

Low Temperature Origin of Sodium Sulfate Deposits, Particularly in Antarctica*

Wakefield Dort, Jr.
Doris Stage Dort
Department of Geology
University of Kansas
Lawrence, Kansas

ABSTRACT

Sodium sulfate is a common deposit in arid and semi-arid parts of the world. Massive, almost pure accumulations of the decahydrate variety (mirabilite) occur in especially large quantities in western United States and Canada and across the southern part of the Soviet Union. The anhydrous form (thenardite) is less common.

The solubility of the hydrate increases with increasing temperature; that of the anhydrous form decreases. The transition point of the two forms alone is 32.38°C , but this temperature is considerably depressed by the presence of other solutes. The hydrate is efflorescent, changing to the anhydrous form quickly in most atmospheres at moderate temperatures. This change is much slower in sub-freezing conditions.

Although sodium sulfate minerals are not present in the suite commonly precipitated from evaporating seas, mirabilite is the first mineral, after ice, to crystallize from cooling sea water, beginning at -8.2°C and continuing alone until sodium chloride dihydrate begins to form at -22.9°C .

In coastal Antarctica, mirabilite beds were deposited from relict sea water trapped in rock basins or behind glacier barriers by isostatic uplift and concentrated by combined evaporation and sublimation from winter ice. Disseminated efflorescences throughout the continent are probably accumulations of windblown sea spray and saline snow, locally redistributed by meltwater.

In other parts of the world, mirabilite is precipitated in winter from saline lakes occupying closed basins where rainfall is deficient. The precipitate may redissolve in summer unless protected by sub-

sequent deposition of clay or other impermeable material, in which case thick beds may build up.

INTRODUCTION

Observations of sodium sulfate as minor though widespread efflorescences and as thick, stratified bodies on the continent of Antarctica have aroused renewed interest in this salt and in the possible origin of its several occurrences in this distant region of the world.

Sodium sulfate is a common salt in the chemistry laboratory and in the industrial world. It is used primarily in the manufacture of kraft paper, glass, and detergents. It occurs naturally in one form or another throughout the world, and is found in commercial quantities in western United States, western Canada, the USSR, parts of South America, and a few other places.

Probably the most familiar form of sodium sulfate is the decahydrate, still commonly known as Glauber's salt. It was first discovered by Johann Glauber (1604-1670) in the deposits of a mineral spring near Vienna, and was also prepared by him in his laboratory. He called the salt *sal mirabile* and attributed to it many remarkable properties (Partington, 1961, pp. 352-353).

Natural deposits of this hydrated salt were observed in the northern Great Plains of the United States as early as the Lewis and Clark Expedition of 1804-1806 (Binyon, 1952; Grossman, 1949). Deposits of the same salt in Antarctica were noted

* Research supported by Grant Nos. 203, 588, and 1685 from the Office of Antarctic Programs, National Science Foundation.

and described by the geologist of Captain Robert Scott's British National Antarctic Expedition of 1901-1904 (Ferrar, 1905, p. 565).

PROPERTIES OF SODIUM SULFATE

Sodium sulfate exists in three known forms, not including high temperature modifications. It can be prepared in the anhydrous form, Na_2SO_4 , and in two hydrated forms, $\text{Na}_2\text{SO}_4 \cdot 7\text{H}_2\text{O}$ and $\text{Na}_2\text{SO}_4 \cdot 10\text{H}_2\text{O}$. The heptahydrate is a metastable form and apparently does not occur naturally. Both the anhydrous form and the decahydrate occur extensively in nature. The anhydrous mineral is called *thenardite*; the decahydrate is *mirabilite*.

The decahydrate is noted for its efflorescence, the spontaneous loss of water of hydration upon exposure to air. As water of hydration is lost, $\text{Na}_2\text{SO}_4 \cdot 10\text{H}_2\text{O}$ changes to powdery anhydrous Na_2SO_4 . This conversion occurs in a matter of minutes or hours in a relatively dry atmosphere at room temperature and has at times caused difficulty with attempted X-ray analysis (Fig. 1). Inasmuch as the conversion is much slower at lower temperatures, efflorescence of specimens can be largely prevented by refrigerating the hydrate in a tightly closed container.

The efflorescence of mirabilite to form thenardite, as when deposits of the decahydrate are exposed at the land surface, is strongly influenced by the relationship between the vapor pressure of water in air and the dissociation pressure for the $\text{Na}_2\text{SO}_4 \cdot 10\text{H}_2\text{O}$ — Na_2SO_4 pair. In Table 1 the vapor pressure of water is given for three selected temperatures. The relative humidity that corresponds to a

Table 1. Interrelationships of Temperature, Dissociation Pressure, and Water Vapor Pressure for Sodium Sulfate.

Temperature ($^{\circ}\text{C}$)	0 $^{\circ}$	15 $^{\circ}$	20 $^{\circ}$
Dissociation pressure of Na_2SO_4 — $\text{Na}_2\text{SO}_4 \cdot 10\text{H}_2\text{O}$ pair (mm Hg)	2.77	9.21	19.20
Water vapor pressure (mm Hg)	4.58	12.79	17.54
Corresponding relative humidity	60.5%	72.0%	>100%

Dissociation pressure data from Maron and Prutton (1965, p. 254); water vapor pressure data from Handbook of Chemistry and Physics (Hodgman, 1962).

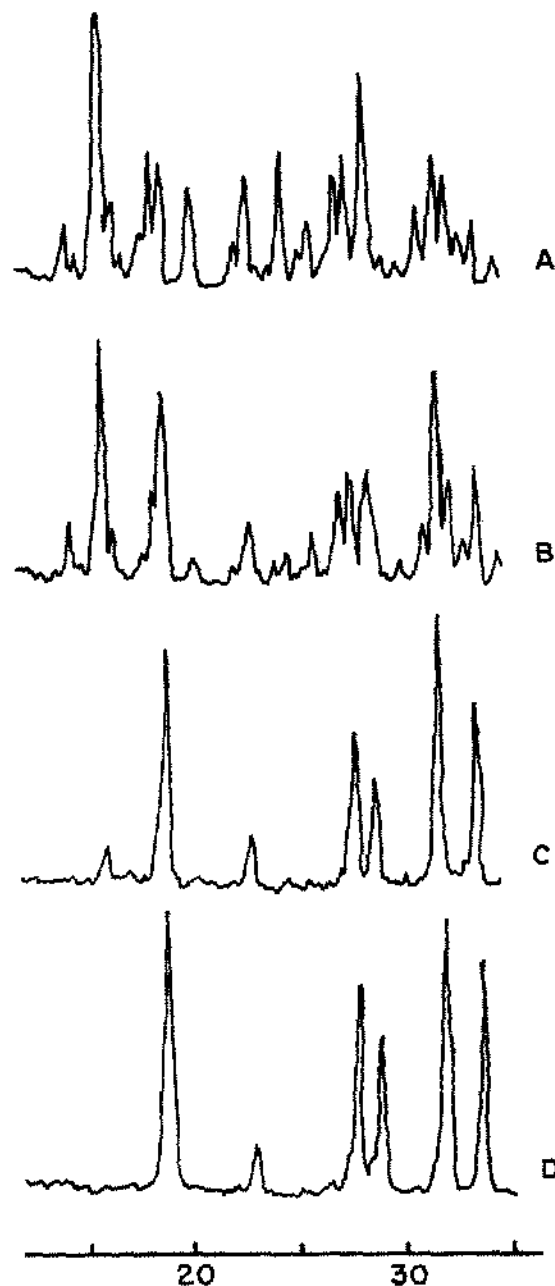


Figure 1. Variation of X-ray diffraction pattern as mirabilite dehydrates to thenardite on exposure to air. (A) mirabilite after 5-minute exposure, (B) after 30-minute exposure, (C) after 60-minute exposure, (D) thenardite. (From Toni et al., 1966).

water vapor pressure equal to the dissociation pressure for the sodium sulfate pair at each of those temperatures is given also. When this dissociation pressure is higher than atmospheric water vapor pressure efflorescence tends to occur. Table 1 shows that at temperatures of 20 $^{\circ}\text{C}$ (68 $^{\circ}\text{F}$) and

higher efflorescence of exposed mirabilite occurs even if the atmosphere is saturated with water vapor. At lower temperatures, efflorescence will occur only if the water vapor pressure of the atmosphere is less than the dissociation pressure of sodium sulfate. The lower the temperature, the lower is the relative humidity required to prevent efflorescence.

The solubility of the sodium sulfate decahydrate increases markedly with increasing temperature while the solubility of the anhydrous salt decreases somewhat with increasing temperature (Fig. 2). Solution of the hydrate is an endothermic reaction;

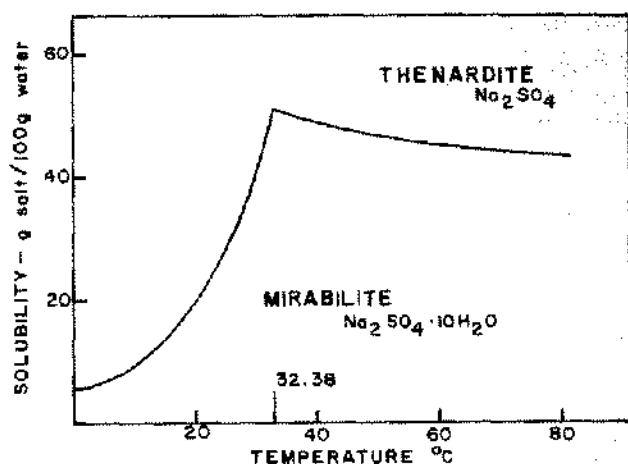


Figure 2. Solubility of sodium sulfate. Data from Handbook of Chemistry and Physics (Hodgman, 1962).

that of the anhydrous form is exothermic. The transition point for the pair $\text{Na}_2\text{SO}_4 - \text{Na}_2\text{SO}_4 \cdot 10\text{H}_2\text{O}$ is 32.38°C (90.28°F) (Dyson, 1961, p. 1009). Below this temperature only the decahydrate will crystallize from a saturated sodium sulfate solution; above this temperature only anhydrous sodium sulfate will crystallize. The transition point is depressed by the presence of other dissolved salts. Figure 3 shows the effect of sodium chloride on the transition point. A solution mutually saturated with sodium sulfate and sodium chloride has a transition temperature of 17.9°C (64.2°F) (Shuttleworth, 1963).

The phase diagram for the $\text{Na}_2\text{SO}_4 - \text{H}_2\text{O}$ system is given in Figure 4. The conditions of concentration and temperature necessary to produce either solid mirabilite or solid thenardite from a

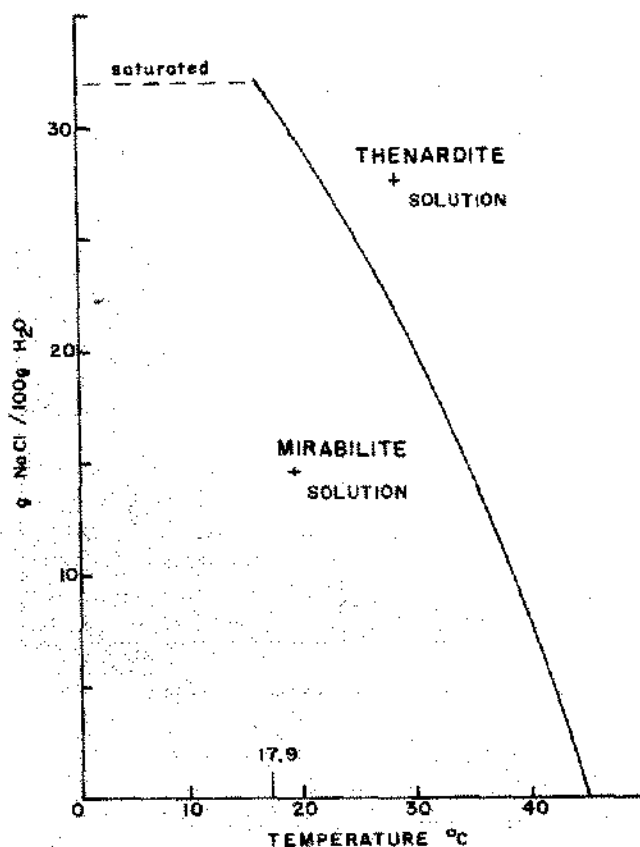


Figure 3. Effect of sodium chloride on the mirabilite-thenardite transition temperature. (From Eugster and Smith, 1965; saturation temperature from Shuttleworth, 1963).

solution of sodium sulfate in the absence of other salts can be determined from this diagram.

CRYSTALLIZATION FROM SALINE SOLUTIONS

Salts may be crystallized from solution by any method that either decreases the volume of water present or decreases the solubility of the salt. Two common processes in nature are evaporation and cooling (the solubility of many, but not all salts decreases with decreasing temperature). Extension of the cooling process to the freezing point and below has the effect of removing water available for solution as well as moving the system into a region of lower solubilities for most salts.

