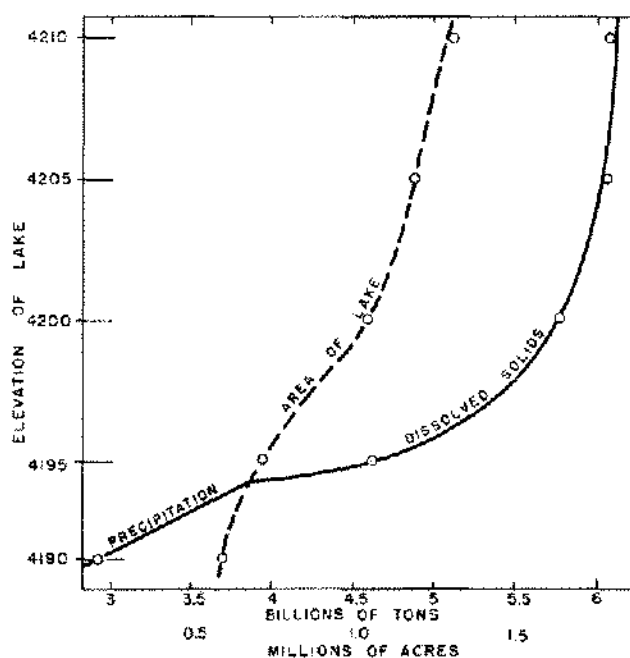


Figure 3. Area of Great Salt Lake and tonnage of dissolved solids in relation to elevation (stage) of the lake.

from a salinity curve along which the plotted data fall fairly close (Eardley 1938, Fig. 4). It may be contended that the salinity data are so scarce and so poorly representative of the lake areally that the tonnages of dissolved solids cannot be used for comparative purposes. Since most of the salinity data fall on a smooth curve, and since the lake seems to be well stirred-up and well-circulated at

Table 7. Fallout Samples from Home (2618 Skyline Dr.)

Date of collection	Inches of precipitation (A)	Parts per million Cl^- (B)	A × B
2/12/68	0.1	4.0	0.400
2/13/68	0.24	0.8	0.192
2/14/68	0.23	1.33	0.319
2/18/68	0.13	4.0	0.520
2/21/68	1.15	0.37	0.425
2/27/68	0.63	0.67	0.422
3/4/68	1.17	0.50	0.583
3/7/68	0.57	0.31	0.177
3/9/68	1.05	0.31	0.325
3/16/68	0.05	3.26	0.163
3/17/68	0.10	0.46	0.046
3/19/68	0.46	0.69	0.317
3/26/68	0.12	7.3	0.876
4/7/68	0.80	0.08	0.640
4/13/68	0.12	2.00	0.240
4/17/68	0.12	17.00	2.040
4/19/68	1.12	0.32	0.358
4/27/68	0.05	5.7	0.028
5/5/68	0.03	54.0	1.620
5/11/68	0.14	52.0	7.280
5/12/68	0.10	3.86	0.386
5/14/68	0.67	2.36	1.581
5/15/68	0.27	0.90	0.243
5/22 - 23/68	2.10	0.50	1.050
5/24/68	0.03	3.50	0.105
6/4/68	0.43	6.70	2.881
6/6/68	0.22	3.7	0.814
6/8/68	0.59	2.2	1.300
6/10/68	0.23	2.2	0.506
6/24/68	0.24	0.17	0.041
7/22/68	0.05	8.67	0.433
8/4/68	0.12	24.8	2.976
8/8/68	0.26	1.44	0.374
8/14/68	0.21	2.9	0.609
8/16/68	0.05	4.22	0.210
8/17/68	0.86	1.49	1.280
8/18/68	0.47	0.27	0.122
8/22/68	1.05	0.12	0.120
8/23/68	0.31	0.53	0.165
9/20/68	0.66	4.57	3.016
10/15/68	1.17	1.95	2.285
10/31/68	0.63	1.94	1.222
Total	19.10	Total	38.620

