Saline Minerals of the Green River Formation

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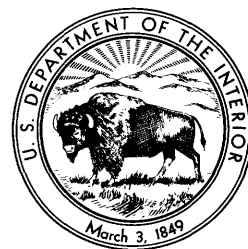
By JOSEPH J. FAHEY

With a section on

X-RAY POWDER DATA FOR SALINE MINERALS OF THE GREEN RIVER
FORMATION

By MARY E. MROSE

GEOLOGICAL SURVEY PROFESSIONAL PAPER 405

A study of the mode of occurrence of the
saline minerals, their paragenetic
relationship, and the economic importance
of the trona

UNITED STATES DEPARTMENT OF THE INTERIOR

STEWART L. UDALL, *Secretary*

GEOLOGICAL SURVEY

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SALINE MINERALS OF THE GREEN RIVER FORMATION

By JOSEPH J. FAHEY

ABSTRACT

A mineralogical study was made by the U.S. Geological Survey of the drill core from the John Hay, Jr., well 1, in Sweetwater County, Wyo., about 18 miles west of the City of Green River. The well penetrated the Wilkins Peak member of the Green River formation of early and middle Eocene age. This study, begun in 1939, revealed a unique assemblage of carbonate minerals in a fine-grained dolomitic marlstone that ranges in content of organic matter from about 1 to 30 percent. The investigation also established the presence of an economically important bed of trona about 10 feet thick, and subsequent drilling showed it extended over an area of at least 60 square miles. As a result of this disclosure the Westvaco mine was opened in 1947; by 1957 it was delivering about two-thirds of the natural soda ash produced in the United States.

The distribution of the six saline minerals—shortite, trona, northupite, pirssonite, gaylussite, and bradleyite—that are present in large quantities in the Wyoming area of the Green River formation, was first shown in the log of the drill core of the John Hay, Jr., well 1. A seventh saline mineral, nahcolite, is present in quantity in the Uinta Basin of Utah and the Piceance Creek basin of Colorado.

Shortite ($Na_2CO_3 \cdot 2CaCO_3$) was first found in the core of the John Hay, Jr., well 1. It is present in this well between depths 1,251 feet and 1,806 feet 6 inches, a vertical distance of 555 feet 6 inches. Shortite marks the saline zone, within which, and only within which, the other five saline minerals are found. It constitutes a visually estimated 10 percent of this saline zone.

Trona ($Na_2CO_3 \cdot NaHCO_3 \cdot 2H_2O$), the next most abundant of the saline minerals, was found between depths of 1,300 feet and 1,665 feet and makes up in volume about 9.7 percent of this interval; which is equivalent to 6.4 percent of the saline zone. The trona is concentrated chiefly in four strata, the approximately 10-foot main bed, the bottom of which is at a depth of 1,600 feet 4 inches, and constitutes the ore body of the Westvaco mine; a 2-foot 3-inch bed at a depth of 1,619 feet 9 inches; a 4-foot bed at 1,646 feet; and a 6-foot 1-inch bed, the bottom of which is at a depth of 1,659 feet 3 inches.

The areal extent of the trona is estimated to be as much as 2,000 square miles. How much of this is suitable for economic exploitation must remain unknown until many more test holes have been put down. The known area of the trona bed that is currently being mined at Westvaco is about 60 square miles, from which can be produced more than 650 million tons of soda ash.

Northupite ($Na_2CO_3 \cdot MgCO_3 \cdot NaCl$) is the saline mineral that is third in abundance in the Wilkins Peak member at the site of the John Hay, Jr., well 1. It occurs between the depths 1,327 to 1,560 feet and occupies 5.2 percent of this interval, which is equivalent to 2.2 percent of the saline zone that is marked by the presence of shortite. Crystals of northupite are rarely found; it usually occurs massive, filling cracks and vugs in the shale.

Nahcolite ($NaHCO_3$) is present in great quantities in the shales of the Green River formation of Colorado and Utah, but it has been found only once in the Wyoming area, and that was as tiny crystals in a small crack in the shale. At Rifle, Colo., at the site of the oil shale mine of the U.S. Bureau of Mines, it is found in lenses, some of which are more than 10 feet across. In Utah, nahcolite occurs associated with shortite.

Bradleyite ($Na_3PO_4 \cdot MgCO_3$), like shortite, was first found in the drill core of the John Hay, Jr., well 1. It occurred at a depth of 1,342 feet 10 inches in intimate association with clay and shortite. During the sinking of the No. 1 shaft of the Westvaco mine, bradleyite was found in low-grade oil shale at a depth of 1,245 feet, and later tiny crystals were recovered from the residue obtained when samples of trona from the main trona bed of the Westvaco mine were leached.

Pirssonite ($Na_2CO_3 \cdot CaCO_3 \cdot 2H_2O$) is present between depths of 1,310 and 1,391 feet in the drill core of the John Hay, Jr., well 1. It makes up about 10 percent of the interval between 1,310 and 1,320 feet and occurs massive in the shale.

Gaylussite ($Na_2CO_3 \cdot CaCO_3 \cdot 5H_2O$) occurs in the drill core of the John Hay, Jr., well 1, between depths of 1,261 and 1,350 feet. It constitutes about 10 percent of the intervals 1,266 feet to 1,267 feet 6 inches and 1,268 feet to 1,270 feet. As with pirssonite, no crystals of gaylussite have been found in the shale; only masses filling cracks have been seen.

Tables of indexed X-ray powder data are given for the seven saline minerals; these include the first published data for natural nahcolite, northupite, and pirssonite.

Shortite, in all instances, is the primary mineral of the six saline minerals present in the Wyoming area. It is seen in thin sections being replaced by the other five saline minerals. Northupite replaces not only shortite, but also trona, pirssonite, and gaylussite. Trona, pirssonite, and gaylussite have not been observed replacing one another.

Chemical and spectrographic analyses were made on 14 samples of measured sections from the drill core of the John Hay, Jr., well 1. The color of each sample before grinding was matched to plates in Robert Ridgeway's "Color Standards and Nomenclature". The size distribution was determined on each of the 14 samples, recording the clay ($<2\mu$), silt (2μ to 64μ), and the sand ($>64\mu$) fractions. A mineral analysis was made by means of X-ray diffraction patterns, and each mineral present was reported in parts in ten.

Organic matter was separated from a sample of very rich oil shale from the drill core of the John Hay, Jr., well 1. The index of refraction of the organic matter was found to be 1.58, the specific gravity 1.01 at 4°C, and a Kjeldahl determination showed that it contained 2.18 percent nitrogen.

Analyses were made of the trona bed at two localities about half a mile apart. Each foot from the top to the bottom of the bed at each location was sampled, and the trona determined by leaching. The water-insoluble portion, composed chiefly of dolo-

mite and detrital material, was treated with hydrochloric acid, and the detrital material weighed. Organic matter was determined on six 1-kg samples, from two other localities, and found to range from 0.001 percent to 0.142 percent.

The length of time of deposition of the trona bed, determined on samples from two locations about half a mile apart in the Westvaco mine, was found to be 973 and 1,463 years, respectively. This divergence is not an alarming one because of the errors inherent in the method used in which the quantity of the water-insoluble material of a vertical column of the trona bed is compared to a similar column of the sedimentary rock, estimated to have required 3,000 years per vertical foot for deposition.

INTRODUCTION

LOCATION

The Green River formation is composed of lacustrine sediments of early and middle Eocene age in the Bridger and Washakie Basins north of the Uinta Mountains in southwestern Wyoming, the Piceance Creek Basin in northwestern Colorado, and the Uinta Basin in northeastern Utah (fig. 1). The fluviatile sediments of the Wasatch formation underlie these deposits, and occupy approximately the lower third of the Eocene epoch.
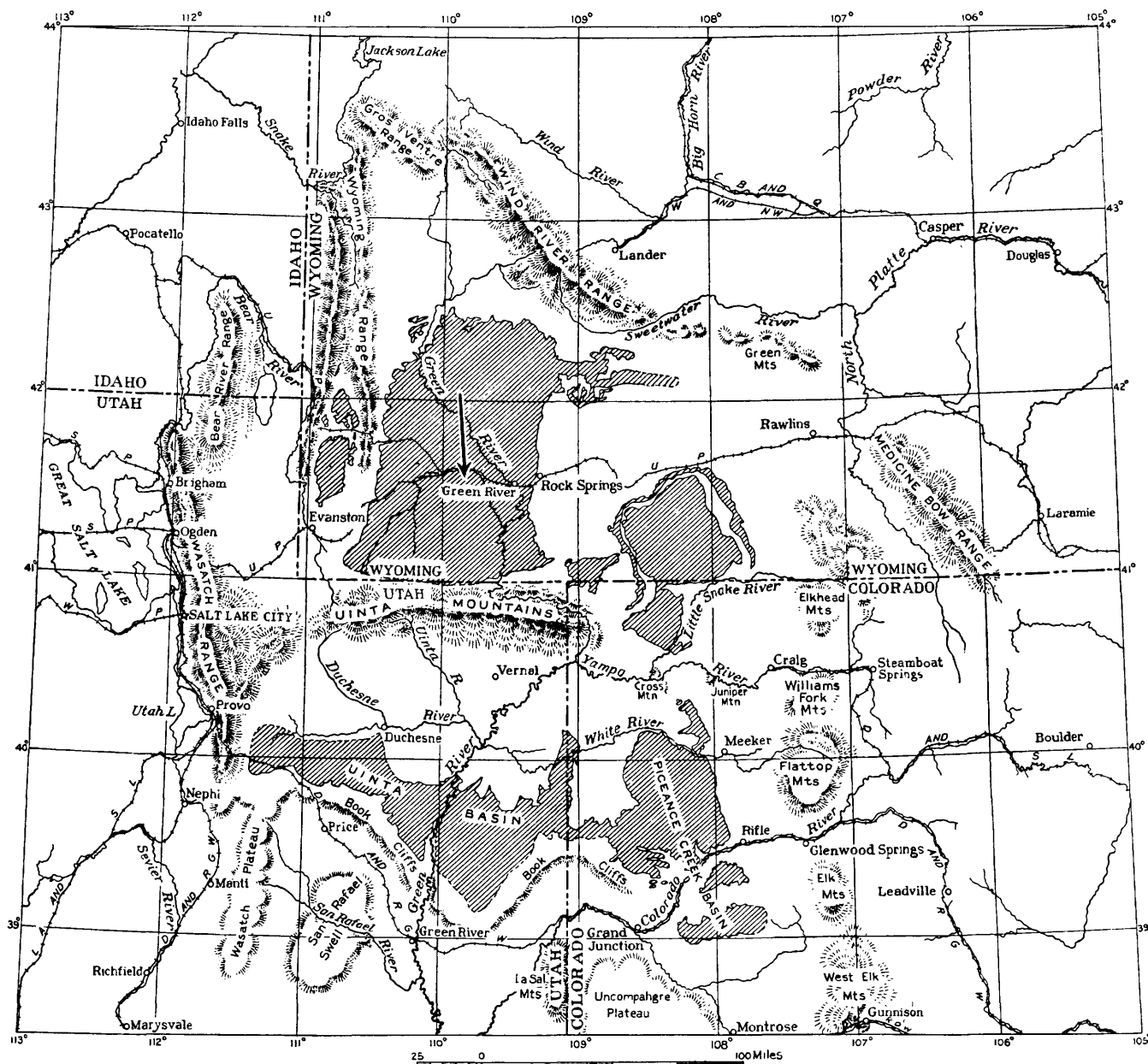
FIGURE 1.—Index map showing location of the Green River formation (shaded areas) in Wyoming, Colorado, and Utah. (From Bradley, 1931, p. 2.) Arrow indicates site of the John Hay, Jr., well 1, Sweetwater County, Wyo.

In the Wyoming area the Green River formation is overlain by the Bridger formation which, like the Wasatch, is of fluviatile origin. Bridger sediments also overlie the Green River rocks in the Uinta Basin and are, in turn, covered by the fluviatile sediments of the Uinta formation. In the Piceance Creek basin in Colorado the rocks of the Green River formation are the youngest rocks exposed, except in an area where they are overlain by 400 feet of sandy beds of fluviatile origin that appear to be lithologically and stratigraphically equivalent to the basal beds of the Bridger formation of the Uinta Basin (Bradley, 1931, p. 19).

EXPLORATION

In 1938 the Mountain Fuel Supply Co., a subsidiary of the Ohio Oil Co., drilled the John Hay, Jr., well 1. This well—on government land in the SE1/4NW1/4 sec. 2 (1,920 feet from the north line and 2,120 feet from the west line), T. 18 N., R. 110 W., about 18 miles west of the city of Green River, Sweetwater County, Wyo.— was put down in the search for oil and gas in the Green River formation. Neither oil nor gas was found, and the drill core was stored in a shed behind the offices of the Mountain Fuel Supply Co. in Rock Springs, Wyo. One year later (in the spring of 1939) Howard I. Smith, of the U.S. Geological Survey, suggested to Dr. William T. Nightingale, chief geologist of the Mountain Fuel Supply Co., that a mineralogical examination of portions of the core would be of scientific interest. Dr. Nightingale thought well of the suggestion, and 30 feet of the core was selected and sent to Washington for study.

In this 30 feet of core, trona and the rare mineral northupite were identified. Also a new mineral, an anhydrous carbonate of sodium and calcium, was found and named shortite. (See p. 24.)

It was decided that this unique assemblage of saline minerals warranted further investigation, so again the Survey was favored by Dr. Nightingale, who, when told that a study of the paragenesis of the saline minerals in the oil shale would be desirable, released to the Survey all the drill core that penetrated the Wilkins Peak member of the Green River formation, which represented a thickness of 627 feet.

In this core a stratum of trona 10 feet thick was found at a depth of about 1,600 feet below the surface. A note published in Science by Walter C. Mendenhall, then director of the U.S. Geological Survey, announced the finding of this trona bed (Mendenhall, 1940).

As a result of this report the Union Pacific Railroad drilled four wells, spaced several miles apart. The core from each of these wells showed the 10-foot thick trona bed at the depth reported by the Survey. This strongly indicated that a potentially economic bed of trona extended over an area of many square miles.

Several years later three wells were drilled and cored by the Westvaco Co.; the Westvaco No. 1 was about 2 miles north of the John Hay, Jr., well 1, and Westvaco wells 2 and 3 were about 2 miles north-northwest of Westvaco well 1. By means of these test holes the depth and thickness of the trona bed was again confirmed and its areal extent further established.

The Westvaco Co. in 1947 sank a shaft in close proximity to their No. 2 and No. 3 test holes. The locations of the 20 wells drilled up to and including the year 1956, and the location of the Westvaco mine, are shown in figure 2. The shaft of the mine, having a diameter of 12 feet and lined with concrete, penetrated down through the trona bed. Room and pillar mining was started and the trona brought to the surface was ground and converted by calcination to sodium carbonate, the soda ash of commerce, in a pilot plant that had a capacity of 200 tons per day.

The soda ash produced was not pure sodium carbonate, but contained as much as 10 percent of water-insoluble material, chiefly clay with some calcium and magnesium carbonates. These impurities rendered the soda ash unsuitable for some of the many uses of this very important heavy chemical that is second only to sulfuric acid in tonnage used by industry in the United States. This condition was overcome in 1954 by the installation of a solution plant wherein the trona was dissolved in hot water, the insoluble material filtered off, and pure sodium carbonate produced by precipitation, filtration, and calcination. Thus a new industry, born of a mineralogical and geochemical investigation, was established in southwestern Wyoming.

ACKNOWLEDGMENTS

Grateful appreciation is expressed for the assistance by many friends, both in and out of the Geological Survey, whose contributions, suggestions, and sound advice have been helpful in writing this paper. Chief among those in the Survey is Wilmot H. Bradley, whose counsel and constructive criticism stemmed from the vast store of information that he acquired through his many years of study of the Green River formation. Also of great assistance were Daniel E. Appleman who made the calculations of the interplanar spacings, and Frank Reed and John Mergner who so skillfully cut the thin sections that were used in determining the paragenetic relationship of the water-soluble saline minerals.

From the time the No. 1 shaft of the trona mine was put down in 1947, the members of the technical staff at Westvaco have been most kind and cooperative, both in the mine where the trona bed was sampled and studied, and in the many conferences and discussions

R. 110 W.   R. 109 W.

6	5	4	3	2	1 O P Q R	6	5	4	3	2	1
7 N	8	9 K	10	11 J	12	7	8	9	10	11	12
18	17	16	15 C G H U	14	13	18	17	16	15	14	13
19	20	21	22	23	24	19 L	20	21	22	23	24
30	29 M	28 I	27	26 F	25	30	29	28	27	26	25
31	32	33	34	35	36	31 D	32	33	34	35	36
6	5 E	4	3 B	2 A	1	6 S	5	4	3	2	1
7	8	9	10	11	12	7	8	9	10	11	12 T
18	17	16	15	14	13	18	17	16	15	14	13
19	20	21	22	23	24	19	20	21	22	23	24
30	29	28	27	26	25	30	29	28	27	26	25
31	32	33	34	35	36	31	32	33	34	35	36

T. 19 N. (left, upper township)   T. 18 N. (left, lower township)

A John Hay Jr., Well 1 (1938)
B Union Pacific Well 1 (1940)
C Union Pacific Well 2 (1940)
D Union Pacific Well 3 (1942)
E Union Pacific Well 4 (1942)
F Westvaco Well 1 (1944)
G Westvaco Well 2 (1945)
H Westvaco Well 3 (1946)

I Westvaco Well 4 (1948)
J Westvaco Well 5 (1954)
K Westvaco Well 6 (1954)
L Westvaco Well 7 (1954)
M Westvaco Well 8 (1954)
N Westvaco Well 9 (1954)
O Westvaco Well 10 (1955)
P Westvaco Well 11 (1955)

Q Westvaco Well 12 (1956)
R Westvaco Well 13 (1956)
S Potash Company of America
 Well 1 (1949)
T Potash Company of America
 Well 2 (1950)
U Westvaco Mine (1947)

FIGURE 2.—Locations of exploratory wells and the Westvaco mine in Sweetwater County, Wyo.

pertaining to problems of mutual interest. Among these were Dr. Max. Y. Seaton, Guilford Gaylord, J. Ward Downey, and John Jacobucci, who were on the staff at the time the mine was started; also later C. A. Romano, N. E. McDougal, Lewis Smith, Dr. William Bauer, Robert Love, L. K. Marshall, Keith Norseth, and John A. Anderson. Time and space do not permit a detailed outline of the great help so willingly given by these pioneers in trona mining. Without this help much of the information contained in this paper could not have been presented.

DRILL CORE OF THE JOHN HAY, JR., WELL 1

DESCRIPTION

The core of the John Hay, Jr., well 1 was obtained by drilling in a brine saturated with sodium carbonate, and marking the depths as each 10-foot section of the 2-inch diameter core was brought to the surface. The core was then placed longitudinally in shallow trays and stored in a shed in the yard of the Mountain Fuel Supply Co. at Rock Springs, Wyo. In the summer of 1939 that part of the core that penetrated the Wilkins Peak member of the Green River formation was transferred to 4 boxes—each containing 6 trays, the total weight being 1,600 pounds—and sent to the Geological Survey in Washington, D.C., for detailed examination.

To obtain a fresh uncontaminated surface for mineral examination the core was split longitudinally, using a core splitter that would open sections as much as 5 inches long. Identification of the saline species usually required no more than the use of a hand lens. Examination of an oil-immersion mount was made with the petrographic microscope when the identification of a mineral was in doubt. Thin sections and polished sections were used to determine genetic and paragenetic relations.

In this report the term "lean" will be used to mean oil shale that, upon distillation, yields up to 5 gallons of distillate per ton, "medium grade" between 5 and 15 gallons per ton, "rich" between 15 and 30 gallons per ton, and the term "very rich" will be applied to shale that would yield more than 30 gallons of distillate per ton. A sample was designated as to grade by visual examination and estimation of density. This was based on the distillation of many samples of each cate-gory (lean, medium grade, rich and very rich) in order to recognize these differences in organic content.

The terms "shale" and "oil shale," as applied to the Green River formation are erroneously used, as will be discussed later in this report. Fissility, that property which characterizes a shale, is lacking in all but a small percentage of these sediments.

The shale of this drill core is a compact bedded rock, containing varying amounts of organic matter, in which the saline minerals and pyrite, loughlinite, and searle-site have precipitated. The composition of the shale varies from predominantly argillaceous material to microcrystalline dolomite with detrital quartz and feldspar. A thin section or semiquantitative chemical analysis is usually required to distinguish between the argillaceous shale and that composed chiefly of dolomite.

CONTINUITY

The log of the drill core of the John Hay, Jr., well 1 shows that shortite is present continuously between 1,251 feet and 1,806 feet 6 inches, a vertical distance of 555 feet 6 inches. The other saline minerals reported in the log are also found only between these depths. In the vertical distances of 555 feet 6 inches there was obtained 489 feet 8 inches of core. The 65 feet 10 inches of missing core is indicated in the log by 23 breaks ranging in length from 6 inches to 16 feet. The longest unbroken section is between 1,592 feet 6 inches and 1,810 feet, a length of core of 217 feet 6 inches. Another long unbroken section is between 1,375 feet and 1,510 feet, a length of 135 feet, and another between 1,526 feet and 1,587 feet 9 inches, a length of 61 feet 9 inches.

In the section of the core between 1,587 feet 9 inches and 1,600 feet 4 inches, a vertical distance of 12 feet 7 inches, massive trona is found in beds of 1 foot 3 inches and 7 feet 10 inches with a 1-foot break between the beds and a 2-foot-6-inch break immediately above the smaller bed. Because of the solubility of the trona, it well may be that it occupied the positions where the breaks of 1 foot and 2 feet 6 inches are recorded in the log and was lost. If such is the case, the trona bed at this horizon is 12 feet 7 inches thick, approximately 2 feet thicker than it is found to be in the Westvaco mine about 4 miles to the north.

Log of John Hay, Jr., well 1

Depth interval Ft	in	Thickness Ft	in	Remarks
1,183	0	0	1	Sandstone with a minor quantity of dolomite.
1,183	1			
				Break, 10 ft 11 in
1,194	0	6	0	Dense dark-gray shale containing calcite crystals as much as 4 mm thick. The first 3 ft of the
1,200	0			shale is lean, the next foot is medium grade and the lower 2 ft lean.
				Break, 8 in
1,200	8		9	Dark dense medium-grade shale having many small crystals of calcite.
1,201	5			
				Break, 3 ft 4 in
1,204	9	5	3	Same as 1,200 ft 8 in to 1,201 ft 5 in
1,210	0			
				Break, 2 ft 0 in
1,212	0	3	0	Same as 1,204 ft 9 in to 1,210 ft 0 in
1,215	0			
				Break, 2 ft 0 in
1,217	0		5	About 50 percent lean shale and 50 percent calcite.
1,217	5			
				Break, 7 in
1,218	0		1	Calcite with minor quantity of lean shale.
1,218	1			
				Break, 3 ft 11 in
1,222	0	1	6	Lean shale containing crystals of calcite.
1,233	6			
				Break, 6 in
1,224	0	3	0	Lean oil shale with small crystals of calcite. A few small lenses (1 cm diameter) of pyrite are
1,227	0			present.
				Break, 13 ft 0 in
1,240	0	1	7	Crystals of calcite and pyrite in lean shale.
1,241	7			
				Break, 1 ft 5 in
1,243	0	1	0	Same as 1,240 ft 0 in to 1,241 ft 7 in
1,244	0			
				Break, 4 ft 0 in
1,248	0		5	Same as 1,243 ft 0 in to 1,244 ft 0 in
1,248	5			
				Break, 2 ft 4 in
1,250	9	1	7	Medium-grade oil shale containing crystals of calcite. Shortite is found at 1,251 ft 0 in and
1,252	4			continues to the end, constituting about 2 percent of this section.
				Break, 7 in
1,252	11		2	Small crystals of shortite (about 2 percent) in medium-grade shale. No calcite present.
1,253	1			
				Break, 1 ft 8 in
1,254	9	1	3	Rich brown oil shale containing crystals of shortite (about 15 percent).
1,256	0			
				Break, 5 ft 0 in
1,261	0	1	0	Lean light-green shale with shortite (about 5 percent) and gaylussite (about 5 percent). Good
1,262	0			contacts show gaylussite replacing shortite. Tiny crystals of pyrite are present throughout
				the section.
				Break, 2 ft 0 in
1,264	0	1	0	Same as 1,261 ft 0 in to 1,262 ft 0 in.
1,265	0			
				Break, 1 ft 0 in
1,266	6	1	6	Lean light-green shale containing shortite (about 5 percent) and gaylussite (about 10 percent).
1,267	0			The sequence shortite to gaylussite is present. Also gaylussite is found in thin veins not in
				contact with shortite. Pyrite is sparingly present.
				Break, 6 in
1,268	0	2	0	Lean light-green shale with shortite (about 5 percent) and gaylussite (about 10 percent).
1,270	0			