Deposits of evaporite salts, both marine and lacustrine, are well known, and the marine deposits, in particular, have been studied rather extensively. Crystallization of mirabilite in Great Salt Lake and other lakes in western United States and

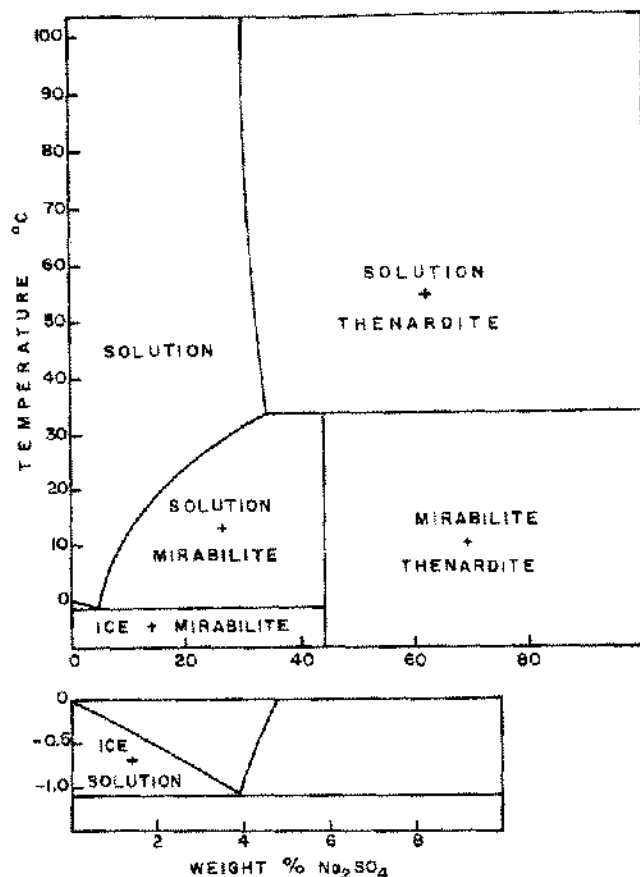


Figure 4. Phase diagram for the system sodium sulfate-water at one atmosphere. (From Wetmore and LeRoy, 1951).

Canada, as well as in many lakes of the USSR, occurs during the autumn and winter seasons and sometimes even on cool summer nights, illustrating the effect of cooling on solubility. The exact temperature at which crystallization occurs depends upon the composition of the solution.

It is not a simple matter to predict the order of formation of salts upon evaporation of a complex system such as that of sea water if conditions under which evaporation takes place are variable. However, it is known that among the first salts to form, in one way or another, upon evaporation of sea water are calcium carbonate, calcium-magnesium carbonate, and calcium sulfate (Borchert, 1969; Phillips, 1947). Sodium chloride begins to separate when only one tenth of the original volume of water remains. After the volume has been reduced to 1.57 percent of the original, salts of magnesium and potassium begin to appear. Neither thenardite nor mirabilite is among the

minerals commonly found in oceanic salt deposits of evaporitic origin.

The sequence of salts obtained upon freezing sea water is quite different. A qualitative understanding of why this should be can be obtained by considering the solubilities of some simple salts in pure water (Fig. 5). Experiments on the freezing of sea water were carried out by W.E. Ringer in 1906 and more recently by Thompson and Nelson (1954, 1956), Nelson and Thompson (1954a, 1954b), and by Levchenko (1956). The results obtained by Ringer and the more limited results of Levchenko are in essential agreement with those of Thompson and Nelson.

The work of Thompson and Nelson on the deposition of salts from sea water by frigid concentration has given very useful information that may well apply to salt deposits in some regions, to the formation of some sulfate lakes, and to certain lakes and deposits in Antarctica. The sea water

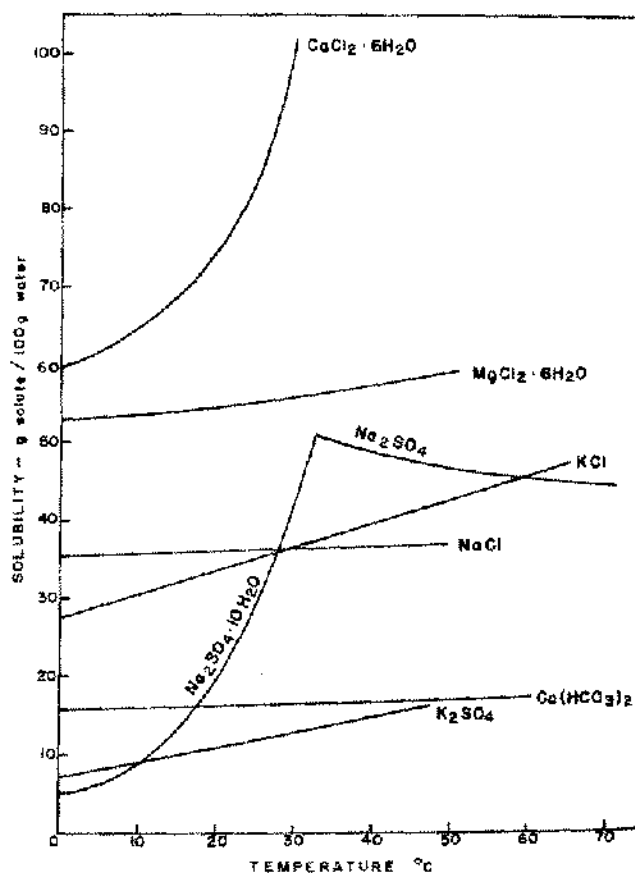


Figure 5. Solubilities of selected salts which could be crystallized from sea water. Data from Handbook of Chemistry and Physics (Hodgman, 1962).

used by them had a salinity of 32.54 ‰. When this water was subjected to freezing conditions, the first solid formed was ice. After approximately 88 percent of the water was frozen (Fig. 6), the first salt, sodium sulfate decahydrate, began to appear at -8.2°C . At -22.9°C sodium chloride dihydrate began to form. The brine remaining at this temperature was only about 2 percent of the original amount. At -36.0°C another salt began to crystallize, and was considered to be a mixture of potassium chloride and magnesium chloride dodecahydrate. An inflection point at -54°C in time-temperature curves indicated the formation of calcium chloride hexahydrate.

OCCURRENCES

General.

Small amounts of sodium sulfate are found in soils, in natural waters, and in aerosol particles in

the atmosphere. It has frequently been pointed out that deposits of sodium sulfate occur widely in closed basins where rainfall is deficient and streams have no outlet to the sea (e.g., Wells, 1923; Tyler, 1935; Goudge and Tompkins, 1960). In such regions there are also many saline lakes containing high proportions of sodium sulfate. The various sodium sulfate deposits generally fall into three categories. (1) Most of the larger deposits are found beneath the beds or around the shores of inland bodies of water or beneath the beds of dry or almost dry lakes. (2) Some deposits are found in mountainous areas as part of a sedimentary sequence. (3) Sodium sulfate occurs widely as surface efflorescences. These are found in soils, clays, and recent lavas, and on the walls of caves and mines. Efflorescences of thenardite are particularly noticeable in parts of Antarctica. Not quite fitting into any of the above categories is the occurrence of sodium sulfate stalactites in caves (Bernasovskii, 1953; Benington, 1959).

Most of the deposits associated with lakes are mirabilite, although thenardite is sometimes also found. Since mirabilite changes to thenardite on exposure to air, unprotected outer surfaces of mirabilite deposits may, of course, be coated with thenardite. It appears that thenardite thus formed protects the mirabilite from further efflorescence, or at least markedly slows the process of conversion. The sodium sulfate deposits associated with other sedimentary layers in mountainous regions are often thenardite. Surface efflorescences are thenardite, but mirabilite may be found in cool caves or mines.

One usual characteristic of the mirabilite deposits is their high purity. At times the product obtained from such deposits may be at least 98 percent sodium sulfate (Martin, 1934). The deposits vary greatly in size. In some instances they are many feet thick and may extend for several miles, as under Great Salt Lake (Eardley, 1962; Cohenour, 1966), or be spread over thousands of acres, as at Soda Lake, California (Ver Planck, 1957).

Naturally-occurring sodium sulfate exists in sufficient quantity and purity that it has been produced commercially in Chile, Italy, Spain, Egypt, USSR, Canada, and the United States (Goudge and Tompkins, 1960; Ver Planck, 1957). Known reserves in the United States are of the magnitude of hundreds of millions of tons; Saskatchewan reserves are estimated at 200 million tons (Arundale, 1956). The enormous deposit of very pure mirabilite at Karabogas on the eastern side of the Caspian Sea has been reported to contain two billion tons (Goudge and Tompkins, 1960).

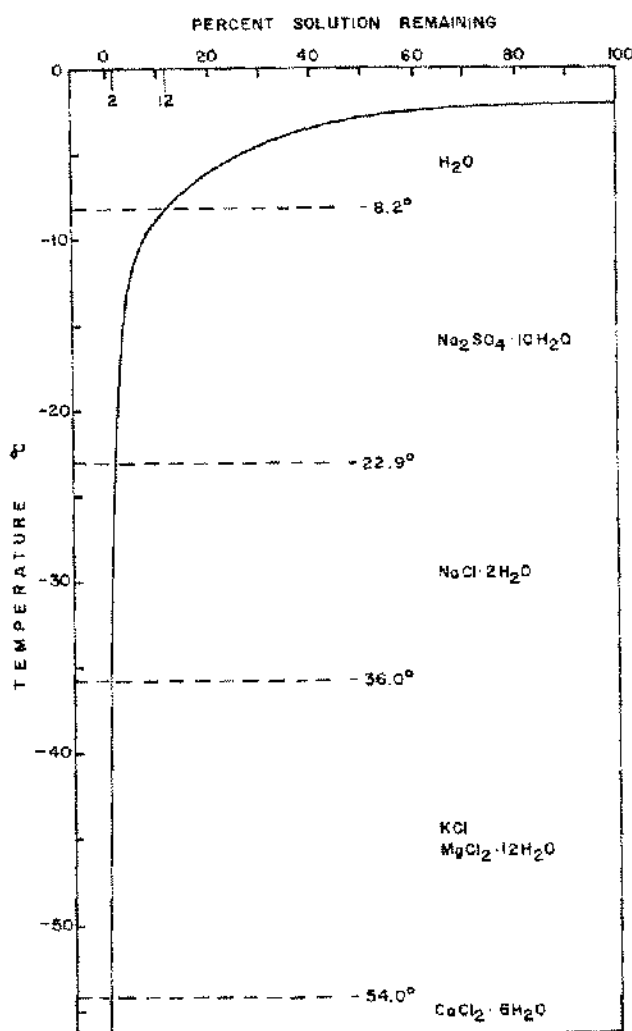


Figure 6. Crystallization of salts caused by freezing of sea water. (After Nelson and Thompson, 1954).

Surveys or extended discussions of naturally-occurring sodium sulfate, both thenardite and mirabilite, have been given by Wells (1923), Tyler (1935), and Arundale (1956). "Dana's System of Mineralogy" (Palache *et al.*, 1951) includes long lists of all types of occurrences of thenardite and of mirabilite. Briefer summaries have been given by Goudge and Tompkins (1960), Kerns (1965), and others.

North America.

Deposits of sodium sulfate, either thenardite or mirabilite or both, have been reported in the United States in Arizona, California, Colorado, Idaho, Montana, Nevada, New Mexico, North Dakota, Oregon, Texas, Washington, and Wyoming (Wells, 1923; Tyler, 1935; Grossman, 1968, and others).

In Canada, extensive deposits are found in Saskatchewan and Alberta (Cole, 1926; Tompkins, 1948; Edmunds, 1957; Grossman, 1968, and others).

Most of these deposits are mirabilite and are found underlying shallow saline lakes or basins of extinct lakes. One set of such deposits occurs in the Great Plains region of Canada and the United States, extending from Saskatchewan and eastern Alberta into northeastern Montana and northwestern North Dakota (Grossman, 1968). All of the deposits in this region are in undrained depressions within areas underlain by glacial drift (Grossman, 1968; Witkind, 1952). Descriptions of these deposits in Canada, Montana, and North Dakota and discussions of possible origins have been given by the authors cited and by Hancock (1919), Lavine *et al.* (1935), Holland (1949), Binyon (1952), Williams (1952), Hansen (1964), and others.

More than 200 saline deposits and lakes containing sodium sulfate are known in western Canada. Cole (1926) described 25 of the deposits that had been studied at that time and summarized their characteristics. In general, these deposits lie beneath lakes which contain from a few inches to a few feet of brine in spring and early summer. They occur in depressions in the morainic drift with no apparent outlet, although subsurface drainage is always relatively good (Edmunds, 1957). Usually the basins in which salts are found in crystallized form are the lowest depressions for a considerable area.

In association with saline lakes, two types of crystalline sodium sulfate beds are recognized, permanent beds and intermittent beds. The latter appear and disappear periodically with the crystallization and subsequent re-solution of mira-

bilite as temperature and amount of water present fluctuate. Intermittent crystal beds generally begin to form in the fall and are redissolved in the spring. However, in late summer or early fall, when the brines are at or near the saturation point, even daily temperature changes may cause crystals to form and redissolve in periods of a few hours. The material in the intermittent beds is generally very pure when first deposited and is present as a mass of loosely compacted, needle-shaped crystals. Later, during the winter, the beds become thicker and the material solidifies into a hard, compact mass. In the spring, with the onset of melting snows and early rain, the whole or part of the intermittent bed goes into solution. These beds range from an inch to two feet or so in thickness.

