

# Geology of the Owens Lake Evaporite Deposit

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## ABSTRACT

The evaporite deposit covering 87 square kilometers of the dry bed of Owens Lake, California, is a complex mixture of salts and brine. This deposit provides a unique opportunity for the detailed study of the formation and alteration of a complex evaporite. The quantities of the chemical constituents in the original brine lake and in the present evaporite deposit are known closely enough to permit the calculation of a rough chemical balance.

The deposit is a slushy mixture of 35% brine and 65% solid phase salts (by volume) having a maximum thickness of about three meters and an average thickness of about one meter. The principal solid phase salts in the mixture are trona ( $\text{Na}_3\text{H}(\text{CO}_3) \cdot 2\text{H}_2\text{O}$ ), burkeite ( $\text{Na}_6\text{CO}_3(\text{SO}_4)_2$ ), thermonatrite ( $\text{Na}_2\text{CO}_3 \cdot \text{H}_2\text{O}$ ), and halite ( $\text{NaCl}$ ). The compositions of the salts and brine change seasonally. During the hot summer months sodium carbonate and sodium sulphate present in the solid phase as decahydrate salts release large amounts of water

and enter the brine phase. During the cold season, the decahydrates crystallize, removing water from the brine phase. These phase changes cause serious alterations in the physical and chemical characteristics of the deposit and effect mining and processing.

The total amount of bicarbonate in the present deposit is about three times the amount in the original lake, suggesting that a natural process of carbonation from carbon dioxide in the atmosphere may have been effective.

Only about 15 per cent of the sodium chloride in the original lake brine can be accounted for within the present evaporite deposit. It is suggested by the author that much of the concentrated brine phase has percolated downward into the lake bed sediments, taking the bulk of the sodium chloride with it. This process may be a mechanism for the enrichment of trona deposits.

## INTRODUCTION

The evaporite deposit on the bed of Owens Lake in southeastern California was formed about sixty years ago when the flow of the Owens River was diverted into the Los Angeles aqueduct. This resulted in desiccation of the pre-existing brine lake. Soda ash (sodium carbonate) had been produced from the original lake brine since 1887, and production continued until 1967, after the desiccation of the lake, from terminal brine contained in the porous salt deposit. The concentrated brine was extracted from the evaporite deposit by means of shallow wells and transported to shore by pipeline where it was processed to produce soda ash. In recent years, crude trona salts (sodium sesquicarbonate) have been harvested from the lake bed by surface mining for limited specialty markets.

The deposit, with reserves of more than 50 million tons of sodium carbonate equivalent, is the third largest resource of natural soda in North America, ranking only behind the deposits of Green River, Wyoming and Searles Lake, California.

Lake Minerals Corporation has been mining trona

salts from the lake bed since 1976, and is currently studying the possibility of producing refined salts by a novel technique. The purpose of this paper, however, is not to discuss the commercial utilization of the deposit. Rather, it is to discuss the formation and alteration of the deposit, drawing on extensive data collected by Lake Minerals Corporation and its predecessors.

The chemical composition of the original lake and its volume are well known from a number of observations dating from 1866 (Chatard, 1890 and Gale, 1915). Within the last two years it has been possible to measure the residual evaporite deposit with considerable accuracy and to calculate a gross chemical balance. The calculation leads to some unanticipated results. The known chemical and physical data are presented along with the proposal of a mechanism to explain the changes that have taken place.

## GEOLOGIC SETTING

Owens Lake is in Inyo County, California, 240 kilometers north of Los Angeles. It occupies the lowest portion