$$\frac{38.62}{19.10} = 2.0 \text{ ppm weighted average of all samples}$$

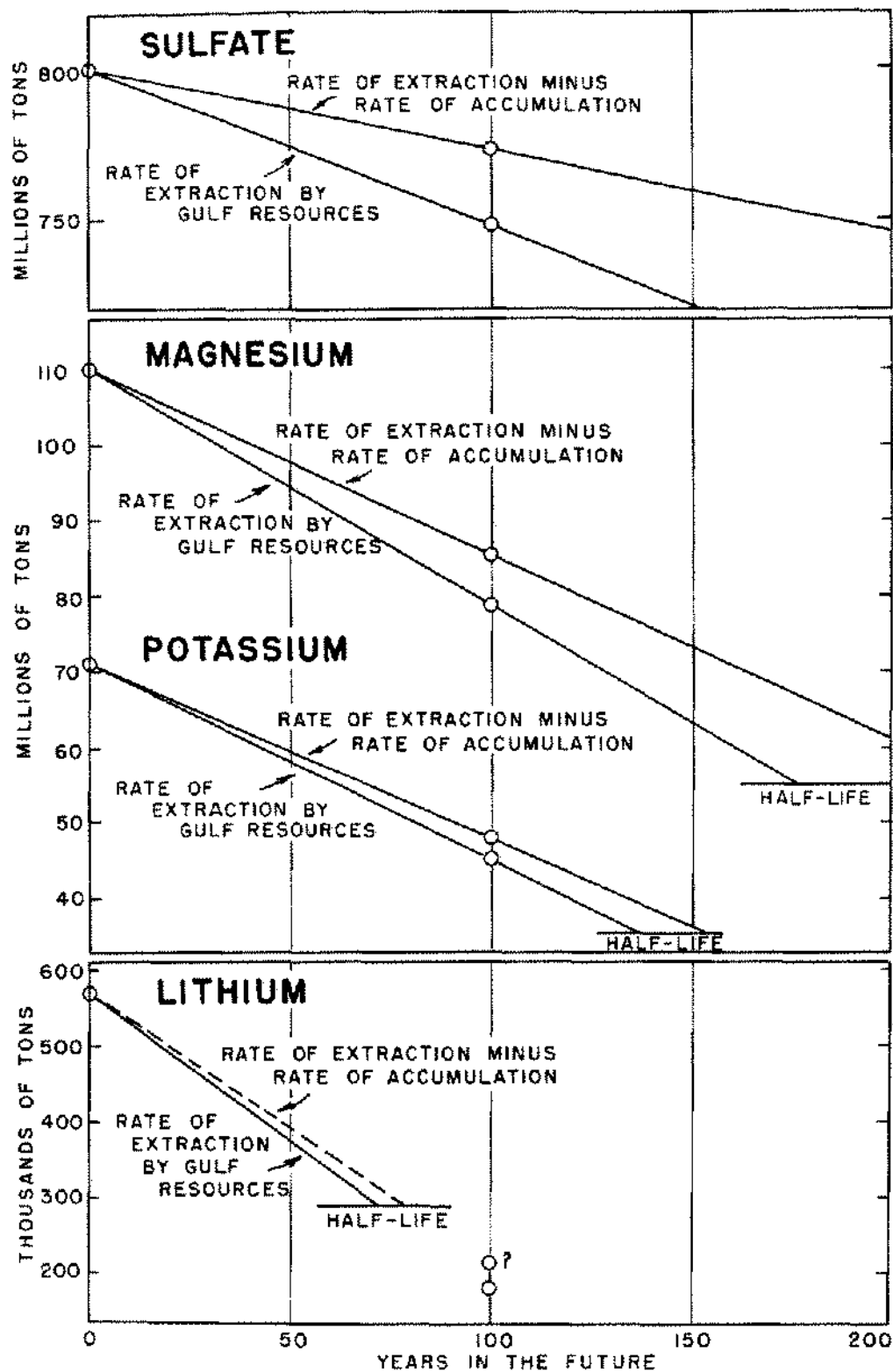


Figure 4. Depletion curves of sulfate, magnesium, potassium, and lithium from Great Salt Lake according to rates of proposed commercial extraction by Gulf Resources and Chemical Corporation, and their half-life periods. The depletion curves are based on the rate of commercial extraction by the one company, Gulf Resources and Chemical Corporation. For each ion the rate is given *without* natural replenishment and also *with* the rate of natural replenishment (rate of accumulation).