In the permanent beds, the salts are generally found interbedded or mixed with small quantities of mud, clay, or organic matter which protect the underlying sodium sulfate from later solution. In some instances, the mud layer is described as being 2 to 3 feet thick. The permanent beds of mirabilite range from a few feet to at least 30 feet in thickness. In one exceptional case, a thickness of 139 feet was measured in part of a deposit in Ingebright Lake, west of Swift Current, Saskatchewan (Cole, 1926). This deposit has a permanent bed which extends over an area of about 680 acres with an average thickness of 22 feet, and was estimated to contain, together with the intermittent bed, approximately 25 million tons of hydrated sodium sulfate.

Springs are associated with many deposits. Many of these are freshwater springs, occurring both around the margins and within the area of the deposits. A few are brine springs. According to Cole, the latter are easily detected during the winter because salt cones build up around the orifices. Mirabilite is deposited in a ring around the spring, building up a cone as much as 10 feet high and 20 feet in diameter. The cones dissolve away with the coming of warmer weather and additional moisture.

Other salts occurring with the sodium sulfate in these Canadian basins include primarily magnesium sulfate, and smaller quantities of sodium chloride, sodium carbonate, calcium sulfate, and calcium carbonate. In general, the sodium sulfate content, excluding insoluble materials, seems to range from about 75 to 95 percent, with even higher percentages occurring often in the intermittent crystal bed and occasionally in parts of the permanent bed.

Muskiki Lake, near Dana, Saskatchewan, is rather different from the other lakes in that a mag-

nesium sulfate layer is deposited on top of the mirabilite bed when the temperature of the brine falls below 5°C (41°F).

Two of the larger mirabilite deposits in North Dakota are Grenora No. 2 and Miller Lake (Grossman, 1949). The former, located northwest of the town of Grenora, was reported to have an area of 500 acres, a maximum thickness of the permanent bed of 80 feet, an average thickness of 12 feet, and a total reserve of 11 million tons. The deposit at Miller Lake, southwest of Alkabo, has about the same area, but the maximum thickness of the permanent bed is 50 feet, the average thickness 7 feet. Reserves are estimated to be 5 million tons.

Several occurrences of mirabilite have been reported at Great Salt Lake, Utah. A bed of mirabilite intercalated with thin clay layers lies 15 to 30 feet below the bottom of the lake west of Promontory Point. It has a thickness of 70 feet near the shore, but feathers out at a distance of about 9 miles (Eardley, 1962; Cohenour, 1966). Other deposits have been found beneath the lake bottom and along the southeastern shore (Martin, 1934, 1938; Wilson and Wideman, 1957). The crude sodium sulfate here contains less than 2 percent soluble impurities.

Each winter, sodium sulfate decahydrate crystallizes from the water of Great Salt Lake; the following summer it redissolves, at least in part. During the winter, the crystals, tending to float on the lake surface, are concentrated by wind and waves along the southeastern shore. Offshore bars several feet high and as much as 200 feet wide extend for many miles (Adams, 1938; Cohenour, 1966). At other places, wave-built ridges of mirabilite crystals accumulate on the beaches. As air temperature rises in the spring, these dissolve in their own water of crystallization. The solutions then move downward through the porous beach sand and mirabilite again precipitates where lower ground temperatures are encountered, usually about 20 inches below the surface (Wilson and Wideman, 1957).

Both thenardite and mirabilite have been reported in the beds of saline lakes and playas in southeastern California and western Nevada. Searles Lake, a playa in the Mojave Desert of California, is underlain by layers of evaporite salts and mud that extend to a depth of at least 875 feet. Thenardite is disseminated throughout the deposit in both mud and salt layers (Eugster and Smith, 1965; Flint and Gale, 1958). One bed of mirabilite, 5 to 11 inches thick, was found in the "Bottom Mud" at a depth of about 150 feet. This layer is believed to indicate that a marked chilling of the

lake water took place at the time of its deposition (Flint and Gale, 1958). Thenardite also occurs mixed with halite in lenses as much as 40 feet thick at Dale Lake, another playa in southeastern California (Tyler, 1935).

At Soda Lake, the lowest part of an undrained basin and the sink of the Mojave River, an inch-thick crust of mirabilite covers an area of 2800 to 3000 acres (Ver Planck, 1957). In filled depressions the accumulation reaches a thickness of 6 feet. This region is estimated to contain more than one million tons of mirabilite. Beneath the crust is a brine-permeated mud containing crystals of mirabilite and bloedite (hydrated magnesium-sodium sulfate).

Rhodes Marsh, near Mina, Nevada, is the drainage center for some 600 square miles of territory. A mineralized section of about 200 acres contains, in the southern half of the deposit, a 15-foot layer of mirabilite underlying an overburden of 6 to 24 inches of silt (Rich, 1933a, 1933b). In the northern half of the deposit, the mirabilite is overlain by 3 to 5 feet of thenardite, formed of crystals so hard that drilling and blasting are necessary in the recovery process. In this part of the deposit the overburden consists of sodium chloride as well as fine silt.

At Bull Lake, south-central Wyoming, beds of mirabilite range in thickness from a few feet to 26 feet, and lie above a thick bed of shale. Soluble salts present, other than sodium sulfate, were reported to be about 1 percent (Young, 1951).

In addition to deposits associated with existing lake basins, thenardite and bloedite have been found interbedded with folded Tertiary shales and sandstones in the Durmid Hills of Imperial County, California (Ver Planck, 1957). Near Camp Verde, Arizona, thenardite has been mined from a 4.5-foot-thick bed which is a member of a thick series of sediments consisting chiefly of clay, rock salt, mirabilite, and glauberite (Young, 1927; McDermid, 1934; Tyler, 1935).

Soviet Union.

There is a fairly extensive, but not always readily available, literature on sulfate lakes and sodium sulfate deposits in the Soviet Union. Most of the lakes and deposits reported upon in detail are found within a broad band bounded by lat 38°N. and 55°N. and extending from long 35°E. to 80°E. This area roughly corresponds to the great southward bulge of the USSR between the Black Sea and western China. Other salt lakes with sodium sulfate deposits exist farther north in the

Krasnoyarsk Region of west-central Siberia and in eastern Siberia (Lepeshkov *et al.*, 1962). Most of the lake deposits are mirabilite, although thenardite sometimes occurs also.

Sodium sulfate occurrences in the USSR are not limited to lake deposits. Three main types of deposits are (1) deposits of former geological periods buried in the sedimentary column, (2) deposits of inland seas such as the Caspian Sea and the Aral Sea, and (3) deposits in recent lakes which precipitate sodium sulfate either permanently or periodically (Dzens-Litovskii, 1956). With regard to the last type, the description of the annual cycles in the Selenga sulfate lake in eastern Transbaikalia (Vlasov and Gorodkova, 1961) seems typical of most of these lakes. During winter, formation of an ice crust and freezing out of mirabilite occurs; in the spring, the ice thaws and the mirabilite dissolves; during the summer, the sodium sulfate dissolves fully and becomes concentrated due to evaporation; in the fall, precipitation of mirabilite occurs before the formation of the new ice cover. In this particular lake the mirabilite crystallization begins when the brine cools to 14° to 16°C (57° to 61°F). At -4°C (25°F) the first ice crystals appear.

Other lakes which deposit mirabilite during cold weather and redissolve it during the spring and summer include the Azhbulat sulfate lake in the northern part of Kazakh SSR, Lake Ebeity west of Omsk, Lake Tengiz in central Kazakh SSR, and the Batalpashinsk salt lake (Lashchenko and Morozova, 1933) and Tambukan lakes (Budrik, 1926) between the Black Sea and the Caspian Sea. Azhbulat Lake deposits about 40 million tons of mirabilite during the winter (Zdanovskii and Ryabchikov, 1935, 1940). Lake Ebeity forms a deposit in winter which is 6 to 30 centimeters thick and contains 84 percent mirabilite and 12 percent thenardite (Druzhinin, 1941; Zdanovskii, 1953). In both Lake Azhbulat and Lake Ebeity, the mirabilite begins to form when the temperature of the brine reaches the range of 15° to 20°C (59° to 68°F) and attains maximum deposition about -10°C (14°F). In Lake Tengiz, crystallization begins at 10°C (50°F) (Bekturov and Mun, 1959).

There are a great number of saline and brackish lakes in eastern Siberia (Vlasov *et al.*, 1960). All belong either to the carbonate or sulfate type, frequently with a rather high concentration of chloride ion. Characteristic of such lakes is the presence of brine deposits regularly represented by mirabilite.

Deposits of mirabilite occur on the bottoms of lakes and in dried-up lakes in the Borovoe State National Park in the Akmolinsk Region, Kazakh

SSR (Usova, 1944). There are several sulfate lakes near the Aral Sea. One preliminary estimation of supplies of mirabilite in a group of these lakes was about 4 million tons (Yasnopol'skii, 1938).

Lake Kuchuk on the Kulunda Steppe southwest of Novosibirsk, western Siberia, has been investigated by several workers. It is a lake of 160 square kilometers, containing about 600 million tons of sulfate in its saline waters and underlying strata. During the winter, 380,000 to 640,000 tons of mirabilite are deposited (Bukhshtein, 1938). The mirabilite layer (permanent bed?) in the lake consists of two parts of which the upper is about 3 meters thick. Chemical contamination in this layer is about 1 percent or less (Nikol'skaya *et al.*, 1964). The concentration of the brine of Lake Kuchuk (averaged for the whole year) increased during a sequence of dry years from 1931 to 1946 and then decreased in 1947 (Bukhshtein, 1949). As a result of increased concentration, the brines deposited substantial quantities of thenardite (Lyapunov, 1962). Lake Azhbulat, which has extensive mirabilite deposits, was also recently observed to be depositing thenardite. In this case, a hydrated calcium sulfate-sodium sulfate double salt was precipitated first, followed by pure thenardite (Lyapunov, 1959).

Some studies have been made to determine the conditions for such formation of thenardite from brines. Visyagin (1951), Visyagin and Vasilevskaya (1952), and Sosipatrov (1958), all suggested that thenardite is formed indirectly. High brine concentrations containing appropriate amounts of sodium chloride seem to favor the formation of the anhydrous sodium sulfate. Visyagin and Vasilevskaya used temperatures of 25° to 40°C (77° to 104°F) to form thenardite experimentally.

On the Kulunda Steppe three salt lakes having brines with high sodium chloride content are reported to deposit chiefly sodium chloride in the upper horizons and mirabilite in deeper layers. Thenardite is present in peculiar spots in flat, dish-like basins, 1 to 25 meters in diameter, on a karst-like surface (Gorbov, 1950). The thenardite, black from abundant inclusions of mud, occurs in very coarse crystals in a layer 20 to 40 centimeters thick above a mud layer. The temperature of the mud layer is 25° to 27°C (77° to 81°F) in summer. Gorbov believed that the thenardite was formed by typical incongruent melting of mirabilite under summer conditions (see Fig. 4).

Mirabilite and thenardite have also been reported in Lake Marfovka on the Kerch Peninsula of Crimea (Ponizovskii *et al.*, 1958; Suprichov and Al'bov, 1966). The thenardite crystallization was

discovered during the summer of 1957; in autumn, the thenardite was converted to mirabilite. The lake bottom was covered with a 2 to 3 millimeter layer of mirabilite. Druses of large crystals, 7 to 8 centimeters in length and up to 1.5 centimeters wide were discovered in some parts of the lake (Ponizovskii *et al.*, 1958). Thenardite efflorescences occur on rocks of the southern slope of the Crimean mountains around sulfate and bicarbonate-sulfate springs (Zuprichov and Al'bov, 1966).

Saline lakes in closed basins are found in eastern Georgia. In one of these there was a mirabilite layer in the bottom mud up to 6 meters thick and consisting of 77 to 94 percent mirabilite (Eristavi *et al.*, 1956). A seasonal layer of mirabilite formed on top of the mud.

Karabogaz Gulf, on the eastern side of the Caspian Sea, must be one of the richest sources of mirabilite in the world. Vast deposits of pure mirabilite lie on the gulf bottom (Lebedintzev, 1930). Seasonal crystallization adds additional large quantities. As noted earlier, the deposits have been estimated to contain two billion tons (Goudge and Tomkins, 1960). The report of an expedition to Karabogaz in 1909 stressed the periodic nature of the deposits. In winter, waves throw the mirabilite out upon the shore in large quantities. In April, the salt begins to dissolve, and in July it is about all in solution (Podkopaev, 1930). A report of the 1921-1922 expedition stated that during the four winter months the water is saturated with sodium sulfate and shores are covered with solid mirabilite (Podkopaev, 1922-23). The mirabilite was deposited while the temperature of the water was about 6°C (43°F) (Podkopaev, 1927). The mirabilite that appears in vast quantities on the shore has been reported to contain no trace of Fe and only 0.03 percent MgSO_4 and CaSO_4 (Kitaigorodskii, 1925). Recovery of the mirabilite from the brine of the gulf was a simple matter up to 1939. Since then, at least until 1947, the concentration of the brine has increased until first halite and later epsomite ($\text{MgSO}_4 \cdot 7\text{H}_2\text{O}$) crystallized out with the mirabilite (Blyumberg, 1947). The water level of the Caspian Sea dropped in 1937 by 103 centimeters as compared with 1929 level, which was the average of the preceding 100 years (Shreders, 1938). This caused a decrease in the amount of water that flowed into Karabogaz Gulf from 19.5 to 9.5 cubic kilometers. The new concentration of salts in the water of the gulf caused the precipitation of halite as well as that of mirabilite. (Blyumberg *et al.*, 1940).