Depth interval Ft	in	Thickness Ft	in	Remarks
				Break, 1 ft 0 in
1, 271	0		6	Lean light green shale containing blebs of shortite (about 15 percent). Gaylussite (5 percent) is
1, 271	6			found in veins filling cracks in the shale.
				Break, 2 ft 6 in
1, 274	0	2	0	Lean light-green shale with shortite (about 20 percent) and gaylussite (5 percent). At 1,275 ft
1, 276	0			8 in to 1,275 ft 10 in a 2-inch stratum of massive shortite is found. A small quantity of the
				rare mineral bromlite is found at 1,276 ft 0 in. Thin sections show the sequence shortite to
				gaylussite to bromlite and dolomite.
				Break, 2 ft 0 in
1, 278	0		3	Massive trona.
1, 278	3			
				Break, 9 in
1, 279	0		6	Colorless trona (about 70 percent) cut by 1-inch stratum of very rich black shale at 1,279 ft 4
1, 279	6			in. Rich brown shale containing shortite (about 5 percent) is found at the bottom of the
				section. Pyrite is present.
				Break, 3 ft 6 in
1, 283	0		2	Lean greenish shale containing small crystals of shortite (about 25 percent).
1, 283	2			
				Break, 1 ft 4 in
1, 284	6	3	0	Medium-grade greenish-yellow shale that grades into very rich dark-brown shale. Shortite
1, 287	6			(about 10 percent) is present. In the last foot the crystals of shortite are oil soaked apparently
				with oil derived from the very rich oil shale.
				Break, 2 ft 6 in
1, 290	0	5	0	Lean shale containing small crystals of shortite (about 10 percent).
1, 295	0			
				Break, 1 ft 0 in
1, 296	0	2	6	Lean shale containing small crystals of shortite (about 15 percent), some of which fill cracks in
1, 298	6			the shale that cut the bedding.
				Break, 1 ft 6 in
1, 300	0	5	0	Lean shale varying from light green through tan to brown in color. Shortite (about 10 percent)
1, 305	0			occurs as small crystals throughout the section. A few thin seams of trona (about 1 percent)
				are found between 1,301 ft 4 in and 1,302 ft 6 in. Very small crystals of dolomite are present
				at 1,302 ft 0 in where shortite is being replaced by trona and dolomite, as shown in thin sec-
				tion. A few tiny crystals having a high birefringence and high index of refraction with a
				small optic angle (2V) are seen in this thin section. The mineral may be bromlite or aragonite.
				No break
1, 305	0	4	0	Lean shale containing small crystals of shortite (about 15 percent). Pyrite is abundant.
1, 309	0			
				Break, 1 ft 0 in
1, 310	0	10	0	Greenish lean shale containing shortite (about 10 percent) and pirssonite (about 10 percent).
1, 320	0			Magnesite and pyrite are present. The transition shortite to pirssonite plus magnesite is
				seen throughout the section.
				No break
1, 320	0	10	0	Greenish lean shale containing shortite (about 10 percent), pirssonite (about 5 percent), trona
1, 330	0			(about 10 percent), and northupite (less than 1 percent). A 1-foot stratum of white massive
				trona occurs at 1,324 ft 10 in to 1,325 ft 10 in. The northupite is found between 1,327 ft 0 in
				and 1,328 ft 0 in.
				Break, 5 ft 0 in
1, 335	0	3	0	Lean shale containing shortite (about 50 percent) and northupite (about 5 percent). Between
1, 338	0			1,336 ft 0 in and 1,337 ft 0 in, well-formed octahedra of northupite are found.
				Break, 6 in
1, 338	6	1	6	Lean shale containing crystals up to 3 mm across of shortite (about 30 percent) and fine-grained
1, 340	0			northupite (about 35 percent) containing residual crystals of shortite.
				No break
1, 340	0	10	0	Lean light-brown shale containing shortite (about 20 percent), northupite (about 15 percent),
1, 350	0			pirssonite (about 1 percent), gaylussite (about 0.5 percent), and trona (about 0.5 percent).
				Nodules of northupite, some of which contain residual fragments of shortite, have flow lines
				in the shale around them. The sequence shortite to northupite and dolomite is found at
				1,340 ft 8 in and also shortite to pirssonite to northupite and dolomite. At 1,342 ft 10 in a

| Depth interval | | Thickness | | Remarks |
Ft	in	Ft	in	
				1-inch stratum is composed approximately of 55 percent bradleyite, 30 percent shortite, and 15 percent clay. Bradleyite is found in a 1½-inch stratum at 1,343 ft 7 in with shortite and clay. Pyrite is sparsely present throughout the 10-foot section.
				No break
1,350	0	2	0	Lean shale containing crystals of shortite (about 10 percent) and trona (about 1 percent).
1,352	0			
				Break, 8 ft 0 in
1,360	0	10	0	Lean shale containing shortite (about 10 percent), trona (about 7 percent), and northupite (about 2 percent). From 1,364 ft 6 in to 1,366 ft 0 in very small crystals of shortite fill cracks in the shale that are normal to the bedding. A 6-inch stratum of pure white trona is present at 1,367 ft and is oriented in such a way that the cleavage is normal to the bedding. A 2-inch stratum of massive trona occurs at 1,369 ft 10 in.
1,370	0			
				Break, 5 ft 0 in
1,375	0	5	0	Lean shale containing shortite (about 30 percent) and northupite (about 7 percent). At 1,379 ft 6 in the sequency shortite to northupite is observed.
1,380	0			
				No break
1,380	0	10	0	Lean shale containing shortite (about 35 percent) and northupite (about 25 percent) with tiny crystals of pyrite throughout. Thin sections cut at 1,380 ft 4 in and 1,382 ft show shortite being replaced by northupite.
1,390	0			
				No break
1,390	0	5	0	Greenish lean shale containing shortite (about 15 percent), trona (about 2.5 percent), northupite (about 1 percent), and pirssonite (about 0.5 percent). The sequence shortite to pirssonite is found at 1,390 ft 2 in. At 1,390 ft 8 in, three small grains of tychite were found. A 1½-inch stratum of trona is present at 1,392 ft 6 in. A minute quantity of an unidentified mineral was found at 1,392 ft 3 in. It is insoluble in H_2O, soluble in HCl, has parallel extinction and negative elongation with indices $\omega = 1.554$ and $\epsilon = 1.497$.
1,395	0			
				No break
1,392	0	17	0	Light-green lean shale containing shortite (about 20 percent) and northupite (about 5 percent). The sequence shortite to northupite is found in thin sections cut at 1,401 ft 6 in and 1,407 ft 1 in.
1,409	0			
				No break
1,409	0	10	0	Rich brown oil shale containing shortite (about 35 percent) and northupite (about 15 percent). In the first 2 feet milky northupite constitutes about 60 percent of the core. The northupite occurs as round nodules that grew in the soft mud, producing flow lines. A thin section at 1,411 ft 2 in shows northupite replacing shortite and shale.
1,419	0			
				No break
1,419	0	5	0	Lean brown shale containing shortite (about 10 percent) and northupite (about 10 percent).
1,424	0			
				No break
1,424	0	6	0	Lean greenish shale containing shortite (about 7 percent) and northupite (about 1 percent)· In the first 4 feet euhedral crystals of northupite are present.
1,430	0			
				No break
1,430	0	6	0	Lean greenish shale broken by a stratum 1-foot thick of rich brown shale at 1,431 ft to 1,432 ft. Shortite (about 10 percent) and northupite (about 10 percent) are found throughout. At 1,431 ft 8 in, a ½-inch stratum of rich brown oil shale contains oolitelike inclusions of northupite. The round blebs of northupite have in cross section, concentric rings made up of microscopic liquid inclusions that give the appearance of oolitic structure. At 1,431 ft 8 in, a small amount of authigenic chert with index of refraction of 1.550 was found.
1,436	0			
				No break
1,436	0	6	0	The section contains shortite (about 15 percent), trona (about 5 percent), and northupite (about 2 percent). The first 2 feet are composed of light-green lean shale that grades to rich brown shale 1 foot thick. Lean green shale makes up the remaining 3 feet of the section. At 1,439 ft 4 in, a crack about 1 mm thick is filled with tiny authigenic crystals of quartz. At 1,441 ft 9 in, a very small amount of the mineral thermonatrite ($Na_2CO_3 \cdot H_2O$) was identified.
1,442	0			
				No break
1,442	0	7	0	The first 2 feet is composed of rich dark-brown oil shale, and the remaining 5 feet of the section is lean light green shale. Northupite (15 percent) and shortite (5 percent) are found throughout. Thin sections at 1,442 ft 6 in and 1,442 ft 8 in show northupite replacing shortite and shale.
1,449	0			
				No break

Depth interval Ft	in	Thickness Ft	in	Remarks
1,449	0	1	0	Greenish shale containing shortite (about 15 percent).
1,450	0			
				No break
1,450	0	10	0	Lean greenish shale contains shortite (about 10 percent), trona (about 6 percent), and northupite (about 3 percent). A thin section at 1,454 ft shows northupite replacing shale. Trona is concentrated between 1,454 ft 4 in to 1,455 ft 8 in.
1,460	0			
				No break
1,460	0	10	0	The lean greenish shale is cut by a 6-inch stratum of dense black rich oil shale at 1,462 ft 6 in. Shortite (about 10 percent), northupite (about 6 percent), and trona (about 4 percent) are present. At 1,462 ft 6 in is found a 2-inch stratum of massive white trona. From 1,466 ft 6 in to 1,466 ft 8 in, the greenish shale contains large plates of searlesite. Trona, northupite, and pyrite are also present. Tiny plates of biotite are found for 3 inches at 1,468 ft 5 in. Massive trona occurs in a 4-inch stratum beginning at 1,468 ft 8 in.
1,470	0			
				No break
1,470	0	5	0	Greenish lean shale contains crystals of shortite (about 10 percent), northupite (about 1 percent), and trona (about 1 percent). A thin stratum of searlesite is found at 1,473 ft 0 in. Thin sections cut at 1,470 ft 1 in and 1,470 ft 3 in, show northupite replacing trona.
1,475	0			
				No break
1,475	0	5	0	Medium-grade shale contains shortite (about 25 percent), northupite (about 15 percent), and trona (about 3 percent). The northupite occurs as glassy nodules up to 5 mm in diameter. At 1,475 ft 3 in a thin section shows northupite replacing shortite and shale, leaving at the contact with the shale, long strings of low birefringent material that is insoluble in cold (1+1) HCl, has positive elongation and parallel extinction. A 2-inch stratum of nearly pure trona occurs at 1,479 ft 0 in.
1,480	0			
				No break
1,480	0	10	0	Medium-grade tan-colored oil shale is found in first 5 feet. The remainder of the section is lean greenish shale. Shortite (about 25 percent), northupite (about 15 percent), and trona (about 3 percent) are present. A $\frac{1}{4}$-inch stratum of searlesite occurs at 1,480 ft 0 in and another at 1,485 ft 0 in. At 1,481 ft 0 in a thin stratum contains plagioclase, feldspar, biotite, and volcanic ash. Five inches of white massive trona begins at 1,481 ft 8 in. Northupite replaces shortite and trona between 1,482 ft 7 in and 1,485 ft 0 in.
1,490	0			
				No break
1,490	0	10	0	Lean shale contains shortite (about 13 percent) and trona (less than $\frac{1}{2}$ percent). At 1,491 ft 3 in a small vug contains many very small crystals of nahcolite. A thin section at 1,491 ft 10 in shows trona replacing shortite. Thin sections show that two $\frac{1}{4}$-inch strata between 1,494 ft 3 in and 1,494 ft 5 in are probably altered ash. volcanic From 1,494 ft 4 in to 1,498 ft 1 in well-formed crystals of shortite up to 1 cm across are present.
1,500	0			
				No break
1,500	0	10	0	Lean gray shale containing shortite (about 5 percent). Cracks in the shale normal to the bedding and as much as 2 feet long, are filled by tiny crystals of shortite. These may have been mud cracks.
1,510	0			
				Break, 16 ft 0 in
1,526	0	4	0	Medium-grade oil shale containing crystals of shortite (about 15 percent).
1,530	0			
				No break
1,530	0	10	0	Medium-grade oil shale containing crystals of shortite (about 15 percent). A polished section normal to the bedding at 1,535 ft 0 in showed sharp folding. A thin section cut at the same place showed shortite being replaced by an unidentified mineral of high birefringence and upper index about 1.55. The fragments of this mineral were very small. No cleavage was evident.
1,540	0			
				No break
1,540	0	10	0	Lean greenish shale containing crystals of shortite (about 15 percent) and massive trona (about 2 percent). A few crystals of northupite are present at 1,544 ft 0 in. A $2\frac{1}{2}$-inch stratum of pure trona is found at 1,548 ft 0 in.
1,550	0			
				No break
1,550	0	10	0	Greenish lean shale containing shortite (about 20 percent) both massive and as crystals, trona (about 15 percent), and northupite (about 1 percent). Trona is present scantily at the top of the section and increases with depth to a 13-inch stratum beginning at 1,557 ft 9 in of dark brown trona, the color due to organic matter. A thin section at 1,559 ft 9 in shows shortite and trona being replaced by northupite.
1,560	0			
				No break

Depth interval		Thickness			Remarks
Ft	in	Ft	in		
1,560	0	1	6		Lean shale containing trona (about 50 percent), shortite (about 5 percent), and northupite (about 1 percent). A 9-inch stratum of yellow-colored trona is found at the top of this 1½-foot section. At 1,560 ft 2 in, a lens of brownish northupite is in the trona where a thin section shows northupite replacing trona. Ghost crystals of trona are present in the northupite.
1,561	6				
					No break
1,561	6	8	6		Medium-grade light-brown oil shale containing crystals of shortite (about 10 percent).
1,570	0				
					No break
1,570	0	10	0		Lean greenish shale cut by an 8-inch stratum of very rich oil shale beginning at 1,576 ft contains crystals of shortite (about 5 percent).
1,580	0				
					No break
1,580	0	7	9		Lean shale containing shortite (about 5 percent) and massive trona (about 5 percent). The trona is present in two strata, one 2 inches thick, and the other 3 inches thick from 1,587 ft 6 in to 1,587 ft 9 in.
1,587	9				
					Break, 2 ft 6 in
1,590	3	1	3		Massive trona.
1,591	6				
					Break, 1 ft 0 in
1,592	6	7	10		Massive trona.
1,600	4				
					No break
1,600	4	11		8	Medium grade and rich oil shale containing shortite (about 10 percent) and trona (about 10 percent). A small amount of searlesite is present, the plates of which are separated by thin veins of loughlinite.
1,612	0				
					No break
1,612	0	4	0		Lean greenish oil shale containing a 1-foot thick stratum of brown rich oil shale. Crystals of shortite (about 10 percent) are present throughout.
1,616	0				
					No break
1,616	0	4	0		Medium-grade oil shale containing shortite (about 10 percent) and trona (about 55 percent). A stratum of massive trona 2 ft 3 in thick is present from 1,617 ft 6 in to 1,619 ft 9 in. At 1,619 ft a tiny bleb of aragonite was identified.
1,620	0				
					No break
1,620	0	10	0		Lean greenish oil shale with about 2 ft of medium-grade shale. Shortite (about 5 percent) is present throughout the section. A small amount of loughlinite is present at 1,620 ft 6 in and searlesite at 1,621 ft 3 in.
1,630	0				
					No break
1,630	0	10	0		The section is composed of 5 ft of lean greenish shale and 5 ft of brown medium-grade oil shale. Shortite (about 5 percent) and trona (about 2 percent) are present. Loughlinite is sparingly present between 1,633 ft 0 in and at 1,639 ft 0 in. A 2-inch stratum of trona is found at 1,635 ft. Pyrite is found to as much as about 5 percent in the medium-grade brown shale between 1,635 ft 2 in and 1,638 ft 6 in.
1,640	0				
					No break
1,640	0	1	0		Lean greenish shale containing crystals of shortite (about 5 percent).
1,641	0				
					No break
1,641	0	9	0		The section contains lean greenish shale, rich dark-brown shale, shortite (about 5 percent) and trona (about 45 percent). Between 1,642 ft 0 in to 1,646 ft 0 in is a 4-ft bed of massive trona.
1,650	0				
					No break
1,650	0	10	0		The section is composed of trona (about 65 percent), shortite (about 3 percent), and both lean and rich oil shale. The first 3 ft is lean shale. From 1,653 ft 2 in to 1,659 ft 3 in is found a 6 ft 1 in bed of massive trona followed by 5 in of dark brown rich-oil shale containing crystals of shortite. A 4-in bed of reddish brown massive trona is present from 1,659 ft 8 in to 1,660 ft 0 in. A thin section cut at 1,659 ft 8 in at the contact between the rich oil shale and the trona shows the shale being replaced by the trona.
1,660	0				
					No break
1,660	0	10	0		The upper two-thirds of the section is medium-grade oil shale and the lower one-third is lean greenish shale. Shortite (about 5 percent) and trona (about 3 percent) are present. Loughlinite is found from 1,665 ft to 1,665 ft 5 in. Pyrite is present in the lower part of the section.
1,670	0				
					No break

| Depth interval | | Thickness | | Remarks |
Ft	in	Ft	in	
1,670	0	5	0	Lean shale containing crystals of shortite (about 10 percent). Small veins of loughlinite are found between 1,672 ft 6 in and 1,673 ft 0 in.
1,675	0			
				No break
1,675	0	5	0	Lean gray shale containing crystals of shortite (about 5 percent).
1,680	0			
				No break
1,680	0	10	0	Shortite (about 5 percent) is present throughout the section. The lean shale is divided by a 2-ft bed of medium-rich shale beginning at 1,684 ft 2 in.
1,690	0			
				No break
1,690	0	10	0	Lean greenish shale containing crystals of shortite (about 10 percent) and crystals of pyrite.
1,700	0			
				No break
1,700	0	4	0	Lean brown shale containing large crystals of shortite (about 10 percent).
1,704	0			
				No break
1,704	0	6	0	Lean brown shale containing large crystals of shortite (about 5 percent).
1,710	0			
				No break
1,710	0	10	0	Lean greenish shale divided by a bed of medium-grade shale from 1,711 ft to 1,712 ft 0 in. Large shortite (about 5 percent) crystals up to 3 cm across are present.
1,720	0			
				No break
1,720	0	5	0	Lean shale, both greenish and brown, containing shortite (about 5 percent).
1,725	0			
				No break
1,725	0	5	0	Lean greenish shale with poorly formed crystals of shortite (about 15 percent) up to 1½ cm across.
1,730	0			
				No break
1,730	0	10	0	Lean greenish shale containing poorly formed crystals of shortite (about 10 percent) up to 1½ cm across.
1,740	0			
				No break
1,740	0	10	0	Shortite (about 3 percent) is present throughout the section. The first 6 ft is composed of lean shale, both greenish and brown in color. From 1,746 ft 0 in to 1,746 ft 4 in a greatly altered bed of volcanic ash containing tiny crystals of pyrite is found. This may be a good horizon marker. The remainder of the section is made up of lean brownish shale containing large crystals of pyrite (about 2 percent).
1,750	0			
				No break
1,750	0	6	0	Lean shale, both brown and greenish, containing large poorly formed crystals of shortite (about 5 percent). Pyrite is present in the upper 2 ft of the section.
1,756	0			
				No break
1,756	0	4	0	Lean greenish shale with a few large crystals of shortite (about 1 percent) as much as 2 cm across.
1,760	0			
				No break
1,760	0	10	0	Lean greenish shale divided by a bed of medium-grade shale from 1,761 ft 0 in to 1,763 ft 0 in. Shortite (about 1 percent) is present.
1,770	0			
				No break
1,770	0	10	0	The first 3 ft is composed of lean greenish shale. From 1,773 ft 0 in to 1,777 ft 6 in medium-grade oil shale is found. The remainder of the section is lean greenish shale. Shortite (about 1 percent) and pyrite are present.
1,780	0			
				No break
1,780	0	3	0	Lean greenish shale containing a few blebs of shortite (about 0.5 percent) and tiny crystals of pyrite.
1,783	0			
				No break
1,783	0	7	0	The first foot is made up of rich black oil shale. The remaining 6 ft of the section is composed of lean greenish shale. Shortite (about 1 percent) and tiny crystals of pyrite are present.
1,790	0			
				No break
1,790	0	10	0	The first 9 ft of this section is composed of lean light-green shale containing an occasional bleb of shortite (about 0.1 percent). From 1,799 ft to 1,800 ft the medium-grade oil shale contains no salines. Tiny crystals of pyrite are sparingly present.
1,800	0			

Depth interval Ft	in	Thickness Ft	in	Remarks
				No break
1,800	0	10	0	The first 2½ ft of the section is composed of medium-grade oil shale, the next 4 ft of lean shale
1,810	0			and the remainder of dark medium-grade shale. Shortite (about 0.1 percent) and pyrite are present. The greatest depth at which shortite is found in the John Hay, Jr., well, 1 is 1,806 ft 6 in.
				Break, 10 ft 3 in
1,820	3		3	Lean dense black shale.
1,820	6			
				Break, 149 ft 6 in
1,970	0	1	0	Lean greenish shale containing blebs of calcite.
1,971	0			
				Break, 20 ft 4 in
1,991	4		8	Limestone containing gastropods.
1,992	0			

MINING OPERATION

DEVELOPMENT OF MINE

Since the first shaft of the Westvaco mine was put down in 1947 to the trona bed, 1,600 feet below the surface, many problems that presented themselves in the mining of the trona and converting it to soda ash (sodium carbonate) have been solved. A pilot plant with a capacity of 200 tons per day was first installed in which the crushed trona brought up from the mine was calcined, sieved, and bagged. This product contained from 5 to 10 percent of extraneous material derived from the detrital minerals and the dolomite in the trona bed, and did not meet the requirement of the most lucrative market, for which a minimum purity of 99.9 percent for the soda ash must be maintained.

By 1952 the pilot plant had served its purpose and a great expansion program was started which by 1954 resulted in a solution plant with a capacity of 300,000 tons of soda ash per year. The buildings were so built that doubling this capacity could be brought about with a minimum of effort.

In the new plant the crushed trona is dissolved in hot water, the insoluble material filtered off, and the sesquicarbonate precipitated, filtered, and calcined to form the soda ash of commerce. This product of better than 99.9 percent purity was by 1958 being produced at a rate of more than 400,000 tons per year.

The expansion and development of the underground workings kept pace with processing advancement on the surface. By 1959, more than 100 miles of corridors, crisscrossed to facilitate room and pillar mining, had been cut into the trona bed.

Working faces in the mine, one of which is shown in figures 3 and 4, are undercut, drilled horizontally to a depth of 9 feet, and loaded with dynamite. Each round of explosive knocks down almost 50 tons of trona. After the blast, loading machines move up to the face, their crablike arms sweep the ore onto a moving belt that carries it to electrically driven cars equipped with rubber tires. These cars shuttle back and forth to a conveyor belt that carries the ore to a crusher at the bottom of a 1,600-foot shaft. Twin skips hoist the trona to the surface at the rate of 6 tons per minute.

A noteworthy feature of the Westvaco mine is the absence of wooden supports underground. Roof bolts driven vertically into the overhead shale support the square-cut main entries. The other development openings are arched and usually require no roof bolts. The absence of timber makes more room for the movement of equipment.

SODA ASH

The trona of the Green River formation will probably be a source of soda ash for hundreds of years. Each square mile of the trona bed contains more than 16 million tons of trona, from which it is estimated, after deducting for impurities in the trona bed, and the in-

FIGURE 3.—Photograph of a working face in the Westvaco mine. Sample B in table 22 was obtained from this location.

FIGURE 4.—Closeup of face in figure 3, showing stratification in the trona bed. The handle of the pick crosses a half-inch stratum of shale.

FIGURE 5.—Photograph showing the calcining house, the screen house, and the superstructure of shaft 1 of the Westvaco mine.

complete recovery by room and pillar mining, about 9 million tons of soda ash can be produced.

Four products are now marketed by Westvaco: crude trona (crushed), soda ash (dense), soda ash (light) and sultron, a specialty product used in the desulfurization of steel.

With this development of the trona resources as a foundation, the manufacture of other basic chemicals from nearby natural resources may be planned to provide the intermountain area with more basic chemicals at new low economic levels.

Figures for the production in this country of both the synthetic soda ash, produced from sodium chloride brines by the Solvay process, and the soda ash produced from natural sources are listed in table 1. The tonnages of soda ash used by the various industries in this country are recorded in table 12.

A photograph (fig. 5) of the calcining house, the screen house, and the superstructure of shaft 1, shows only a small part of the surface development of the new mine that produces the trona and the plant that converts it to soda ash.

TABLE 1.—*Production figures and value of soda ash produced in the United States from 1948 through 1957*

[From the Minerals Yearbook, v. 1, 1957, U.S. Bureau of Mines]

Year	Manufac-tured short tons	Natural short tons	Value
1948–52 average	4,403,809	[1] 302,901	[1] $6,905,367
1953	4,879,396	419,206	10,627,460
1954	4,701,364	527,282	13,536,345
1955	4,906,971	613,594	15,000,966
1956	4,997,579	652,891	17,400,347
1957 [2]	4,650,588	652,717	17,792,301

[1] Exclusive of Wyoming in 1948–49.
[2] Preliminary figures.

ROCKS CONTAINING THE SALINE MINERALS

DEFINITION

To understand better some of the many problems that were faced in the study of the genesis and paragenesis of the saline minerals, a careful look at the rocks in which they occur was taken. The saline minerals of the Green River formation that are found north of the Uinta Mountains in the Wyoming area are exclusively in the Wilkins Peak member of this formation. The term "oil shale," applied in the description of these sediments, and so used in this report, is firmly established in the literature of the Green River formation. However, from a look at the definition of shale, in which fissility is the physical property that characterizes the structure, one must conclude that the term "oil shale" is incorrectly used when applied to all but a very small percentage of the Wilkins Peak in which the saline minerals occur.

Regarding the term "shale", Lewis (1924, p. 568) says:

It implies no particular composition except so far as certain materials of fine texture lend themselves to the development of the characteristic structure. This structure, or fissility, may be defined as the capacity of clayey strata for splitting into somewhat uneven flakes, thin chips, and wedgelike fragments approximately parallel to the bedding.

The American Geological Institute's Glossary of Geology and Related Sciences, 1957, on page 262 states:

Shale includes the indurated, laminated or fissile claystones and siltstones. The cleavage is that of bedding and such other secondary cleavage or fissility that is approximately parallel to the bedding. The secondary cleavage has been produced by the pressure of overlying sediments and plastic flow.

In a vertical section through the Wilkins Peak member, only rarely would one see strata that could be classified as oil shale. Bradley (1931, p. 22) in his paper on the oil shale of Colorado and Utah points out that most of the oil shale of the Green River formation could not be regarded strictly as shale, but instead it is practically a magnesian marlstone rich in organic matter.

The Wilkins Peak sediments that vary in content of dolomite from approximately 20 to 75 percent do not fit into the category of any single rock type. They vary, with increasing dolomite, from magnesian marlstone to argillaceous dolomite.

SELECTION OF SAMPLES

To determine the variations in chemical composition, physical properties, and mineral content of the "oil shale", 14 samples were chosen from the drill core of the John Hay, Jr., well 1, care being taken to select material having a minimum amount of saline minerals. The criteria used in deciding what intervals of the drill core should be sampled were chiefly the depth, the color, the visually estimated content of organic material, and the amount of acid insoluble portion, the latter having been previously determined semiquantitatively by treatment of a roughly weighed sample with dilute hydrochloric acid. On all these samples the color was recorded, and on six the bulk specific gravity was determined. The samples were then ground to pass an 80-mesh sieve.

COLOR

A freshly broken surface was used to determine the color of each of the 14 samples of oil shale. Comparison was made, in daylight from a north window, with the plates in Robert Ridgway's Color Standards and Nomenclature, and the results are recorded in table 2. There was no noticeable variation in the color within the individual section of core from which each of the samples was taken. The color of the samples after grinding was not recorded.

CHEMICAL ANALYSIS

Complete quantitative chemical analyses were made of 14 samples from the drill core of the John Hay, Jr., well 1 and these are listed in table 3. For all but 6 of the 20 constituents determined, the classical methods of Hillebrand, Lundell, Bright and Hoffman (1953) were used. An ion-exchange column was employed to isolate sodium and potassium, lithium was determined spectrographically, and carbon dioxide was collected and the volume at standard conditions converted to mass by applying the appropriate factor (Fahey, 1946).

TABLE 2.—*Color of samples from the drill core of the John Hay, Jr., well 1, matched to Robert Ridgway's "Color standards and nomenclature"*

Laboratory No.	From—		To—		Plate	Name
	Ft	in	Ft	in		
148137	1,275	0	1,276	0	XL	Pale olive buff.
148138	1,320	0	1,321	0	XL	Pale olive buff..
148139	1,390	0	1,391	0	XXXII	Pale turtle green.
148140	1,623	6	1,624	6	XLI	Yellowish glaucous.
148141	1,646	0	1,647	0	XLVI	Fuscous.
148142	1,710	0	1,711	0	XL	Pale olive buff.
148143	1,711	0	1,712	0	XL	Deep olive buff.
148144	1,712	0	1,713	0	XL	Olive buff.
151391	1,365	0	1,365	3	XL	Olive buff.
151392	1,624	0	1,624	1	XXXII	Pale turtle green.
151393	1,654	6	1,654	7	XVIII	Pale veronese green.
151394	1,663	0	1,663	3	XLVI	Chaetura drab.
151395	1,668	0	1,668	1	LII	Pearl gray.
151396	1,700	0	1,700	3	XLVI	Grayish olive.

Organic matter was determined by treating the sample for about 2 hours on the steam bath with (1+1) HCl and filtering, using a 41H Whatman filter paper. The residue was then transferred from the paper, by means of a stream of water, to a 100-ml platinum crucible, to which was then added about 20-ml (1+1) HCl and 70 ml of HF. A well-fitting cover was placed on the crucible and it was allowed to remain on the steam bath over night. The residue was then filtered on 41H paper, using a polyethylene funnel and beaker, and washed well with hot (1+3) HCl. The residue was transferred to a 25-ml platinum crucible by means of a stream of water, the water was removed by evaporation on the steam bath and the crucible, plus contents, was then allowed to remain overnight in an oven at 90° C. After cooling in a desiccator and weighing, the organic matter was burned off and determined by difference. A correction must be applied for the sulfur of the pyrite present after determining iron in the residue following the burning off of the organic matter.

The water lost above 110° C ($H_2O + 110°$ C) was determined by slowly burning off the organic matter of a sample in a platinum crucible and then heating over night in a furnace held at 900° C. The loss of weight after correcting for the organic matter, the CO_2, the $H_2O - 110°$ C, the sulfur of the pyrite, and the oxidation of the FeO present to Fe_2O_3, is a measure of the $H_2O + 110°$ C.

Because of the inertness of the organic matter, FeO can be determined in the usual manner. An excellent end point is obtained when titrating with twentieth-normal permanganate.