intervals (personal observations) the writer is inclined to believe the salinity data, although scattered in time and space, do represent the lake generally at the several levels.

Concurrent with the study of Handy and Hahl was the construction of the rock causeway of the Southern Pacific Railway across the central part of the main body of water, and this proved to isolate fairly effectively the northern arm of the lake. In the dry years of 1962 and 1963 much salt was precipitated in the northern arm—possibly 1 billion tons of the previously existing 4.6 billion tons of solution. This was an artificial condition imposed on the lake. In the writer's studies of the lake during the drouth years of 1933 and 1934 when the lake had reached a low stage of 4,194 feet above sea level, a thin layer of halite crystals precipitated over the entire bottom in mid-summer, but it was dissolved during the following winter. The rock causeway probably helped nature to lower the lake to the all-time low of 4,191.5 feet in the summer of 1963, during which time much salt was precipitated north of the causeway while none was dropped south of the causeway. It is concluded that the linear curve of concentration under pre-causeway conditions would break at the 4,194 foot level, and that any lowering below this level would result in precipitation of NaCl , and also in the winter months of $\text{Na}_2\text{SO}_4 \cdot 10\text{H}_2\text{O}$. Thus a readily understandable loss of salt through precipitation will occur below 4,194 feet, but the great loss of salt as the lake falls from 4,205 to 4,195 as given by Handy and Hahl must have another explanation.

Langbein (1961) cites two examples of closed-basin saline lakes that have a somewhat similar history, Devils Lake, North Dakota, and Lake Eyre, Australia. Lake Eyre, however, forms a salt crust soon after the evaporation cycle begins, which is partially dissolved as the lake rises and thickens as the lake falls. In spite of this immediate source of salt for the lake waters Langbein concludes that saline perennial lakes generally lose salt without precipitation during a falling hemicycle, gain during a rising cycle, but that the loss exceeds the gain. The lake must hold for some time at the high level to regain its former salt content.

In a similar manner the salt economy of Great Salt Lake is complicated by losses and gains that occur during lake level falls and rises.

Absorption in bottom clays.

Loss of salt from Great Salt Lake by wind removal has already been discussed. In addition, much salt is absorbed and retained in the fine sediments of the lake bottom. In mid-lake coring to a depth of 44 feet the calcarenites were plastic and wet with water high in salt. Upon the least drying halite in hair-like crystals was extruded from the cores. Coring to a depth of 600 feet in the Great Salt Lake Desert produced calcarenites also wet with salt water. Thus, undoubtedly a great deal of salt is held in the bottom "clays," perhaps much more than in the lake waters themselves.

The problems of the salt in the underclays are several. Has it been retained from former salty lakes? How much is due to impregnation from the present lake? Could the rate of impregnation of the bottom clays go on faster in a falling lake hemicycle than the rate of release of salt to the lake waters in a rising hemicycle? Detailed quantitative analyses of the deeper brines that wet the clays as well as perhaps isotope analyses of the sulfur and oxygen would help answer these questions. Such analyses are not as yet available.

The loss of the salt in a falling lake is related, qualitatively at least, to the area of bottom land covered or relict by the lake. This is shown in Figure 3. As the lake falls from 4,200 to 4,195 most of the bottom becomes exposed in Bear River Bay, Ogden Bay and Farmington Bay. Extensive areas are also relict at the north and south ends of the main body of water. This happens to be the elevation change in which the major gains and losses of salt occur. It is thus suggested that absorption and release of salt by and from the bottom sediments is a controlling factor. The bay areas are mostly those of fine calcareous silts and clays, and these are more effective in the exchange process than the oolitic sand.