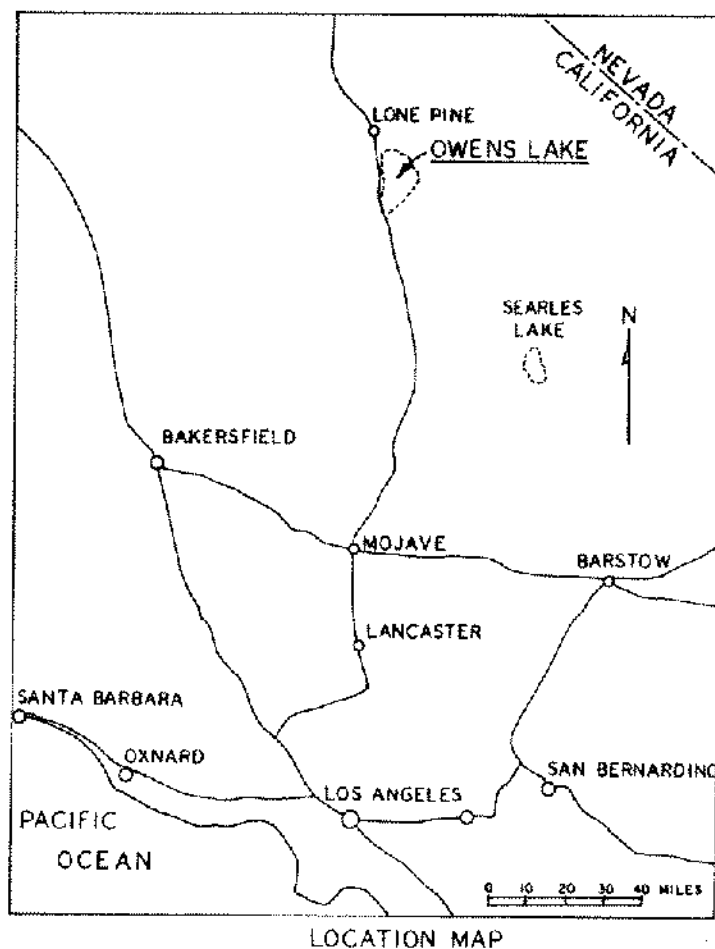


Figure 1.

or topographic "sink" of Owens Valley, a deep, narrow, northwest trending graben lying between the uplifted blocks of the Sierra Nevada to the west and the Inyo Range to the east. The valley is about 160 kilometers long and 24 kilometers wide at its widest point. The elevation of the lowest point in the valley is 1,081 meters above sea level. Mount Whitney, with an elevation of 4,417 meters, the highest point in the Sierra Nevada, is about 20 kilometers northwest of the lake bed.

The geomorphic history of the lake basin started in the late Miocene or early Pliocene with the block faulting that created the Owens Valley graben. The great fault system that forms the eastern scarp of the Sierra Nevada mountain block probably dates back to the Cretaceous, but only the latest major movements near the end of the Tertiary concern us here. Prior to that time, the entire area had been reduced to a terrain of low relief. This terrain was subsequently buried under volcanic flows and pyroclastics of intermediate composition. The Owens Valley basin has probably existed with internal drainage since mid Pliocene time.

During the early stages of the drainage basin, most of

the region was underlain by volcanic rocks. At the present time, the volcanics have been largely removed from the mountain blocks, exposing Paleozoic sediments in the Inyo Range and deep seated acidic igneous rocks in the Sierra.

Although the details are not known, it is probable that Owens Lake existed as a fluvial lake alternately expanding and contracting in response to climatic changes during most of the Quaternary (Smith, 1966). There is no evidence that it ever evaporated to dryness prior to the interference of man early in this century. It did, however, expand and overflow the southern margin of the basin on several occasions.

The divide into the next valley to the south is about 80 meters higher than the lake bed, and to reach this point, the lake only has to triple or quadruple in volume from its normal interglacial size. During each period of overflow, a portion, if not all of the accumulated salts in the lake were flushed into the lower basins. The last period of overflow and flushing of salts ended not more than about ten thousand years ago (Smith, 1966, p. 170). For practical purposes we can say that most of the salts now present