The specific gravity was determined by using a fused silica Adams-Johnston pycnometer. The interstitial air was removed by allowing the sample in the pycnometer (about half filled with boiled and

TABLE 3.—*Chemical analyses (in percent) of samples from the drill core of the John Hay, Jr., well 1, Sweetwater County, Wyo.*

[Joseph J. Fahey, analyst. Samples are listed by laboratory number. Depths of samples given in table 2]

	148137	148138	148139	148140	148141	148142	148143	148144	151391	151392	151393	151394	151395	151396
SiO_2	15.70	27.84	29.88	25.91	17.61	35.03	29.86	29.09	24.00	27.38	15.42	24.97	31.87	24.80
Al_2O_3	1.98	6.11	4.06	3.87	1.89	5.35	2.74	8.64	4.03	6.33	3.82	4.78	7.67	3.23
Fe_2O_3	.61	1.92	1.34	.89	1.89	.83	2.48	.50	1.14	1.42	.31	2.45	.83	.95
FeO	.95	.80	.90	.73	.55	1.25	1.08	1.10	1.00	1.08	.68	.65	1.05	1.05
TiO_2	.10	.24	.13	.18	.14	.31	.25	.22	.19	.25	.13	.17	.27	.12
P_2O_5	.22	.17	.00	.04	.01	.03	.01	.01	.02	.01	.02	.00	.01	.01
CaO	21.37	13.02	9.35	17.89	16.84	12.89	13.06	16.16	16.75	14.03	21.26	11.06	14.58	18.01
MgO	4.74	4.96	7.42	10.44	8.01	10.36	7.77	10.47	10.64	8.30	16.69	8.32	7.31	12.98
BaO	.00	.00	.00	.00	.02	.00	.00	.00	.00	.00	.00	.00	.02	.00
MnO	.02	.03	.05	.08	.03	.10	.04	.09	.08	.08	.05	.04	.06	.11
Na_2O[1]	12.15	10.84	12.03	5.57	4.49	1.45	2.39	2.61	4.01	5.63	1.29	1.98	5.24	1.04
K_2O[1]	2.07	4.37	2.75	2.69	1.98	4.76	4.25	2.80	2.47	3.70	2.54	2.22	4.93	1.94
Li_2O[2]	.04	.06	.03	.04	.04	.09	.04	.07	.02	.09	.04	.04	.02	.09
SO_3	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00
S	.37	1.09	.08	.39	1.26	.34	2.17	.23	.88	.63	.03	1.57	.30	.52
Cl	.30	.85	2.38	.21	.04	.06	.05	.47	.31	.25	.06	.10	.05	.05
CO_2	29.76	20.22	14.44	26.49	21.74	20.05	16.19	19.80	21.82	20.86	33.10	15.00	21.57	27.28
$H_2O-110°C$	7.78	1.79	4.40	2.09	.87	.93	.50	.56	1.17	2.40	.69	.95	1.51	.44
$H_2O+110°C$	.81	5.90	6.76	.32	.30	1.88	.52	2.79	1.32	2.22	1.16	1.29	1.79	1.06
Organic matter	1.07	1.08	4.78	2.23	21.11	4.10	17.28	5.77	10.49	5.43	3.21	25.32	1.45	7.04
	100.04	101.29	100.78	100.06	100.35	99.81	100.68	100.96	100.50	100.15	100.69	100.87	100.58	100.72
Oxygen correction for Cl and S[3]	-.16	-.46	-.56	-.15	-.13	-.10	-.25	-.07	-.32	-.23	-.06	-.16	-.10	-.14
	99.88	100.83	100.22	99.91	100.22	99.71	100.43	100.89	100.18	99.92	100.63	100.71	100.48	100.58
Specific gravity at 4°C	2.479	2.644	--------	2.603	2.091	2.593	2.342	2.518	2.458	2.560	2.697	1.978	2.648	2.519

[1] Determined by Laura Reichen using ion-exchange method.
[2] Determined by Janet Fletcher by means of visible spectrum.
[3] The sulfur correction was made on the basis of the sulfur present as pyrite.

cooled distilled water) to remain under a bell jar at reduced pressure until no bubbles were forced to the surface by gentle tapping.

SPECTROGRAPHIC ANALYSIS

The 14 samples from the John Hay, Jr., well 1 were examined quantitatively for minor elements spectrographically and the results are given in table 4. Each sample was ignited before placing it in the arc. Sixteen minor elements were found and 24 more were looked for but not detected.

PARTICLE SIZE

Each sample was ground in a jaw crusher and rolls and a 5-gram portion (2 grams of sample 148139) of each was dispersed in distilled water. Particles larger than 64μ (sand fraction) were removed by wet seiving and the clay ($<2\mu$) and silt ($2-64\mu$) were separated by repeated centrifuging and decanting. The fractions obtained were dried and weighed and their proportions calculated as percentages. The loss in weight from the original sample is presumed to be due to the loss of water-soluble material. The consolidated nature of the shales makes it improbable that the figure shown in table 5 represent the true particle size distribution in the shale. The sand fractions of most of the samples contain aggregates of finer material.

MINERAL ANALYSIS

The proportions of the minerals in the clay and silt fractions listed in table 5 were semiquantitatively

TABLE 4.—*Quantitative spectrographic analyses for minor elements in samples from the drill core of the John Hay, Jr., well 1, Sweetwater County, Wyo.*

[Janet D. Fletcher, analyst. Samples are listed by laboratory number. Depths of samples given in table 2]

Laboratory	148137	148138	148139	149140	148141	148142	148143	148144	151391	151392	151393	151394	151395	151396
Cu[1]	0.022	0.047	0.24	0.038	0.014	0.021	0.028	0.010	0.0072	0.038	0.027	0.033	0.018	0.013
Mo	0	0	0	0	.022	0	0	0	.002	0	0	.001	.002	.002
Pb	.001	.002	.002	.002	.002	.002	.004	0	0	.001	0	0	0	0
Mn	.02	.04	.07	.05	.03	.08	.04	.09	.02	.07	.05	.07	.03	.02
Co	.0007	.001	.001	0	.002	.001	.001	.001	.001	.006	.001	.001	.0009	.001
Ni	.003	.003	.005	.002	.008	.003	.005	.003	.003	.002	.004	.004	.003	.005
Cr	.003	.005	.003	.003	.003	.005	.005	.004	.004	.003	.005	.004	.005	.004
V	.006	.009	.007		.01	.008	.006	.008	.005	.006	.006	.009	.008	.009
Sc	0	.0002	.0002	.0002	.0002	0	.0002	.0002	.0002	.0002	0	.0002	0	0
Y	.002	.002	0	0	0	0	.001	0	0	0	0	0	0	0
Ti	.08	.2	.2	.009	.1	.2	.1	.2	.06	.07	.1	.1	.08	.09
Zr	.003	.005	.003	.003	.002	.004	.002	.003	.001	.002	.004	.007	.002	.003
Sr	.09	.09	.5	.09	.09	.08	.1	.1	.1	.08	.2	.2	.2	.08
Ba	.06	.06	.2	.02	.05	.02	.05	.02	.02	.04	.006	.01	.04	.04
Li[2]	.02	.03	.01	.02	.02	.04	.02	.03	.01	.04	.02	.02	.01	.04
B	.002	.02	.02	.009	.007	.02	.009	.009	.003	.01	.01	.008	.008	.007

[1] Two significant figures for Cu are given because results were obtained on highly diluted samples.
[2] A special exposure in the visible region was made to obtain better sensitivity for lithium.

Note.—0 in unit column means element not detected. All samples were ignited prior to analysis.
Looked for but not found: Ag, Au, Hg, Pd, Os, Ir, Pt, W., Ge, Sn, As, Sb, La, Be, Bi, Zn, Cd, Tl, In, Th, Nb, Ta, U, and P.

TABLE 5.—*Particle-size analysis, in percent, of 14 samples of oil shale from the drill core of the John Hay, Jr., well 1, Sweetwater County, Wyo.*

[John C. Hathaway, analyst. Depths of samples given in table 2]

Laboratory No.	Sand (>64μ)	Silt (2-64μ)	Clay (<2μ)	Difference (H₂0 soluble)
148137	26	37	11	26
148138	15	33	28	24
148139	15	61	5	19
148140	10	58	22	10
148141	53	25	4	18
148142	23	46	27	4
148143	66	19	7	8
148144	47	32	10	11
151391	64	28	8	0
151392	55	29	10	6
151393	44	31	14	11
151394	72	20	5	3
151395	24	49	20	7
151396	70	19	7	4

estimated by means of their X-ray diffraction patterns, and are reported as parts in ten in table 2. X-ray diffraction patterns were made for each sample as follows:

Clay fraction:

1. Oriented aggregate, air dried.
2. Oriented aggregate, treated with ethylene gylcol.
3. Oriented aggregate, heated at 400° C in diffractometer furnace.
4. Oriented aggregate, heated at 500° C in diffractometer furnace.
5. Randomly oriented powder, air dried.
6. Randomly oriented powder, treated with formic acid.
7. Randomly oriented powder, treated with hot concentrated HCl.

Silt fraction:

1. Randomly oriented powder, air dried.
2. Randomly oriented powder, treated with formic acid.
3. Randomly oriented powder, treated with hot concentrated HCl.

As the estimates of minerals present, listed in table 10, are derived from the relative intensities of the diffracted lines, and as many factors in addition to the quantity of a mineral affect the diffraction intensity, the estimates are not intended to give more than a very general indication of the relative amounts of the various minerals present. A measure of the acid-soluble portion (table 7) of the sand, silt, and clay fractions of samples 151391 to 151396, inclusive, listed in table 5, was obtained by treating on the steam bath with (1+1) HCl for about 30 minutes a weighed sample of each fraction, filtering on a preweighed fine-mesh sintered-glass filter, drying overnight in an oven held at 90° C, and weighing. The difference between the weight of the sample and

TABLE 6.—*Semiquantitative estimation, by means of X-ray diffraction patterns, of the minerals present in the clay and silt fractions of samples from the John Hay, Jr., well 1, Sweetwater County, Wyo.*

[John C. Hathaway, analyst. Depths of samples given in table 2]

Laboratory No.	Fraction	Minerals present	Estimated amount (parts in 10)
148137	Clay (<2μ)	Orthoclase	3
		Calcite	2
		Dolomite	1
		Loughlinite	2(?)
		Mica	1
		Quartz	Tr.
	Silt (2-64μ)	Dolomite	4
		Calcite	2
		Quartz	1
		Orthoclase	1
148138	Clay	Orthoclase	5
		Mica	2
		Loughlinite	2(?)
		Calcite	Tr.
	Silt	Calcite	3
		Quartz	2
		Orthoclase	2
		Dolomite	2
		Mica	Tr.
148139	Clay	Loughlinite	4
		Aragonite (residue from shortite).	3
		Orthoclase	2
		Mica	Tr.
	Silt	Loughlinite	4
		Aragonite	3
		Orthoclase	2
148140	Clay	Dolomite	3
		Quartz	2
		Orthoclase	1
		Loughlinite	2
		Mica	Tr.
	Silt	Dolomite	6
		Quartz	2
		Orthoclase	Tr.
		Calcite	Tr.
148141	Clay	Dolomite	3
		Mica	2
		Orthoclase	2
		Calcite	1
		Quartz	1
		Loughlinite	Tr.
	Silt	Dolomite	4
		Calcite	3
		Quartz	2
		Orthoclase	Tr.
148142	Clay	Dolomite	3
		Mica	3
		Orthoclase	2
		Quartz	1
		Montmorillonite	Tr.
	Silt	Dolomite	6
		Quartz	3
		Orthoclase	Tr.
148143	Clay	Dolomite	4
		Orthoclase	2
		Mica	2
		Quartz	1
	Silt	Dolomite	6
		Quartz	2
		Orthoclase	1
148144	Clay	Dolomite	3
		Quartz	2
		Mica	2
		Orthoclase	1
	Silt	Dolomite	6
		Quartz	2
		Orthoclase	1
151391	Clay	Mixed layered mica-montmorillonite.	2
		Dolomite	5
		Quartz	1

TABLE 6.—*Semiquantitative estimation, by means of X-ray diffraction patterns, of the minerals present in the clay and silt fractions of samples from the John Hay, Jr., well 1, Sweetwater County, Wyo.*—Continued

[John C. Hathway, analyst. Depths of samples given in table 2]

Laboratory No.	Fraction	Minerals present	Estimated amount (parts in 10)
		Feldspar	1
		Calcite	Tr.
	Silt	Dolomite	5
		Quartz	2
		Calcite	2
151392	Clay	Feldspar(?)	Tr.
		Mixed layered mica-montmorillonite.	3
		Dolomite	3
		Quartz	1
		Feldspar	1
		Montmorillonite	Tr.
	Silt	Dolomite	5
		Quartz	2
		Calcite	1
		Feldspar	1
151393	Clay	Mixed layered mica-montmorillonite.	3
		Dolomite	3
		Feldspar	3
	Silt	Dolomite	7
		Feldspar	2
151394	Clay	Dolomite	6
		Quartz	1
		Feldspar	1
		Mixed layered mica-montmorillonite.	Tr.
	Silt	Dolomite	5
		Quartz	3
		Feldspar	1
151395	Clay	Mica[1]	4
		Feldspar	2
		Quartz	1
		Dolomite	2
	Silt	Dolomite	4
		Quartz	3
		Calcite	1
		Feldspar	1
151396	Clay	Dolomite	4
		Quartz	3
		Mica[1]	1
		Feldspar	1
	Silt	Dolomite	6
		Quartz	2
		Feldspar	1

[1] May have small number of interstratified montmorillonite layers.

TABLE 7.—*Solubility in hydrochloric acid of the clay, silt, and sand fractions of samples from the John Hay, Jr., well 1, Sweetwater County, Wyo.*

[Joseph J. Fahey, analyst. Depths of samples are given in table 2. Particle-size analyses are given in table 5]

Laboratory No.	Solubility of fraction in (1+1) HCl
151391	Clay, 50 percent of 8 percent = 4 percent
	Silt, 58 percent of 28 percent = 16 percent
	Sand, 58 percent of 64 percent = 37 percent
	57
151392	Clay, 39 percent of 10 percent = 4 percent
	Silt, 53 percent of 29 percent = 15 percent
	Sand, 55 percent of 55 percent = 30 percent
	49
151393	Clay, 40 percent of 14 percent = 6 percent
	Silt, 78 percent of 31 percent = 24 percent
	Sand, 81 percent of 44 percent = 36 percent
	66
151394	Clay, 70 percent of 5 percent = 4 percent
	Silt, 40 percent of 20 percent = 8 percent
	Sand, 36 percent of 72 percent = 26 percent
	38
151395	Clay, 27 percent of 20 percent = 5 percent
	Silt, 52 percent of 49 percent = 25 percent
	Sand, 70 percent of 24 percent = 17 percent
	47
151396	Clay, 44 percent of 7 percent = 3 percent
	Silt, 62 percent of 19 percent = 12 percent
	Sand, 61 percent of 70 percent = 43 percent
	58

the residue is recorded in table 7 as percent of the clay, silt, and sand fractions soluble in (1+1) HCl. This soluble portion was made up chiefly of the carbonates present in each sample.

ORGANIC MATTER

The organic matter contained in the Green River formation is the contribution of countless numbers of tiny organisms that, having finished their life cycle, sank to the muddy bottom of the lake, and were buried and changed through millions of years to form this vast accumulation of fossil fuel. The "oil shale" constitutes a tremendously large source of energy that awaits only propitious economic conditions to perform the thousands of tasks now done by crude petroleum.

The concentration of organic matter in the Wilkins Peak sediments ranges from less than 1 percent to probably more than 30 percent. In the 14 chemical analyses listed in table 3, the lowest content of organic matter is 1.07 percent and the highest is 25.32 percent. A sample from the drill core of the John Hay, Jr., well 1, which was obviously high in organic matter, was selected to serve as a source of organic matter on which the specific gravity could be determined and the index of refraction measured. This sample contained 26.88 percent organic matter and had a bulk specific gravity of 1.898 at 25° C. This was determined on the Jolly balance by using a piece that weighed between 16 and 17 grams, the entire surface of which had been made smooth by applying fine sandpaper. This was done to eliminate the possibility of air entrapment in tiny surficial cavities, which would result in a figure for the specific gravity that would be lower than the correct one.

The organic matter and the pyrite were separated from the other material of the sample by treatment as follows:

1. A sample weighing 10 grams that had been ground to pass a 200-mesh sieve was treated in a beaker with about 100 ml of (1+1) HCl and allowed to

remain on the steam bath for about 1 hour. This removed the carbonates.

2. The solution was filtered using a 41H Whatman filter paper and washed with warm dilute HCl. The residue was transferred with a stream of water to a platinum crucible of 100-ml capacity, and 5 ml of concentrated HCl and 50 ml of HF were added. A well-fitting cover was applied and the crucible was allowed to remain on the steam bath overnight.

3. It was filtered on 41H Whatman paper using a polyethylene funnel and beaker, washed with warm dilute HCl and the residue was returned to the same crucible and 50 ml of dilute HCl was added. It was covered and heated on the steam bath about an hour.

4. The residue which consisted of the organic matter and the pyrite was filtered on a 41H Whatman paper, washed with warm water, and transferred with a stream of water back to the same crucible.

5. The crucible and contents were placed on the steam bath until the water was evaporated and then transferred to an oven held at 80° C and allowed to remain overnight. After cooling, the residue was lightly ground to destroy caking and passed through a 200-mesh sieve.

The specific gravity of the organic matter plus pyrite was found to be 1.064 at 4° C. A 0.5480-gram sample was used and placed in a fused-silica Adams-Johnston pycnometer of 25-ml capacity. The sample was covered with boiled and cooled distilled water to which a drop of aerosol wetting agent had been added. The pycnometer and contents were then placed under a bell jar and the pressure reduced to about 3 cm of mercury and held there for about 2 hours. During this time the pycnometer was repeatedly agitated to cause air bubbles trapped by the fine-grained organic material to rise to the surface of the water. The pycnometer was then removed from the bell jar to a water bath held at 33° C and allowed to remain there until the temperature of the pycnometer and contents reached the temperature of the bath. This required about 45 minutes. The pycnometer was then filled with boiled distilled water that had been brought to the temperature of the bath, and the cap of the pycnometer was immediately put on. After the pycnometer was dried with a soft towel and allowed to remain on the balance pan for 45 minutes, its weight, plus the weight of the sample and water contained therein, was obtained. Likewise, without the vacuum treatment, the figure for pycnometer plus water was obtained. From these figures and the weight of the sample the specific gravity at 33°C was obtained and computed to 4° C by applying the proper factor.

The pyrite content of the organic material was found by determining the iron and computing to FeS_2. This gave the figure 6.28 percent pyrite. On another sample sulfur was determined that when computed gave the figure 6.70 percent pyrite. The figure 6.28 percent was arbitrarily selected on the reasoning that the organic matter may have contained the sulfur equivalent of the difference between 6.70 and 6.28 percent pyrite. An X-ray powder pattern confirmed the presence of pyrite.

The specific gravity of the pyrite in the organic matter was assumed to be 5.000. Using this figure, the percent of pyrite present, and the determined specific gravity of the organic matter plus the pyrite, the specific gravity of the organic matter was computed, as follows:

$$\frac{6.28}{5.000}+\frac{100.00-6.28}{x}=\frac{100}{1.064};$$

$x = 1.01$, which is the specific gravity of the organic matter at 4° C.

The index of refraction of the organic matter is 1.60. A 0.2500-gram sample was treated for about an hour with $CS_2 + Br + HNO_3$, after which it was filtered, washed, and dried overnight on the steam bath, and allowed to remain for 4 hours in an oven at 80° C. The sample was then cooled in a desiccator and was found to weigh 0.3410 grams, an increase of 36 percent over the original 0.2500 gram weight. The index of refraction dropped 0.01 to 1.59. The increase in weight was undoubtedly due to oxidation and possibly bromination of organic compounds that make up the heterogeneous mixture of saturated and unsaturated hydrocarbons.

Nitrogen was determined by the Kjeldahl method on a ½-gram sample of the organic matter, and found to be 2.04 percent. After correcting for the 6.28 percent pyrite, the pure organic matter was found to contain 2.18 percent nitrogen.

SALINE MINERALS

DISTRIBUTION

The term "saline mineral" as used in this report, refers to those minerals having sodium occupying one or all of their cation positions, and the carbonate radical supplying all or part of the negative charge. Saline minerals found in more than trace quantities in the Green River rocks are shortite ($Na_2CO_3 \cdot 2CaCO_3$), pirssonite ($Na_2CO_3 \cdot CaCO_3 \cdot 2H_2O$), gaylussite ($Na_2CO_3 \cdot CaCO_3 \cdot 5H_2O$), trona ($Na_2CO_3 \cdot NaHCO_3 \cdot 2H_2O$), nahcolite ($NaHCO_3$), northupite ($Na_2CO_3 \cdot MgCO_3 \cdot NaCl$), and bradleyite ($Na_3PO_4 \cdot MgCO_3$). Traces of tychite ($2Na_2CO_3 \cdot 2MgCO_3 \cdot Na_2SO_4$) and thermonatrite ($Na_2CO_3 \cdot H_2O$) also have been found.

During the long period of time required for the deposition of the sediments that are now the Green River formation, there were great variations in the conditions that brought about precipitation of the saline minerals. Changes in the composition and concentration of the lake waters caused by successive periods of rainfall and drought, varying amounts of carbon dioxide made available by decaying organic matter on and above the lake bottom, variations in the tempera-

ture of the brine at the bottom of the lake—all of these, singly and collectively, determined which of the saline minerals was precipitated at any given horizon. In the PCO_2-T diagram (fig. 6) of the system $NaHCO_3$-Na_2CO_3-H_2O, it is seen that at a given partial pressure of CO_2, trona precipitates at a higher temperature than does nahcolite. A rise in temperature of less than 1°C could cause the precipitation of trona instead of nahcolite. If temperatures were the only factor, this would indicate
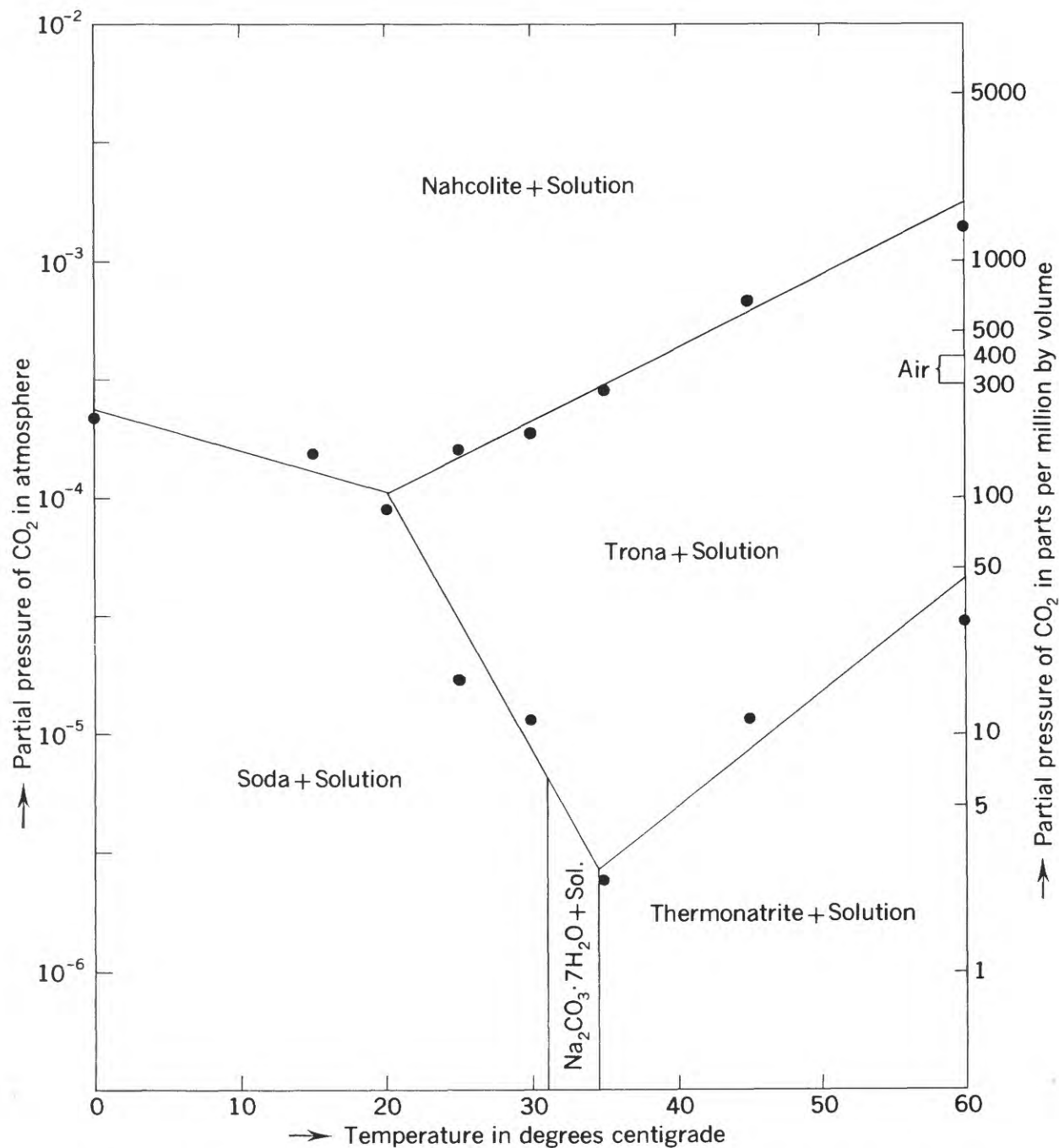
FIGURE 6.—PCO_2-T diagram of the system Na_2CO_3-$NaHCO_3$-H_2O. (From Carnegie Institute of Washington Yearbook 1957, p. 182.)
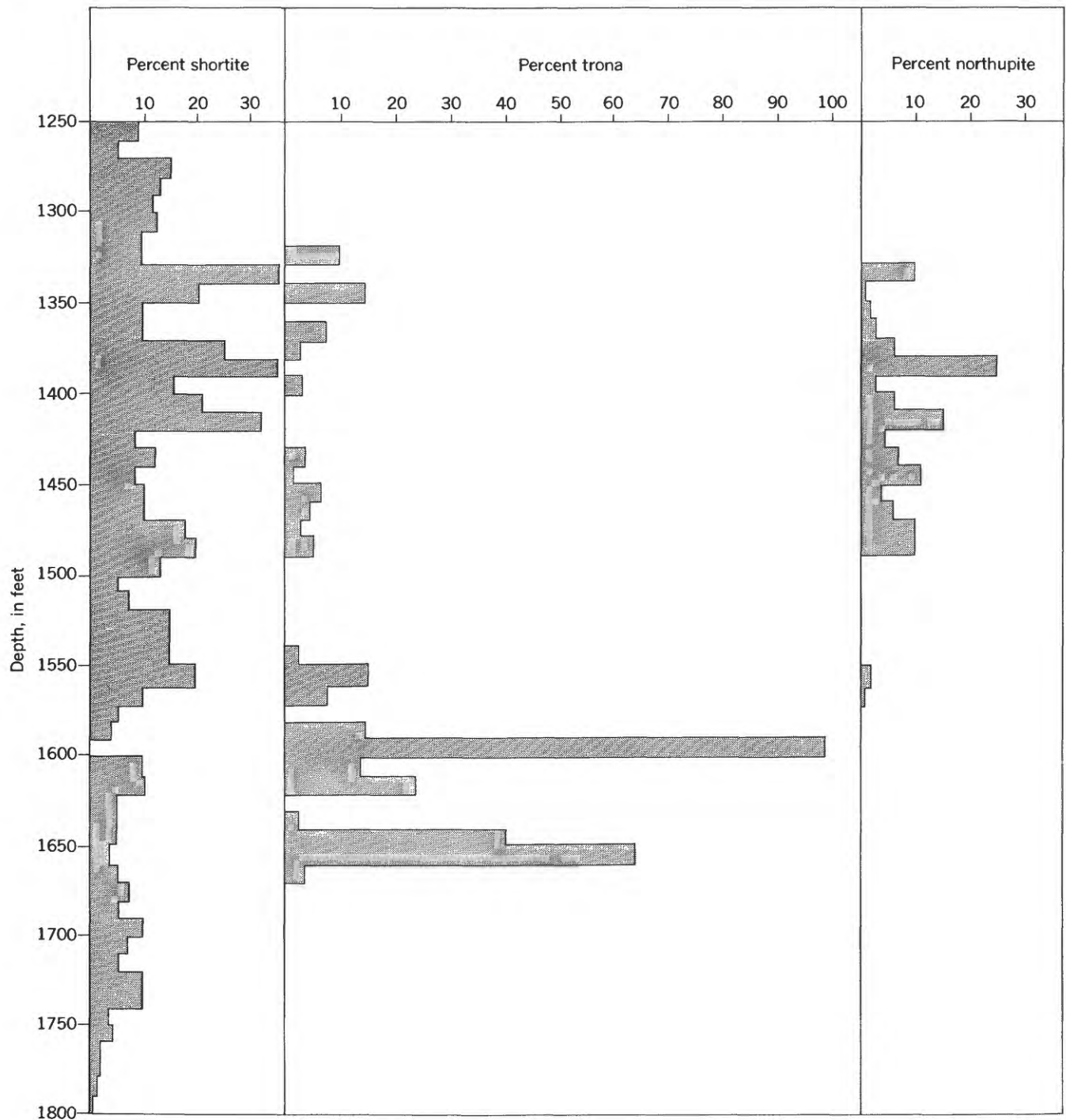
FIGURE 7.—Histogram showing the percentages of shortite, trona, and northupite in the drill core of the John Hay, Jr., well 1, Sweetwater County, Wyo.

that a warmer climate prevailed north of the Uinta Mountains—when the sediments were laid down in Gosiute Lake in what is now the Wyoming area where trona is found in great abundance—than to the south of these mountains in the Uinta Basin of Utah, and in the Piceance Creek basin of Colorado, where nahcolite (Ertl, 1947) is common and trona has rarely been found and then only in a few tiny isolated crystals. However,

other factors such as the partial pressure of CO_2, the depth of the lake, the thickness and translucence of the relatively fresh stratum of water above the brine, which in limnological parlance is called the epilimnion, probably played a greater part than the climate in the precipitation of trona and nahcolite.