Representative of other types of sodium sulfate deposits in the USSR are salt deposits of Sham-

Shikal in the Ketmen-Tyubinsk Basin (Kirgiz SSR), characterized by rock salt, bloedite, mirabilite, and thenardite in Tertiary sandy clays and marls of lacustrine origin (Khvostova, 1948); the salt marsh Shor-Kan (Tadjik SSR), rich in mirabilite, thenardite, glauberite ($\text{CaSO}_4 \cdot \text{Na}_2\text{SO}_4$), and gypsum (Vorob'ev and Kadysev, 1951); deposits of sodium sulfate in the Kiuren-Dag Mountains (western Turkmen SSR) of a mixed type, either thenardite and mirabilite or thenardite and halite (Iskylul, 1930; Reineke, 1930); boulders of fossil NaCl , Na_2SO_4 , and $\text{CaSO}_4 \cdot \text{Na}_2\text{SO}_4$ found preserved in the morainic clay and alluvial-deluvial deposits in different parts of the USSR (Dzens-Litovskii, 1959); and salt minerals, including gypsum, glauberite, halite, mirabilite, thenardite, and bloedite in the Tien Shan comprising what was described as residuum of an intracontinental high-level, high-sulfate water reservoir or reservoir chain, which had never been connected to an ocean (Bergman and Shcherbina, 1950).

Mirabilite is widespread in Tertiary halite deposits of the Tien Shan. Its presence is easily recognized from sodium sulfate efflorescences on the ground surface (Shcherbina, 1949). According to Shcherbina, and later Dzens-Litovskii (1962), Tertiary salt deposits of mountain valleys in Tien Shan are 98.9 percent glauberite which is decomposed into gypsum and mirabilite by water. The underground waters contain chiefly sodium sulfate which precipitates upon cooling, forming mirabilite bodies up to 7.5 meters thick and spread over an area of 30,000 square miles. These deposits can be either permanent or temporary.

The narrow portion of the Shor-Kan mirabilite deposit is 200 meters long, 20 meters wide, and 3 to 4 meters thick (Feodotiev, 1945). Drill data show variable amounts of insoluble residue and a sodium chloride content ranging from 2 to 12 percent. The central portion is 200 meters by 175 meters and up to 5.5 meters thick. The purity of the deposit is higher in this section with 2 to 4 percent sodium chloride and 9 to 19 percent insoluble residues. Mineral springs were found at the deposit. Feodotiev believed that the deposit was formed by redeposition of soluble sulfates of the "gypsiferous" series (clays, sandstones, and gypsum) underlying the deposit. In various parts of the region the gypsiferous series has been found to contain thenardite intercalations.

Spain.

There are several deposits of thenardite in Spain. One deposit in Aleandre (Logrono) consists of beds 10 meters thick. Another bed at Villarubia de San-

tiago (Toledo) is mined. It has an average thickness of 10 meters, lies upon a rock salt bank 15 meters in thickness, and can be followed a distance of 2 kilometers. It is interbedded with glauberite (Rios, 1968).

India.

Salt lakes occur in Rajasthan State, India. The brines of these lakes contain carbonates and sulfates and sodium chloride (Brown and Dey, 1955, p. 516; Sapre, 1956). Salt (NaCl) is crystallized in open pans from brine obtained from wells.

Beds of thenardite, one to four feet in thickness, were discovered below the salt pans (Spencer, 1943, 1944). The thenardite is more than 91 percent pure with the major contaminant being insoluble material (about 6 percent). The total estimated accumulation over the whole of the salt pan area is of the order of 250,000 tons.

Africa.

In southern Africa, thenardite and mirabilite are found in salt pans (Foshag, 1933; Shuttleworth, 1963). Shuttleworth found that in a mixture of Na_2SO_4 and NaCl in solution in ratios greater than 1:3 and at a temperature higher than 17.9°C (64.22°F), thenardite deposits on the pan floor; at less than 17.9°C mirabilite deposits. At ratios less than 1:3 NaCl crystallizes first.

South America.

Sodium sulfate deposits have been reported in Chile (Peña i Lillo, 1933; Leiding, 1942) and in Argentina (Kittl, 1946). A large sodium sulfate lake is known in Brazil (Freise, 1932).

Antarctica.

Occurrences of sodium sulfate minerals in the McMurdo Sound area of Southern Victoria Land, Antarctica (165° E. Longitude), have been known since land exploration of that region began. Ferrar (1905, p. 465; 1907, p. 91), reported deposits of well-formed sodium sulfate crystals among the moraines on the western side of McMurdo Sound, on one of the Dellbridge Islands, and on the sea ice between Black and White Islands (Fig. 7). He specifically identified mirabilite, and termed the occurrences "freaks of nature." He also reported that a bed of mirabilite 45 centimeters thick was exposed for a distance of 10 meters along the face of a moraine on the western side of the Sound.

During Shackleton's Expedition of 1907-09, David and Priestley (1909), and Mawson (1909), found mirabilite near Cape Barnes on Ross Island and attributed its origin to evaporation of a former small lake. Mawson (op. cit.) suggested that mix-

tures of magnesium and sodium sulfates at nearby Cape Royds were deposited from sea spray and saline snow. Taylor (1922, p. 140), with Scott's Second Antarctic Expedition (1910-1912), found beds of mirabilite in the moraine in front of Hobbs Glacier (perhaps those seen earlier by Ferrar). Debenham (1920, 1948, 1965) described these and other deposits then known and suggested that the basic origin of the mirabilite was by concentration and crystallization from sea-water brines sealed into small sea-floor basins by overlying shelf ice.

More recently, with establishment of permanent bases on Ross Island by both the United States and New Zealand, there has been a quantum increase in field research in the McMurdo area. Deposits of sodium sulfate have been at least briefly described and discussed by many of the scientists who have worked in the nearby dry-valley areas of Southern Victoria Land during the past decade and a few specialized studies have been made of these occurrences (Torii *et al.*, 1966; Black and Bowser, 1967a, 1967b; Dort, 1967; Siegel and Dort, 1968).

Powdery, spongy, or solid mineral coatings or efflorescences can be found on rock surfaces, beneath rock fragments, and within surficial debris in almost any of the ice-free areas of Southern Victoria Land, and sometimes on perennial snowbanks or even actual glacier ice. In many instances, the deposit is largely or entirely composed of mirabilite or thenardite; other minerals frequently present are calcite, gypsum, and halite, and several more-complex salts, such as epsomite and bloedite, have been found. These disseminated deposits have been encountered by many field investigators and have frequently been commented upon in published literature (Ferrar, 1907; Ball and Nichols, 1960; Hamilton *et al.*, 1962; Rivard and Pewe, 1962; Angino *et al.*, 1962; Gibson, 1962; Black and Berg, 1963; Nichols, 1963a).

Of much more limited extent are occurrences of beds of pure or nearly pure mirabilite, usually bearing a coating of powdery thenardite on exposed surfaces. In the southwestern corner of McMurdo Sound, the vast Ross Ice Shelf is separated from the continental shore by the Koettlitz Glacier (Fig. 7). To the west of this glacier rise the foothills and then the great main scarp of the Royal Society Range. The foothill belt is cut by several parallel valleys oriented about at right angles to the coast. The wide floors of these valleys slope gradually eastward and the mouths are broadly open toward the Koettlitz Glacier and the Ross Ice Shelf, afloat on the southward extension of the Sound. Bedded deposits of mirabilite have been found beneath and in front of the snout of

the Hobbs Glacier near the northern end of this foothills belt (Black and Bowser, 1967; Dort, 1967; Siegel and Dort, 1968) and in Miers Valley farther south (Torii *et al.*, 1966).

Between the terminal face of the Hobbs Glacier and the shore of what is at present the southernmost tip of McMurdo Sound lies a roughly square area 2 kilometers across of highly irregular terrain developed on ice-cored moraine. On the flanks of some of the jumbled knobs and along the sides of some of the meltwater stream valleys are exposures of bedded mirabilite. Many of the beds are horizontal with thicknesses of 1 to 2 meters or perhaps more (Fig. 8A). Exposures do not extend laterally for more than a few tens of meters, but the ready slumping of topographically higher morainic debris may conceal greater lengths.

The mirabilite overlies the ice core of the moraine and is itself commonly overlain by a few centimeters of algal peat, some tens of centimeters of coarse well-sorted sand, and then angular rubble of the moraine. Faint lines within the thick beds reveal the presence of subtle laminations indicative of a periodically fluctuating rate of accumulation of the mirabilite. Some of the beds have a high content of sand, algal debris, or morainic rubble; others are remarkably pure. When present, the enclosed detritus usually has an apparently random distribution, but in one bed was observed to occur in irregular vertical tubes or columns.

Some of the beds of mirabilite have clearly been deformed, presumably by push of either the Hobbs Glacier or an expanded Koettlitz Glacier, so that the laminations reveal irregular contortions and isoclinal folding (Fig. 8B). Masses of mirabilite also are present directly beneath the frontal scarp of the Hobbs Glacier and enclosed within the glacier ice itself. (Black and Bowser, 1967). Exposures of mirabilite are present from near sea level to elevations of almost 200 meters. Minor amounts of gypsum, halite, and sylvite are believed to be present locally (Black and Bowser, 1967).

The mirabilite deposits in Miers Valley appear to be in horizontal beds not disturbed by glacier push (Torii *et al.*, 1966). They occur at elevations of approximately 150 to 200 meters above sea level. Gypsum and calcite are present in some places.

The occurrences of bedded mirabilite in Hobbs and Miers Valleys are radically different from the efflorescences and thin layers of mirabilite and thenardite found elsewhere in Southern Victoria Land. The same contrast can be found in other parts of the Antarctic Continent (Fig. 9).

Because the attention of field parties engaged in preliminary exploration of remote areas in Antarctica is generally focused on bedrock units, there is scanty published description of surficial secondary minerals. Furthermore, analyses of such deposits as were observed usually lack detail. Nevertheless, efflorescences in ice-free areas appear to be widespread.

Craddock *et al.* (1964) mentioned deposits of secondary carbonate adhering to the undersides of loose rocks in the Jones Mountains (74°S., 94°W.). Tasch and Angino (1968) discussed sparse occurrences of calcitic efflorescences in the Sentinel Range (78°S., 86°W.), and white powdery efflorescences and crusts in the Ohio Range (85°S., 112°W.). Analysis of the latter revealed gypsum and magnesium sulfate hexahydrate. Van Autenboer (1964) found gypsum efflorescences in the Sør Rondane Mountains (72°S., 25°E.), and Revnov (1964) described mirabilite crystals found at depths of 5 to 10 centimeters in surficial debris at an elevation of 1220 meters in approximately the same area.

Along the coast, efflorescences of mirabilite and halite encrust rocks in the Vestfold Hills (68°S., 78°E.), described by McLeod (1964), and efflorescences having the taste of salt or else of soda occurring on rocks in Bunger's Oasis (66°S., 100°E.) are mentioned by Avsyuk *et al.*, (1956).

Closer to the McMurdo Sound region, Smith (1965) described encrustations near the Darwin Glacier (80°S., 157°E.) that were composed mainly of gypsum and thenardite, but also included halite, calcite, and epsomite. In Northern Victoria Land, Gair (1967) found efflorescences widespread on most rocks. These included gypsum, calcite, and, especially noteworthy, mirabilite and thenardite on the top of Scarab Peak (73°S., 163°E., elevation 10,350 feet).

The only occurrence of bedded mirabilite outside of the McMurdo Sound area of which mention was found in the published literature is at Deep Lake in the Vestfold Hills (68°S., 78°E.). A layer at least 1 meter thick is exposed over an area of 5 meters by 10 meters by the lakeshore (McLeod, 1964). A strikingly similar deposit is present at the edge of an unnamed lake in the Skarvs Nes district of the Prince Olaf Coast (69°S., 40°E.). Layers of mirabilite 2 to 3 centimeters thick are interbedded with sand and laminated silt. Efflorescences are common at both localities.

ORIGIN OF ANTARCTIC DEPOSITS

It is clear that there are two fundamentally different types of deposits of sodium sulfate in Antarctica. On the one hand are widespread efflorescences of mirabilite and thenardite, often associated with other secondary salts, on or just beneath the ground surface. In distinct contrast are the beds of mirabilite that have been found at only a few localities. It appears certain that these unlike deposits had unlike origins, but that the origins of both are directly related to peculiarities of the Antarctic environment.

Skarvs Nes.