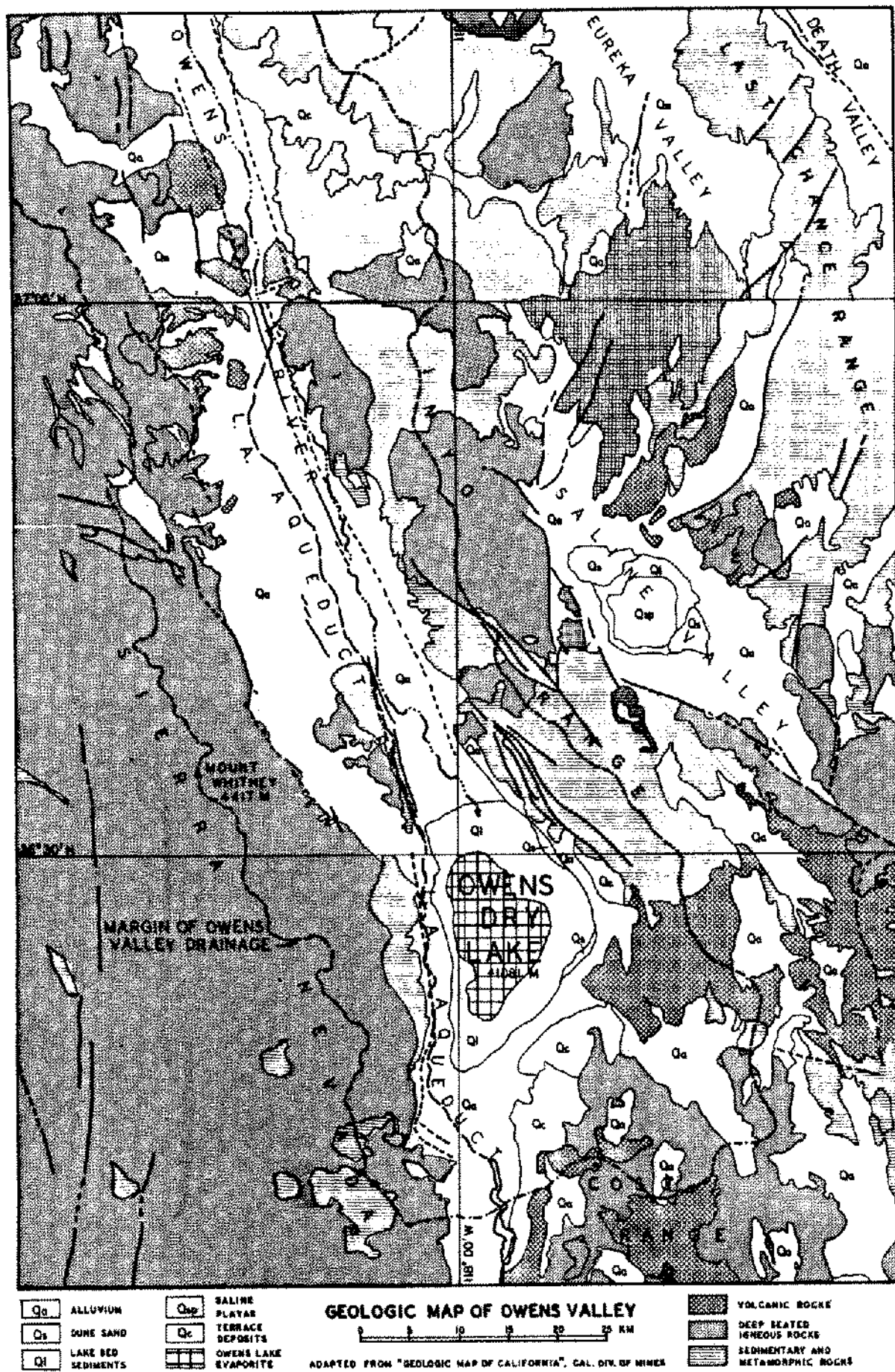


Figure 2.

in the deposit were accumulated during the past ten thousand year period.

In 1917, the Los Angeles aqueduct was completed and the flow of the Owens River was diverted and carried out of the basin. Deep drilling into the lake bed has found no evidence of evaporites or of concentrated brines below the surface, and it can be assumed that the lake had never been deprived of its inflow prior to the diversion of the river by man. The average net evaporation in the Owens Valley is about 1.5 meters per year on fresh water, and it took only about four years to bring the lake to saturation. By the end of 1922, most of the carbonate salts had been precipitated, leaving a dense terminal brine saturated with respect to all remaining components. Since that time, the deposit has been subject to minor localized inflow with occasional flooding, partial re-solution and recrystallization, the details of which will be described later.

### THE LAKE PRIOR TO DESICCATION

The best available information on the pre-1917 lake was published in 1915 by the U.S. Geological Survey (Gale, 1915, pp. 252-264). Ten chemical analyses dating from 1866 to 1914 are presented and are in fairly good agreement. The sample taken by Gale in 1912 and analyzed by the U.S.G.S. laboratory is probably the most reliable. Reported as ions in the 1912 lake water in weight per cent, it shows:

Chemical composition of 1912 Owens Lake

Na	K	Cl	CO <sub>3</sub>	HCO <sub>3</sub>	SO <sub>4</sub>	B <sub>4</sub> O <sub>7</sub>	Total
4.17%	0.23%	2.80%	1.97%	0.48%	1.09%	0.21%	10.95%

Reported as salts in weight per cent:

Na <sub>2</sub> CO <sub>3</sub>	NaHCO <sub>3</sub>	NaCl	Na <sub>2</sub> SO <sub>4</sub>	KCl	Na <sub>2</sub> B <sub>4</sub> O <sub>7</sub>
3.5%	0.7%	4.4%	1.6%	0.5%	0.3%

Fortunately, the elevation of the lake surface in 1912, at the time of Gale's sample, is known with reasonable accuracy and it has been possible to compute the volume of the 1912 lake water from modern topographic maps, correcting for the volume of the residual evaporite deposit. Knowing the volume, the specific gravity, and the chemical composition, the tons (metric) of contained anhydrous salts are derived as follows:

Salts contained in 1912 Owens Lake

Na <sub>2</sub> CO <sub>3</sub>	53,600,000	Tons
NaHCO <sub>3</sub>	10,100,000	Tons
NaCl	64,500,000	Tons
Na <sub>2</sub> SO <sub>4</sub>	24,300,000	Tons
KCl	6,700,000	Tons
Na <sub>2</sub> B <sub>4</sub> O <sub>7</sub>	4,100,000	Tons
Total	163,300,000	Tons

It is realized, of course, that the salts do not occur in the simplified combinations shown above. Nevertheless, the artificial components can be used to make valid comparisons with later data, as will be shown.

### THE PRESENT EVAPORITE DEPOSIT

The following quotation from an observer on the site during the period immediately after the diversion of the Owens River (Hirschkind, 1931, p. 658) is of interest:

"The city of Los Angeles was able to divert the entire flow of the Owens River into the aqueduct during 1917, and has continued to do so ever since. Consequently, the lake receded constantly and the brine became saturated with trona during the fall of 1920. During the winter of 1920-21, very substantial quantities of the sodium carbonate content of the brine, together with sodium sulphate, were precipitated and would not go into solution again during the following spring. During the summer of 1922 trona was precipitated until the entire bicarbonate content was removed and the brine finally reached saturation with sodium chloride and sodium sulphate. Subsequently these salts, together with sodium carbonate mono- and deca-hydrate were also precipitated and the lake reached a stationary condition consisting of a salt bed through which brine saturated with all constituents circulated."

Between 1960 and the present, several thousand auger, drive-pipe, and bore hole samples of the deposit were taken by Lake Minerals Corporation and Pittsburgh Plate Glass Company. The chemical composition, mineralogy, and physical characteristics of the deposit are now known with accuracy. The deposit covers an area of 87.5 square kilometers and has an average thickness of 0.8 meters. The maximum thickness measured is 3.0 meters. It consists of a layered mixture of porous salts of various kinds filled with saturated brine. The mixture contains 65% salts by volume or 70% salts by weight. In cross section, the deposit is lenticular, with the thickest section near the western margin (Figure 4).

The approximate average mineral composition (solid and liquid phases), expressed in weight per cent, of the entire deposit is as follows:

Trona Na <sub>3</sub> H(CO <sub>3</sub> ) <sub>2</sub> ·H <sub>2</sub> O	46.0%
Burkeite Na <sub>6</sub> CO <sub>3</sub> (SO <sub>4</sub> ) <sub>2</sub>	11.6%
Thermonatrite Na <sub>2</sub> CO <sub>3</sub> ·H <sub>2</sub> O	4.4%
Halite NaCl	1.8%
Insol*	6.2%
Brine	30.0%

\*The insoluble constituents consist of varying amounts of clastic material, including quartz and mica, clay minerals, and transported grains of the sodium-calcium carbonate double salts, shortite, pirssonite, and geylussite.