It is in the sediments to the north of the Uinta Mountains, in the Wyoming area, that the greatest

concentration of saline minerals is found. These are recorded in the log of the John Hay, Jr., well 1, and the quantitative distribution of the three most abundant of these minerals, shortite, trona, and northupite, is graphically shown in the histogram (fig. 7).

As recorded in this log, shortite is ubiquitous between the depths 1,251 feet and 1,806 feet 6 inches, a vertical distance of 555 feet 6 inches. This is in sharp contrast to the saline-mineral content of the sediments of the Piceance Creek basin in Colorado, where the presence of shortite has never been reported, and the only saline mineral found is nahcolite (Ertl, 1947).

In the Uinta Basin, shortite (Erickson, 1952) and nahcolite are the only saline minerals that have been reported in greater than trace quantities. The shortite occurs abundantly as individual crystals in the shale, and nahcolite is likewise liberally distributed throughout these sediments. Massive nahcolite has not been reported in the Uinta Basin, but at the site of the oil-shale mine near Rifle, Colo., in the Piceance Creek

basin, lenses of this mineral as much as 10 feet in diameter are not uncommon.

Pirssonite and gaylussite are found between depths of 1,261 and 1,390 feet, and constitute about 1¼ and ½ percent, respectively, of this 129-foot thickness of sediments. Each of these minerals occurs as anhedral crystals that are seen, in thin section, replacing shortite, and frequently in turn being replaced by northupite (fig. 8).

Bradleyite (Fahey and Tunnell, 1941) was found in a 1-inch stratum at a depth of 1,342 feet 10 inches in the core of the John Hay, Jr., well 1, in intimate association with shortite and clay. A thin section (fig. 9) shows crystals of shortite in the process of replacement by bradleyite. During the sinking of the No. 1 shaft of the Westvaco mine, about 4 miles north of the John Hay, Jr., well 1, bradleyite (fig. 10) was found in low-grade oil shale from a depth of 1,245 feet. Authigenic subhedral crystals of bradleyite (fig. 11) have been found in minute quantities in the residue obtained when

Northupite
$Na_2CO_3 \cdot MgCO_3 \cdot H_2O$

Pirssonite — northupite
$Na_2CO_3 \cdot CaCO_3 \cdot 2H_2O$

Shortite
$Na_2CO_3 \cdot 2CaCO_3$

Gaylussite — northupite
$Na_2CO_3 \cdot CaCO_3 \cdot 5H_2O$

Trona — northupite
$Na_2CO_3 \cdot NaHCO_3 \cdot 2H_2O$

Bradleyite
$Na_3PO_4 \cdot MgCO_3$
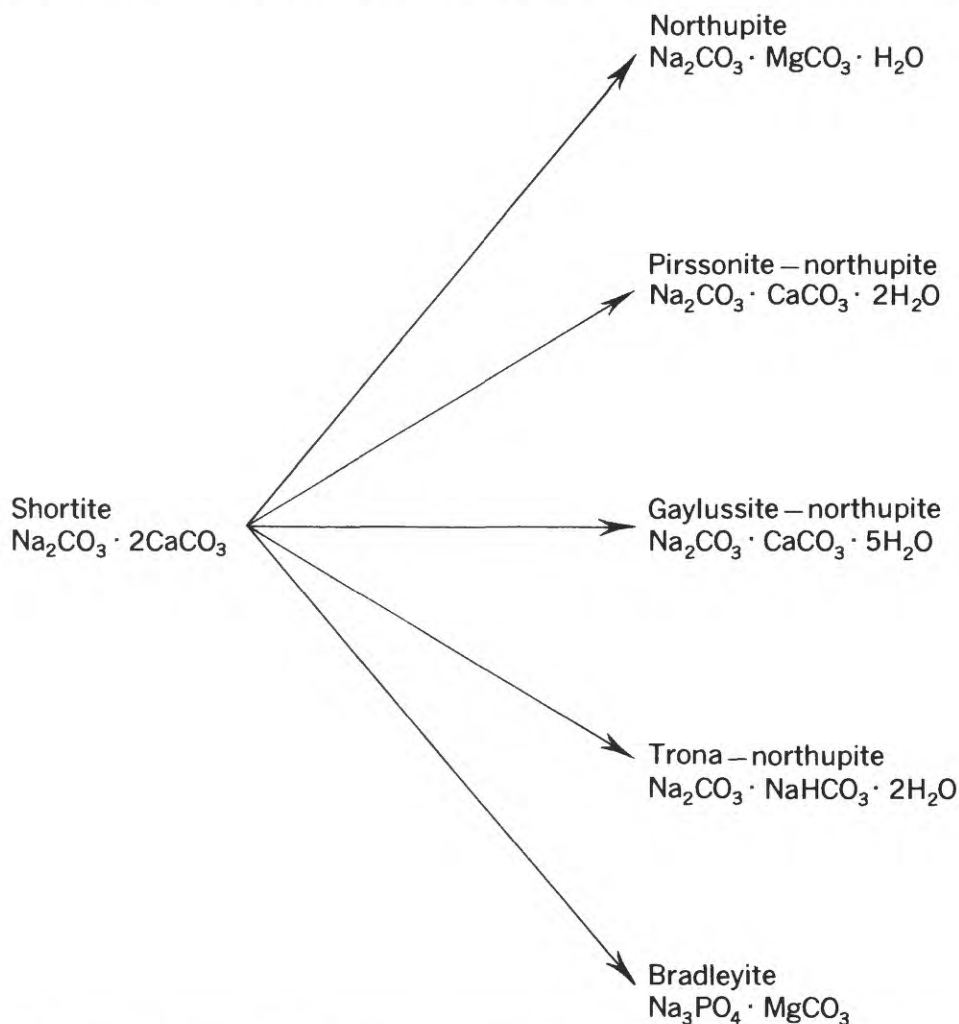
FIGURE 8.—Diagrammatic representation of the paragenetic sequence of six saline minerals of the Green River formation in Wyoming.

FIGURE 9.—Photomicrograph of thin section from drill core of the John Hay, Jr., well 1, depth 1,342 ft. 10 in., showing the sequence shortite to bradleyite. Plane-polarized light. ×15.

trona from the Westvaco mine was dissolved in water (Mrose, Fahey, and Chao, in preparation).

Three small grains of tychite ($2Na_2CO_3 \cdot 2MgCO_3 \cdot Na_2SO_4$), the sulfate analogue of northupite, were found at a depth of 1,390 feet 8 inches in the core of the John Hay, Jr., well 1. A very small amount of thermonatrite ($Na_2CO_3 \cdot H_2O$) was identified at a depth of 1,441 feet 9 inches. Identification of these two minerals was made by their indices of refraction.

SHORTITE

NAME OF MINERAL

The mineral shortite (Fahey, 1939), which has the formula ($Na_2CO_3 \cdot 2CaCO_3$), was found in the drill core of the John Hay, Jr., well 1 in 1939 and was named in honor of Dr. Maxwell N. Short, a geologist who had been a member of the U.S. Geological Survey until he joined the faculty of the University of Arizona. His name was given to this new carbonate in recognition of his excellence as a teacher of mineralogy and for his untiring efforts to stimulate in the chemists, who were his associates while he was a geologist of the U.S. Geological Survey, an interest not only in minerals but also in the optical and physical methods used in their identification.

OCCURRENCES

The Wilkins Peak member of the Green River formation in southwestern Wyoming, formerly called the

FIGURE 10.—Photograph of bradleyite (light-colored area at top center) on low-grade oil shale. From a depth of 1,245 ft, shaft 1, Westvaco mine.

Laney shale member (Bradley, 1959), contains the zone in which the saline minerals occur. In the core of the John Hay, Jr., well 1 that pierces these sediments, the upper limit of this saline zone at the depth 1,251 feet and the lower limit at 1,806 feet 6 inches, is marked by the mineral shortite. Between these depths shortite is omnipresent and constitutes a visually estimated 10 percent of this vertical column of sedimentary rock (fig. 7). A simple calculation leads to the astounding figure of approximately 125 million tons of shortite under each square mile of this area. Shortite occurs as individual undeformed crystals in the dolomitic sediments and presents a unique pattern of saline deposition.

The only other known location of shortite is also in the Green River formation but, in the Uinta Basin in northeastern Utah, it is found abundantly in association with nahcolite (Erickson, 1952).
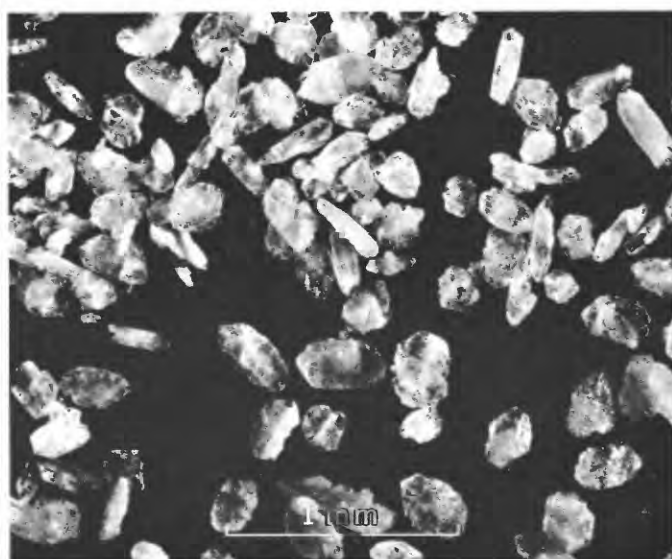
FIGURE 11.—Authigenic crystals of bradleyite from the trona bed of the Westvaco mine.

CRYSTALLOGRAPHY

Shortite occurs as orthorhombic hemimorphic crystals that range in size from about 2 mm to as much as 3 cm in the longest direction of the crystal, which is usually parallel to the *b* axis. Less frequently the small crystals will have their longest direction parallel to the *a* axis. These crystals, referred to in the original description (Fahey, 1939, p. 515) as nearly equant, are much less common than those having the tabular habit.

The crystals (figs. 12 and 13) are simple in habit, bounded by only five well-developed faces, the front and back pinacoids (100) and ($\bar{1}$00), two domes (011) and (0$\bar{1}$1), and the base (00$\bar{1}$). There is a distinct cleavage parallel to the brachypinacoid (010) that does not occur as a crystal form.

Each of the crystal faces other than the base forms a smooth uninterrupted plane. No crystal has been observed that shows terraced growth lines on these faces such as one sees on crystals of quartz. This could be interpreted as indicating that during the growing period of the crystal there were no environmental changes of sufficient magnitude to halt the growth of the crystal temporarily. However, it is most unlikely that such an interpretation would be correct, because shortite is found throughout the saline zone that has a vertical thickness of 555 feet and which was deposited through a period of approximately 1 million years. It is evident then that environmental changes, even though they may have temporarily halted the growth of an individual crystal of shortite, did not produce terraced growth lines on the crystal faces.

OPTICAL AND PHYSICAL PROPERTIES

Shortite varies from colorless to a pale yellow. The yellow color is due to minute traces of organic matter that cause a light amber fluorescence in ultraviolet light of wavelength 2,537A.
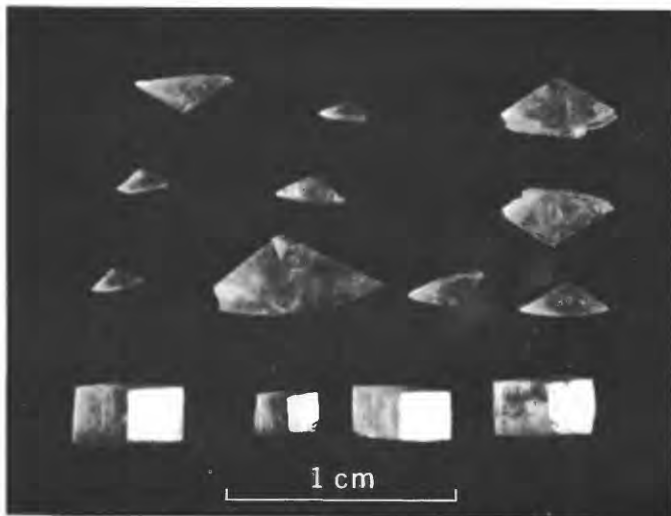
FIGURE 12.—Crystals of shortite, small and medium sizes.
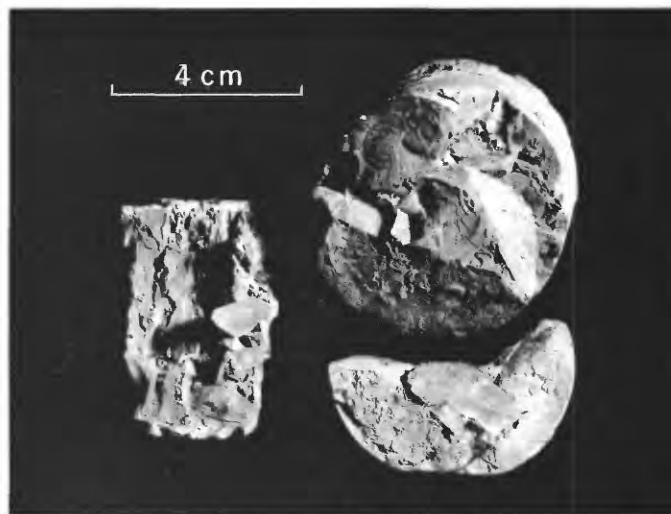
FIGURE 13.—Large crystals of shortite in place, in sections of core from the John Hay, Jr., well 1.

The indices of refraction are:

$$\left. \begin{array}{l} \alpha \text{----------------------}1.531 \\ \beta \text{----------------------}1.555 \\ \gamma \text{----------------------}1.570 \end{array} \right\} \pm 0.002$$

$2V = 75°$, optically negative (calculated).
The dispersion is $r < v$ (slight).
The optical orientation is:

X, α (acute bisectrix) $= c$
Y, β $= a$
Z, γ (obtuse bisectrix) $= b$

Optical and physical properties of the seven saline minerals are listed in table 8.

Shortite is strongly pyroelectric, has a vitreous luster and a conchoidal fracture. Rarely will a blow cause the crystal to break along the cleavage parallel to the brachypinacoid (010). The hardness is reported as 3 in the original description of the mineral (Fahey, 1939, p. 516). A redetermination of the hardness indicates that it is nearer to 3½ and it is so recorded. The specific gravity was determined as 2.629 by the pycnometer method, using water as the liquid medium. At 25° C, water attacks shortite so slowly that no measurable error was introduced by differential solution.

CHEMICAL PROPERTIES

The chemical analysis of shortite is given in table 9. Shortite is soluble in cold dilute acids with effervescence, and is differentially decomposed by water, the sodium carbonate going into solution and the calcium carbonate remaining in the solid phase as calcite and forming a pseudomorph of the original crystal.

When a crystal of shortite is heated in a test tube to about 200°C, inversion takes place accompanied by violent decrepitation. By means of an X-ray powder pattern taken of this residual material, calcite was identified as one of the phases. It was not established

TABLE 8.—*Optical and physical properties of the saline minerals*

[Determined by Joseph J. Fahey]

	Shortite (orthorhombic)	Pirssonite (orthorhombic)	Gaylussite (monoclinic)	Trona (monoclinic)	Nahcolite (monoclinic)	Bradleyite (monoclinic)	Northupite (isometric)
α	1.531	1.504	1.445	1.417	1.375	1.487	$n=1.513$
β	1.555	1.509	1.514	1.494	1.498	1.546	
γ	1.570	1.573	1.524	1.543	1.583	1.560	
Birefringence	0.039	0.069	0.079	0.126	0.208	0.073	
2V (calc.)	75°	27°	40°	74°	74°	50°	
Optic sign	Negative	Positive	Negative	Negative	Negative	Negative	
Dispersion	$r<v$	$r<v$	$r<v$	$r<v$	$r<v$	$r<v$	
Specific gravity	2.629	2.382	2.037	2.147	2.238	[1] 2.720	2.407
Hardness	3½	3–3½	2½–3	2½–3	2½	3½	3½–4
Luster	Vitreous	Vitreous	Vitreous	Vitreous	Vitreous	Vitreous	Vitreous
Fracture	Conchoidal	Conchoidal	Conchoidal	Uneven to subconchoidal	Conchoidal	Conchoidal	Conchoidal

[1] Determined on Berman balance by Mary E. Mrose.

whether the other material present was one or more of the many polymorphs of sodium carbonate, or a phase containing both sodium and calcium carbonate.

SPECTROGRAPHIC ANALYSIS

The spectrographic analysis (table 10) was made on a powdered sample of shortite, using d-c arc excitation in which a steady current of 16 amperes was maintained between the graphite electrodes. The spectra in the region, 2,350A to 4,750A were recorded on spectroscopic plates, using a grating spectrograph having a reciprocal linear dispersion of 5A per millimeter. The spectral lines of shortite and the synthetic standards were evaluated by means of a nonrecording densitometer.

The elements looked for but not found are recorded in table 10 where it is seen that the copper content of shortite and that of the five other saline minerals is very nearly the same. Shortite contains the same percentage of tin, manganese, chromium, beryllium, and barium as the other saline minerals, with the following exceptions: Gaylussite contains more tin, chromium, and barium; the percentage of manganese in northupite is greater by two orders of magnitude; and trona has a higher content of beryllium. The 0.10 percent strontium in shortite is higher than the strontium percentage of any of the other saline minerals.

TABLE 9.—*Chemical analyses, in percent, of shortite, pirssonite, gaylussite, and northupite from the John Hay, Jr., well 1, Sweetwater County, Wyo.*

[Joseph J. Fahey, analyst]

	Shortite	Pirssonite	Gaylussite	Northupite
Na$_2$O	19.91	25.45	20.80	36.59
CaO	36.34	22.75	19.20	.04
MgO	.04	.18	.00	15.98
CO$_2$	42.90	35.38	29.39	35.72
Cl				14.01
H$_2$O		14.70	29.97	.04
Insoluble (HCl)	.66	1.40	.50	.68
Total	99.85	99.86	99.86	103.06
Oxygen correction				3.16
Total	99.85	99.86	99.86	99.90
Depth_____ft	1,649	1,391	1,261	1,452

INDUSTRIAL USE

The composition of shortite is such that it could be used as a replacement for all or part of the limestone and soda ash that are necessary constituents in the manufacture of the more common types of commercial glass. However, although it is the most abundant saline mineral in the Wilkins Peak member of the Green River formation, the cost of recovery for industrial use probably would be prohibitive. Even though this were not so, the presence of inclusions of pyrite would raise the iron content beyond the range allowable in the manufacture of any but the cheaper grades of colored glasses.

Shortite could by utilized as a source of sodium carbonate by leaching with hot water. This, too, would require concentration and be much more costly than would the extraction of sodium carbonate from thick beds of trona. It must be concluded, then, that it is unlikely shortite will be of economic value.

GENESIS

COMPOSITION OF SEDIMENTS

The sediments that make up the Wilkins Peak member of the Green River formation in southwestern

TABLE 10.—*Spectrographic analyses (in percent) of saline minerals from the Green River formation from the John Hay, Jr., well 1, Sweetwater County, Wyo.*

[Harry Bastron, analyst]

	Shortite	Trona	Nahcolite [1]	Pirssonite	Gaylussite	Northupite
Cu	0.0005	0.0005	0.0003	0.0005	0.0006	0.0004
Sn	<.002	<.002	<.002	<.002	.004	<.002
Mn	<.0002	<.0002	<.0002	<.0002	<.0002	.048
Fe	.008	.003	.002	.023	.050	.17
Cr	<.0004	<.0004	<.0004	<.0004	.0006	<.0004
Al	.013	<.001	.001	.052	.14	.012
Ti	.001	<.001	.001	.004	.004	<.001
Be	<.0002	.0012	<.0002	<.0002	<.0002	<.0002
Mg	.022	<.001	.001	.080	.20	Major
Ca	Major	<.0002	<.0002	Major	Major	.052
Sr	.10	<.0002	<.0002	.068	.022	.0009
Ba	<.0002	<.0002	<.0002	.0080	.0004	<.0002

[1] From the Bureau of Mines' oil-shale mine near Rifle, Colo.

NOTE.—Looked for but not found: Ag, Au, Hg, Ru, Rh, Pd, Ir, Pt, Mo, W, Re, Ge, Pb, As, Sb, Bi, Te, Zn, Cd, Tl, In, Co, Ni, V, Ga, Sc, Y, Yb, La, Zr, Th, Nb, Ta, U, Li, P, B.

The above results have an overall accuracy of ±15 percent except near limits of detection where only one digit is reported.

Wyoming differ vertically in their content of organic matter, dolomite, and detrital minerals. The content of organic material in these rocks ranges from less than 1 percent to approximately 30 percent. Dolomite, computed from the 14 analyses in table 3, ranges from 22 to 68 percent. Throughout the vertical column there are undoubtedly strata having less than 22 percent dolomite, and it is probable that 68 percent is not the highest percentage of dolomite in these sediments. The content of detrital minerals, chiefly quartz, feldspar, and montmorillonite, ranges from a lower limit of approximately 20 percent, but in some samples may be as high as 50 percent. This great variation in the composition of samples taken at many depths between the top and the bottom of the saline zone reflects the equally variable composition of the bottom muds that, when compacted, became the sediments as they are today. It was in these muds that shortite precipitated and grew as individual crystals, probably after partial compaction due to the gradual addition of the overlying sediments. At this stage much of the brine had been squeezed out, and in the beds that contained a relatively high amount of organic matter a condition of sticky plasticity was attained.

COMPACTION OF SEDIMENTS

As several thousand feet of overburden was added to the partly compressed semiplastic bottom mud in which shortite had participitated, and as the individual crystals completed their growth, all the brine was squeezed out and the sediment tightly pressed around the crystals of shortite. The overburden was made up of the Laney shale member of the Green River formation, formerly called the Morrow Creek member of the Green River formation (Bradley, 1959), and the fluviatile sediments of the Bridger formation.

FLOW LINES

Many thin sections were cut normal to the bedding in order to study the effect of the compaction of the sediments around the crystals of shortite. The following conditions were observed:

1. Flow lines bending around crystals of shortite in sediments that were moderate to high in content of organic matter. In these specimens there are less than average amounts of dolomite, and enough montmorillonite and flat-lying flakes of mica to lend tensile strength to the bedding laminae, which flow around the crystal instead of being broken or cut by it. A good example of such flow is seen in a thin section (fig. 14) cut from a specimen obtained by W. H. Bradley from an outcrop in the canyon of the Green River, close to the tunnel of the old oil-shale mine about half
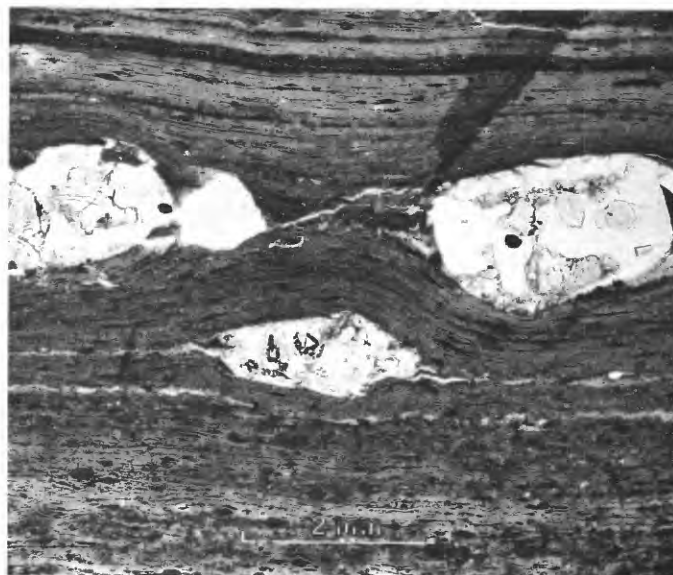
FIGURE 14.—Photomicrograph taken with plane-polarized light showing flow lines around pseudomorphs after shortite. Specimen collected by W. H. Bradley from the canyon of the Green River, about half a mile upstream from Green River, Wyo.

a mile west of the city of Green River. The photomicrograph, taken in plane-polarized light, shows the bending of the bedding around pseudomorphs of crystals of shortite. The sodium carbonate of the original shortite has been leached by rain water, and the residual calcite now forms a pseudomorph in each of the crystal cavities. The photomicrograph has a magnification of 15 diameters and shows very little tearing of the bedding that was pressed around the crystals of shortite during the compaction of the sediments.

2. Absence of flow lines in sediments that are low in content of organic matter. An example of this condition is seen in a photomicrograph (fig. 15) of another thin section from Bradley's specimen. The upper half of the pseudomorph is embedded in sediment low in organic matter and relatively high in dolomite. No flow lines are evident. This is in sharp contrast to the appearance of the lower half of the crystal that is embedded in sediment such as described above in condition 1 where the content of organic matter is moderate to high and flow lines are readily discernible.

3. Absence of flow lines in sediments with a moderate to high content of organic matter. These samples have a smaller percentage of montmorillonite and clay than those that show flow lines as described under condition 1, and hence the laminae, lacking the tensil strength afforded by flat-lying minerals, are cut by the crystals of shortite upon compaction of the sediments. This condition is shown in a photograph of a polished section from
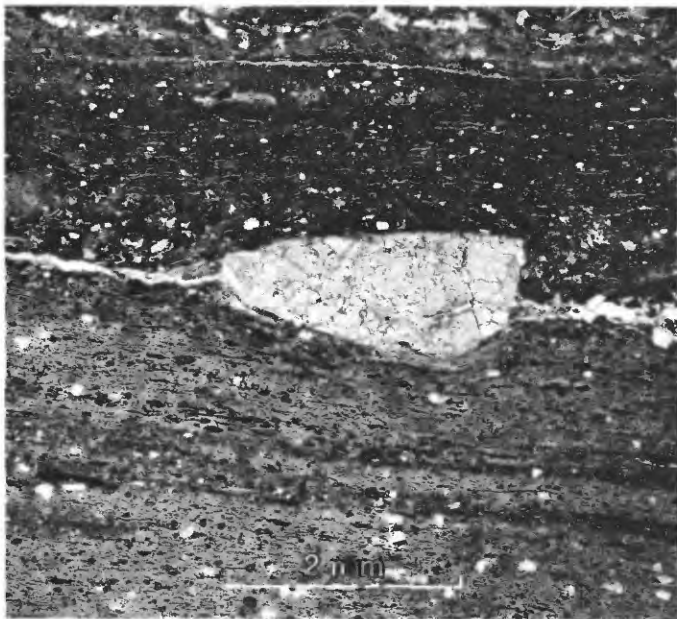
FIGURE 15.—Photomicrograph showing flow lines around pseudomorphs after shortite.

the core of the John Hay, Jr., well 1 (fig. 16), and in the photomicrograph (fig. 17) of a thin section cut from the core of the Westvaco well 3 at a depth of 1,464 feet 2 inches. In the polished section the randomly oriented crystals of shortite are seen cutting the bedding. The photomicrograph of the Westvaco core shows poorly defined bedding and only faintly visible flow lines, both around and cut by the crystals of shortite. The magnification is 15 diameters and was made in plane-polarized light. These two pictures indicate that at the time of compaction the sediments

FIGURE 16.—Photograph of polished section of core from the John Hay, Jr., well 1, depth 1,695 ft to 1,695 ft 3 in, showing randomly oriented crystals of shortite cutting across the poorly defined bedding.
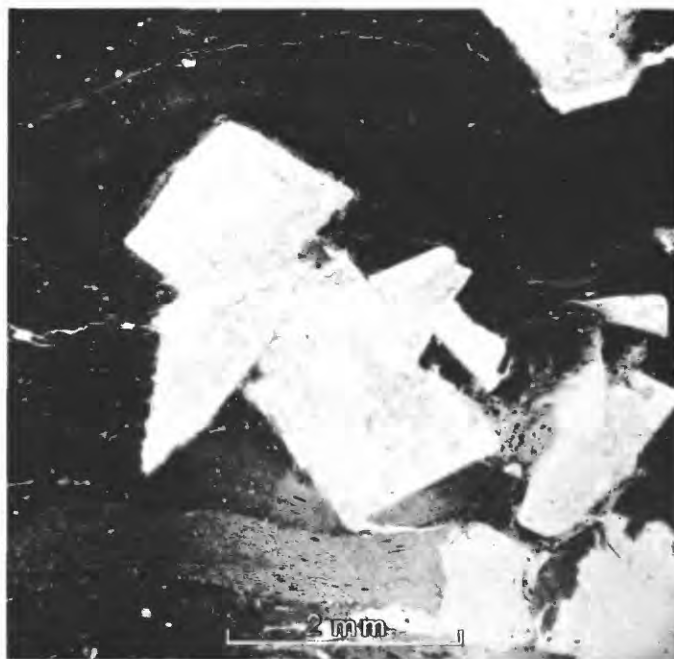
FIGURE 17.—Photomicrograph of thin section from the drill core of Westvaco well 3, depth 1,464 ft 2 in, showing crystals of shortite in matrix with no bedding. Plane-polarized light.

readily flowed, owing to the high percentage of organic matter, but no bedding was developed because of the relatively small amount of clay and mica present.