The Langbein theory is difficult to support in Great Salt Lake's rises and falls, partly because of inadequate density or concentration measurements. During the period 1940 to 1952 the lake rose through the critical interval, 4,195-4,200, but no density readings are available. The scattered measurements from 1968 to 1960 seem to show that the lake regains as much as it loses as it rises and falls.

PROBLEM OF THE SALT BALANCE

Total inventory.

To itemize all the stores of salt in the Bonneville basin that have accumulated since Provo times we must take into account those in the Great Salt Lake Desert as well as those in the Great Salt Lake basin. This need has been called to my attention by J.W. Hood of the U.S. Geological Survey. If Great Salt Lake should rise only 26 feet from its current level it would spill over into the Great Salt Lake Desert. That a saline lake occupied the basin in the past is indicated by a salt crust (Eardley and others, 1957). It has been calculated that the Bonneville (Salduro) and Pilot Valley salt crusts contain about 350 million tons of salt. Also, if it is assumed that the brine of post-Bonneville time has penetrated 20 feet into the bottom clays, the clays in the Desert would contain about 1 billion tons. In addition, there is another billion tons of salt in the upper 25 feet of clays under Great Salt Lake. This depth of 25 feet carries well into the sediments deposited in the last fresh water lake stage. The estimated amounts of salts in the basin are

Great Salt Lake	4.7 billion tons
Salts in the recycling regimen	2.0 billion tons
Salt crusts in Great Salt Lake Desert	0.35 billion tons
Salts in the upper 20-25 foot layer of the bottom clays	2.0± billion tons
Total	9.0± billion tons.

It has been estimated (1) on the basis of accumulation of salt by desiccation from the Provo level, (2) from fallout salt, and (3) from spring input that there should be only a little more than this much, and thus the measured or assessed amounts seem to approach the theoretically calculated amounts, and in view of the several uncertainties this is a satisfying achievement.

LITHIUM PROBLEM

James Masey informed the writer of a disparity in the proportions of Li^+ in sea water and Great Salt Lake, and thought that this might argue against the origin of the salts in Great Salt Lake from the Pacific by wind transportation. James Whelan also points out that there is at least twice as much K^+ (ratio wise), perhaps three times as much, in Great Salt Lake as in sea water, and feels that this argues for a more complex origin than

simply by atmospheric fallout (See Table 1). Regarding lithium, the facts are these: it is reported in the oceans to have a concentration of 70 mg per cubic meter of water (McLellan, 1965) whereas it has a concentration of 37-60 parts per million in Great Salt Lake (Table 1). Taking into account the concentration of salts in Great Salt Lake (6-7 times as great as in sea water), the ratio of Li^+ to Cl^- in Great Salt Lake is about 100 times as great as in the oceans. This is a conspicuous difference and undoubtedly should be explained, if possible.

The concentration of other minor constituents may be compared as follows:

	ppm Sea Water	ppm G.S.L.
Borate	27	570±
Bromide	65	Evidently very little
Fluoride	1.4	5

The figures under Great Salt Lake should be divided by six or seven to find the abundances relative to abundances in sea water. Thus, fluoride is in comparable relation, borate seems five times as abundant in Great Salt Lake, and bromide is problematical because of the paucity of analyses. Br^- is undoubtedly very small in amounts and routine analyses have not picked it up. It may be concluded, however, that fluoride and perhaps bromide compare closely in ratio with the other salts in both sea water and Great Salt Lake, but that potassium, lithium and boron are in excess in Great Salt Lake. Since boron is known to be common in lakes of volcanic areas, it may be tentatively concluded that lithium, boron and possibly potassium have been introduced by volcanic action somewhere in the collecting system of the general Lake Bonneville basin since the establishment of internal drainage, and that they have been retained and recycled to supply Great Salt Lake with the present amounts. Fluoride and bromide, on the other hand it is concluded, have followed the other major ions in the marine cycle of the origin.