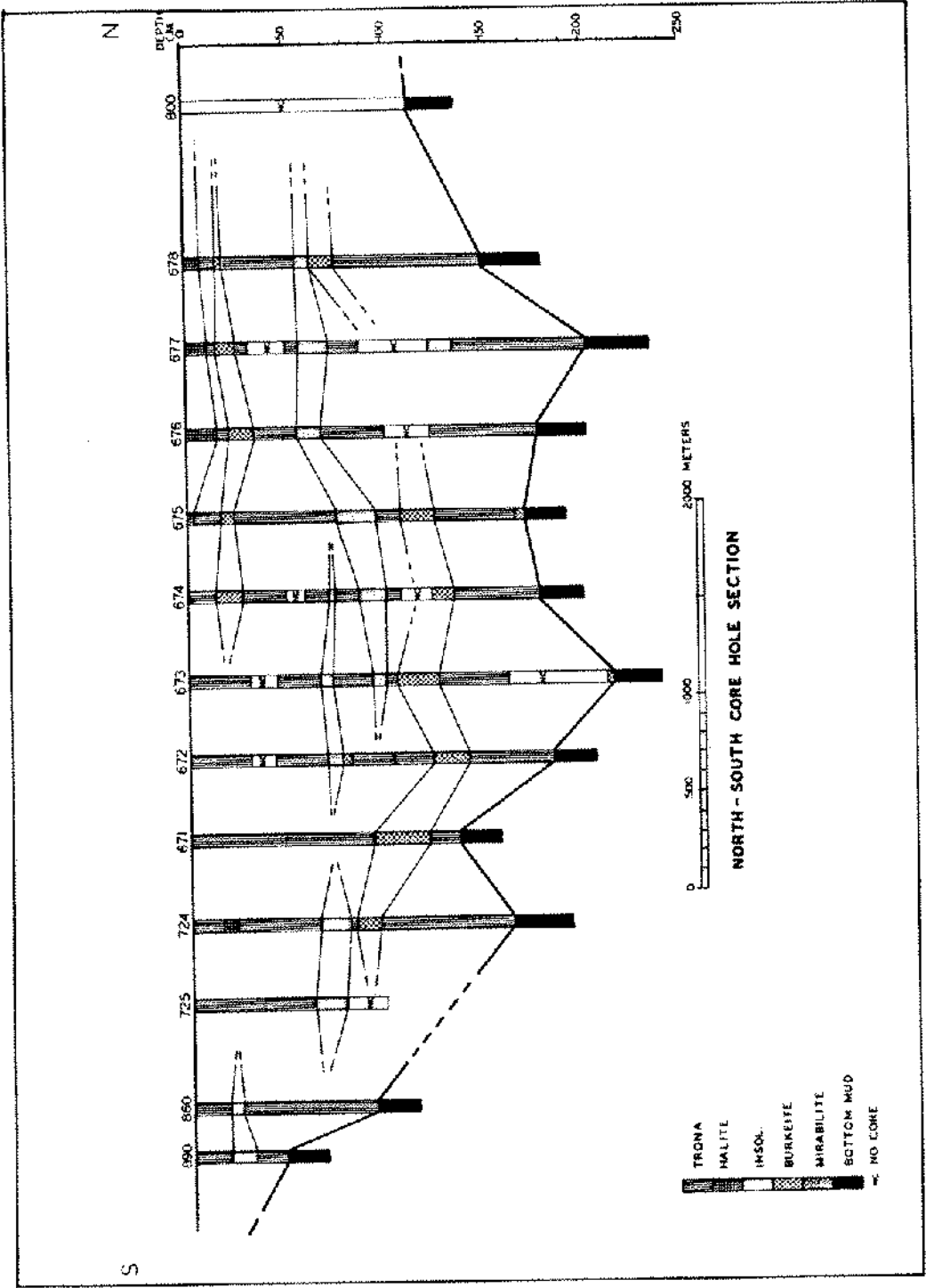


Figure 3.