SIZE OF CRYSTALS

Crystals of shortite found in medium- to rich-oil shale rarely attain a size as great as 1 cm in the longest direction (fig. 12). This condition is also found in most of the lean shale, as observed in the core of the John Hay, Jr., well 1. In this core, however, at depth 1,700 to 1,725 feet, the crystals are much larger, some measuring 3 cm across (fig. 13). These crystals have a light-yellow color that is due to traces of organic matter. This is in contrast to the colorless condition of almost all the smaller crystals found in the medium-rich oil shale.

The large light-yellow crystals are very fragile. It is unusual to find one of these large crystals unbroken when the core is split longitudinally for visual examination. During this same treatment, small crystals fall out of the shale or with very little difficulty may be picked out intact.

CONSOLIDATED SHORTITE AGGREGATE

In the drill core of the John Hay, Jr., well 1, consolidated aggregates of shortite crystals have been found in only a few places. These occur as flat-lying beds not more than one inch thick. A thin section (fig. 18) cut from the core at a depth 1,382 feet 6 inches, shows
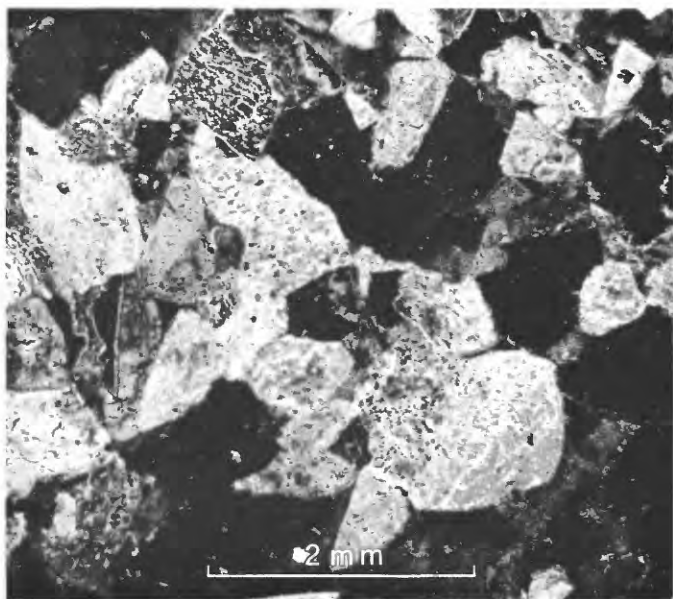
FIGURE 18.—Photomicrograph of thin section from the drill core of the John Hay, Jr., well 1, depth 1,382 ft 6 in, showing massive shortite. Crossed nicols. ×15.

small randomly oriented, subhedral and probably anhedral crystals of shortite. The magnification is 15 diameters. The picture was taken under crossed nicols. Dark areas are caused by crystals in the extinction position. There is little, if any interstitial filling by detrital material or dolomite.

The rare occurrence of these aggregates of crystals of shortite indicates that at the time of formation very unusual conditions obtained, causing crystals of shortite to be abraded by rolling and tumbling and finally concentrated to form thin monomineralic beds. It is unlikely that the rounded edges and dearth of crystal faces found in the crystals that make up these thin beds were due to differential solution during the periodic flushing of the lake that removed chlorine and potassium from the system. Had this been so, the crystals of shortite would be rimmed by calcite that would remain after the sodium carbonate had been removed by leaching. No calcite has been seen in the thin section.

There is no evidence of cementing material between the individual crystals that make up the shortite aggregates. However, fractures caused by a hammer blow cut across individual grains much as when quartzite is broken. It must be assumed then that surface welding of adjacent crystals, because of the pressure resulting from several thousand feet of overburden acting during a long interval of time, caused the consolidation of the rock.

In sharp contrast to the tightly packed small rounded crystals that characterize the shortite aggregates, a polished section (fig. 19) of the drill core of the John

Hay, Jr., well 1, at depth 1,710 feet 4 inches to 1,710 feet 6 inches, shows large sharp-edged crystals of shortite. These crystals make up at least 75 percent of the specimen and undoubtedly grew in place. The other 25 percent is composed of detrital material that contains a small amount of organic matter.

PYRITE INCLUSIONS

An estimated 10 percent of the many hundreds of crystals of shortite examined contain either single cubes of pyrite as much as 2 mm across, or twinned crystals of pyrite approximately the same size. Less commonly, crystals of shortite are seen with pyrite only partly embedded and protruding from one of the faces of a crystal of shortite. This would seem to indicate that the crystal of shortite grew around the older cube of pyrite rather than that the pyrite was later and had penetrated the crystal of shortite as rutile enters a crystal of quartz.

TEMPERATURE OF FORMATION

Ingerson (1947, p. 376) in his paper on liquid inclusions in geologic thermometry states:

The fundamental assumption has not changed since Sorby's time—that a liquid inclusion cavity was just filled with fluid at the temperature and pressure under which it was formed. These conditions, and the composition of the solution, determine the degree of filling of the cavity as it is observed at room temperature. If a crystal containing such inclusions is heated, the liquid will expand and fill the cavity at the temperature of formation if the original pressure did not exceed significantly the vapor pressure of the solution.

A close approximation of the temperature of formation of shortite was made by observing liquid inclusions in polished "thick" thin sections of crystals of shortite and applying the technique of Ingerson and other work-

FIGURE 19.—Photograph of polished section from the drill core of the John Hay, Jr., well 1, depth 1,710 ft 4 in to 1,710 ft 6 in, showing large crystals of shortite.

ers in that field. These "thick" thin sections were made by cementing the crystal to a glass slide and grinding to a thickness of about half a millimeter. The ground surface of the crystal was then polished. As it was necessary that the entire operation be done at room temperature, cement was used rather than canada balsam, because the balsam requires heating to about 90°C in making thin sections.

Many liquid inclusions were observed under the microscope in the "thick" thin sections. These inclusions ranged in size from about 0.07 mm to 0.005 mm in the longest direction. By actual count about 95 percent of the inclusions contained only the liquid phase. The remaining 5 percent contained both the liquid and the gas phase. It was observed that the volume occupied by the gas phase ranged from less than 5 percent to at least 50 percent of the volume of the cavity. Single inclusions containing the two phases were frequently found in clusters of cavities wherein only the liquid phase was present. It was therefore assumed that the inclusions containing the gas phase had acquired the gas by leakage. The temperature of crystallization of the shortite, as indicated by the cavities having only the liquid phase, was probably within 10°C of room temperature which was 27°C. This would mean that shortite crystallized at a temperature no higher than 40°C. However, if supercooling of the tiny liquid inclusions took place, the correct figure may be considerably higher than this.

TRONA

OCCURRENCES

The earliest known and most used by man of the saline minerals present in the Green River formation is trona ($Na_2CO_3 \cdot NaHCO_3 \cdot 2H_2O$). It is found in many saline lake deposits and efflorescences throughout the world, including the ancient deposits of natural sodium carbonates near Memphis, in the lower Nile River valley. Other African locations are Lake Mandara in the province of Tezzan, Tripoli; the Oasis of Bilma in the Sahara Desert; and the Otjiwalundo Salt Pan in South West Africa. In Asia it is found in Iran, Armenia, and the alkali deserts of Mongolia and Tibet. On the continent of Europe trona has been reported as efflorescences on lava on Mount Vesuvius, and in the Szegedin district, Hungary. In Venezuela it is associated with gaylussite in the mud of an alkali lake at Lagunillas, 48 miles southeast of the City of Merida.

Trona occurs in many alkali lakes in the western part of the United States. Deposits are located at Soda Lake, Butterfield Marsh, and Double Springs Marsh in Nevada. Searles Lake in San Bernardino County and Borax Lake in Lake County are the two best known locations in California.

The largest known deposit of trona in the world is in the Wilkins Peak member of the Green River formation in Sweetwater County, Wyo. Here a stratum that approximates 10 feet in thickness and is at a depth of about 1,600 feet at the site of the John Hay, Jr., well 1, has an area of many tens, and probably many hundreds, of square miles. Below this 10-foot bed of trona are beds 6, 4, and 2 feet thick, each having an areal extent at present unknown. Many strata as much as 1 foot thick lie both above and below this main trona bed, between depths of 1,300 and 1,665 feet. Trona comprises 6.4 percent (fig. 7) of the saline zone that is 555 feet thick at the site of the John Hay, Jr., well 1.

The temperature of formation of the trona is estimated to be between 20° and 40°C by the liquid-inclusion technique.

CRYSTALLOGRAPHY

Trona crystallizes in the monoclinic system and has a perfect cleavage parallel to the front pinacoid (100). The crystal habit ranges from finely crystalline aggregates, which make up the main trona bed, to large radiating crystals up to 4 cm in length which form rosettelike clusters in the shale at various places above the main trona bed. About a dozen strata, also at shallower depths than this bed and ranging in thickness from 2 to 13 inches, are composed of pearly-white trona, the whole mass of which has the same orientation throughout, as would a large fragment of a single crystal. The c axis is normal to the bedding of the shale. Figure 20 shows such a crystal fragment that was brought up from a depth of 1,370 feet during the excavation of the No. 1 shaft of the Westvaco mine. A large radiating crystal cluster (fig. 21) was obtained from a depth of 1,350 feet in the same shaft.

A specimen from the main trona bed (fig. 22) shows the tiny interlocking crystals that make up this 10-foot stratum and lend a quality of toughness that often prevents fracture after many lusty blows of a geologist's hammer. The photomicrograph was taken under crossed nicols and shows a large crystal of shortite (dark area) at the extinction position.

OPTICAL AND PHYSICAL PROPERTIES

Trona ranges in color from pearly white through yellow to brown. The pearly-white trona as much as 13 inches thick, is that found in the beds referred to above. The trona is fibrous and oriented as a single crystal with the c axis and the fibers normal to the bedding. The yellow and brown color of the main trona bed and the large radiating crystal clusters, is due to contamination by trace quantities of organic matter. Like the yellow shortite, the yellow and brown trona fluoresces in ultraviolet light of 2,537 A wavelength.

FIGURE 20.—Photograph of pearly-white trona from the Westvaco No. 1 shaft; depth 1,370 feet.

The indices of refraction are:

$$\left.\begin{array}{l}\alpha=1.417\\ \beta=1.494\\ \gamma=1.543\end{array}\right\}\pm0.002$$

$2V=74°$ negative (calculated).

Other optical properties are given in table 8.

The hardness of trona is between 2½ and 3; the fracture can best be described as uneven to subconchoidal, and the luster is vitreous. A piece of clear pearly-white trona had the specific gravity 2.147 at 25° C, determined by means of the Jolly balance and absolute alcohol for the liquid medium.

CHEMICAL PROPERTIES

Trona is soluble in water and when treated with acid vigorously give off CO_2. When heated, water is driven off, followed by CO_2, as the sodium bicarbonate is converted to sodium carbonate. This occurs at 270° C. The sodium carbonate melts at 850° C.

The chemical analysis given in table 11 was made on clear pearly-white trona, the same as that on which the specific gravity was made, and on which the indices of refraction were determined. The high order of purity of the sample is indicated by the small amount (0.02 percent) of insoluble material and by the spectrographic analysis given in table 10.
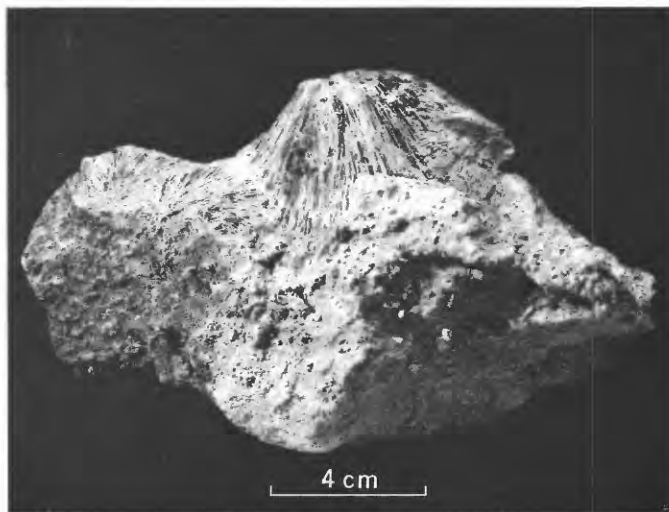
FIGURE 21.—Photograph of radiating crystals of trona from the Westvaco No. 1 shaft, depth 1,350 feet.

In the P_{CO_2}-T diagram (fig. 6) of the system Na_2CO_3—$NaHCO_3$—H_2O the phase boundary between trona and nahcolite is shown. Trona is stable only above 21.4°C, whereas nahcolite, at higher concentrations of CO_2, forms throughout the 0 to 60°C range of the diagram.

SPECTROGRAPHIC ANALYSIS

The spectrographic analysis was made on a powdered sample of trona in the way described for shortite.

The percentages of the elements present in minor quantities are Cu, 0.0005; Sn, <0.002; Mn, <0.0002; Fe, 0.003; Cr, <0.0004; Al, <0.001; Ti, <0.001; Be, 0.0012; Mg, <0.001; Ca, <0.0002; Sr, <0.0002; and
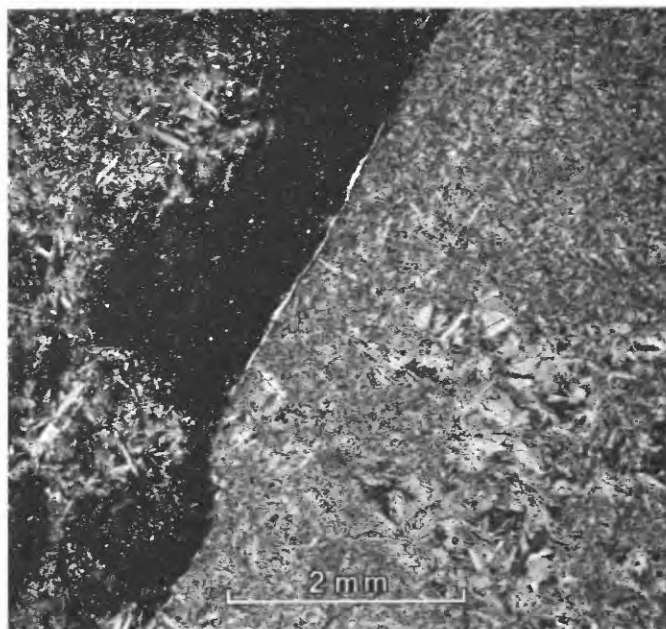
FIGURE 22.—Photomicrograph of thin section from the trona bed of the Westvaco mine showing tiny interlocking crystals. Crossed nicols. X15.

TABLE 11.—*Chemical analyses of trona and nahcolite*

[Joseph J. Fahey, analyst]

	Trona [1] (percent)	Nahcolite [2] (percent)
Na	30. 47	27. 33
CO_3	26. 66	
HCO_3	27. 11	72. 87
H_2O	16. 11	
Insoluble (H_2O)	. 02	. 00
Total	100. 37	100. 20

[1] From the John Hay, Jr., well 1, Sweetwater County, Wyo.
[2] From the Bureau of Mines oil-shale mine near Rifle, Colo.

Ba, <0.0002. The above results have an overall accuracy of ± 15 percent except near limits of detection where only one digit is reported. The elements looked for but not found in the spectrographic analysis of trona are listed in table 10. Trona and nahcolite, the two saline minerals that are completely water soluble, have almost the same spectrographic analysis except for beryllium. Trona was found to contain 0.0012 percent beryllium whereas nahcolite had less than 0.0002 percent beryllium reported.

INDUSTRIAL USE

Trona of the Green River formation in southwestern Wyoming affords an enormous source of sodium carbonate (soda ash). Soda ash is second only to sulfuric acid in tonnage used by industry in the United States, most of which is produced synthetically by the Solvay process from sodium chloride brines. The manufacture of glass and soap, the softening of water, and the production of metallic sodium and sodium chemicals are only a few of the many uses of sodium carbonate. (See table 12.)

NAHCOLITE

NAME OF MINERAL

Naturally occurring sodium bicarbonate was first described by F. A. Bannister, of the British Museum of Natural History, and was named nahcolite (Bannister, 1929) at the suggestion of his colleague L. J. Spencer, who said that the name, derived from the chemical formula of sodium bicarbonate, would serve as a memory aid in recalling the composition of the new mineral.

TABLE 12.—*The tonnage of soda ash used in 1957 by industries in the United States*

[From the Minerals Yearbook, v. 1, 1957, U.S. Bureau of Mines]

Industry	Tons	Industry	Tons
Glass	1, 590, 000	Pulp and paper	339, 000
Caustic and bicarbonate	696, 000	Metal processing	614, 000
Water treatment	120, 000	Exports and miscellaneous	672, 000
Other chemicals	1, 383, 000		
Soap	80, 000	Total	5, 654, 000
Other cleaners	160, 000		

Nahcolite was first found in an efflorescence from hot springs in an old Roman underground conduit at Stufe de Nerone about 9 miles west of Naples in the Phlegrean Fields. Because it occurred in such small crystals intimately mixed with thermonatrite, trona, and thenardite, no separation of the new mineral was made.

The presence of nahcolite was first indicated by a complete analysis of the crusts and proper allotment of the constituents to the three identified saline minerals. Three such analyses showed an excess of sodium bicarbonate of 20, 20, and 25 percent. An examination with the petrographic microscope readily identified the new mineral with artificially prepared sodium bicarbonate. Thus, though the new mineral was not separated and purified, its presence was established by chemical and optical means.

Nahcolite was found in 1937 in the same area in an incrustation in a lava grotto (Quercigh, 1937). There also the mineral was not isolated and thoroughly investigated. An earlier report of naturally occurring sodium bicarbonate (Walther, 1922) at Little Mogadi dry lake, 40 km south of Mogadi Lake in British East Africa, was presented but no confirmatory evidence was given.

Nahcolite was first isolated and studied by Dr. William F. Foshag, of the U.S. National Museum (Foshag, 1940). The material he used was part of a drill core from a stratum containing saline minerals in Searles Lake, San Bernardino County, Calif., between depths of 122 and 289 feet. The associated minerals were gaylussite, trona, thenardite, borax, northupite, and burkeite. Many of the beds of nahcolite consisted of loosely friable crystal aggregates or porous masses with crystal-lined vugs. He found that single crystals rarely were greater than 1 cm long.

In the Green River formation, nahcolite (Ertl, 1947) is present in the oil-shale mine of the Bureau of Mines at Anvil Points, 10 miles west of Rifle, Colo. It occurs in cleavable masses as concretions as much as 10 feet in diameter in the oil shale. A fragment from one of these concretions is seen in figure 23. Nahcolite is also found in layers as much as 4 inches thick intercalated between rich oil-shale beds. It was found in only one place in the John Hay, Jr., well 1, and there only as a trace quantity.

OPTICAL AND PHYSICAL PROPERTIES

Nahcolite has a vitreous luster and is colorless unless pigmented by extraneous material. The color of the mineral from the concretions in the oil-shale mine of the Bureau of Mines near Rifle, Colo., is usually reddish brown due to the presence of organic matter, but locally
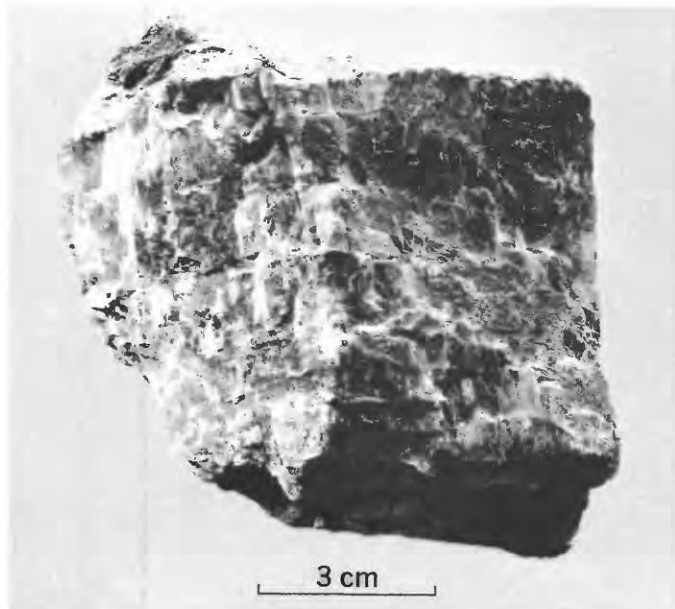
FIGURE 23.—Photograph of nahcolite from the oil-shale mine of the Bureau of Mines at Anvil Points, 10 miles west of Rifle, Colo.

the color ranges from colorless through white, yellow, brown to black. The mineral, when found in layers between oil-shale beds, is usually white and translucent and occurs as fibrous crystals with the c axis normal to the bedding.

The indices of refraction are:

$$\left.\begin{array}{l}\alpha=1.375\\\beta=1.498\\\gamma=1.583\end{array}\right\}\pm0.002$$

$2V=74°$ negative (calculated).

Optical properties are listed in table 8.

Nahcolite is harder than gypsum but is easily scratched by calcite; hence the hardness is estimated to be 2½. It has a conchoidal fracture and perfect (101) cleavage. A good (111) cleavage and distinct (100) cleavage are present. As with trona, the specific gravity (2.238 at 25°C) was determined by means of the Jolly balance using absolute alcohol as the liquid medium.

CHEMICAL PROPERTIES

Nahcolite is readily soluble in water. It is vigorously attacked by the common acids giving off CO_2. When it is heated to 270°C, water and CO_2 are driven off, and the more stable sodium carbonate is formed.

The analysis in table 11 was made on a sample prepared from the pure white translucent nahcolite found in layers between oil-shale beds in the oil-shale mine of the Bureau of Mines, 10 miles west of Rifle, Colo. The purity of the sample is indicated by the lack of a measurable quantity of insoluble material as shown in this analysis. The optical and physical constants were also determined on this sample.

The stability range of nahcolite shown in the P_{CO_2}-T diagram (fig. 6) is between 0° and 60°C. At a given CO_2 pressure on the phase boundary between nahcolite and trona, an increase in temperature would cause trona to precipitate, whereas a decrease in temperature would make nahcolite the stable phase.

SPECTROGRAPHIC ANALYSIS

The spectrographic analysis was made on a powdered sample of nahcolite, by the method used for shortite.

The percentages of the elements present in trace amounts are Cu, 0.0003; Sn, <0.002, Mn, <0.0002; Fe, 0.002; Cr, <0.0004; Al, <0.001; Ti, <0.001; Be, <0.0002; Mg, <0.001; Ca, <0.0002; Sr, <0.0002; and Ba, <0.0002. These results have an overall accuracy of ±15 percent except near the limits of detection where only one digit is reported. The elements looked for but not found are recorded in table 10. Here it is seen that in both nahcolite and trona the Mg and Ca percentage is <0.001 and <0.0002 respectively. In view of the fact that these two water-soluble minerals crystallized from a brine that was contemporaneously yielding dolomite, such small traces are noteworthy.

NORTHUPITE

OCCURRENCES

Searles Lake, San Bernardino County, Calif., that most bountiful source of both rare and common saline minerals, is the original locality of the mineral northupite ($Na_2CO_3 \cdot MgCO_3 \cdot NaCl$). It was described by Foote (1895) and named in honor of C. H. Northup of San Jose, Calif., who found the first specimens of this mineral in a boring known as the "New Well" in Searles Lake. According to Mr. Northup, the mineral was formed in a stratum of clay about 450 feet below the surface.

The second location of northupite is Borax Lake, Lake County, Calif., where it was found by Vonsen (1935) in association with pirssonite and gaylussite in massive trona.

The Wilkins Peak member of the Green River formation is the third recorded locality of northupite, and it is here the third most abundant saline mineral, only shortite and trona being present in greater quantities. At the location of the John Hay, Jr., well 1, northupite is present between the depths 1,327 and 1,560 feet, and comprises a visually estimated 5.2 percent of this 233-foot interval, or 2.2 percent of the 555-foot thick saline zone. Like pirssonite and gaylussite, it has not been found at depths below the main trona bed.

CRYSTALLOGRAPHY

Northupite crystallizes in the isometric system as octahedra. Euhedral crystals are rare in the Green

River formation. They vary in size up to about 4 mm across. A photograph of one of these crystals, magnified 8 times (fig. 24) shows the octahedron in low-grade shale. This specimen was found at a depth of 1,245 feet during the sinking of the first shaft of the Westvaco mine in 1947.

A photomicrograph (fig. 25) of a thin section of a cluster of small crystals of northupite, taken in plane-polarized light, shows in several of these crystals the symmetry of the octahedron, marked by collodial clay that was entrapped as the crystals grew. The thin section was cut from the core of the John Hay, Jr., well. 1, at a depth of 1,336 feet 6 inches.

OPTICAL AND PHYSICAL PROPERTIES

Northupite is usually colorless in ordinary light, but a pale yellow color due to traces of organic matter in the massive crystalline material is not uncommon. Such material fluoresces in ultraviolet light of 2,537 A wavelength. Crystal fragments are translucent and have a vitreous luster.

The index of refraction of northupite is : $n=1.513$. An anomalous birefringence has been noted in a few oil-immersion mounts, but this is unusual.

The fracture of northupite is conchoidal, and it has a hardness of $3\frac{1}{2}$ to 4. The specific gravity, 2.407, was determined on material passing an 80-mesh seive and retained on 100-mesh. A fused silica Adams-Johnston pycnometer was used.

CHEMICAL PROPERTIES

The chemical analysis of northupite is given in table 9. The analyzed sample was prepared by grinding

FIGURE 24.—Photograph of a euhedral crystal of northupite. ×8.

shale that contained northupite to pass a 10-mesh sieve, and then hand-picking the crystal fragments of northupite which, in turn, were ground to pass an 80-mesh sieve. The specific gravity, index of refraction, and the chemical analysis were all made on this sample, as was also the X-ray powder diffraction pattern.

Northupite is readily soluble in acids with effervescence of carbon dioxide. It is very slowly differentially decomposed by cold water and more rapidly by hot water. The sodium carbonate and the sodium chloride are dissolved, leaving the magnesium carbonate in the solid phase. When heated in the closed tube, northupite decrepitates violently and fuses to a very viscous liquid.

SPECTROGRAPHIC ANALYSIS

The spectrographic analysis was made on a powdered sample of northupite, by the method used for shortite.

The percentages of the elements present in trace amounts are Cu, 0.0004; Sn, <0.002; Mn, 0.048; Fe, 0.17; Cr, <0.0004; Al, 0.012; Ti, <0.001; Be, <0.0002; Ca, 0.052; Sr, 0.0009; and Ba, <0.0002. These results have an overall accuracy of ±15 percent except near the limits of detection where only one digit is reported. The elements looked for but not found are recorded in table 10, where also it is seen that the percentages of manganese and iron are higher in northupite than in any of the other five saline minerals listed. The calcium content of northupite is greater by a factor of more than 200 than that of the two water-soluble saline minerals trona and nahcolite.

GENESIS

Northupite occurs as euhedral crystals and globular masses. The crystals are rare, probably constituting less than 0.01 percent of all the northupite present, and are invariably in shale low in organic matter, and with a relatively high percentage of dolomite. The massive northupite is found in shale of medium to low content of organic material.

The euhedral crystals of northupite probably formed in the fluid mud at the bottom of the lake, and in that same mud after much of the brine had been squeezed out by the gradual addition of overburden that brought about a condition of sticky plasticity or semifluidity in the partially compressed sediment. That the crystals grew in this fluid mud is indicated by the entrapped colloidal clay (fig. 25) that marks the symmetry of the octahedron and also by the perfectly formed crystals, none of which shows any distortion that could have resulted from pressure applied to the growing crystal in a fixed nonfluid environment.