In order that hydrothermal volcanic solutions raise the proportions of K, Li, and B over the maritime proportions, the volcanic solutions must be especially rich in these elements and relatively poor in Na, Ca, and Mg. This thought suggests that

Table 8. Fallout Samples from Alta (Avalanche Station)

Date of collection	Inches of precipitation (A)	Parts per million Cl^- (B)	A × B
12/17/67	0.8 (20 cm snow)	2.0	1.60
12/26/67	1.85 (47 cm snow)	1.0	1.85
1/11/68	0.4 (10 cm snow)	0.92	0.368
1/29/68	1.4 (35 cm snow)	0.66	0.924
2/2/68	0.3 (7 cm snow)	1.43	0.429
2/14/68	2.0 (50 cm snow)	0.096	0.20
2/14/68	2.0 (50 cm snow)	0.10	0.20
2/21/68	2.0 (50 cm snow)	0.05	0.10
2/23/68	2.0 (48 cm snow)	0.05	0.10
3/11/68	1.6 (40 cm snow)	0.05	0.08
3/15/68	0.6 (15 cm snow)	0.05	0.8
3/19/68	2.3 (56 cm snow)	0.30	0.69
4/4/68	1.7 (43 cm snow)	0.30	0.51
4/9/68	2.4 (60 cm snow)	0.30	0.72
6/12/68	1.3	0.029	0.038
6/23/68	0.5	0.037	0.018
7/22/68	0.42	1.96	0.823
6/21-22/68	0.50	5.9	2.950
8/8-9/68	0.06	1.96	0.117
8/13/68	0.12	0.83	0.100
8/13-14/68	0.25	0.58	0.145
8/16/68	0.58	0.53	0.318
8/17-19/68	0.57	0.53	0.316
8/22/68	0.90	1.236	1.112
10/31/68	0.75	0.155	0.116
	<u>27.30</u>		<u>14.624</u>

$$\frac{14.624}{27.3} = 0.536 \text{ ppm weighted average of all samples}$$

Weighted average of snows - 0.35 ppm

Weighted average of rains - 1.02 ppm

One rain (7/21-2/68) dropped 25% of salt for the year

Table 9. Fallout Samples from Ely

Date of collection	Inches of precipitation (A)	Parts per million Cl^- (B)	A × B
1/4/68	0.13	1.42	0.185
2/4/68	1.17	0.50	0.585
2/17/68	0.09	3.8	0.342
2/21/68	0.31	3.5	1.085
2/23/68	0.09	4.15	0.374
3/6/68	0.08	5.02	0.402
3/9/68	0.11	2.61	0.287
4/5/68	0.27	1.4	0.378
4/20/68	0.13	6.2	0.806
4/21/68	0.02	0.65	0.013
4/24/68	snow	5.0	
5/11/68	0.12	0.70	0.084
5/11/68	0.15	1.30	0.195
5/11/68	0.12	1.10	0.132
5/23/68	0.40	1.3	0.520
5/23/68	0.07	31.3	2.191
6/7/68	0.14	6.3	0.882
7/8/68	0.11	0.47	0.052
7/21/68	0.12	5.45	0.654
7/24-5/68	0.25	2.41	0.625
7/28/68	0.15	0.46	0.069
7/29/68	0.12	0.27	0.033
8/11/68	0.22	3.74	0.823
8/18/68	0.02	4.57	0.091
10/14/68	0.65	1.89	1.228
	<hr/> 5.04		<hr/> 12.036

$$\frac{12.036}{5.04} = 2.24 \text{ ppm } \text{Cl}^- \text{ - weighted average}$$