The deposit for which the mode of origin seems most clear is that found beside an unnamed, highly saline lake in the ice-free Skarvs Nes district of the Prince Olaf Coast. This lake is on the order of 1.5 kilometers long and 0.5 kilometers wide. On three sides, hills of bare igneous and metamorphic rock slope steeply upward to heights of a few hundred meters (Fig. 10). At one end, however, the narrow bedrock ridge that separates this lake from the ocean rises only about 35 meters above the lake. During a brief reconnaissance visit to this area, it was estimated that the lake surface itself was perhaps 10 meters below the level of the sea on the other side of this barrier. A wedge of gravel topped by a well-developed horizontal surface extends along one side of the rock basin. This terrace surface appeared to be just slightly above the crest of the barrier that separates lake from sea. The beds of mirabilite, interlayered with sand and silt that contain large clam shells, are exposed in the side of a low mound 1 to 2 meters above lake level. X-ray analysis of a specimen from this locality showed it to be composed of very pure sodium sulfate decahydrate.

Because the terrace surface, when projected along the sides of the lake basin, would pass above the barrier at the seaward end and continue along the shore area as a marine terrace, it seems certain that this rock basin was once occupied by a long, narrow arm of the sea. Isostatic rebound resulting from deglaciation caused the land to rise slowly (Dort and Yoshida, 1968). First the rock barrier, still below sea level, merely inhibited circulation of water from the open ocean; on rising higher, it created a lake of entrapped sea water. The mirabilite must have been precipitated from this sea water.

The lake surface was not frozen when observed at the beginning of February; air temperature was a few degrees above 0°C at mid-day. The temperature of the lake water was not determined. However, in a nearby quiet cove, the surface of the ocean became covered by a 1 centimeter thick layer of ice during the daily twilight period. On the basis of taste, it was believed that the lake water had a much higher salinity than that of sea water, and would therefore freeze at a markedly lower temperature.

In order that mirabilite be crystallized from sea water, considerable concentration must take place. Nelson and Thompson (1954a, 1954b; Thompson and Nelson, 1956) found that 88 percent of the original volume of sea water must become ice before the next solid, mirabilite, begins to crystallize (Fig. 6). When the lake at Skarvs Nes was first cut off from the sea it had a depth of about 35 meters plus the present depth, which is unknown. It is unreasonable to suggest that most of that body of water froze. For purposes of comparison, it may be noted that in Southern Victoria Land, where the mean annual temperature is probably slightly lower than that of Skarvs Nes, Lake Vanda has a maximum depth of 66 meters and Lake Bonney has a maximum depth of 33 meters, yet each has an ice cover only about 4 meters thick (Angino and Armitage, 1963; Angino *et al.*, 1964, 1965a).

Inasmuch as concentration by freezing alone would not have been sufficient to cause crystallization of mirabilite from the entrapped sea water, it follows that the required loss of water must have been the result of combined evaporation from the water surface during summers and sublimation from the ice surface during winters, as shown by Yamagata *et al.* (1967a). This conclusion is further supported by the fact that the lake-water level has dropped approximately 35 meters since separation from the ocean occurred. As water was removed by evaporation, the concentration of the brine increased. At some point, concentration and temperature attained a relationship at which mirabilite began to crystallize. Studies of saline lakes in the interior of North America and the USSR, even though the brines in those lakes were not formed from entrapped sea water, have shown that the temperature range at which mirabilite crystallizes varies with the composition of the brine, but may be several degrees above 0°C.

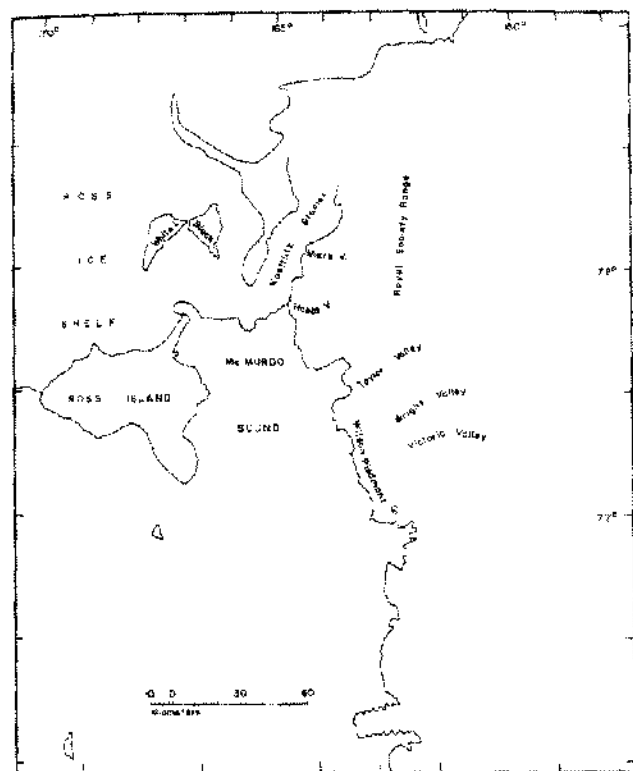


Figure 7. Map of McMurdo Sound and adjacent portions of Southern Victoria Land, Antarctica showing localities mentioned in text.

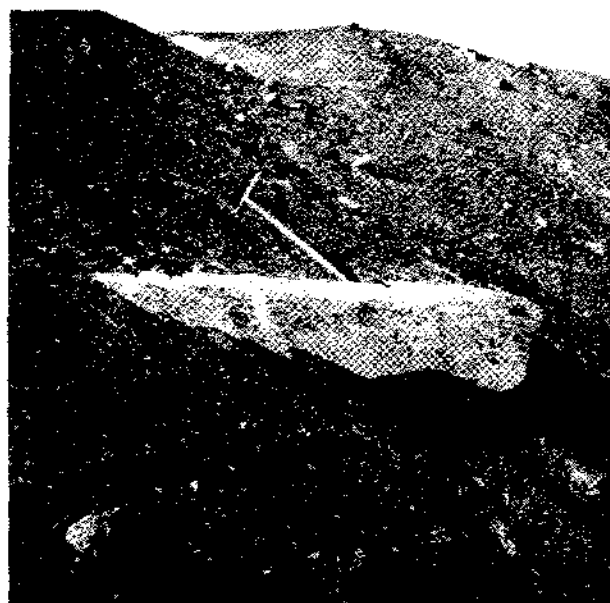
The presence of clam shells, worm tubes, and similar remains of marine organisms demonstrate that other lakes in the Skarvs Nes district also were once arms of the sea. Their waters are highly saline, but no beds of mirabilite were seen, perhaps because such deposits happen to be covered by water or sediment at those localities.

Vestfold Hills.

Evidence that mirabilite was deposited from sea water that had undergone concentration by evaporation and freezing-sublimation is also present in the Vestfold Hills district of Princess Elizabeth Land, some 1500 kilometers east of Skarvs Nes (McLeod, 1964). Of the many lakes and ponds scattered among the metamorphic-rock hills of this area, a few are highly saline and have water levels that range up to 56 meters below sea level. These lakes lie in valleys that extend to the sea. The surficial detritus on the valley floors is impregnated with salts, and remains of marine organisms are common. A terrace present along parts of the lake basins stands a few meters above sea level, at about the same elevation as the divides separating the

lakes. Deposits of mirabilite were found in the lower parts of some of the valleys.

In the Vestfold Hills, as at Skarvs Nes, it is clear that the saline lakes are remnants of bodies of sea water entrapped when the land rose by isostatic



(A)



(B)

Figure 8. Sodium sulfate deposits in front of Hobbs Glacier. (A) Horizontal bed containing glacial debris and overlain by algal peat, sand, and glacial moraine. Large inclusion below end of ice ax is seal vertebra. (B) Deformed laminated bed. Clear, colorless mirabilite is coated by white thenardite efflorescence.

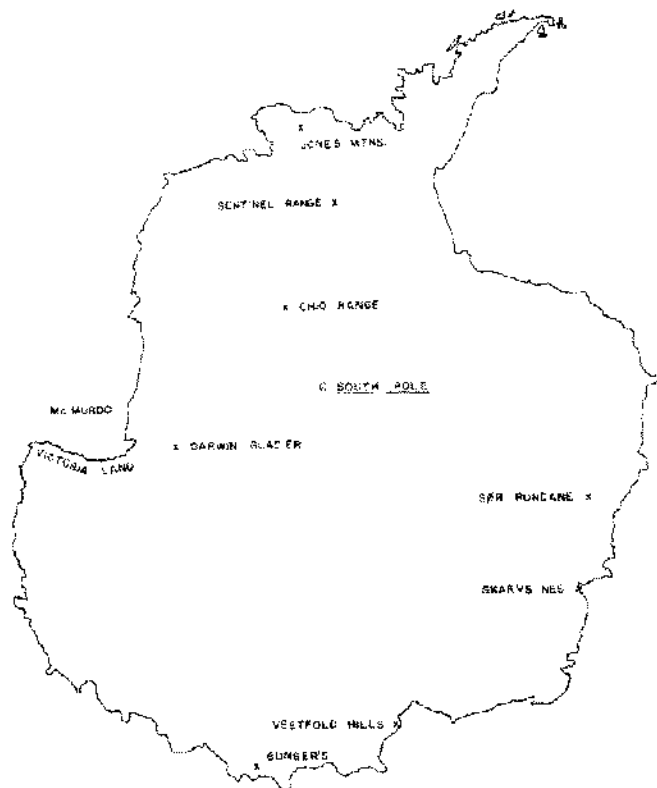


Figure 9. Map of Antarctica showing localities mentioned in text.

rebound. The mirabilite deposits, and the other salts as well, must have been precipitated from the concentrated sea water. The depths of these lakes when newly formed were too great to permit concentration by freezing alone; Deep Lake has a depth of more than 100 meters measured from the present surface 56 meters below sea level. Therefore, concentration must have been accomplished by evaporation and freezing-sublimation, and crystallization of mirabilite occurred when the temperature-concentration relationship became favorable.

McMurdo Sound.

Unlike the situation at Skarvs Nes and the Vestfold Hills, observed occurrences of bedded mirabilite in the McMurdo Sound area do not lie in deep lake basins or closed bedrock depressions. The deposits in Miers Valley lie on the broad valley floor that has a gentle, continuous, unobstructed slope to the sea less than 5 kilometers distant. The deposits in front of the Hobbs Glacier are in a morainic area that descends directly to the strand-

line. At neither locality is it possible for sea water to have been entrapped by existing topographic features when isostatic rebound brought about emergence of the land.

Nevertheless, relatively large quantities of essentially pure sodium sulfate are present, and the shape, size, laminated structure, and purity of the beds indicate that accumulation took place in bodies of standing water. The only reasonably possible obstruction which could have formed a dam across the mouths of these valleys would have been a coastal ice mass that stood against the land to elevations at least 200 meters above present sea level. That this ice mass was most probably an earlier stage of the Koettlitz Glacier is indicated by the presence in the mouths of all of the valleys in this area of moraines deposited by ice flowing in an upvalley direction.

In order to secure the quantities of sodium sulfate that now constitute the beds of mirabilite, it appears necessary to postulate entrapment of sea water in the lower parts of these valleys by the higher level stage of the Koettlitz Glacier and its moraines. It is conceivably possible that copious supplies of meltwater from a large drainage basin could wash disseminated efflorescent salts into a lake where concentration could then occur through selective crystallization. However, the drainage basins of the Hobbs and Miers Valleys each contain only about 120 square kilometers, hardly enough to yield sufficient quantities of soluble mineral matter unless surface efflorescences were far thicker and more pervasive than those now seen elsewhere in Southern Victoria Land. Furthermore, the beds of mirabilite do not contain intercalations of sand or silt that would expectably accompany such runoff.

It therefore appears that sea level formerly stood at least 200 meters higher on this coast than it does now, that a higher-level Koettlitz Glacier (probably higher because it was a floating tongue adjusted to sea level as at present) blocked the mouths of the adjacent valleys, and sea water was effectively trapped in the ice-free portions of these valleys. Concentration of the dissolved salts as a result of simple freezing of shallow lakes or evaporation and freezing-sublimation of deeper lakes could then have resulted in the deposition of beds of mirabilite. It is probable that mirabilite was deposited in all of the valleys in this area, although occurrences are presently known only in Hobbs and Miers Valleys.

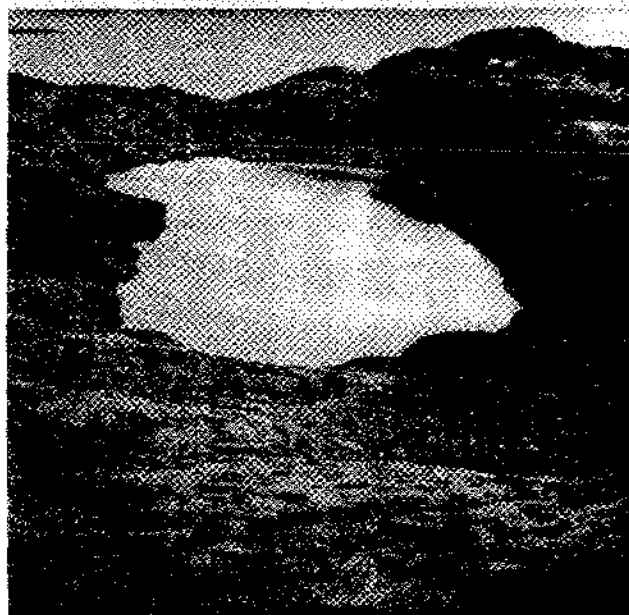
A few kilometers farther north along the coast of McMurdo Sound are the famous Taylor, Wright, and Victoria dry (i.e., ice free) valleys. Lakes are present in each of these. Their waters are highly saline, but no deposits of bedded mirabilite or other salts have been found. During the past decade there has been a lively debate regarding the origin of the dissolved salts.