Massive northupite is found filling vugs and cracks in medium- to low-grade oil shale, and in thin section has been seen replacing shortite (fig. 31), pirssonite

FIGURE 25.—Photomicrograph of thin section from the drill core of the John Hay, Jr., well 1, depth 1,336 ft 6 in, showing the symmetry of crystals of northupite marked by collodial clay. Plane-polarized light. ×35.

FIGURE 27.—Photomicrograph of thin section from the drill core of the John Hay, Jr., well 1, depth 1,431 feet 8 inches. Tiny liquid inclusions in concentric rings give the appearance of oolitic structure. Plane-polarized light. ×20.

(fig. 32), gaylussite (fig. 34), and trona (fig. 37). In no instance has northupite been observed being replaced by any of the other saline minerals.

The drill core of the John Hay, Jr., well 1, at a depth of 1,431 feet 8 inches, contains many small round masses of northupite (fig. 26) that, when sectioned, show imperfect concentric circles, giving somewhat the appearance of oolitic structure. A photomicrograph (fig. 27) magnified to 20 diameters, and taken in plane-polarized light, shows that the concentric rings are made up of a great many tiny liquid inclusions. A "thick" thin section of a group of these pseudo-oolites was cut and cemented without heating. A microscope examination of this thin section showed many liquid inclusions with no gas phase, and others with a liquid and gas phase, the latter occupying as much as about 50 percent of the volume of the

cavity. A few cavities containing a solid phase in addition to the liquid and gas phase (fig. 28) were observed.

From the above it was concluded that the gas phase resulted from a leakage of the liquid from the cavity, and those cavities containing only the liquid phase gave evidence of the temperature of formation of the northupite. Hence this temperature was estimated to be within 10° C of the temperature of the room

FIGURE 26.—Photograph of a section of core from the John Hay. Jr., well 1, depth 1,431 ft. 8 in., showing round masses of northupite that have an oolitic structure.

FIGURE 28.—Photomicrograph of the thin section of figure 26 showing liquid inclusion containing a gas and solid phase. Plane-polarized light. ×800.

when the observations were made, or roundly between 20° C and 40° C. This is the temperature range, determined in the same manner, within which both shortite and trona were estimated to have formed.

In a thin section (fig. 29) cut from the drill core of the John Hay, Jr., well 1, at a depth of 1,454 feet, northupite is seen replacing the highly dolomitic shale. The magnification is 10 diameters and the photomicrograph was taken in plane-polarized light. The dark areas are the remnants of the shale in which traces of the bedding can be seen.

Northupite is the only chlorine-containing saline mineral that has been found in more than trace quantities in the drill core of the John Hay, Jr., well 1. Although it is the third most abundant saline mineral present in the Wilkins Peak shale, only shortite and trona being present in greater amounts, the quantity is much too small to have fixed all the chlorine that was brought into the lake by the streams. Periodic flushing of the lake was probably the means by which the greater part of the chlorine and also most of the potassium was removed.

BRADLEYITE

NAME OF MINERAL

The second new mineral that was found in the Green River formation was bradleyite (Fahey and Tunell, 1941), an anhydrous carbonate-phosphate of sodium and magnesium ($Na_3PO_4 \cdot MgCO_3$). It was named in honor of Wilmot H. Bradley, geologist of the U.S. Geological Survey, in recognition of his many contributions to our knowledge of the Green River formation.

OCCURRENCES

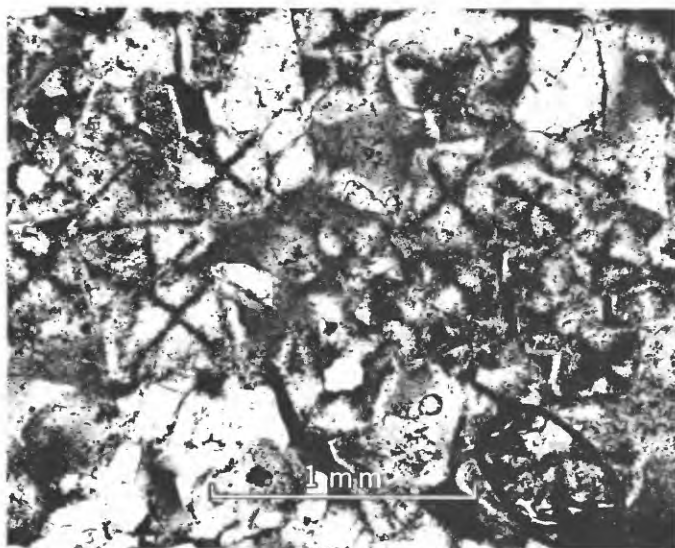Bradleyite was first found in the drill core of the John Hay, Jr., well 1 at a depth of 1,342 feet 10 inches
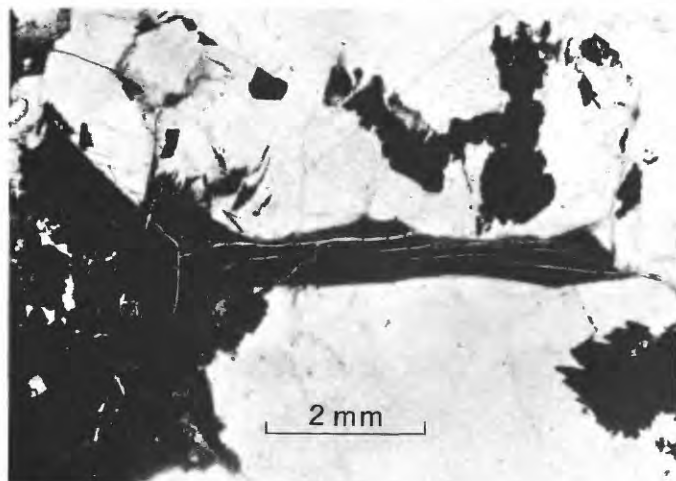
FIGURE 29.—Photomicrograph of thin section from the drill core of the John Hay, Jr., Well 1, depth 1,454 feet, showing northupite replacing the dolomitic shale. Plane-polarized light. ×10.

in a horizontal layer 1 inch thick. This layer contained about 60 percent bradleyite, 30 percent shortite, and 10 percent detrital material. A small percentage of organic matter was present, which yielded tiny droplets of oil when heated in the closed tube.

Immediately above the bradleyite the core consists mainly of shortite and northupite with a minor quantity of clay, while below is found brown clay containing much shortite and northupite. Both above and below the stratum containing the bradleyite, the northupite is later than the shortite.

In 1947, 6 years after the bradleyite was found in the drill core of the John Hay, Jr., well 1, bradleyite was found in shale at a depth of 1,245 feet during the sinking of the No. 1 shaft of the Westvaco trona mine. Bradleyite is seen in figure 10 at the top center of the specimen of shale as fine-grained light-colored material. It contains less shortite and clay than the bradleyite found in the John Hay, Jr., well 1, but the presence of several percent of finely divided chert was visually estimated in thin section.

Tiny crystals of bradleyite were found by Charles Milton, geologist of the U.S. Geological Survey, in the residue obtained when a quantity of several kilograms of trona from the Westvaco trona bed was leached. Laborious hand-picking by Milton produced about 90 mg of these crystals on which a chemical analysis was made and the optical, physical, and X-ray constants were determined (Mrose, unpublished data).

OPTICAL AND PHYSICAL PROPERTIES

The bradleyite from the core of the John Hay, Jr., well 1 (Fahey and Tunell, 1941, p. 647) was extremely fine-grained, most individual particles being less than 0.002 mm across. The α and γ indices of refraction were determined as 1.49 and 1.56 respectively. No determination of the β index was attempted.

The indices of refraction were measured on the bradleyite picked by Milton from the residue obtained upon leaching trona from the Westvaco mine and found to be

$$\left.\begin{array}{l} \alpha = 1.487 \\ \beta = 1.546 \\ \gamma = 1.560 \end{array}\right\} \pm 0.002$$

$2V = 50°$, optically negative (calculated)
$2V = 49°$, optically negative (measured)
Optic axial plane $\perp$ to (010)
$Y \wedge c = 7°$
$X = b$ axis = elongation
Habit: flattened crystal $\parallel$ to (001).

The optical orientation was determined on the universal stage by Edward C. T. Chao, of the U.S. Geological Survey. (See table 8 for optical properties.)

Bradleyite has a vitreous luster and a conchoidal fracture. The hardness is 3 1/2. The specific gravity 2.720 was the average of seven determinations made on the Berman balance by Mary Mrose, X-ray crystallographer, on tiny subhedral crystals picked by Milton from the trona residues. The value 2.720 agrees with that of 2.734 determined by an indirect method on the original material from the core of the John Hay, Jr., well 1. It also checks the figure 2.725 obtained by applying the Gladstone-Dale equation (Fahey and Tunell, 1941, p. 647).

CHEMICAL PROPERTIES

Cold water very slowly attacks bradleyite dissolving the sodium phosphate and leaving a residue of magnesium carbonate. Hot water produces the same effect but in a much shorter time. The common acids dissolve bradleyite, with evolution of carbon dioxide. In the closed tube bradleyite becomes opaque but does not melt.

A chemical analyses of two samples of bradleyite are listed in table 13. Sample A was from the drill core of the John Hay, Jr., well 1, and included 14.46 percent of clay that was recorded as insoluble in HCl. Sample B weighed 80.2 mg and was from the residue obtained by Milton upon leaching material from the trona bed of the Westvaco mine.

SPECTROGRAPHIC ANALYSIS

The spectrographic analysis was made on powdered bradleyite from sample B (table 13) by the method used for shortite.

The percentages of the elements found in trace amounts are Mn, 0.1; V, 0.01; Ti, 0.2; Ca, 0.4; Sr, 0.05; Ba, 0.7; Sc, 0.004; and Si, 0.5. The elements looked for but not found are Ag, Au, Hg, Pd, Pt, Mo, W, Re, Ge, Sn, Pb, As, Cu, Sb, Nb, Bi, Zn, Cd, Tl, Co, Ni, Cr, Ga, Y, Yb, La, Ce, Nd, Zr, Th, Ta, U, Be, and B.

A comparison of the spectrographic analysis of bradleyite with those of the six other saline minerals listed in table 10 shows that the elements copper, tin, chromium, and beryllium are among the elements that were looked for but not found in the bradleyite, but are present in trace quantities in the other six saline minerals. Bradleyite contains 0.7 percent barium whereas pirssonite and gaylussite contain 0.0080 and 0.0004 percent, respectively, and the other four saline minerals have less than 0.0002 percent of this element. The relatively high percentages of iron, aluminum, copper, and silica found in bradleyite are probably due to the presence of foreign material in the samples.

TABLE 13.—*Chemical analyses of bradleyite*

[Joseph J. Fahey, analyst]

	Sample A (percent)	Sample B (percent)
MgO	12. 91	14. 3
Na₂O	31. 62	[1] 35. 3
K₂O	. 00	[1] . 0
P₂O₅	22. 03	26. 1
CO₂	15. 80	15. 8
Insoluble in HCl	14. 46	1. 9
H₂O	. 30	. 5
Fe₂O₃	. 52	2. 6
Al₂O₃	. 24	1. 5
CaO	. 36	. 6
TiO₂	----------	. 2
MnO	----------	. 1
SiO₂	. 02	----------
SO₃	. 46	----------
Cl	. 35	----------
BaO	----------	[2] . 8
Total	99. 07	99. 7

[1] Alkalies determined by Laura E. Reichen.
[2] Determined spectroscopically by Harry Rose.

Sample A. From drill core of John Hay, Jr., well 1.
Sample B. Analysis made on 80.2 mg of individual crystals obtained from the trona bed of the Westvaco mine.

PIRSSONITE

NAME OF MINERAL

Pirssonite ($Na_2CO_3 \cdot CaCO_3 \cdot 2H_2O$) was described and named in 1896 by J. H. Pratt in honor of his friend and associate, Professor L. V. Pirsson of the Sheffield Scientific School at Yale University (Pratt, 1896).

OCCURRENCES

The new mineral was found very sparingly associated with northupite in material from a bore hole drilled into the sediments of Borax Lake, San Bernardino, Calif., which was discovered in 1863 by John W. Searles. The name Borax Lake was later changed to Searles Lake to avoid confusion with Borax Lake in Lake County, Calif. (Bailey and Aubury, 1902).

The second occurrence was in the Otjiwalundo Salt Pan, South West Africa (Foshag, 1933), where it was found associated with trona, thenardite, and sulphohalite.

M. Vonsen, an amateur mineral collector, in 1935 recorded the third locality of pirssonite (Vonsen,1935) He found it embedded in trona with gaylussite and northupite near the western shore of Borax Lake, Lake County, Calif.

The fourth location at which pirssonite has been reported is the Wilkins Peak member of the Green River formation in Sweetwater County Wyo. It occurs here with shortite and northupite.

Pirssonite was found between depths 1,310 and 1,391 feet in the drill core of the John Hay, Jr., well 1, about 18 miles west of the town of Green River, Wyo. It was visually estimated to make up 10 percent of the drill core between 1,310 and 1,320 and 5 percent of the core between 1,320 and 1,330 feet. In the core, between depths 1,340 and 1,350 feet, pirssonite is found in association with gaylussite and bradleyite in addition to shortite and northupite.

CRYSTALLOGRAPHY

Pirssonite crystallizes in the orthorhombic system. No crystal faces were observed on samples of pirssonite from the core of the John Hay, Jr., well 1. The mineral forms as masses in vugs and cracks in the shale. It is usually found replacing shortite and then being replaced by northupite, both replacements taking place within the area covered by a photomicrograph of the thin section (figs. 32 and 33).

OPTICAL AND PHYSICAL PROPERTIES

Most of the pirssonite found in the shales of the Green River formation is transparent. In ordinary light it ranges from colorless to a very pale yellow owing to traces of organic matter.

The indices of refraction are:

$$\left.\begin{array}{l}\alpha=1.504 \\ \beta=1.509 \\ \gamma=1.573\end{array}\right\} \pm 0.002$$

$2V=27°$ positive (calculated).

Optical properties are listed in table 8.

Pirssonite is brittle and has a vitreous luster and a conchoidal fracture. The hardness is 3 to $3\frac{1}{2}$. An Adams-Johnston fused silica pycnometer was used to determine the specific gravity on a sample that passed 80-mesh and was retained on a 100-mesh sieve. The value 2.382 for the specific gravity was obtained.

CHEMICAL PROPERTIES

Pirssonite is differentially soluble in water, leaving calcium carbonate in the solid phase. It is readily dissolved in acids, vigorously giving off carbon dioxide. When heated in the closed tube it loses its water and fuses.

The phase-equilibrium diagram (fig. 30) of the system Na_2CO_3—$CaCO_3$—H_2O (Bury and Redd, 1933) shows that at one atmosphere of pressure pirssonite forms between 37.5° C and 103.2° C in a saturated solution of sodium carbonate in the presence of sodium carbonate and calcium carbonate in the solid phase. Under these conditions equilibrium was attained in 7 to 14 days.

The sample for chemical analysis was prepared by hand-picking clear fragments of pirssonite from coarsely crushed shale that contained this mineral and then grinding to pass an 80-mesh sieve. Though great care was taken to prepare the sample as free as possible from contaminating shale, the chemical analysis in table 9 shows that 1.40 percent was insoluble in acid.

SPECTROGRAPHIC ANALYSIS

The spectrographic analysis was made on a powdered sample of pirssonite, by the method used for shortite.

The percentages of the elements measured on the spectrographic plate are: Cu, 0.0005; Sn, <0.002; Mn, <0.0002; Fe, 0.23; Cr, <0.0004; Al, 0.052; Ti, 0.004; Be, <0.0002; Mg, 0.080; Sr, 0.068; and Ba, 0.0080. These results have an overall accuracy of ±15 percent except near the limits of detection where only one digit is reported. The elements that were looked for but not found are listed in table 10. As is seen in the spectrographic analysis the barium content of pirssonite is greater than that of any of the other saline minerals.

GAYLUSSITE

NAME OF MINERAL

The pentahydrate of sodium and calcium carbonate ($Na_2CO_3 \cdot CaCO_3 \cdot 5H_2O$) was described and named gaylussite (Boussingault, 1826) in honor of the great French chemist L. J. Gay-Lussac. The mineral was found in the mud of an alkali lake at Lagunilla, a small Indian village located about 48 miles southeast of the City of Merida, Venezuela.

OCCURRENCES

In addition to the original location gaylussite has been found in many places throughout the world in alkali lakes, including Taboos-nor (Salt Lake) in the eastern Gobi Desert, Mongolia.

Gaylussite is present in the United States at several sinks in the Carson Desert near Ragtown, Nev., at Independence Rock in the Sweetwater Valley, Wyo., and Mono Lake, Lake County, Calif. It has been found with northupite and pirssonite embedded in trona near the western shore of Borax Lake, Lake County, Calif., and at Searles Lake, San Bernardino County, Calif.

Gaylussite is found associated with shortite, northupite, pirssonite, and trona in the Wilkins Peak member of the Green River formation. At the site of the John Hay, Jr., well 1, it is found between depths 1,261 feet and 1,350 feet. Between 1,266 feet and 1,267 feet 6 inches and the 2-foot stratum between 1,268 feet and 1,270 feet, gaylussite is visually estimated to constitute about 10 percent of the core.

CRYSTALLOGRAPHY

Gaylussite crystallizes in the monoclinic system. In the Wilkins Peak member of the Green River formation,
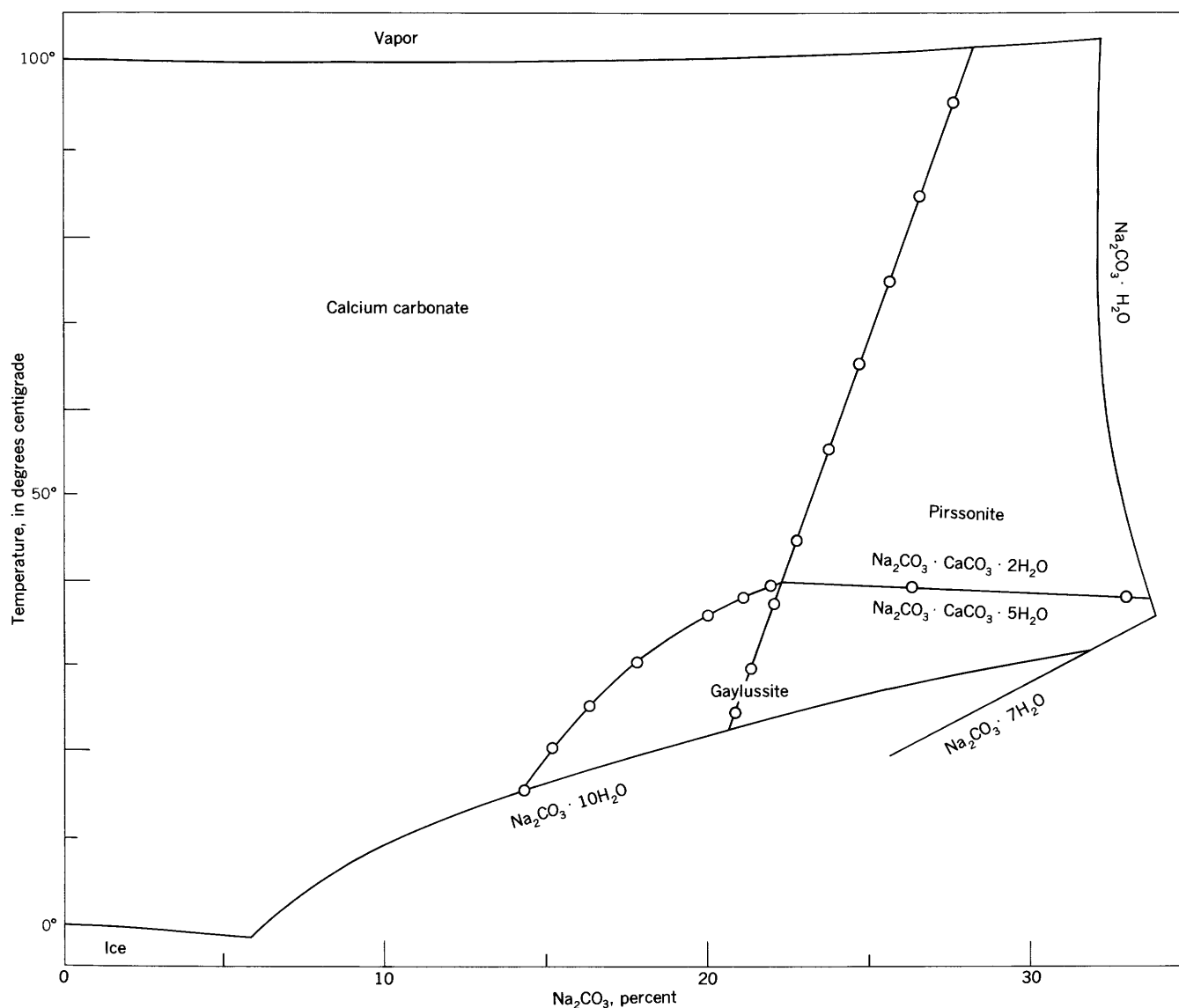
FIGURE 30.—Phase equilibrium diagram of the system Na_2CO_3—$CaCO_3$—H_2O (Bury and Redd, 1933).

gaylussite, like pirssonite, is found only massive in vugs and cracks in the shale. In thin section it is seen replacing shortite and in turn being replaced by northupite (fig. 34). Another thin section shows gaylussite replacing portions of several crystals of shortite (fig. 35).

OPTICAL AND PHYSICAL PROPERTIES

Gaylussite is transparent to translucent. Like pirssonite, it ranges from colorless to a pale yellow that is due to traces of organic matter.

The indices of refraction are:

$$\left.\begin{array}{l} \alpha=1.445 \\ \beta=1.514 \\ \gamma=1.524 \end{array}\right\} \pm 0.002$$

$2V=40°$ negative (calculated).

Optical constants are listed in table 8.

Like pirssonite, gaylussite is brittle and has vitreous luster and a conchoidal fracture. The hardness is $2\frac{1}{2}$ to 3. It slowly loses water in dry air, reverting to the lower hydrate pirssonite.

The specific gravity (2.037 at 25° C) was determined by using a fused silica Adams-Johnston pycnometer on material that passed an 80-mesh sieve and was retained on 100-mesh. Water saturated with sodium carbonate was the liquid medium.

CHEMICAL PROPERTIES

When heated in the closed tube, gaylussite decrepitates, loses water, and fuses to a white mass. It is readily dissolved in acids with effervescence of carbon dioxide, and is differentially soluble in water, leaving calcium carbonate in the solid phase.

Gaylussite is one of the stable phases (Bury and Redd, 1933) in the system sodium carbonate-calcium carbonate-water (fig. 30) from 15° to 40° C. These authors also found that gaylussite is in equilibrium with pirssonite between 37.5° and 40° C. In the 10-foot stratum between depths of 1,340 and 1,350 feet in the core of the John Hay, Jr., well 1, gaylussite and pirssonite are found, suggesting that the temperature of of deposition of this stratum was for at least part of the time during diagenesis between 37.5° and 40°C.

The chemical analysis was made on carefully hand-picked material and is given in table 9.

SPECTROGRAPHIC ANALYSIS

The spectrographic analysis was made on a powdered sample of gaylussite, by the method used for shortite.

The percentages of the elements measured on the spectrographic plate are Cu, 0.0006; Sn, 0.004; Mn, $<$0.0002; Fe, 0.050; Cr, 0.0006; Al, 0.14; Ti, 0.004; Be, $<$0.0002; Mg, 0.20; Sr, 0.022; and Ba, 0.0004. These results have an overall accuracy of $\pm$ 15 percent except near the limits of detection, where only one digit is reported. The elements looked for but not found are listed in table 10. In this tabulation it is shown that gaylussite contains a higher percentage of tin, chromium, and aluminum than any of the other saline minerals and also has a higher content of magnesium than any of these minerals except northupite, of magnesium is a major constituent.

PARAGENESIS OF THE SALINE MINERALS

GOSIUTE LAKE

The Green River formation north of the Uinta Mountains had its origin in a lake of vast size that was named Gosiute Lake by Clarence King (1878, p. 446). This name was used by Bradley (1929, p. 88) in his study of the varves and climate of the Green River epoch.

During its long life span Gosiute Lake left in its bottom muds a chronological record of events and conditions of that time. Bradley has read much of this record and in his papers has shown that the climate was similar to that now found in our Gulf States, and that the heavy rains of the springtime were followed by low precipitation during the fall months. He deduced that for long periods of time the lake had no outlet, that solar evaporation balanced the inflow of the streams, and that an abundant flora and fauna grew in the lake waters. This, and much more, was obtained from the varves and fossils of the Green River rocks.

The aggregate of saline minerals found in the oil shale gives clues to other conditions of that time. The mineral trona ($Na_2CO_3 \cdot NaHCO_3 \cdot 2H_2O$), because of its bicarbonate ion, could have precipitated only in the presence of abundant carbon dioxide. This was furnished by the decaying organic remains of plants and animals that, having passed through their life cycle, sank to the bottom ooze, there to begin that series of changes the end product of which is oil shale.

From the meager knowledge we have of the stability relations of the complex alkaline brine of the lake, we find that on the phase boundary between nahcolite and trona (fig. 6) at a given pressure of carbon dioxide, a slight lowering of the temperature causes nahcolite to be the stable phase whereas only trona will precipitate if the temperature is raised. This suggests that when the trona beds in Wyoming were deposited, the temperature may have been too high for nahcolite to be precipitated, whereas at the time of deposition of the nahcolite in Colorado and Utah the temperature may have been too low for the precipitation of trona. Another factor which may and probably did play a part is the partial pressure of· carbon dioxide. At a given temperature at which trona is precipitating, nahcolite can be made the stable phase by sufficiently increasing the partial pressure of the carbon dioxide.

The variations of concentration, composition, and temperature of solution that define the stability range of shortite ($Na_2CO_3 \cdot 2CaCO_3$)—the most abundant of the saline minerals found in the shale—are not known. However, whatever these conditions may be, they were maintained uninterruptedly throughout that vast period of time required for the deposition of sediment that, when compacted, formed oil shale having a thickness of more than 550 feet at the site of the John Hay, Jr., well 1. Between depths of 1,251 feet and 1,806 feet 6 inches, shortite is found throughout the entire vertical column. This includes the four trona beds of approximately 10, 2, 4, and 6 feet in thickness, between the depths 1,590 feet 3 inches and 1,600 feet 4 inches; 1,617 feet 6 inches to 1,619 feet 9 inches; 1,642 feet to 1,646 feet; and 1,653 feet 2 inches to 1,659 feet 3 inches, respectively, throughout which crystals of shortite are sparsely distributed. Likewise the physical and chemical conditions that permit the precipitation of trona (fig. 6) were maintained for the duration of time required for the deposition of each of these four beds.

Sulfates in quantity greater than a trace are not found among the saline minerals. The sulfate in the waters of the streams flowing into the lake was reduced to sulfide in the strongly reducing environment brought about by decaying plant and animal remains. The small amount of iron that was in solution in the lake water was in turn precipitated by the hydrogen sulfide and formed pyrite, tiny crystals of which are present throughout the oil shale.

No potassium saline minerals are found in the salines of the Green River formation. Sodium and calcium in

combination with the carbonate radical, as in shortite ($Na_2CO_3 \cdot 2CaCO_3$), pirssonite ($Na_2CO_3 \cdot CaCO_3 \cdot 2H_2O$), and gaylussite ($Na_2CO_3 \cdot CaCO_3 \cdot 5H_2O$) form more insoluble double salts than would potassium and calcium. Sodium is also found in the triple salt northupite ($Na_2CO_3 \cdot MgCO_3 \cdot NaC1$) and in combination with phosphate in bradleyite ($Na_3PO_4 \cdot MgCO_3$). This absence of potassium among the Green River saline minerals is in sharp contrast to the abundance of potassium-containing minerals in the marine evaporites of Permian age in New Mexico and Texas. In these, the sulfate mineral, polyhalite ($K_2SO_4 \cdot MgSO_4 \cdot 2CaSO_4 \cdot 2H_2O$), is found in great quantities whereas no sodium analogue has been reported. Had there not been a periodic flushing of Gosiute Lake that removed the potassium, vast deposits of sylvite (KCl) would undoubtedly have been laid down, as in the Permian deposits of New Mexico and Texas.

During that long period between the precipitation of the shortite in the partly compressed mud that had been the lake bottom, and the final compaction of this mud to form oil shale, there was, percentagewise, very little alteration of the shortite. That which was observed in the many thin sections studied, is graphically outlined (fig. 8) to give a condensed picture of the paragenetic sequence of the six saline minerals found in the Wyoming area. Shortite alters to (figs. 32–35), or is replaced by (figs. 9, 31, and 36), five saline minerals—northupite, pirssonite, gaylussite, trona, and bradleyite. Shortite has in no instance been observed replacing any of the saline minerals. It is always the oldest mineral in the sequence. Pirsonnite (fig. 32), gaylussite (fig. 34), and trona (fig. 37) are replaced by northupite. No replacement of northupite or bradleyite has been observed. Eight photomicrographs of thin sections, cut from the core of the John Hay, Jr., well 1, have been selected to show the paragenetic relationships among the six saline minerals.