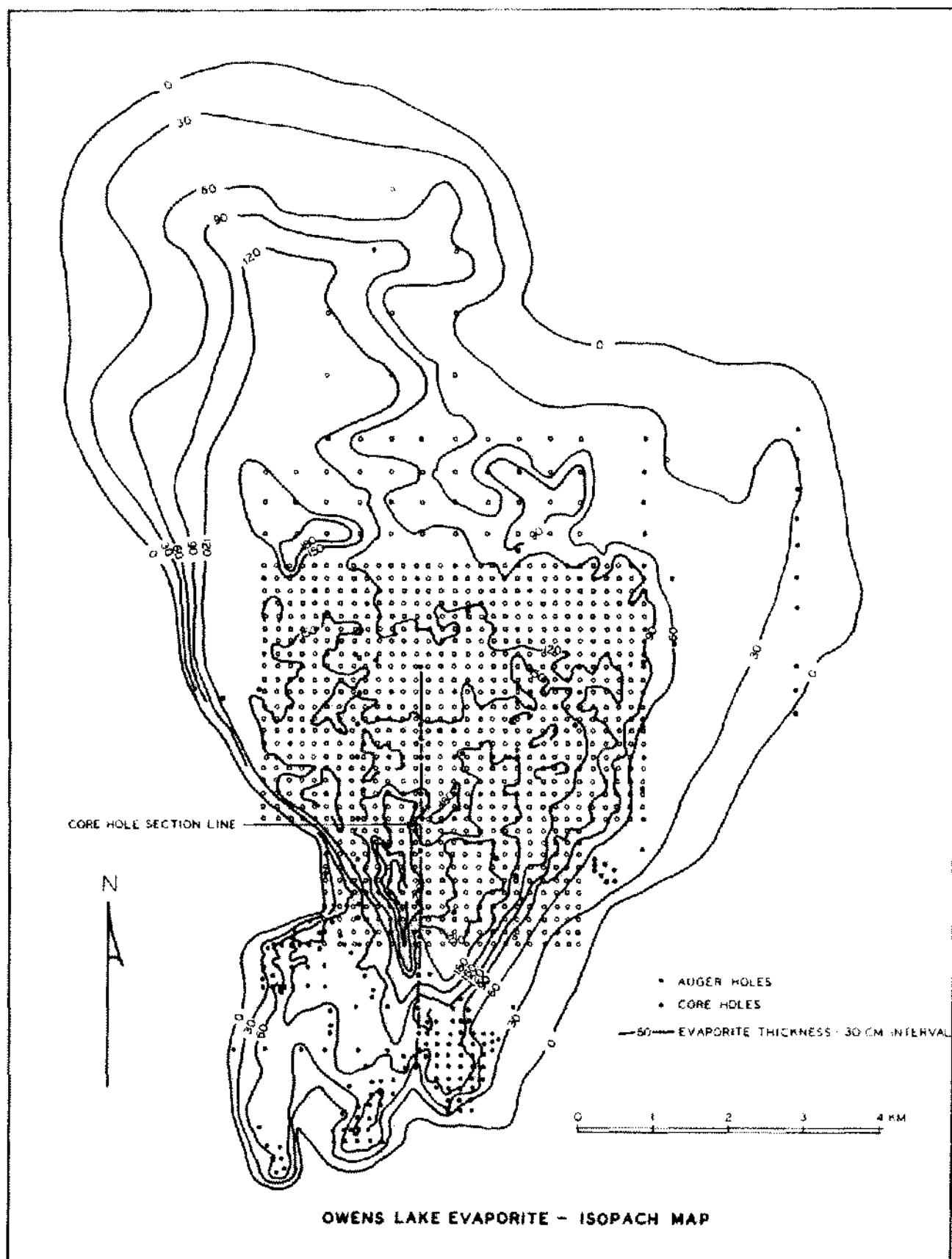


Figure 4.

The chemical composition of the brine phase, expressed in weight per cent is:

$\text{Na}_2\text{CO}_3$ .....	8.9%
$\text{NaHCO}_3$ .....	0.2%
$\text{NaCl}$ .....	18.0%
$\text{Na}_2\text{SO}_4$ .....	4.5%
$\text{H}_2\text{O}$ .....	68.4%

The chemical composition (weight per cent) of the solid phase is:

$\text{Na}_2\text{CO}_3$ .....	41.5%
$\text{NaHCO}_3$ .....	25.0%
$\text{NaCl}$ .....	2.6%
$\text{Na}_2\text{SO}_4$ .....	12.4%
Insol .....	9.1%
$\text{H}_2\text{O}$ .....	9.4%

The chemical and mineralogical compositions of the deposit are quite variable vertically and horizontally (see Figure 3). Underlying the evaporite is the original lake bed, mostly soft black mud in the center of the deposit but with increasing amounts of silt and sand toward the edges. Large areas of the lake bed on the eastern edges are made up of cemented calcium carbonate oolites. The first evaporite layer throughout the deposit is trona, followed in the thicker sections by burkeite. As the lake evaporated and receded, the first salts to crystallize were left on the exposed edges and the subsequent salts were deposited in the center of the basin. This explains why the thin edges of the present deposit contain much less sulphate and chloride than the thicker portions.

Above the main burkeite layer a complex sequence of trona, insolubles, and burkeite appears, representing recrystallization following the major flood of 1967-68. Halite appears only in small quantities near the surface and mirabilite occurs abundantly on the surface during the winter months and on the bottom of the lowest trona layer next to the bottom mud.

The sequence of crystallization of original lake brine evaporated under laboratory conditions is:

1. Trona
2. Burkeite
3. Thermonatrite
4. Halite
5. Thenardite ( $\text{Na}_2\text{SO}_4$ )

Under actual field conditions, this sequence was followed only approximately because of daily and seasonal temperature changes and periodic inflows of fresh water. Two major floods, one in 1937-38 and another in 1967-68 caused partial resolution of salts and disrupted the crystallization sequence. The general trend of alteration through the years has been the solution of salts on the thin edges of the deposit and recrystallization near the center, resulting in a thicker deposit with less surface area.