One of the major suggestions that has been offered is that these lakes also are the relicts of long, narrow arms of the sea trapped in rock basins as the land emerged. The topographic barrier at the mouth of Taylor Valley rises about 80 meters above sea level; those at the mouths of Wright and Victoria Valleys are concealed beneath the Wilson Piedmont Glacier, but they may rise considerably higher. Even so, these barriers are probably lower than the at-least-200 meters stand of sea level postulated to explain the mirabilite beds in Hobbs and Miers Valleys. The highest raised beaches yet described for this part of the coast are only about 20 meters above sea level (Nichols, 1963a, 1963b, 1965, 1966). Nevertheless, Black and Bowser (1967) enumerate other evidence from Taylor Valley that is suggestive of a recent uplift above the sea to an unspecified height, and Jones and Faure (1968) state unequivocally that raised strand lines demonstrate that at one time the sea did extend into Taylor Valley.

Detailed studies of the ionic constituents of the waters of the various lakes has led to the consensus that those in the lower and middle reaches of Taylor Valley may contain at least some relict sea water, but those in Wright and Victoria Valleys probably do not (Angino *et al.*, 1962, 1964, 1965a, 1965b; Angino and Armitage, 1962, 1963; Armitage and House, 1962; Nichols, 1963, 1965; Boswell *et al.*, 1967a, 1967b; Jones *et al.*, 1967; Jones and Faure, 1967, 1968). In direct contrast is the conclusion reached by Yamagata *et al.* (1967a) that the compositions of the several lakes constitute points on a continuum that begins with normal sea water and undergoes progressive modification as a consequence of an intricate combination of evaporation, freezing, sublimation, and fractional crystallization. They noted that the final salt found to crystallize from freezing sea water is calcium chloride hexahydrate (Nelson and Thompson, *op. cit.*) and that the only known natural occurrence of this salt is in Don Juan Pond in Wright Valley. It was named antarctite by Torii and Ossaka (1965), and was later erroneously identified as hydrophilite (hygroscopic calcium chloride, Palache *et al.*, 1951) by House *et al.* (1966).



(A)



(B)

Figure 10. Saline lake at Skarvs Nes. (A) View from above ocean. Marine terrace shows faintly at far end of lake. (B) View toward ocean. Marine terrace shows clearly on left side. Deposit of mirabilite coated with thenardite is in area of delta at lower left corner of lake. Figures in middle distance indicate scale.

Efflorescences of sodium sulfate and other salts are probably ubiquitous throughout ice-free areas of Antarctica. Occurrences of this type are especially common in the dry valleys of Southern Victoria Land and have therefore been the subject of some study, especially in relation to the origin of the saline lakes. The various salts have been attributed to (1) redistribution of ancient salt deposits, (2) exhalation from volcanoes, (3) precipitation from thermal springs, (4) weathering of local bedrock, (5) crystallization from relict sea water, (6) deposition by sea spray, aerosols, or saline snow.

There is little evidence of the existence of the first three suggested sources, and patterns of distribution of types of bedrock or of possible locations of relict sea water do not correspond to the distribution of the efflorescences. Deposition by sea spray, aerosols, or saline snow appears to be the only mechanism that will adequately explain the widespread occurrences of efflorescent salts at all elevations and far inland as well as in coastal areas.

During the early exploration of Ross Island, Mawson (1909) commented briefly on efflorescences of sulfate minerals near Cape Royds, stating that "sea spray and blown saline snow have no doubt carried these salts to their resting place." More recently, several field investigators have suggested that sea spray from McMurdo Sound and/or saline snow have transported at least some of the salts into the ice-free areas of Southern Victoria Land (Ball and Nichols, 1960; Kelley and Zumberge, 1961; Angino *et al.*, 1962, 1965; Gibson, 1962; Hamilton *et al.*, 1962; Nichols, 1963; Black *et al.*, 1965; House *et al.*, 1966; Jones and Faure, 1967; Yamagata *et al.*, 1967b; Boswell *et al.*, 1967; Wilson, 1968). Brocas and Delwiche (1963) found sodium in the snow, firn, and ice of Queen Maud Land, and Wilson and House (1965) detected both sodium and sulfate ions in snow at South Pole Station.

The early explorers of the McMurdo Sound area reported occurrences of sodium sulfate on the sea ice (Ferrar, 1905; Debenham, 1920, 1948, 1965). Of particular interest to the present discussion is a more recent report by Wellman and Wilson (1963). In November, 1962 (at the beginning of the austral summer) they observed long windrows of accumulated salts on the sea ice near the southern end of Ross Island and in zones several miles wide along each shore of McMurdo Sound. It was determined by chemical analysis that the substance was almost perfectly pure hydrated sodium sulfate. X-ray analysis did not produce a pattern indicative of

mirabilite, but that may have been the result of partial alteration of the specimen to thenardite (see Fig. 1). They suggested that the source was probably sea water that percolated through the snow of the Ross Ice Shelf. The mirabilite would have formed as a result of freezing of the sea water.

It is not likely that conditions leading to the accumulation of mirabilite on the sea ice of McMurdo Sound during the austral winter of 1962 were unique. Therefore, it is probable that similar accumulations form during almost every winter, the quantity perhaps lesser or greater depending on prevailing conditions. Wellman and Wilson estimated that as much as one million tons of mirabilite might be deposited on the sea ice of the Sound each year. The windrows of crystals would then be moved about by the winds, and at least some of the salt would be blown onto the ice-free areas to the west.

THE ARCTIC

The Arctic regions of the world have been explored and even inhabited to a vastly greater extent than Antarctica. The land there has also been subjected to isostatic rebound and coastal emergence as a result of deglaciation. It is therefore highly appropriate to ask why there are no deposits of bedded mirabilite associated with entrapped bodies of sea water, or if these do exist, why there seem to be no descriptions in the published literature.

Powell Lake, 130 kilometers north of Vancouver, British Columbia, occupies a long, narrow fiord now separated from the ocean by a rock sill 46 meters above sea level (Williams *et al.*, 1961). Separation and entrapment of sea water was the result of postglacial isostatic rebound. The deeper waters of the lake are saline, but no deposits of precipitated salts have been found. In southern Norway, Lake Tokke contains sea water that was trapped and raised 60 meters above present sea level by isostatic rebound (Strøm, 1957). It is reported that sulfides have been formed from the original sulfate in the water. No salt deposits are known.

These localities are apparently too far south, where temperature and precipitation are sufficiently high to prevent concentration of salts and the resulting crystallization of mirabilite or other salts. Such deposits would, however, be expectable along the emerged coasts of northern Scandinavia and the islands of northern Canada.

REFERENCES

- Note: In certain instances an article was not available or could not be translated in time for publication of this paper. Information from these articles was obtained from abstracts, primarily Chemical Abstracts. In such instances, references are given for both the original article and the abstract(s).
- Adams, T.C., 1938, Recent deposition of salt from Great Salt Lake: *Jour. Geology*, v. 46, p. 637-646.
- Angino, E.E., and Armitage, K.B., 1962, Geochemical study of Lakes Bonney and Vanda, Victoria Land, Antarctica (abs.), in *Abstracts for 1961: Geol. Soc. America Spec. Paper 68*, p. 129.
- , 1963, A geochemical study of Lakes Bonney and Vanda, Victoria Land, Antarctica: *Jour. Geology*, v. 71, p. 89-95.
- , and Tasch, J.C., 1962, Chemical stratification in Lake Fryxell, Victoria Land, Antarctica: *Science*, v. 138, no. 3536, p. 34-36.
- , 1964, Physiochemical limnology of Lake Bonney, Antarctica: *Limnology and Oceanography*, v. 9, p. 207-217.
- , 1965a, A chemical and limnological study of Lake Vanda, Victoria Land, Antarctica: *Kansas Univ. Sci. Bull.*, v. 45, p. 1097-1118.
- , 1965b, Ionic content of Antarctic ice samples: *Polar Rec.*, v. 12, no. 79, p. 407-409.
- Armitage, K.B., and House, H.B., 1962, A limnological reconnaissance in the area of McMurdo Sound, Antarctica: *Limnology and Oceanography*, v. 7, p. 36-41.
- Arundale, J.C., 1956, Sodium compounds, in *Mineral facts and problems: U.S. Bur. Mines Bull.* 556, p. 795-800.
- Avsyuk, G.A., Markov, K.K., and Shumskii, P.A., 1956, Geographical observations in an Antarctic "oasis": *Izv. Vsesoyuznogo Geog. Obshchestva*, v. 88, p. 316-350. English translation: *Program Sci. Translations Cat. No. 6*, Office Tech. Service, U.S. Dept. Commerce.
- Ball, D.G., and Nichols, R.L., 1960, Saline lakes and drill-hole brines, McMurdo Sound, Antarctica: *Geol. Soc. America Bull.*, v. 71, p. 1703-1707.
- Bekturov, A.B., and Mun, A.I., 1959, Natural salts of central Kazakhstan and prospects for their use: *Proizvoditel'nyi Sily Tsentral'nyi Kazakhstan Sbornik*, v. 4, p. 227-254. Referativnyi Zhur., Khimiya, 1961, Abs. no. 5G90. *Chem. Abs.*, v. 55, no. 26890g.
- Benington, F., 1959, Preliminary identification of crystalline phases in a transparent stalactite: *Science*, v. 129, p. 1227.
- Bergman, A.G., and Shcherbina, V.N., 1950, Tertiary salt-bearing halite-sulfate region of Tien Shan: *Doklady Akad. Nauk SSSR*, v. 72, p. 1083-1086. *Chem. Abs.*, v. 44, no. 10622f.
- Bernasovskii, V.Ya., 1953, Natural dehydration of mirabilite: *Vestnik Akad. Nauk Kazakhskoi SSR*, v. 10, no. 12 (whole no. 105), p. 87-90. *Chem. Abs.*, v. 48, no. 6327f.
- Binyon, E.O., 1952, North Dakota sodium sulfate deposits: *U.S. bur. Mines Rept. Inv.* 4880, 41 p.
- Black, R.F., and Berg, T.E., 1963, Hydrothermal regimen of patterned ground, Victoria Land, Antarctica: *I.A.S.H., Comm. Snow and Ice*, Pub. 61, p. 121-127.
- , and Bowser, C.J., 1967a, Patterned ground studies in Victoria Land: *Antarctic Jour. United States*, v. 2, p. 116-118.
- , 1967b, Salts and associated phenomena of the termini of the Hobbs and Taylor Glaciers, Victoria Land, Antarctica: *Comm. Snow and Ice, Gen. Assembly of Bern, 1967*, p. 226-238.
- , Jackson, M.L., and Berg, T.E., 1965, Saline discharge from Taylor Glacier, Victoria Land, Antarctica: *Jour. Geology*, v. 73, p. 175-181.
- Blyumberg, Ya. B., Nikolaev, V.I., and Egorov, V.S., 1940, Changes in chemical composition of the waters of the Karabogaz Gulf during the period 1936-38: *Zaliv Kara-Bogaz-gol, Trudy Kompleksnomu Izucheniyu Kaspiiskogo Morya*, no. 11, p. 22-34. Referativnyi Zhur., Khimiya, 1941, v. 4, no. 1, p. 43. *Chem. Abs.*, v. 37, no. 2891³.
- , 1947, The complexity of exploitation of salt brine from Karabogaz-gol: *Khimicheskaya Promyshlennost*, p. 192-195. *Chem. Abs.*, v. 48, no. 5448g.
- Borchert, H., 1969, Principles of oceanic salt deposition and metamorphism: *Geol. Soc. America Bull.*, v. 80, no. 5, p. 821-864.