SHORTITE TO NORTHUPITE

The replacement of shortite by northupite is shown in a thin section (fig. 31) cut from the drill core of the John Hay, Jr., well 1, depth 1,339 feet 4 inches. The shortite crystals are corroded and embayed by the isometric mineral northupite that occupies the black area. The three prominent crystal remnants that are seen do not extinguish at the same time, hence are not parts of a single crystal. No evidence is presented on the thin section as to the size of the crystals of shortite before the replacement by northupite started. An examination of this thin section and many others showing the replacement of shortite by northupite, leads to the conclusion that the entire area seen in the photomicrograph had been occupied by randomly oriented

FIGURE 31.—Photomicrograph of thin section from the drill core of the John Hay, Jr., well 1, depth 1,339 ft 4 in, showing the sequence shortite to northupite. Crossed nicols. × 25.

crystals of shortite before the replacement by northupite began.

SHORTITE TO PIRSSONITE TO NORTHUPITE

The thin section was cut from core of the John Hay, Jr., well 1 from a depth of 1,342 feet. The magnification is 25 diameters under crossed nicols.

The photomicrograph (fig. 32) shows randomly oriented crystals of shortite altering to pirssonite (P), which in turn is being replaced by the isometric mineral northupite (N). A crystal of shortite (S_1) is almost in the extinction position and is rimmed by pirssonite. Other crystals of shortite (S_2, S_3, S_5, S_6, and S_8) are in or near the extinction position and are rimmed and deeply embayed by the highly birefringent mineral pirssonite. Near the center of the picture the crystal of shortite (S_4) is not in or near the extinction position and shows deep embayment by pirssonite. Likewise, at the top of the photomicrograph the crystal of shortite marked S_7 is not in or near the extinction position and is deeply corroded by pirssonite. Throughout the section, the isometric mineral northupite (N) is seen replacing pirssonite. All the pirssonite that is marked by the letter (P) extinguishes at the same time under crossed nicols, thereby strongly indicating it to be the remainder of what had been a single crystal that has been partly replaced by northupite (N). The shale

FIGURE 32.—Photomicrograph of thin section from the drill core of the John Hay, Jr., well 1, depth 1,342 ft, showing the sequence shortite (S_1 through S_8) to pirssonite (P) to northupite (N). Sh indicates shale. Crossed nicols. $\times25$.

(Sh) is dark brown in the thin section because of the presence of organic matter.

The chemical changes in the sequence shortite to pirssonite to northupite are shown by their formulas:

$$Na_2CO_3\cdot 2CaCO_3 \rightarrow Na_2CO_3\cdot CaCO_3\cdot 2H_2O \rightarrow$$
$$\text{shortite} \qquad\qquad \text{pirssonite}$$
$$Na_2CO_3\cdot MgCO_3\cdot NaCl$$
$$\text{northupite}$$

Each of the three minerals in the sequence contains one molecule of Na_2CO_3 which is joined in northupite by a molecule each of $MgCO_3$ and $NaCl$. The moles of $CaCO_3$ per mole Na_2CO_3 diminishes from two in shortite to one in pirssonite to none in northupite. The $CaCO_3$ may have been reprecipitated to form the fine-grained dolomite that is seen in the thin section under higher magnification.

SHORTITE TO PIRSSONITE

The thin section was cut from core of the John Hay, Jr., well 1 from a depth 1,344 feet 4 inches. Magnification is 40 diameters with crossed nicols.

The photomicrograph (fig. 33) shows randomly oriented crystals of shortite that are rimmed and embayed by pirssonite. Two crystals of shortite (S_1 and S_6) are in the extinction position and are shown rimmed and embayed by pirssonite (P). Near the position of extinction are crystals of shortite (S_2, S_3 and S_7) that

are seen going over to pirssonite. Two crystals of shortite (S_4 and S_5) are not in or near the position of extinction, and are rimmed by pirssonite that is readily discernible because it has a much higher birefringence than shortite. The three small areas marked (Sh) are occupied by low-grade oil shale.

SHORTITE TO GAYLUSSITE TO NORTHUPITE

Core of the John Hay, Jr., well 1, from a depth of 1,340 feet 10 inches was the source of the thin section. The magnification is 25 diameters with crossed nicols.

The photomicrograph (fig. 34) shows randomly oriented crystals of shortite being replaced by gaylussite that is in turn being replaced by northupite. The crystal of shortite (S_1), oriented so that it is near the position of extinction, is seen in the process of replacement by gaylussite (G) that is going over to northupite (N), as is seen by the embayment of the gaylussite and the pitting that results in the small black areas in this highly birefringent mineral. Another crystal of shortite (S_2) is almost at maximum extinction and is embayed by gaylussite which is under attack by the northupite.

The molecular replacements are the same as those of the sequence shortite to pirssonite to northupite because gaylussite is compositionally different from pirssonite only because it has $5H_2O$ whereas pirssonite has $2H_2O$ as water of crystallization. Here also tiny crystals of dolomite can be seen under higher magnification.
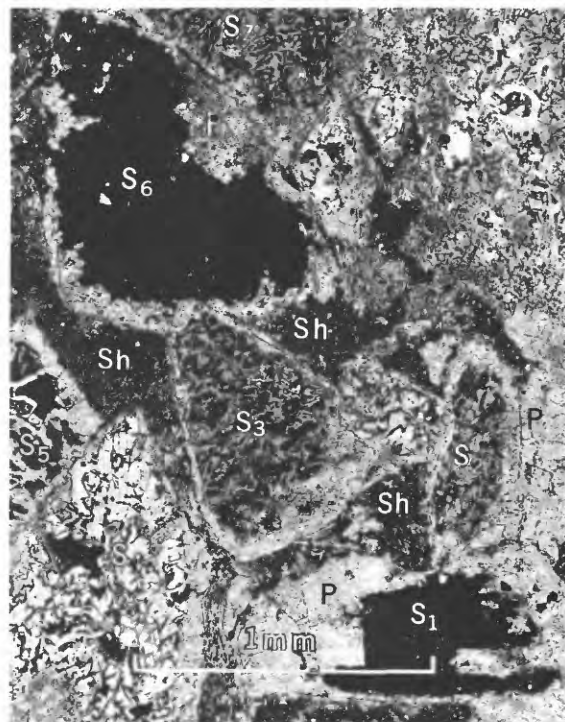
FIGURE 33.—Photomicrograph of thin section from the drill core of the John Hay, Jr., well 1, depth 1,344 ft 4 in, showing the sequence shortite (S_1 through S_7) to pirssonite (P). Sh indicates shale. Crossed nicols. $\times40$.
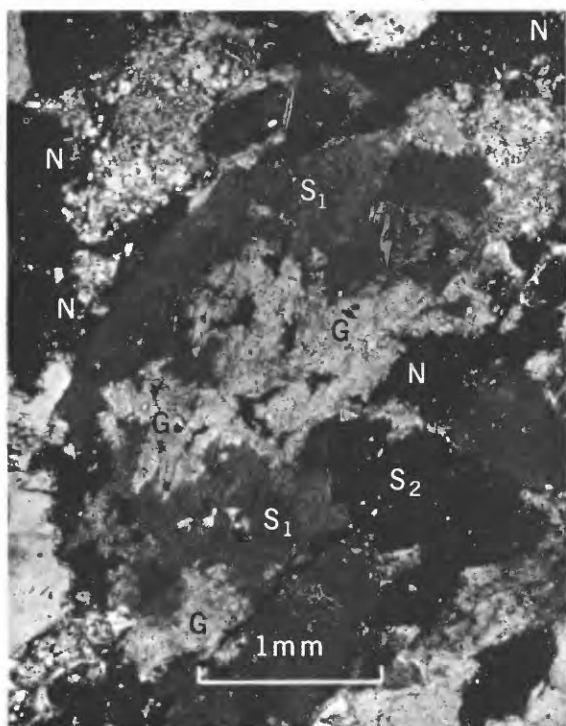
FIGURE 34.—Photomicrograph of thin section from the drill core of the John Hay, Jr., well 1, depth 1,340 ft 10 in., showing the sequence shortite (S_1, S_2) to gaylussite (G) to northupite (N). Crossed nicols. × 25.

FIGURE 35.—Photomicrograph of thin section from the drill core of the John Hay, Jr., well 1, depth 1,268 ft, showing the sequence shortite (S) to gaylussite (G). Sh indicates shale. Crossed nicols. × 40.

SHORTITE TO GAYLUSSITE

The thin section was cut from core of the John Hay, Jr., well 1 from depth of 1,268 feet. The magnification is 40 diameters under crossed nicols.

Three randomly oriented crystals of shortite (fig. 35) are shown rimmed by gaylussite (G). The gaylussite was photographed near the extinction position to afford good contrast to the shortite (S). No northupite is present in this section. The dark area (Sh) is occupied by low-grade oil shale.

SHORTITE TO TRONA PLUS DOLOMITE

The thin section was cut from core of the John Hay, Jr., well 1 from a depth of 1,302 feet. The magnification is 25 diameters; the nicols are crossed.

Trona is seen replacing shortite with the formation of many tiny crystals of dolomite in figure 36. That which remains of a crystal of shortite (S_1) is seen in a diagonal position. The dark area within this crystal's boundaries is occupied by the replacing mineral trona (T) in the extinction position. Very small crystals of dolomite, too small to give more than a point of light under crossed nicols at this magnification, are present throughout the area of the picture. Another crystal of shortite (S_2) is also being replaced by trona. A third crystal of shortite (S_3), almost in the extinction position, is embayed by trona. All the trona seen in the picture is occupying areas where there had been shortite, and

though these crystals of shortite were randomly oriented, all the replacing trona has the same orientation, all of it extinguishing at the same time. Though the trona forms a single crystal unit, it is obvious in this thin section, and in others, that the sequence is shortite to trona and not trona to shortite. Sharp boundaries and isolated remnant areas of the shortite crystals leave no doubt as to the paragenetic relationship.

The chemical composition of the solution that caused the replacement of shortite by trona, and the formation of the tiny crystals of dolomite, is not known. However, if a brine rich in magnesium and the bicarbonate ion were to have come in contact with shortite, the following reaction is not an improbable one:

$$3(Na_2CO_3 \cdot 2CaCO_3) + 6MgCO_3 + CO_2 + 5H_2O \rightarrow$$
$$\text{shortite}$$
$$2(Na_2CO_3 \cdot NaHCO_3 \cdot 2H_2O) + 6(CaCO_3 \cdot MgCO_3)$$
$$\text{trona} \qquad \text{dolomite}$$
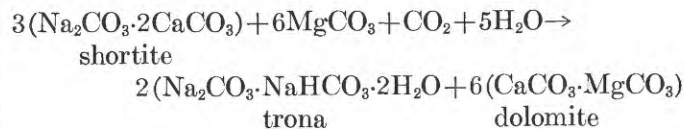
Until a phase equilibrium study is made, the conditions necessary for the replacement of shortite by trona must remain unknown.

TRONA TO NORTHUPITE

Core from the John Hay, Jr., well 1 from a depth of 1,560 feet 2 inches furnished the material for the thin section that shows the transition of trona to northupite
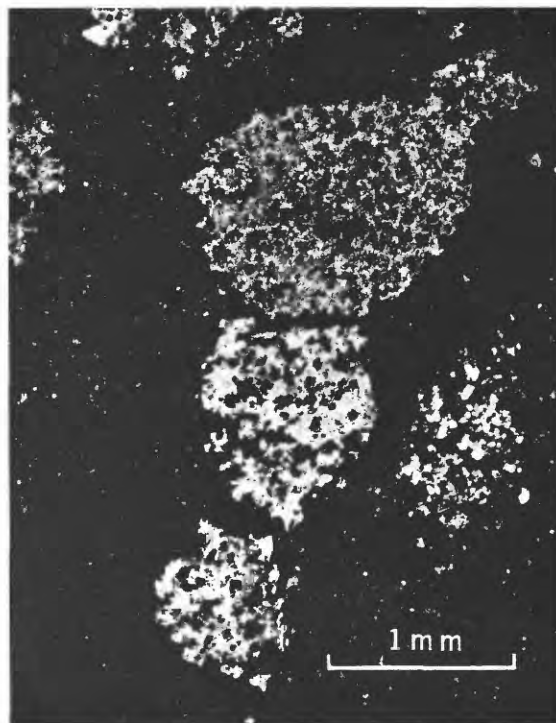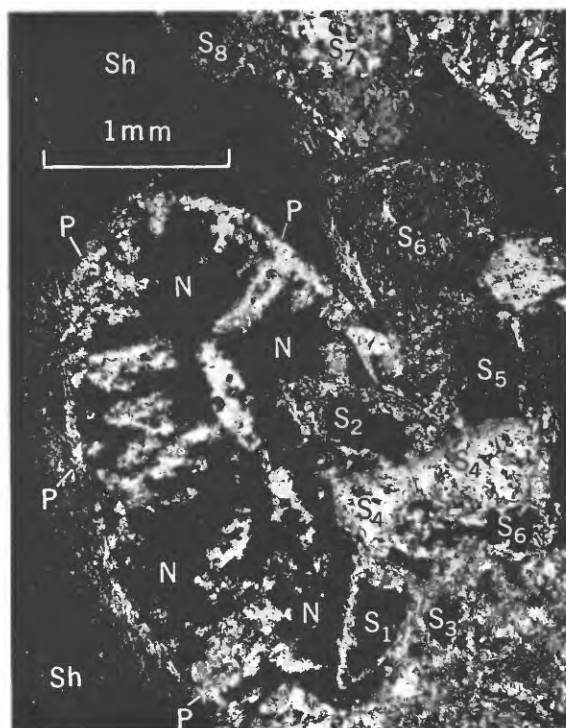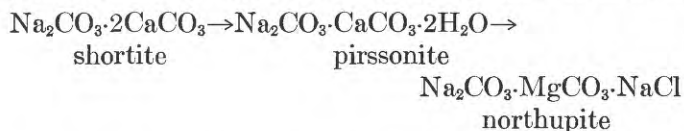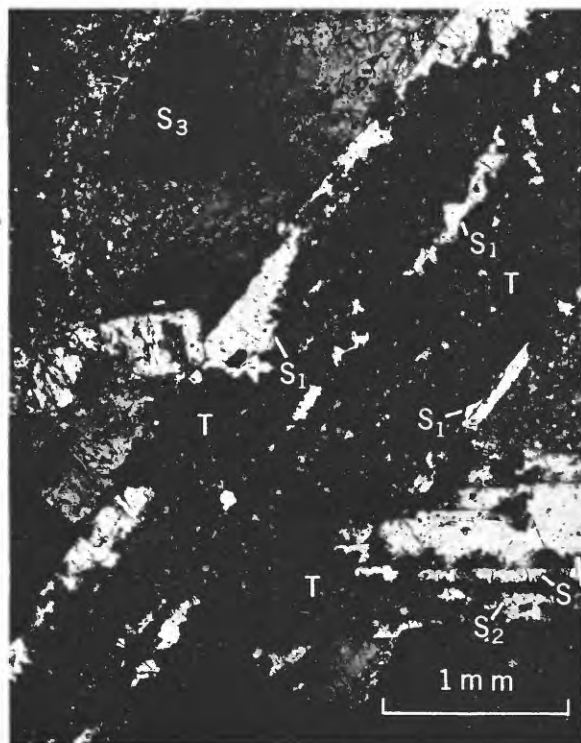
FIGURE 36.—Photomicrograph of thin section from the drill core of the John Hay, Jr., well 1, depth 1,302 feet, showing the sequence shortite (S_1, S_2, S_3) to trona (T). Crossed nicols. × 25.
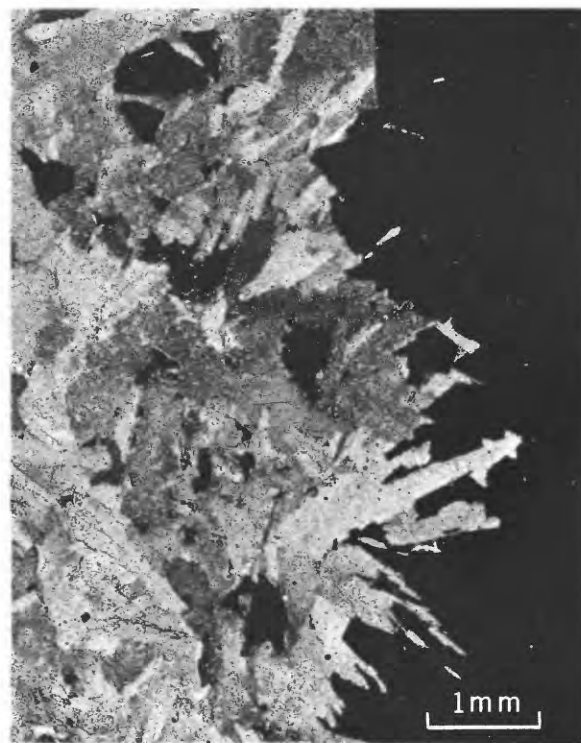
FIGURE 37.—Photomicrograph of thin section from the drill core of the John Hay, Jr., well 1, depth 1,560 ft 2 in, showing the sequence trona to northupite. Crossed nicols. × 15.

(fig. 37). A magnification of 15 diameters was used with crossed nicols.

The black areas in the photomicrograph are occupied by the isometric mineral northupite. The embayment and pitting of the highly birefringent mineral trona, and the tiny remnant islands of trona slightly removed from the main mass, all indicate that the sequence is trona to northupite.

SHORTITE TO BRADLEYITE

The thin section (fig. 9) that shows bradleyite replacing shortite was cut from core of the John Hay, Jr., well 1, from a depth of 1,342 feet 10 inches. The magnification is 15 diameters in plane-polarized light.

The ground mass is composed of approximately 80 percent bradleyite and 20 percent clay. The randomly oriented particles of bradleyite are much too small to be distinguished at this magnification, the largest being approximately 0.002 mm in the longest direction. Much-corroded edges and the embayment of the crystals of shortite leave no doubt that the bradleyite is in the process of replacing the shortite. The tiny black areas in the picture are due to crystals of pyrite.

MAIN TRONA BED

AREAL EXTENT

The number of square miles in southwestern Wyoming underlain by trona cannot be even approximately estimated from the data available at this time. Fragmentary reports of drilling in the area during 1959, in conjunction with data already at hand, indicate that trona may be present under an area of as much as 2,000 square miles. This does not mean that the trona bed approximately 10 feet thick found at the Westvaco mine has such an extent. Nor does it necessarily follow that minable trona underlies the entire area. Many more test holes must be put down before the boundaries of the trona can be established and the thickness and quality of the beds determined.

The minimum area, underlain by the trona bed that is now being mined at Westvaco, was determined to be about 30 square miles. This determination was made from measurements of cores of the John Hay, Jr., well 1 put down in 1938, and the Union Pacific wells 1 and 2 drilled in 1940, and 3 and 4 drilled in 1941. Between 1944 and 1956, 13 drill cores, Westvaco Nos. 1 to 13, were obtained. The Potash Co. of America put down

their No. 1 and No. 2 wells in 1949 and 1950. These 15 drill cores doubled the size of the proven trona area to about 60 square miles, and showed that the thickness of the main trona bed ranged from 7 to 16 feet.

It became evident as additional wells were drilled and the cores logged that minable trona extended far beyond the area in which the wells were located. On April 29, 1954, the Geological Survey made available for leasing 287,904 acres, or approximately 450 square miles, for prospecting for trona. This extended the area more than 20 miles to the south and west of T. 19 N., R. 110 W., in which most of the exploratory wells have been drilled.

COMPOSITION

CHEMICAL

To determine variations in the chemical composition of the main trona bed between the top and the bottom, two locations (A and B) about half a mile apart, were selected. A representative sample of each foot of the main trona bed was taken. At location A nine samples were obtained and at location B, where the trona bed was less thick, eight were collected. A similar procedure was followed at two other locations (C, 10 samples, and D, 9 samples) about 500 feet apart. The samples from C and D were examined spectrographically for lithium and the results are given in table 14.

TABLE 14.—*Spectrographic determination of lithium in channel samples from each foot, top to bottom, of the main trona bed at locations C and D about 500 feet apart, Sweetwater County, Wyo.*

[Harry J. Rose, analyst]

Sample	Lithium (percent)	Sample	Lithium (percent)
C1	0. 001	D1	0. 004
C2	. 002	D2	. 003
C3	. 004	D3	. 002
C4	. 004	D4	. 004
C5	. 001	D5	. 0004
C6	. 0005	D6	. 0003
C7	. 0009	D7	. 0008
C8	. 0004	D8	. 0003
C9	. 0002	D9	. 0003
C10	. 0009		

Fifty grams of each of the samples from locations A and B were ground to pass a 100-mesh sieve and then placed in a 1-liter beaker to which was added about 900 ml of distilled water. Each sample was repeatedly stirred, and after remaining on the steam bath overnight, the insoluble residue was filtered off, dried in an oven overnight at 80°C, and weighed. Aliquots of the filtrate were taken for the determination of P_2O_5, SO_3, Cl, Br, and I, and the results are given in table 15. The percentage of the water-insoluble residue subtracted from 100 percent is a very close approximation of the trona present in the sample. Treatment of the water-insoluble residue with (1+1) HCl on the steam bath for

1 hour removed the dolomite. The insoluble residue, which was chiefly detrital material and a very small amount of organic matter, was filtered on a preweighed sintered glass filter, dried in an oven at 80°C for 2 hours, and weighed.

At both locations A and B, as shown in table 15, less contaminating material is found in the middle, or near the middle, of the trona bed than at the top or the bottom. This is usually true in the main trona bed, though location E in table 16 is a notable exception. The phosphate, sulfate, and chloride, though present in very low percentages are, in most instances, higher where the concentration of water-insoluble material is greater.

TABLE 15.—*Chemical analysis of channel samples of each foot from top to bottom of the main trona bed at locations A and B about one-half mile apart, Sweetwater County, Wyo.*

[Joseph J. Fahey, analyst]

Sample	Insoluble in H_2O (percent)	Insoluble in (1+1) HCl (per cent)	P_2O_5 (percent)	SO_3 (percent)	Cl (percent)	Br (percent)	I (percent)
A1	12. 40	2. 71	0. 024	0. 015	0. 10	0. 002	0. 0002
A2	. 38	. 21	. 002	. 002	. 07	. 002	. 0002
A3	14. 18	6. 13	. 013	. 008	. 16	. 002	. 0002
A4	1. 40	. 65	. 014	. 012	. 08	. 002	. 0002
A5	. 31	. 16	. 014	. 008	. 06	. 002	. 0002
A6	. 14	. 08	. 015	<. 002	. 12	. 002	. 0002
A7	1. 00	. 47	. 014	<. 002	. 07	. 002	. 0002
A8	. 73	. 35	. 015	. 002	. 05	. 002	. 0002
A9	1. 91	. 39	. 004	<. 002	. 09	. 002	. 0002
Average	3. 61	1. 24	0. 013	0. 006	0. 09	0. 002	0. 0002
B1	29. 22	13. 18	0. 014	0. 030	0. 50	0. 002	0. 0002
B2	9. 04	4. 14	. 026	. 028	. 15	. 002	. 0002
B3	8. 04	3. 58	. 012	. 028	. 12	. 002	. 0002
B4	. 61	. 25	. 014	. 012	. 08	. 002	. 0002
B5	. 87	. 24	. 014	. 010	. 05	. 002	. 0002
B6	. 08	. 04	. 006	<. 002	. 08	. 002	. 0002
B7	. 13	. 08	. 012	. 004	. 15	. 002	. 0002
B8	. 77	. 43	. 013	. 006	. 07	. 002	. 0002
Average	6. 10	2. 74	0. 014	0. 015	0. 15	0. 002	0. 0002

P_2O_5, SO_3, Cl, Br, and I were determined on the water-insoluble fraction.

The average concentration of trona in the trona bed at any given locality is not likely to be higher than about 96 percent, which is found in the bed at location A. The percentage of trona at location B, which is approximately 93 percent, is closer to the average content of the trona bed.

MINERALOGICAL

A mass of trona weighing about 20 pounds was taken from the top, middle, and bottom of the trona bed at each of two locations E and F about a quarter of a mile apart. On these six samples the density was measured by cutting from each sample a rectangular solid that was approximately a cube, polishing each side with fine sandpaper, and measuring its dimensions in centimeters and its mass in grams. The mass of the six samples ranged from 73.692 g to 147.770 g. The density in grams per cubic centimeter is listed in table 16.

TABLE 16.—*Density and composition of bulk samples from the top, middle, and bottom of the main trona bed at locations E and F, about a quarter of a mile apart, Sweetwater County, Wyo.*

[Joseph J. Fahey, analyst]

Sample	Density (g per cc)	Insoluble in H₂O (percent)	Insoluble in (1+1) HCl (percent)	Organic matter (percent)
E (top) _____	2.117	1.55	0.79	0.037
E (middle)_____	2.179	3.06	1.61	.142
E (bottom)_____	2.126	.12	.06	.002
F (top) _____	2.156	1.83	.78	.014
F (middle)_____	2.124	1.02	.41	.001
F (bottom)_____	2.119	.74	.35	.001

The six samples from locations E and F were ground to pass a 100-mesh sieve and leached with water overnight on the steam bath in the same manner as previously described for samples A and B. The water-insoluble residue was filtered off and dried at 80° C. An X-ray powder pattern showed the material to be predominantly dolomite. Treatment with (1+1) HCl removed the dolomite, and the residue, after it was filtered and dried, was examined under the petrographic microscope and found to be a mixture of quartz and clay. The organic matter of the original sample was concentrated in this small fraction.

Subhedral crystals, as much as 10 inches long, of the rare mineral searlesite ($NaBSi_2O_6 \cdot H_2O$) have been found sparsely disseminated throughout the main trona bed. The mineral is also present as micalike books in the shale, both above and below the trona bed. This is the third recorded location of searlesite (Fahey and Axelrod, 1950). It was orginally found in clay from Searles Lake (Larsen and Hicks, 1914) as white spherulites about 1 mm in diameter. The second locality of searlesite is the Silver Peak Range, Esmeralda County, Nev. (Foshag, 1934), where it is found as prismatic crystals that seldom exceed 3 mm in length.

ORGANIC MATTER

To obtain an accurate measurement of the organic matter contained in the six samples from locations E and F, a 1-kg sample of each was taken and, after crushing to about pea size, was placed in a 2-liter beaker. To this was slowly added (1+2) HCl until the carbonate was destroyed. After the solution was diluted it was filtered through a Whatman 41H paper and the residue washed with (1+9) HCl and transferred, by means of a stream of water, to a 100-ml platinum crucible. A well-fitting cover was put on the crucible after 10 ml of HCl and 50 ml of HF were added. After the solution remained on the stream bath overnight it was filtered through a Whatman 41H paper, using a polyethylene funnel and beaker. The residue was washed with distilled water and transferred by means of a stream of water to a preweighed platinum crucible of 25-ml capacity. After taking to dryness on the steam bath, the crucible and contents were allowed to remain overnight in an oven held at 80° C. After cooling and weighing, the organic matter was burned off, the crucible weighed, and the organic matter recorded as the difference in the weights. The very small percentages of organic matter in the samples listed in table 16 necessitated taking a 1-kg sample.

The color of the trona bed resembles that of maple sugar. This is due in great part to the organic matter which, though only present in trace quantities, pigments the trona bed.

LENGTH OF TIME OF DEPOSITION

Bradley, in his study of the varves of the Green River formation, found the average range in thickness in the sandstone, marlstone, and oil shale to be from 0.037 to 1.16 mm (Bradley, 1929, p. 99). He considered each varve to represent a period of time of 1 year and thus computed the time required to accumulate the material necessary to produce a thickness of 1 foot of these sedimentary rocks ranged from 250 to 8,200 years, with a weighted average of 2,200 years. In an oral communication (1960) Bradley estimated that 3,000 years was the length of time required for the deposition of a thickness of 1 foot of the sediments of the Wilkins Peak member of the Green River formation in which the saline minerals are found. This means that a period of time of about 3,000 years was required for the deposition of the detrital material and organic matter plus the minerals that precipitated from the lake water to form a thickness of 1 foot of rock. This rock material is composed chiefly of dolomite, other water-insoluble minerals, the detrital minerals, and organic material.