Table 10. Fallout Samples from Elko

Date of collection	Inches of precipitation (A)	Parts per million Cl^-	A × B
2/16-17/68	0.24	2.1	0.504
2/18-20/68	0.52	1.07	0.556
2/21-22/68	0.45	0.96	0.432
2/22-29/68	0.12	3.14	0.377
3/6-9/68	0.65	1.55	1.007
3/16-18/68	0.30	0.96	0.288
3/25/68	0.15	2.9	0.435
4/16/68	0.30	5.0	1.500
5/9-14/68	0.63	18.7	11.781
5/22/68	0.36	6.3	2.268
5/23/68	1.94	1.8	3.438
8/5-8/68	0.72	6.7	4.824
	<u>6.38</u>		<u>27.410</u>

$$\frac{27.410}{6.30} = 4.35 \text{ ppm } \text{Cl}^-, \text{ weighted average}$$

Table 11. High Chloride Rains of G.S.L. Watershed for 1968

Date	Airport	Home	Alta
Mar. 26		7.3	
Apr. 4	17.0	17.0	
May 5		54.0	
May 11		52.0	
May 14	35.0		
May 15	15.0		
May 15	8.7		
May 22	5.17		
May 25	8.4		
June 4		6.7	
July 22		8.67	5.9
Aug. 13-14	6.65	24.8	
Aug. 17	7.06	4.22	
Sept. 13	14.7		
Sept. 20	8.9		
Sept. 22		4.57	

somewhere in the Bonneville basin, and probably in the Great Salt Lake basin, is a buried deposit rich in soluble salts of K, Li, and B, that has been accessible to meteoric waters but not yet discovered by the drill.

Some evidence is at hand that during the formation of sea spray and its transport inland it undergoes changes in composition. Over the continent the airborne sea salts are mixed with salts picked up from the desert floors so that the fallout ratios may differ from the maritime ratios. Fallout salt is thus usually relatively richer in sulfate, bicarbonate, calcium, potassium, nitrogen compounds and bromine (Yaalon, 1967). Thus, the high potassium ratio in Great Salt Lake may be due to desert floor pick-up by the wind across the wide stretches of the Great Basin, particularly from the igneous rock terrains.

CONCLUSIONS REGARDING THE ORIGIN OF THE SALT IN GREAT SALT LAKE

It must be clear that the several ions that make up the salts in Great Salt Lake are of complex origin. The traditional view that the salts have originated in large measure by weathering of the rocks of the watershed has not been supported quantitatively by the writer's observations. The time available since the last overflow of Lake Bonneville limits the amount of production of soluble salts by weathering. If more time were available this source would undoubtedly be more important. Excesses of boron, lithium, and possibly potassium seem to be due to volcanic contributions. Salt pick-up by the wind and its consequent fallout may have

added to the overage of potassium beyond the maritime ratio, but the chief primary source of the salt in the lake is believed to have been atmospheric fallout with the salts derived from the oceans. Quantitatively, this source is sufficient and assessable.

In all considerations recycling must be recognized, and undoubtedly the various recycling processes have produced the variations from the maritime ratios of the salts in the lake.

COMMERCIAL EXTRACTION OF SALTS

Reserves and Natural Replenishment.

An ore body is finite, and after considerable exploration and development, its size, volume, and amount of the various metals may generally be approximately determined. The amount of the various metals in Great Salt Lake may also be determined, but unlike an ore deposit the valuable minerals in the lake are being constantly replenished, recycled, and lost by natural processes.

The reserves that may be processed for the extraction of the several valuable ions must include not only the lake waters but the salts that are in the process of recycling. These are the salts that rest in the salt flats and in the soils of the watershed up to an elevation of 4,500 feet, and which are being gathered by the runoff and returned to the lake. Judging from the fact that the lake loses 1.5 billion tons of salt to the bottom sediments falling from 4,205 to 4,195 feet, there must be two or three times this much salt in the recycling process. Thus, it would be reasonable to conclude that there is a total reserve to process of 6-7 billion tons. But the excess over 4.6 billion tons will on