During the early phases of Lake Mineral's study of the deposit, much confusion resulted from a failure to appreciate the seasonal changes that take place. Sodium carbonate decahydrate and sodium sulphate decahydrate (natron and mirabilite) both have highly temperature sensitive solubilities. During the cold winter months, these salts crystallize out of the brine phase, carrying with them large volumes of water of crystallization. The brine phase shrinks and the deposit becomes hard and workable. In the hot summer months, the reverse happens and what was thought to be a solid crystalline body becomes soft mush. Two samples taken at the same place during different times of the year will give different chemical analyses, and worse yet, a sample taken during the winter undergoes drastic phase changes between the field and the warm laboratory.

The chemical compositions and mineralogy given in this paper represent the best estimate of average yearly conditions. Despite these uncertainties and seasonal changes, the composition of the deposit as a whole is constant because the variations represent exchanges between the solid and liquid phases.

#### THE 1912 LAKE COMPARED WITH THE PRESENT EVAPORITE

With this brief background, a comparison can be made between the quantities of salts in the 1912 lake and the quantities found today in the evaporite deposit to see what general conclusions can be drawn concerning the formation and alteration of the deposit.

The gross chemical compositions of the 1912 lake and the present evaporite (including interstitial brine), expressed as weight per cent of insol-free anhydrous salts, are compared below.

	1912 Lake*	Present Evaporite
$\text{Na}_2\text{CO}_3$	35.0%	47.8%
$\text{NaHCO}_3$	6.1%	27.0%
$\text{NaCl}$	43.9%	11.9%
$\text{Na}_2\text{SO}_4$	15.0%	13.3%

\*KCl and  $\text{Na}_2\text{B}_4\text{O}_7$  are reported as NaCl and  $\text{Na}_2\text{CO}_3$  respectively to correspond with present data.

The comparison shows that in percentage, sodium carbonate and sodium bicarbonate have both increased, sodium chloride has been greatly reduced, while sodium sulphate has remained about the same.

The tonnages of salts give additional information on what may have happened.

	1912 Lake	Present Evaporite
$\text{Na}_2\text{CO}_3$	53,600,000	38,600,000
$\text{NaHCO}_3$	10,100,000	21,800,000
$\text{NaCl}$	64,500,000	9,600,000
$\text{Na}_2\text{SO}_4$	24,300,000	10,700,000
Totals	152,500,000	80,700,000

Comparing the totals, it can be seen that only a little over one half of the salts in the 1912 lake are accounted for in the present evaporite deposit. More surprising is that the quantity of bicarbonate has doubled. The sodium sulphate has decreased in proportion to the total, but only 15 per cent of the sodium chloride is now present.

Considering the increase in bicarbonate as the first problem, a possible mechanism is natural carbonation of the lake brine by carbon dioxide in the atmosphere. Resolution of this question is beyond the scope of this paper, however. Whether the measured increase could have taken place in a period of about 60 years under ambient conditions while the lake was being evaporated and the evaporite deposit was exposed to the atmosphere is a question that should be investigated by phase chemists or geochemists.

The second observed discrepancy is the very large decrease in the amount of sodium chloride, and the overall loss of salts. Only two possible explanations present themselves: removal of the brine by seepage, or wind transport of dry salts. Removal of salts from the deposit to date by commercial operations has only been about one million tons, or less than two per cent of the observed loss of salts.

It is evident from common dust storms emanating from the lake bed that large tonnages of salts can be transported by wind erosion. On closer examination, however, this mechanism does not explain the preferential loss of sodium chloride. The only salts subject to removal by the wind are salts contained in the thin dry edges of the deposit. The central part of the deposit is saturated with brine and is not subject to wind erosion. The dry edges are relatively high in carbonates and low in sodium chloride, and removal of these salts by the wind would result in a net loss of carbonate and an increase in sodium chloride, just the opposite of what has occurred. Therefore, some other mechanism must be responsible for the loss of 72,000,000 tons of total salts and about 54,900,000 tons of sodium chloride.

If the missing 54,900,000 tons of sodium chloride were entirely contained in terminal brine, the volume of the brine would be 235,000,000 cubic meters. Within the area of the deposit, this volume would be contained in about seven meters of underlying lake bed sediments.