- Boswell, C.R., Brooks, R.R., and Wilson, A.T., 1967a, Some trace elements in lakes of the McMurdo Oasis, Antarctica: *Geochim. et Cosmochim. Acta*, v. 31, p. 731-736.
- , 1967b, Trace element content of Antarctic lakes: *Nature*, v. 213, p. 167-168.
- Brocas, J. and Delwiche, R., 1963, Cl, K, and Na concentrations in Antarctic snow and ice: *Jour. Geophys. Research*, v. 68, p. 3999-4000.
- Brown, J.C., and Dey, A.K., 1955, *India's mineral wealth* (3rd ed.): London, Oxford Univ. Press, 761 p.
- Budrik, W.M., 1926, *The Tambukan lakes*: Verlag des Balneologischen Instituts der Kaukasischen Mineralwasser, Pt. 1, 190 p. *Chemisches Zentralbl.*, 1927, Pt. 2, p. 1938. *Chem. Abs.*, v. 22, no. 4424.
- Bukshtein, V.M., 1938, Industrial utilization of the Kulunda salt deposits: *Byulleten Inst. Halurgii*, no. 7, p. 40-50. *Referativnyi Zhur., Khimiya*, 1939, v. 2, no. 3, p. 26. *Chem. Abs.*, v. 34, no. 860.
- , 1949, Variation of the chemical composition of the brine of Lake Kuchuk in a many-year cycle: *Trudy Vsesoyuznogo Nauchno-Issledovatel'skogo Inst. Galurgii*, no. 21, p. 243-253. *Chem. Abs.*, v. 46, no. 8911c.
- Cohenour, R.E., 1966, Great Salt Lake, Utah, and its environment, in *Second symposium on salt*, Northern Ohio Geol. Soc., 1966, v. 1, p. 201-214.
- Cole, L.H., 1926, Sodium sulfate of western Canada: Canada Dept. Mines, Mines Branch Pub. 646, 160 p.
- Craddock, C., Bastien, T.W., and Rutford, R.H., 1964, Geology of the Jones Mountains area, in *Antarctic Geology*: New York, John Wiley and Sons, p. 171-187.
- David, T.W.E., and Priestley, R.E., 1909, Geological observations in Antarctica by the British Antarctic Expedition, 1907-1909, in *Shackleton, E.H., The heart of the Antarctic*: London, William Heinemann, v. 2, app. 2, p. 268-307.
- Debenham, F., 1920, A new mode of transportation by ice: the raised marine muds of South Victoria Land (Antarctica): *Geol. Soc. London Quart. Jour.*, v. 75, pt. 2, p. 51-76.
- , 1948, The problem of the Great Ross Barrier: *Geog. Jour.*, v. 112, p. 196-218.
- , 1965, The genesis of the McMurdo Ice Shelf, Antarctica: *Jour. Glaciology*, v. 5, p. 829-832.
- Dort, W., Jr. 1967, Geomorphic studies in southern Victoria Land: *Antarctic Jour. of the United States*, v. 2, p. 113.
- , and Y., Y., 1968, Isostatic and eustatic changes in antarctic sea level (Abs.), in *Abstracts for 1967: Geol. Soc. America Spec. Paper 115*, p. 51.
- Druzhinin, I.G., 1941, Salt reserves of Lake Ebeity: *Acad. sci. U.R.S.S. Comptes rendus*, v. 31, p. 901-902 (In English).
- Dyson, G.M., 1961, Sodium sulfate, in *McLor's comprehensive treatise on inorganic and theoretical chemistry*: New York, John Wiley & Sons, 1961, v. 2, supp. 2, pt. 1, p. 994-1053.
- Dzens-Litovskii, A.I., 1956, Sodium sulfate deposits in U.S.S.R.: *Trudy Vsesoyuznogo Nauchno-Issledovatel'skogo Inst. Galurgii*, v. 32, p. 87-101. *Chem. Abs.* v. 52, no. 19734e.
- , 1959, Fossil salt boulders: *Priroda*, v. 48, no. 10, p. 91-93. *Chem. Abs.*, v. 54, no. 7456h.
- , 1962, Underground waters of the gypsum-mirabilite weathering crust of mountain valleys in Tien Shan: *Sbornik Statei po Voprosy Hidrogeol. i Inzhenernoi Geol.* p. 190-210. *Referativnyi Zhur., Khimiya*, 1963, no. 13E124. *Chem. Abs.* v. 60, no. 13011h.
- Eardley, A.J., 1962, Glauber's salt bed west of Promontory Point, Great Salt Lake: *Utah Geol. and Mineralog. Survey, Spec. studies no. 1*, p. 1-12.
- Edmunds, F.H., 1957, Sodium sulfate in Saskatchewan, in *The geology of canadian industrial mineral deposits: Commonwealth Mining and Metall. Cong., 6th, Vancouver, 1957*, p. 226-231.
- Eristavi, D.I., Pomerantseva, N. Ya., and Chilingarishvili, T.I., 1956, Description of the Azambursk mirabilite deposit: *Zhur. Neorganicheskoi Khimii*, v. 1, no. 11, p. 2627-2632. English translation in *Russian Jour. Inorganic Chemistry*.
- Eugster, H.P., and Smith, G.I., 1965, Mineral equilibrium in the Searles Lake evaporites, California: *Jour. Petrology*, v. 6, p. 473-522.

- Feodotiev, K.M., 1945, Shor-Kan, a sulfate deposit of a new type in the Soviet Union: *Doklady Akad. Nauk SSSR*, v. 47, p. 366-368. *Acad. sci. U.R.S.S., Comptes rendus*, v. 47, p. 357-359 (in English).
- Ferrar, H.T., 1905, Summary of the geological observations made during the cruise of the S.S. "Discovery," 1901-1904, in Scott, R.F., *The voyage of the "Discovery"*; London, Smith, Elder and Co., v. 2, app. 1, p. 437-468.
- , 1907, Report of the field-geology of the region explored during the "Discovery" Antarctic Expedition, 1901-4, in *National Antarctic Expedition, 1901-1904, Natural history*, v. 1, *Geology*: London, The British Museum, p. 1-100.
- Flint, R.F., and Gale, W.A., 1958, Stratigraphy and radiocarbon dates at Searles Lake, California: *Am. Jour. Sci.*, v. 256, p. 689-714.
- Foshag, W.F., 1933, Sulfohalite and other minerals from the Otjwalundo Salt Pan, South West Africa: *Am. Mineralogist*, v. 18, p. 431-434.
- Freise, F.W., 1932, Brazilian salt lakes: *Chemie der Erde*, v. 7, p. 24-34. *Chem. Abs.*, v. 26, no. 3755⁹.
- Gair, H.S., 1967, The geology from the upper Renwick Glacier to the coast, Northern Victoria Land, Antarctica: *New Zealand Jour. Geol. and Geophys.*, v. 10, p. 309-344.
- Gibson, G.W., 1962, Geological investigations in Southern Victoria Land, Antarctica. Part 8—Evaporite salts in the Victoria Valley regions: *New Zealand Jour. Geol. and Geophys.*, v. 5, p. 361-374.
- Gorbov, A.F., 1950, Formation of thenardite in lakes of the Kulunda Steppe: *Doklady Akad. Nauk SSSR*, v. 74, p. 975-977. *Chem. Abs.*, v. 45, no. 7921i.
- Goudge, M.F., and Tomkins, R.V., 1960, Sodium sulfate from natural sources, in *Industrial minerals and rocks*, 3rd ed.: New York, Am. Inst. Mining Metall. and Petroleum Engineers, p. 809-814.
- Grossman, I.G., 1949, The sodium sulfate deposits of western North Dakota. Progress report: *North Dakota Geol. Survey, Rept. Inv. 1*, p. 1-66.
- , 1968, Origin of the sodium sulfate deposits of the northern great plains of Canada and the United States: *U.S. Geol. Survey Prof. Paper 600-B*, p. 104-109.
- Hamilton, W., Frost, I.C., and Hayes, P.T., 1962, Saline features of a small ice platform in Taylor Valley, Antarctica: *U.S. Geol. Survey Prof. Paper 450-B*, p. 73-76.
- Hancock, C.W., 1919, Natural sources of magnesium, sodium, and potassium salts located at Dana, Saskatchewan: *Canadian Chem. Jour.*, v. 3, p. 399-401.
- Hansen, M., 1964, A review of sodium sulfate deposits in North Dakota, in *Mineral resources of North Dakota: North Dakota Econ. Devel. Comm. Symposium, 1964*, p. 80-86.
- Hodgman, C.D., Editor, 1962, *Handbook of chemistry and physics*, 43rd Ed.: Cleveland, Chem. Rubber Publishing Co., p. 1694-1705.
- Holland, A.A., 1949, The Chaplin sodium sulfate plant, Saskatchewan, in *Canadian Mining Metall. Bull.* 446, p. 276-279. *Chem. Abs.*, v. 43, no. 9394f.
- House, D.A., and others, 1966, Chemistry in the Antarctic: *Jour. Chem. Education*, v. 43, p. 502-505.
- Iskyl, V., 1930, Sodium sulfate deposits of Kiuren-Dag Mountains, their composition and use in the glass industry: *Trudy Gosudarstvennogo Issledovatel'skogo Keramicheskogo Inst.*, no. 19, p. 4-32 (p. 33-34 in German). *Chem. Abs.*, v. 24, no. 5675b.
- Jones, L.M. and Faure, G., 1967, Origin of the salts in Lake Vanda, Wright Valley, Southern Victoria Land, Antarctica: *Earth and Planetary Sci. Letters*, v. 3, p. 101-106.
- , 1968, Origin of the salts in Taylor Valley: *Antarctica Jour. United States*, v. 3, p. 177-178.
- and Montigny, R.J.E., 1967, Geochemical studies in Wright Valley: *Antarctic Jour. United States*, v. 2, p. 114.
- Kelly, W.C. and Zumberge, J.H., 1961, Weathering of a quartz diorite at Marble Point, McMurdo Sound, Antarctica: *Jour. Geology*, v. 69, p. 433-446.
- Kerns, Wm. H., 1965, Sodium and sodium compounds, in *Minerals yearbook: U.S. Bur. Mines*, v. 1, 855-861.
- Khvostova, V.A., 1948, Thenardite from the Sham-Shikal deposits: *Zapiski Vsesoyuznogo Mineralog. Obshchestva*, v. 77, p. 317-320. *Chem. Abs.* v. 44, no. 6352g.

- Kitaigorodskii, A.I., 1925, Glauber's salt from Karabogaz and its dehydration: *Zhur. Khimicheskoi Promyshlennosti*, v. 2, p. 666-668. *Chem. Zentralbl.*, 1926, pt. 2, p. 1169. *Chem. Abs.*, v. 21, no. 4031.
- Kittl, E., 1946, A new deposit of thenardite located in the Cerro Blanco hills to the east of Las Flores, Iglesia department, San Juan Province (Argentina): *Rev. minera, geologia y mineralogia, soc. argentina de mineria y geologia*, v. 17, p. 61-69. *Chem. Abs.*, v. 41, no. 7329b.
- Lashchenko, P.N., and Morozova, A.I., 1933, The Batalpashinskii salt lake: *Zhur. Prikladnoi Khimii*, v. 6, p. 416-434 (p. 434-435 in English). *Chem. Abs.*, v. 28, no. 2581².
- Lavine, I., Feinstein, H., and Skene, E., 1935, Glauber salt in North Dakota: *Chem. Metall. Eng.*, v. 42, p. 681-682.
- Lebedintzev, A.A., 1930, The Gulf of Karabogaz and its importance for the Russian and world chemical industries: *Akad. Nauk, USSR, Material No. 73*, 3rd ed., p. 17-22. *Chem. Abs.*, v. 24, no. 4246².
- Leiding, B., 1942, Nonmetallic mineral reserves in Chile: *Cong. Panam. de Ingenieria de Minas y Geologia*, 1st Cong. Santiago de Chile, *Anales*, v. 4, p. 1651-1678. *Chem. Abs.*, v. 45, no. 94299e.
- Lepeshkov, I.N., and others, 1962, Natural salts in the Krasnoyarsk region: *Poleznye Iskopaemye Krasnoyarskogo Kraya*, *Trudy Krasnoyarskoi Kompleksnoi Ekspeditsii*, *Akad. Nauk SSSR*, p. 178-189. *Chem. Abs.*, v. 58, no. 9975b.
- Levchenko, V.M., 1956, Thermal analysis of sea water: *Zhur. Neorganicheskoi Khimii*, v. 1, no. 3, p. 528-531. English translation in *Russian Journal of Inorganic Chemistry*.
- Lyapunov, M.F., 1959, The formation of thenardite in Lake Bol'shoi Azhbulat: *Izv. Sibirskogo Otdeleniya Akad. Nauk SSSR*, no. 6, p. 95-100. *Chem. Abs.*, v. 54, no. 6414ef.
- , 1962, The formation of thenardite in Lake Kuchuk: *Izv. Sibirskogo Otdeleniya Akad. Nauk SSSR*, no. 2, p. 118-120. *Chem. Abs.*, v. 57, no. 6917a.
- Maron, S.H., and Prutton, C.F., 1965, *Principles of physical chemistry*, 4th ed.: New York, Macmillan, 868 p.
- Martin, G., 1934, Salt Lake company working bed of Glauber salt: *Eng. Mining Jour.*, v. 135, p. 165.
- , 1938, Sodium sulfate from the shore of Great Salt Lake: *Eng. Mining Jour.*, v. 139, no. 6, p. 55.
- Mawson, D., 1909, Mineralogy and chemistry: notes, in Shackleton, E.H., *The heart of the Antarctic*: London, William Heinemann, v. 2, p. 344.
- McDermid, A.I., 1934, Meeting the demand for sodium sulfate. Mining and processing this non-metallic at Cape Verde, Arizona: *Eng. Mining Jour.*, v. 135, p. 164.
- McLeod, I.R., 1964, The saline lakes of the Vestfold Hills, Princess Elizabeth Land, in *Antarctic geology*: New York, John Wiley and Sons, p. 65-72.
- Nelson, K.H., and Thompson, T.G., 1954a, Deposition of salts from sea water by frigid concentration: *Dept. Oceanography, Univ. Washington Tech. Rept.* 29, 30 p.
- , 1954b, Deposition of salts from sea water by frigid concentration: *Jour. Marine Research*, v. 13, p. 166-182.
- Nichols, R.L., 1963a, Geologic features demonstrating aridity of McMurdo Sound area, Antarctica: *Am. Jour. Sci.*, v. 261, p. 20-31.
- , 1963b, Geomorphology of the McMurdo Coast, South Victoria Land, Antarctica (Abs.) in *Abstracts for 1962: Geol. Soc. America Spec. Paper* 73, p. 211.
- , 1965, Antarctic interglacial features: *Jour. Glaciology*, v. 5, no. 40, p. 433-449.
- , 1966, Geomorphology of Antarctica, in *Antarctic soils and soil forming processes: Antarctic Research Ser. Am. Geophys. Union*, v. 8, p. 1-46.
- Nikol'skaya, Yu. P., and others, 1964, Beneficiation of mirabilite from the Kuchuk Lake: *Razrabotka Mestorozhdenii Poleznykh Iskopaemykh Akad. Nauk SSSR, Sibirskoe Otdelenie*, 1964, p. 193-200. *Chem. Abs.*, v. 63, no. 14429b.
- Palache, C., Berman, H., and Frondel, C., 1951, *Dana's system of Mineralogy*, 7th ed.: New York, John Wiley and Sons, v. 2, 1124 p.