Table 12. Dissolved Solids in Great Salt Lake at Various Levels

Elevation	Area in Acres	Volume in Acre Feet	Concentration in Percent	Dissolved Solids in Billions of Tons
4210	1,512,000	32,352,000	14	6.15
4205	1,341,000	25,232,000	18	6.15
4200	1,103,000	18,327,000	24	5.77
4195	747,000	11,830,000	29	4.64
4190	601,000	7,200,000	29	2.84

become available as the rivers gather the salt, and this will take a long time, viz., about 2,000 years. As the lake becomes impoverished in certain ions, so eventually will the recycled salt. But as far as commercial extraction is concerned over the next 100 years the salt that the rivers bring to the lake will be additional reserve, and thus must be included in figuring the half-life of each ion.

Table 13 lists the concentrations of the commercially valuable ions in Great Salt Lake according to the analyses of the Utah Geological and Mineralogical Survey and the U.S. Geological Survey. Those of the Utah Geological and Mineralogical Survey are from 15 gallon surface samples taken in June, 1966 after the effects of the rock causeway had become conspicuous, and show the difference in concentration of the south half of the lake from the north half. The U.S. Geological Survey analyses come from the lake before it was effectively divided and are averages of samples collected from June, 1959 to November, 1961. The Utah Geological Survey's analyses run somewhat higher than those of the U.S. Geological Survey's in magnesium, potassium, and lithium, and the meaning and industrial significance of this will be determined in the near future. For the present the figures of the U.S. Geological Survey will be used for they represent the entire lake before the causeway altered the lake's regimen of lake level oscillation.

With the above listed concentrations (Hahl and Langford, 1964) the reserves of magnesium, potassium, and lithium may be calculated (Table 14). Thus, with projected rates of commercial extraction the time can be determined when the concentrations will be reduced 50 percent. It is assumed that this half-life period will end profitable production.

The figures in the third column of Table 14 indicate the time in years necessary to restore the ions if they were suddenly depleted, or the time necessary to double the amounts present. Now if the annual gains, plus the reserve in the lake are charted against the projected commercial extraction rates the results shown in Figure 4 are obtained. One curve is charted for depletion assuming that no replenishment occurs, and another assuming that replenishment *does* occur and adds to the reserves.

Effect of a receding lake.

With a falling lake the reserve diminishes, and since the lake has generally fallen since 1870, the reserve has diminished by about 1.5 billion tons of total salt. In addition, with the building of new dams for more irrigation in the Wasatch watershed, progressively more water will be lost by evaporation before it reaches the lake, and the lake will continue to suffer.

Actually the total reserve does not diminish with

Table 13. Commercially Valuable Ions in Great Salt Lake

	UTAH GEOLOGICAL SURVEY		U.S. GEOL. SURVEY
	SOUTH HALF	NORTH HALF	WHOLE LAKE, 1960 & 1961
Mg ⁺⁺	3.66	4.24	3.20
Na ⁺	32.67	33.66	31.00
K ⁺	2.45	2.69	1.78
Li ⁺	(40)	(55)	(33)
Bo	-	-	.01
Br	(90)	(155)	
Cl ⁻	53.36	51.21	54.59
SO ₄ ⁻	7.50	7.90	7.40

All figures are in percentage composition except those in parentheses which are in parts per million. The analyses of the Utah and Mineralogical Geological Survey have been furnished by Dr. James Whelan, and represent work done in 1967.

Table 14.

	Present reserve	Annual accretion	Ratio reserve/accretion	Rate of yearly extraction by Gulf Resources
Magnesium	110,000	76	1,600 years	305
Potassium	71,000	31	2,300 years	253
Lithium	570	no analyses available	2,000+ years	3.9

Reserve, annual accretion, extraction data for 1961 in thousands of tons (after Hahl and Langford (1964)).

a falling lake, but rather salt is taken out of the commercial extraction regimen. Thus, a falling lake diminishes the workable reserve much faster than the rivers and springs build it up.

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