Downward seepage or percolation of the dense terminal brine into the lake bed sediments appears to offer a reasonable explanation. Physically, the movement would take place because the terminal brine, with a specific gravity of 1.30, will displace the original lake brine which has a specific gravity of less than 1.10. As determined from measurements on a number of core samples in various parts of the lake bed, the permeability of the sediments underlying the deposit averages about  $5 \times 10^{-6}$

cm/sec. Using this value, it turns out that the differential head caused by the dense brine will result in a downward movement of about 30 centimeters per year and in the time since the deposit was formed (about sixty years), the movement should be about 18 meters. Allowing for dilution of the brine as it seeps downward and displaces the original interstitial brine and for the uncertainty of the estimated permeability, the calculated movement appears to be more than enough to explain the loss of brine.

The downward movement of the terminal brine actually is an "overturning." The dense brine replaces the interstitial brine in the lake bed sediments, and this lighter brine moves upward into the pore spaces in the evaporite salts. The light brine, having the composition of the pre-1917 lake, is unsaturated and will preferentially dissolve sodium chloride in order to reach equilibrium with the solid phase salts. The overturning probably dies out with time as the specific gravities of the brine in the evaporite and the brine in the underlying lake bed approach equilibrium.

The evidence from the chemical balance is perhaps even more compelling than the physical or hydrologic evidence. Assuming a downward seepage of 235 million cubic meters of terminal brine, how does the overall chemical balance fit with the observed changes?

The volume of lost terminal brine would contain the following tonnages of salts:

$\text{Na}_2\text{CO}_3$ .....	27,400,000
$\text{NaHCO}_3$ .....	600,000
$\text{NaCl}$ .....	54,900,000
$\text{Na}_2\text{SO}_4$ .....	13,900,000

If the computed losses are added to the amounts measured in the deposit and the results are compared with the amounts in the original lake, the following result is obtained:

	Losses	+	Deposit	=	Total	1912 Lake
$\text{Na}_2\text{CO}_3$	27,400,000		38,600,000		66,000,000	53,600,000
$\text{NaHCO}_3$	600,000		21,800,000		22,400,000	10,100,000
$\text{NaCl}$	54,900,000		9,600,000		65,000,000	64,500,000
$\text{Na}_2\text{SO}_4$	13,900,000		10,700,000		24,600,000	24,300,000
Totals	96,800,000		80,700,000		177,500,000	152,500,000

The computed loss of terminal brine accounts for the loss of sodium sulphate, as well as the loss of sodium chloride. The increase in sodium carbonate and sodium bicarbonate have to be explained by natural atmospheric carbonation or some other chemical reaction. The tabulation shown above ignores the salts that move into the evaporite by "overturning."

The proposed differential seepage of the terminal brine is a possible explanation of the chemical alteration or differentiation of thin bedded evaporites after deposition. The seepage of the terminal brine should remove the most soluble constituents, leaving an enrichment of the



less soluble components. The process would not work in the case of thick bedded evaporites such as potash layers within massive halite deposits because the terminal brine in this case would be in hydrostatic equilibrium with the underlying pore fluids. However the process should be applicable to most lake bed evaporites.

As long as the evaporite is unburied and exposed on the surface, the lost terminal brine will be replaced partly by dilute brine from the underlying lake bed and partly by inflows of fresh water from surface runoff. The new brine will reach chemical equilibrium with the solid phase salts by a combination of solution and evaporation. The process probably slowly dies out as the interstitial brine in the lake bed sediments increases in specific gravity.

### CONCLUSIONS

1. A comparison of the quantities of salts held in 1912 Owens Lake with the quantities measured in the present residual evaporite deposit indicates major losses of sodium chloride and sodium sulfate and a gain of sodium bicarbonate.

2. The increase in sodium bicarbonate content may be explained by natural carbonation from the atmosphere as the concentration of the brine increases.

3. A possible explanation of the loss of sodium chloride and sodium sulfate is the downward percolation or seepage of the terminal brine into the underlying lake bed sediments. Calculations based on hydrologic parameters indicate that the rate of seepage caused by the differential hydrostatic head is the right order of magnitude. Loss of the terminal brine also satisfies the chemical balance.

4. Periodic flooding of the lake bed and washing by rain water tend to move salts from the thin edges into the center of the deposit, replacing the lost terminal brine. These processes reduce the surface area of the deposit and thicken it. Sodium carbonate and bicarbonate are enriched and sodium chloride and sodium sulphate are depleted within the solid phase evaporite.

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