- Partington, I.R., 1961, A history of chemistry: London, Macmillan, v. 2, p. 352-53.
- Peña i Lillo, O., 1933, Sodium sulfate: Bol. minera soc. nac. de mineria (Chile), v. 45, p. 73-76. Chem. Abs., v. 28, no. 1143⁴.
- Phillips, F.E., 1947, Oceanic salt deposits: Quart. Reviews (London), v. 1, p. 91-111.
- Podkopaev, N.I., 1922-23, Karabogaz (sodium sulfate deposit): Zhur. Russkogo Fiziko-Khimicheskogo Obshchestva, v. 54, p. 767. Chem. Abs., v. 18, no. 3160.
- , 1927, Scientific expedition to Karabogaz in the years 1921-1923: Annales inst. analyse phys. chim. (USSR), v. 3, no. 2, p. 683-702. Chem. Abs., v. 22, no. 4417⁴.
- , 1930, Work of the Karabogaz expeditions. 1. From report of an expedition in 1909: Akad. Nauk, USSR, Material 73, 3rd ed., p. 107-138. Chem. Abs., v. 24, no. 4591.
- Ponizovskii, A.M., and others, 1958, Thenardite and mirabilite in Lake Marfovka: Dopovidi Akad. Nauk Ukrain's'koi RSR, no. 6, p. 651-653 (English summary). Chem. Abs., v. 52, no. 19733f.
- Reineke, V.I., 1930, Salt deposits of Uzun-Su: Annales inst. analyse phys. chim. (USSR), v. 4, no. 2, p. 29-40. Chem. Abs., v. 24, no. 5675⁵.
- Revnov, B., 1964, Findings of mirabilite: Soviet Antarctic Expedition, Inf. Bull., v. 4, Issue 4, p. 227-228.
- Rich, P.C., 1933a, Rhodes Marsh yields its sodium sulfate: Chem. Metall. Eng. v. 40, p. 304-305.
- , 1933b, Sodium sulfate from Nevada finds ready market: Eng. Mining Jour., v. 134, p. 252-253.
- Rios, J.M., 1968, Saline deposits of Spain, in Saline Deposits: Geol. Soc. America Spec. Paper 88, p. 59-74.
- Rivard, N.R., and Pewe, T.L., 1962, Origin and distribution of mirabilite, McMurdo Sound region, Antarctica (Abs.), in Abstracts for 1961: Geol. Soc. America Spec. Paper 68, p. 119.
- Sapre, R.K., 1956, Sodium sulphate in India: Chem. Age India, v. 7, no. 1, p. 55-58.
- Shcherbina, V.N., 1949, Genesis of mirabilite from salt deposits of northern Kirgisa: Doklady Akad. Nauk SSSR, v. 67, p. 357-359. Chem. Abs., v. 44, no. 2893h.
- Shreders, N.A., 1938, The composition of water of the Karabogaz Gulf in connection with the drop of the Caspian Sea level: Byulleten Inst. Halurgii, no. 6, p. 54-68. Referativnyi Zhur., Khimiya, v. 2, no. 4, p. 47. Chem. Abs., v. 34, no. 1136⁹.
- Shuttleworth, R.G., 1963, Production of anhydrous sodium sulfate and of sodium sulfate decahydrate (Glauber's salt) at South African salt pans: South African Indus. Chemist, v. 17, no. 10, p. 207-214.
- Siegel, F.R., and Dort, W., Jr. 1968, Mirabilite and associated seal bones, Southern Victoria Land, Antarctica: Antarctic Jour. United States, v. 3, p. 173.
- Smith, G.J., 1965, Evaporite salts from the dry valleys of Victoria Land, Antarctica: New Zealand Jour. Geol. and Geophys., v. 8, p. 381-382.
- Sosipatrov, T.M., 1958, Formation of thenardite in the sulfate-chloride lakes of the Kulunda Steppe: Izv. Sibirskogo Otdeleniya Akad. Nauk SSSR, no. 3, p. 65-76. Chem. Abs., v. 53, no. 995e.
- Spencer, E., 1943, Origin of the "Rohr" or anhydrous sodium sulfate beds below the salt pans at Didwana, India: Current Sci. (India), v. 12, p. 176-180. Chem. Abs., v. 38, no. 937⁹.
- , 1944, An unusual occurrence of bedded thenardite: Mineralog. Mag., v. 27, p. 29-31.
- Strøm, Kaare, 1957, A lake with entrapped sea water: Nature, v. 180, p. 982-983.
- Suprichov, V.A., and Al'bov, S.V., 1966, New data on thenardite from the Tauria formation of mountains of Crimea: Dopovidi Akad. Nauk Ukrain's'koi RSR, no. 4, p. 523-526 (English summary). Chem. Abs., v. 65, no. 3568c.
- Tasch, P., and Angino, E.E., 1968, Sulphate and carbonate salt efflorescences from the Antarctic interior: Antarctic Jour. United States, v. 3, p. 239-241.
- Taylor, G., 1922, The physiography of the McMurdo Sound and Granite Harbour region, in British Antarctic (Terra Nova) Expedition 1910-13: London, Harrison and Sons, 187 p.
- Thompson, T.G., and Nelson, K.H., 1956, Concentration of brines and deposition of salts from sea water under frigid conditions: Am. Jour. Sci., v. 254, p. 227-238.

- Tomkins, R.V., 1948, Natural sodium sulfate in Saskatchewan: Saskatchewan Dept. Nat. Resources and Indus. Devel., Tech. Econ. Ser., Rept. 1, 99 p.
- Torii, T., and Ossaka, J., 1965, Antarcticite: a new mineral, calcium chloride hexahydrate, discovered in Antarctica: *Science*, v. 149, no. 3687, p. 975-977.
- Torii, T., and others, 1966, Report of the Japanese summer parties in dry valleys, Victoria Land, 1963-1965. 1. On the evaporites found in Miers Valley, Victoria Land, Antarctica: *Antarctic Rec. (Japan)*, no. 27, p. 2109-2120 (English abs., Japanese text).
- Tyler, P.M., 1935, Sodium sulfate: U.S. Bur. Mines Inf. Circ. 6833, 39 p.
- Usova, A.A., 1944, A description of the deposits of mirabilite, white clays, and pure quartz sands of the Borovoe State National Park in the Akmolinsk region: *Acad. Sci., U.R.S.S. Bull., Ser. geol.*, p. 115-118 (p. 118 in English). *Chem. Abs.*, v. 39, no. 478⁵.
- Van Autenboer, T., 1964, The geomorphology and glacial geology of the Sor-Rondane, Dronning Maul Land, in *Antarctic Geology*: New York, John Wiley and Sons, p. 81-103.
- Ver Planck, W.E., 1957, Sodium sulfate, in *Mineral commodities of California*: California Dept. Nat. Resources, Div. Mines, Bull. 176, p. 543-545.
- Visyagin, N.I., 1951, Intensification of the process of thenardization of the mirabilite from brines: *Doklady Akad. Nauk SSSR*, v. 78, p. 689-691. *Chem. Abs.*, v. 47, no. 2097c.
- , and Vasilevskaya, A.G., 1951, New data on formation of thenardite: *Doklady Akad. Nauk SSSR*, v. 86, p. 537-538. *Chem. Abs.*, v. 50, no. 1533c.
- Vlasov, N.A., and Gorodkova, M.M., 1961, Physicochemical analysis of annual cycles in the Selenga sulfate lake: *Izv. Fiz.-Khimiya, Nauchno-Issledovatel'skogo Inst. pri Irkutskom Universitet*, v. 5, no. 2, p. 110-128. *Referativnyi Zhur., Khimiya, Abs.* no. 17G121. *Chem. Abs.*, v. 58, no. 2269g.
- Vlasov, N.A., Chernyshev, L.A., and Pavlova, L.I., 1960, Particularities of the formation and character of mineral lakes of Eastern Siberia: *Fiz.-Khimicheskie Analizy, Akad. Nauk SSSR*, Sibirskoe Otdelenie, Inst. Neorganicheskoi Khimii, Trudy Yubileinoi Konferentsii, Novosibirsk 1960, p. 158-166 (Pub. 1963). *Chem. Abs.*, v. 61, no. 14355g.
- Vorob'ev, A.L. and Kadysev, E.M., 1951, Mineralogy of the salt marsh Shor-Kan (Central Asia, USSR): *Zapiski Uzbekistanskogo Otdeleniya Vsesoyuznogo Mineralog. Obshchestva*, v. 2, p. 78-80. *Chem. Abs.*, v. 49, no. 6040g.
- Wellman, H.W., and Wilson, A.T., 1963, Salts on sea ice in McMurdo Sound, Antarctica: *Nature*, v. 200, no. 4905, p. 462-463.
- Wells, R.C., 1923, Sodium sulfate, its sources and uses: *U.S. Geol. Survey Bull.* 717, 43 p.
- Wetmore, F.E.W., and LeRoy, D.J., 1951, *Principles of Phase Equilibria*: New York, McGraw-Hill, 200 p.
- Williams, A.J., 1952, Saskatchewan's industrial minerals: *Mining Eng.*, v. 4, p. 396-400.
- Williams, P.M., Matthews, W.H., and Pickard, G.L., 1961, A lake in British Columbia containing old sea-water: *Nature*, v. 191, p. 830-832.
- Wilson, A.T., 1968, Chemistry and the Quaternary in the Antarctic: unpub. manuscript, 1968.
- , and House, D.A., 1965, Chemical composition of the South Polar snow: *Jour. Geophys. Research*, v. 70, p. 5515-5518.
- Wilson, S.R., and Wideman, F.L., 1957, Sodium sulfate deposits along the southeast shore of Great Salt Lake, Salt Lake and Tooele counties, Utah: *U.S. Bur. Mines Inf. Circ. No. 7773*, 10 p.
- Witkind, I.J., 1952, The localization of sodium sulfate deposits in northeastern Montana and northwestern North Dakota: *Am. Jour. Sci.*, v. 250, p. 667-676.
- Yamagata, N., Torii, T., and Murata, S., 1967, Report of the Japanese summer parties in dry valleys, Victoria Land, 1963-65. V. Chemical composition of lake waters: *Antarctic Rec. (Japan)*, no. 29, p. 53-75.
- Yamagata, N., and others, 1967, Report of the Japanese summer parties in dry valleys, Victoria Land, 1963-1965: VII. Chemical composition of pond waters in Ross Island with reference to those in Ongul Islands: *Antarctic Rec. (Japan)*, no. 29, p. 82-89.

- Yasnopol'skii, B.V., 1928, Sources of natural sulfates in USSR: Byulleten Inst. Khurgii, no. 8, p. 1-26. Referativnyi Zhur., Khimiya, v. 2, no. 4, p. 45. Chem. Abs., v. 34, no. 1134⁹.
- Young, G.J., 1927, Mining sodium sulfate at Camp Verde, Arizona: Eng. Mining Jour., v. 124, no. 3, p. 97-98.
- Young, W.A., 1951, Investigation of sodium sulfate deposits in Bull Lake, Carbon County, Wyoming: U.S. Bur. Mines, Rept. Inv. 4816, 9 p.
- Zdanovskii, A.B., 1953, Hydrochemistry of Lake Ebeity: Trudy Vsesoyuznogo Nauchno-Issledovatel'skogo Inst. Galurgii, no. 27, p. 193-204. Referativnyi Zhur., Khimiya, 1954, no. 32274. Chem. Abs., v. 49, no. 7157g.
- , and Ryabchikov, D.I., 1935, Azhbulat sulfate lake and the possibilities of its exploitation: Zhur. Prikladnoi Khimii, v. 8, p. 981-993. Chem. Abs., v. 30, no. 5733².
- , 1940, The mirabilite lake Azhbulat: Annales secteur analyse phys.-chimique, Inst. chimie gen. (USSR), v. 13, p. 363-375. Chem. Abs., v. 37, no. 4535⁸; v. 36, no. 5589⁷.