To arrive at an approximate figure for the length of time required for the deposition of the trona bed, the period of time, 3,000 years, is used as that required for the accumulation of the material of which a thickness of 1 foot of the average rock of the Wilkins Peak member of the Green River formation is composed. If it is assumed that this rate of deposition of water-insoluble material was maintained during the time that the trona bed was laid down, it seems that the length of time required for the deposition of a thickness of 1 foot of trona would be proportional to the percentage of water-insoluble material present. Thus, if a 1-foot thick section of trona contained 10 percent of water-insoluble material, the time required for deposition would be 10 percent of 3,000 years, or 300 years. Taking the percentage of water-insoluble material of the channel samples A and B (table 15) and applying the factor 3,000, a figure for the time required for the deposition of the trona bed is obtained (table 17).

TABLE 17.—*Length of time of deposition of the trona bed, based on the percentage of water-insoluble material in the vertical section*

[Joseph J. Fahey, analyst]

Sample	Insoluble in H_2O (percent)	Length of time (years)
A1	12. 40	372
A2	. 38	11
A3	14. 18	425
A4	1. 40	42
A5	. 31	10
A6	. 14	4
A7	1. 00	30
A8	. 73	22
A9	1. 91	57
Total		973
B1	29. 22	877
B2	9. 04	271
B3	8. 04	241
B4	. 61	18
B5	. 87	26
B6	. 08	3
B7	. 13	4
B8	. 77	, 23
Total		1, 463

Table 17 shows that in both sample A and sample B there is a very large range in the time of deposition per foot of the trona bed between the top and the bottom of the column. However, the difference in total time of deposition between that at location A and that at location B, as indicated by this procedure, is not so great. Table 17 also shows a moderate rate of deposition at the bottom of the bed. This rate rapidly increased in the next several feet but by the time the top of the bed was reached the rate was very greatly reduced, indicating gradually diminishing conditions propitious to the precipitation of trona.

In this method for the estimation of the time duration of the deposition of the trona bed, there are inherent errors, chiefly among these being the uncertainty of the factor 3,000 for the years required for the deposition of a stratum 1 foot thick of water-insoluble material. Bradley estimated this figure as a weighted average. However, the correct factor for the water-insoluble material of the trona bed well may be one-half of 3,000, or it may be twice as great. This would place the correct figure for the time required for the deposition of the trona bed between 500 and 3,000 years, based on the data obtained from the channel samples of locations A and B. A 9-foot stratum of fine-grained sandstone, according to Bradley, would be laid down in about 2,000 years whereas a rich oil-shale bed of the same thickness would require more than 70,000 years. In view of these figures, it is apparent that the time re-

quired for the deposition of the trona bed is probably a small fraction of the time required for the deposition of the same thickness of shale immediately above or below the trona bed.

X-RAY POWDER DATA FOR THE SALINE MINERALS OF THE GREEN RIVER FORMATION

By MARY E. MROSE

Indexed X-ray powder data are presented in this section for the following minerals from the Green River formation: Shortite, $Na_2Ca_2(CO_3)_3$, table 18; trona, $Na_3H(CO_3)_2 \cdot 2H_2O$, table 19; nahcolite, $NaHCO_3$, table 20; northupite, $Na_3MgCl(CO_3)_2$, table 21; bradleyite, $Na_3Mg(PO_4)(CO_3)$, table 22; pirssonite, $Na_2Ca(CO_3)_2 \cdot 2H_2O$, table 23; and gaylussite, $Na_2Ca(CO_3)_2 \cdot 5H_2O$, table 24. These saline minerals, with the exception of nahcolite and bradleyite, are from the John Hay, Jr. well 1, Sweetwater County, Wyo.; the nahcolite is from oil-shale mine of the Bureau of Mines, near Rifle, Colo.; the bradleyite, from Westvaco mine, Sweetwater County, Wyo. Powder data for natural nahcolite, northupite, and pirssonite are given for the first time.

EXPERIMENTAL TECHNIQUES

All the patterns for which X-ray powder data are given in tables 18 through 24 were made on chemically analyzed samples of the saline minerals, the analyses of which are listed in tables 9 and 11, and table 13 (analysis B). For each powder pattern a spindle-type mount having a diameter averaging 0.15 mm was made from the finely powdered mineral and a binder that consisted of a 10-percent solution of granular low-viscosity ethyl cellulose dissolved in toluene. The patterns were taken with Debye-Scherrer powder cameras (114.59 mm diameter) using the Straumanis and Wilson techniques with Cu/Ni radiation ($\lambda CuK\alpha =$ 1.5418 A, $\lambda CuK\alpha_1 = 1.5405$ A, $\lambda CuK\alpha_2 = 1.5443$ A). Two powder patterns were taken with each spindle: one, with the camera in a spot-focus position, for obtaining intensity data; the other, with the camera in a line-focus position, for best possible resolution for film measurement. The observed cut-off, that is, the lower limit measurable for 2θ, was approximately 7.0° (12.6 A).

The films were measured with a Hilger-Watts film-measuring rule with a vernier precision of 0.05 mm. All measurements were corrected for film shrinkage. Intensities were estimated visually by direct comparison with calibrated intensity film strips of successive step line-exposures related to each other by a factor of $\sqrt{2}$.

Indexed calculated interplanar spacings are listed for each mineral for comparison with the observed spacings. These data were calculated from the cell constants cited at the head of each table. Calculations were carried down to $d_{hkl} \geq 2.00$ A for trona, nahcolite, bradleyite, and gaylussite; to $d_{hkl} \geq 1.570$ A for northupite; and down to $d_{hkl} \geq 1.500$ A for shortite and pirssonite. Cell constants originally given in kX units have been converted to A units for convenience of comparison with the observed spacings. All observed lines were found to be satisfactorily accounted for by the given X-ray cell data. Calculated interplanar spacings for nahcolite, northupite, and pirssonite were carried out on a digital computer by a program devised by Daniel E. Appleman.

Tables 18 through 24 also contain powder data found by other investigators for these saline minerals as well as for corresponding synthetic compounds; these are presented for comparative purposes.

TABLE 18.—*X-ray powder data for shortite*, $Na_2Ca_2(CO_3)_3$, from the John Hay, Jr., well 1, Sweetwater County, Wyo.

[Orthorhombic, $Amm2$-C^{14}_{2v}; a=4.961±0.005A, b=11.03±0.02, c=7.12±0.01 [1]]

ASTM (Card 8-109) [2]		Mrose (unpublished data) [3]			
Measured		Measured (film 14139)		Calculated	
I	d_{hkl}	I	d_{hkl}	d_{hkl}	hkl
75	6.03	50	5.985	5.981	011
75	5.37	71	5.515	5.516	020
75	4.98	71	4.957	4.960	100
60	3.82	50	3.818	3.818	111
		2	3.685	3.687	120
50	3.56	25	3.555	3.560	002
50	3.26	25	3.267	3.267	031
50	2.99	25	2.992	2.990	022
50	2.89	18	2.888	2.891	102
50	2.75	13	2.758	2.758	040
		35	2.725	2.729	131
100	2.57	100	2.562	2.561	122
75	2.48	50	2.476	2.480	200
		9	2.412	2.410	140
50	2.31	35	2.321	2.320	013
50	2.29	13	2.287	2.291	211
				2.261	220
75	2.17	71	2.179	2.180	042
60	2.11	50	2.106	{ 2.107	051
				2.102	113
50	2.03	35	2.032	2.035	202
75	2.00	60	1.996	{ 1.996	142
				1.994	033
20	1.98	18	1.972	1.975	231
10	1.94	6	1.941	1.939	151
50	1.90	18	1.905	1.909	222
				1.849	133
75	1.845	35	1.841	{ 1.844	240
				1.839	060
20	1.778	9	1.778	1.780	004
		5	1.722	1.723	160
35	1.695	25	1.690	{ 1.694	213
				1.694	024
20	1.680	13	1.672	1.675	104
		5	1.649	1.653	300
		13	1.634	{ 1.637	242
				1.633	062
		2	1.612	1.616	053
		50	1.603	{ 1.606	251
				1.603	124
				1.594	311
				1.584	320
		5	1.552	{ 1.554	233
				1.552	162
		9	1.537	{ 1.539	071
				1.536	153
				1.500	302
		13	1.471		
		13	1.446		

See footnotes at end of table.

TABLE 18.—*X-ray powder data for shortite*, $Na_2Ca_2(CO_3)_3$, from the John Hay, Jr., well 1, Sweetwater County, Wyo.—Continued

ASTM (Card 8-109) [2]		Mrose (unpublished data) [3]			
Measured		Measured (film 14139)		Calculated	
I	d_{hkl}	I	d_{hkl}	d_{hkl}	hkl
		5	1.429		
		6	1.397		
		9	1.352		
		2	1.328		
		5	1.316		
		3	1.306		
		9	1.281		
		3	1.269		
		2	1.246		
		9	1.236		
		9	1.207		
		2	1.196		
		9	1.182		
		18	1.162		
		2	1.145		
		2	1.137		
		5	1.127		
		3	1.094		
		5	1.088		
		6	1.077		
		2	1.069		
		5	1.064		
		6	1.052		
		3	1.033		
		1	1.027		
		3	1.016		
		6	1.008		
		3	1.006		
		9	.9969		
		1	.9830		
		2	.9763		
		3	.9691		
		1	.9609		
		1	.9553		
		1	.9481		
		3	.9400		
		2	.9218		
		3B	.9056		
		3B	.8897		
		3B	.8767		
		3	.8646		

[1] Single-crystal data obtained from a crystal of shortite from the John Hay, Jr. well 1, Sweetwater County, Wyo. (Mrose, unpublished data).

[2] Powder diffraction data for shortite from the Green River formation, Sweetwater County, Wyo., by G. Gottardi, Instituto di Mineralogia e Petrografia, Universita di Pisa, Italy. Camera diameter, 57.3 mm. Copper radiation, nickel filter (λ=1.541 A). Cut-off at 8.0° (5.5 A). Intensities estimated visually.

[3] Film corrected for shrinkage. Camera diameter, 114.59 mm. Copper radiation, nickel filter (λ=1.5418 A). Lower limit 2θ measurable: 7.0° (12.6 A). B=broad.

TABLE 19.—*X-ray powder data for trona*, $Na_3H(CO_3)_2 \cdot 2H_2O$, from the John Hay, Jr., well 1, Sweetwater County, Wyo.

Monoclinic, $I2/c$-C^6_{2h}, a=20.11±0.03 A, b=3.49±0.01, c=10.31±0.01, β=103°08'[1]]

ASTM (Card 2-0601) Measured [2]		Present study Measured [3] (film 14141)		Pabst (1959) Measured [4]		Calculated	
I	d_{hkl}	I	d_{hkl}	I	d_{hkl}	d_{hkl}	hkl
80	9.42	50	9.804	ms	9.88	9.79	200
						5.02	002
		35	4.920	m	4.92	4.95	$20\bar{2}$
70	4.87					4.90	400
				vs	4.12	4.11	202
40	4.00	6	3.990	w	4.00	3.99	$40\bar{2}$
60	3.43	5	3.442	w	3.43	3.44	110
						3.30	011
		6	3.262			3.26	600
60	3.20	18	3.196	ms	3.21	3.20	$21\bar{1}$
						3.17	402
		85	3.075	s	3.08	{ 3.08	310
						3.07	$60\bar{2}$
100	3.06					3.06	211
60	2.95					2.89	$11\bar{2}$
						2.83	$41\bar{1}$
60	2.78			vw	2.79	2.79	112
		13	2.763	mw	2.76	2.76	$31\bar{2}$
100	2.66	100	2.650	vs	2.659	2.645	411
						2.606	510

See footnotes at end of table.

TABLE 19.—*X-ray powder data for trona*, $Na_3H(CO_3)_2 \cdot 2H_2O$, *from the John Hay, Jr., well 1, Sweetwater County, Wyo.*—Con.

ASTM (Card 2-0601)[2] Measured		Present study[3] Measured (film 14141)		Pabst (1959)[4] Measured		Pabst (1959)[4] Calculated	
I	d_{hkl}	I	d_{hkl}	I	d_{hkl}	d_{hkl}	hkl
		9	2.583	w	2.587	2.578	$\bar{2}04$
		18	2.513			2.512	004
				mw	2.510	2.508	312
				vw	2.485	2.491	602
		6	2.480			2.475	$\bar{4}04$
						2.471	$\bar{5}12$
70B	2.45	35	2.446	ms	2.447	2.448	800
						2.441	$\bar{2}13$
		6	2.419	w	2.426	2.429	$\bar{8}02$
						2.417	013
						2.411	$\bar{6}11$
						2.323	$\bar{4}13$
						2.310	204
70	2.25	35	2.258	m	2.259	2.262	213
						2.238	611
		5	2.185	vw	2.186	2.183	710
						2.182	512
40D	2.16	9	2.147	w	2.149	2.146	$\bar{7}12$
		6	2.116	w	2.119	2.115	$\bar{6}13$
						2.067	$\bar{1}14$
70	2.05	2	2.059	w	2.060	2.057	$\bar{3}14$
						2.053	404
				m	2.040	2.039	$\bar{8}11$
						2.038	413
		25	2.030	m	2.032		
		9	1.995	mw	1.996		
60D	1.95	13	1.963	mw	1.965		
40	1.88	9	1.884	w	1.886		
40	1.83	5	1.851	Plus more than 30 additional lines			
		3	1.807				
60	1.78	18	1.779				
70	1.73	25	1.743				
		5	1.720				
		5	1.682				
		25	1.662				
70	1.65	5	1.650				
		3	1.632				
		2	1.614				
60	1.59	13	1.598				
20	1.55	5	1.554				
40	1.51	9	1.519				
		3	1.495				
20	1.46	3	1.471				
		3	1.449				
		3	1.433				
		6	1.413				
40B	1.40	9	1.398				
40	1.37	3	1.379				
		2	1.371				
40	1.35	2	1.356				
60	1.32	5	1.330				
40	1.30	9	1.304				
		3	1.287				
		2	1.269				
		3	1.258				
40B	1.25	2	1.247				
40	1.21	2	1.212				
		2	1.188				
40	1.17	3	1.173				
20	1.15	2	1.152				
50	1.13	3	1.130				
		2	1.120				
40	1.11	5	1.109				
		2	1.100				
		1	1.090				
		1	1.065				
40D	1.06	2	1.057				
		1	1.044				
50	1.03	1	1.034				
50	1.02	1	1.015				
50	1.00	3	1.006				
		2	.9961				
		2	.9897				
		2	.9809				
		2	.9755				
		2	.9660				
		Plus additional weak lines					

[1] X-ray crystallographic data from Brown, Peiser, and Turner-Jones (1949).
[2] Powder diffraction data by British Museum of Natural History for trona from Lake Magadi, Kenya Colony. Camera diameter not indicated. Copper radiation, aluminum filter (λ=1.541 A). B=broad; D=diffuse.
[3] Film corrected for shrinkage. Camera diameter, 114.59 mm. Copper radiation, nickel filter (λ=1.5418 A). Lower limit 2θ measurable: 7.0° (12.6 A).
[4] Powder diffraction data for trona from Searles Lake, California. Camera diameter not indicated. Copper radiation, nickel filter.

TABLE 20.—*X-ray powder data for nahcolite*, $NaH(CO_3)$, *from the oil-shale mine of the Bureau of Mines, near Rifle, Colo.*

[Monoclinic, $P2_1/n - C^5_{2h}$; $a=7.525\pm0.04$ A, $b=9.72\pm0.04$, $c=3.53\pm0.03$, $\beta=93°19'$]

Measured[2] (film 14040)		Calculated		Measured[2] (film 14040)		Calculated	
I	d_{hkl}	d_{hkl}	hkl	I	d_{hkl}	d_{hkl}	hkl
6	5.92	5.94	110	13	1.613		
13	4.85	4.86	020	6	1.580		
5	4.07	4.08	120	2	1.559		
2	3.74	3.76	200	2	1.539		
15	3.48	3.50	210	13	1.522		
		3.32	011	3	1.480		
6	3.25	3.27	$\bar{1}01$	3	1.465		
		3.13	101	3	1.442		
25	3.08	3.10	$\bar{1}11$	2	1.422		
100	2.97	2.98	111	2	1.399		
		2.98	130	2	1.372		
		2.97	220	3	1.354		
13	2.69	2.71	$\bar{1}21$	2	1.343		
90	2.60	2.63	121	2	1.334		
		2.56	$\bar{2}11$	4	1.298		
2	2.453	2.453	230	2	1.284		
		2.430	040	2	1.272		
		2.425	310	2	1.246		
2	2.418	2.424	211	2	1.236		
5	2.390	2.388	031	2	1.221		
		2.328	$\bar{2}21$	2	1.211		
		2.312	140	2	1.208		
13	2.305	2.302	$\bar{1}31$	2	1.196		
2	2.254	2.251	131	3	1.182		
		2.226	320	1	1.159		
18	2.217	2.225	221	2	1.151		
2	2.108	2.101	$\bar{3}01$	3	1.139		
		2.054	$\bar{3}11$	2	1.127		
		2.052	$\bar{2}31$	2	1.113		
18	2.032	2.040	240	2	1.098		
5	1.984			2	1.088		
13	1.965			1	1.078		
5	1.931			3	1.069		
15	1.900			1	1.047		
3	1.872			3	1.042		
2	1.823			2	1.032		
2	1.778			3	1.029		
9	1.735			2	1.014		
5	1.687			Plus additional weak lines			
6	1.658						
3	1.637						

[1] Single-crystal data from Laue and rotation methods by Zachariasen (1933); converted to angstrom units from the original values given by Zachariasen.
[2] Film corrected for shrinkage. Camera diameter, 114.59 mm. Copper radiation, nickel filter (λ=1.5418 A). Lower limit 2θ measurable: 7.0° (12.6 A).

TABLE 21.—*X-ray powder data for northupite*, $Na_3MgCl(CO_3)_2$, *from the John Hay, Jr., well 1, Sweetwater County, Wyo.*

[Isometric, $Fd3m = O^7_h$ $a=14.08$ A[1]]

Measured[2] (film 14090)		Calculated		Measured[2] (film 14040)		Calculated	
I	d_{hkl}	d_{hkl}	hkl	I	d_{hkl}	d_{hkl}	hkl
60	8.132	8.130	111	2	1.240		
25	4.983	4.980	022	1	1.229		
1	4.240	4.244	113	1	1.205		
9	4.062	4.063	222	1	1.192		
18	3.520	3.520	004	5	1.189		
18	3.226	3.230	133	<1	1.171		
18	2.874	2.874	224	<1	1.159		
71	2.706	2.709	333	<1	1.142		
		2.709	115	2	1.138		
100	2.488	2.489	044	2	1.129		
13	2.375	2.380	135	<1	1.112		
		2.347	244	5	1.109		
9	2.225	2.226	026	2	1.101		
6	2.146	2.147	335	2	1.099		
35	2.122	2.123	226	2	1.085		
9	2.030	2.033	444	3	1.075		
9	1.970	1.971	117	2	1.073		
		1.971	155	2	1.069		
6	1.881	1.883	246	<1	1.061		
5	1.831	1.833	137	2	$1.052\alpha_1$		
		1.833	355	2	$1.050\alpha_2$		
30	1.758	1.760	008	2	$1.037\alpha_1$		
		1.720	337	1	$1.036\alpha_2$		
5	1.657	1.659	066	2	$1.015\alpha_1$		
		1.659	288	2	$1.015\alpha_2$		
3	1.623	1.626	555	2	$1.007\alpha_1$		
25	1.614	1.615	266	2	$1.006\alpha_2$		
2	1.572	1.574	048	<1	$1.000\alpha_1$		
<1	1.546			<1	$.9998\alpha_2$		
3	1.535			5	$.9841\alpha_1$		
5	1.498			2	$.9835\alpha_2$		

See footnotes at end of table.

TABLE 21.—X-ray powder data for northupite, $Na_3MgCl(CO_3)_2$, from the John Hay, Jr., well 1, Sweetwater County, Wyo.—Continued

Measured [2] (film 14090)		Calculated		Measured [2] (film 14040)		Calculated	
I	d_{khl}	d_{hkl}	hkl	I	d_{khl}	d_{hkl}	hkl
2	1.473			1	.9744α1		
13	1.455			<1	.9740α2		
5	1.413			2	.9650α1		
3	1.379			1	.9647α2		
5	1.360			2	.9499α1		
5	1.353			2	.9491α2		
5	1.312			3	.9393α1		
2	1.283			2	.9387α2		
1	1.269			Plus additional			
9	1.243			weak lines.			

[1] Converted to angstrom units from original value of 14.05 kX (Shiba and Watanabe, 1931).
[2] Shrinkage negligible. Camera diameter, 114.59 mm. Copper radiation, nickel filter (λ=1.5418 A). Lower limit 2θ measurable: 7.0° (12.6 A).

TABLE 22.—X-ray powder data for bradleyite, $Na_3Mg(PO_4)(CO_3)$, from the Westvaco mine, Sweetwater County, Wyo.

[Monoclinic, $P2_1/m$—C^2_{2h}; a=8.85 A, b=6.63, c=5.16 (all ±0.01 A), β=90°25'±05' [1]]

Fahey and Tunell (1941)[2] Measured		Mrose (unpublished data)[3] Measured (film 12960)		Calculated	
I	d_{hkl}	I	d_{hkl}	d_{hkl}	hkl
3	8.939	50	8.85	8.850	100
		3	5.308	5.306	110
		18	4.468	4.472	$\bar{1}01$
				4.443	101
				4.425	200
				4.072	011
				3.707	$\bar{1}11$
5	3.680	25	3.694	3.691	111
				3.680	210
		3	3.368	3.371	$\bar{2}01$
				3.347	201
10	3.319	71	3.312	3.315	020
		3	3.105	3.104	120
				3.005	$\bar{2}11$
2	2.969	9	2.986	2.988	211
		4	2.946	2.950	300
		2	2.789	2.789	021
				2.695	310
				2.663	$\bar{1}21$
10	2.658	100	2.655	2.657	121
				2.653	200
		35	2.576	2.580	002
				2.569	$\bar{3}01$
8	2.566	18	2.556	2.553	301
½	2.467	6	2.480	2.482	102
				2.472	102
		2	2.401	2.404	012
				2.395	$\bar{3}11$
½	2.388	13	2.383	2.382	311
				2.364	$\bar{2}21$
				2.355	221
		3	2.321	2.324	$\bar{1}12$
½	2.313	9	2.312	2.316	112
		2	2.233	2.236	$\bar{2}02$
				2.222	202
3	2.209	13	2.208	2.212	400
		3	2.200	2.204	320
		6	2.144	2.144	130
4	2.116	13	2.115	2.119	$\bar{2}12$
				2.107	212
				2.099	410
				2.039	$\bar{4}01$
		6	2.034	2.036	022
				2.032	031
				2.031	$\bar{3}21$
½	2.025			2.028	401
				2.023	321
		3	1.979		
		9	1.948		
4	1.935	9	1.933		
8	1.842	30	1.839		
½	1.760	5	1.769		
		9	1.708		
		9	1.673		
6	1.658	25	1.655		
		3	1.628		
½	1.598	3	1.603		
3	1.562	6	1.569		
		3	1.556		

See footnotes at end of table.

TABLE 22.—X-ray powder data for bradleyite, $Na^3Mg(PO_4)(CO_3)$, from the Westvaco mine, Sweetwater County, Wyo.—Continued

Fahey and Tunell (1941)[2] Measured		Mrose (unpublished data)[3] Measured (film 12960)		Calculated	
I	d_{hkl}	I	d_{hkl}	d_{hkl}	hkl
		3	1.550		
		6	1.501		
4	1.494	4	1.489		
		2	1.470		
		4	1.455		
3	1.443	4	1.443		
		3	1.418		
4	1.385	18	1.389		
2	1.331	4	1.329		
2	1.288	4	1.292		
1	1.251	4	1.254		
½	1.224				
1B	1.186	4	1.193		
2	1.151				
3	1.101	3	1.103		
2	1.068	4	1.072		
		6	1.058		
1	1.038				
½	1.011				
½	.987				

[1] X-ray crystallographic data obtained by Mrose (Mrose, unpublished data) by the Buerger precession method on crystals of bradleyite from the Green River formation, Westvaco mine, Sweetwater County, Wyo.
[2] B=broad. Camera diameter and wavelength not indicated. Copper radiation, nickel filter.
[3] Film corrected for shrinkage. Camera diameter, 114.59 mm. Copper radiation, nickel filter (λ=1.5418 A). Lower limit 2θ measurable: 7.0° (12.6 A).

TABLE 23.—X-ray powder data for pirssonite, $Na_2Ca(CO_3)_2 \cdot 2H_2O$, from the John Hay, Jr., well 1, Sweetwater County, Wyo.

[Orthorhombic, $Fdd2$—$D^{24}_{2h}=V^{24}_h$; a=11.32 A, b=20.06, c=6.00 [1]]

ASTM (Card 2-0157)[2] Measured		Present study[3] Measured (film 14588)		Calculated	
I	d_{hkl}	I	d_{hkl}	d_{hkl}	hkl
100	5.14	71	5.133	5.125	111
				5.015	040
		60	4.928	4.929	220
40	4.17	18	4.157	4.154	131
		6	3.752	3.754	240
90−	3.18	25	3.198	3.199	151
		50	3.153	3.154	311
90−	2.88	50	2.885	2.882	331
				2.879	260
				2.874	022
		6	2.829	2.830	400
70	2.72	35	2.726	2.724	420
90−	2.66	90	2.654	2.651	202
90−	2.57	80	2.565	2.563	222
				2.521	171
100	2.49	100	2.506	2.508	080
				2.499	351
				2.465	440
10	2.35	13	2.348	2.343	242
		25	2.294	2.293	280
20	2.22	5	2.234	2.233	062
		3	2.160	2.160	460
90−	2.13	35	2.130	2.133	371
70	2.10	25	2.105	2.107	511
				2.077	262
		18	2.055	2.055	191
90	2.02	71	2.020	2.019	531
				2.017	422
10	1.96	3	1.963	1.960	113
				1.904	442
60	1.89	18	1.893	1.891	2.10.0
				1.889	133
		6	1.876	1.877	480
				1.873	551
		9	1.853	1.854	620
				1.828	391
70	1.82	25	1.823	1.822	282
90	1.77	50	1.770	1.768	153
				1.766	640
				1.760	313
		3	1.753	1.753	462
				1.724	1.11.1
60	1.71	13	1.710	1.708	333

See footnotes at end of table.

TABLE 23.—*X-ray powder data for pirssonite,* $Na_2Ca(CO_3)_2 \cdot 2H_2O$, *from the John Hay, Jr., well 1, Sweetwater County, Wyo.*—Continued

| ASTM (Card 2-0157) [2] | | Present study [3] | | | |
| Measured | | Measured (film 14588) | | Calculated | |
I	d_{hkl}	I	d_{hkl}	d_{hkl}	hkl
		13	1.702	1.703	571
30	1.67	13	1.668	1.672	0.12.0
		6	1.640	1.643	660
				1.637	4.10.0
30	1.63	6	1.627	1.623	173
				1.617	353
30	1.60	13	1.602	{ 1.603	2.12.0
				1.600	2.10.2
				1.597	602
				1.591	482
				1.584	3.11.1
		5	1.579	1.577	622
20	1.56	9	1.555	1.557	711
				1.535	592
60	1.52	18	1.521	1.522	641
				1.521	731
30	1.50	9	1.505	{ 1.508	680
				1.504	373
30	1.47	6	1.465		
60	1.44	18	1.439		
20	1.41	6	1.413		
40	1.38	9	1.388		
20	1.36	5	1.359		
10	1.34	3	1.335		
		9	1.318		
		9	1.296		
		3	1.287		
		9	1.278		
		6	1.258		
		5	1.246		
		6	1.235		
		6	1.228		
		6	1.216		
		3	1.203		
		5	1.194		
		5	1.186		
		5	1.177		
		5	1.155		
		5	1.146		
		6	1.132		
		9	1.107		
		9	1.077		
		2	1.065		
		2	1.053		
		5	1.038		
		2	1.030		
		2	1.021		
		9	1.010		
		5	1.001		
		5	.9822		
		Plus additional weak lines			

[1] X-ray crystallographic data obtained by Evans (1948) by the Buerger precession method on crystal of pirssonite from Searles Lake, Calif.
[2] Powder diffraction data by Imperial Chemical Industries of Northwich, England, presumably on synthetic material. Camera diameter not indicated. Molybdenum radiation ($\lambda = 0.709$ A).
[3] Film corrected for expansion. Camera diameter, 114.59 mm. Copper radiation, nickel filter ($\lambda = 1.5418$ A). Lower limit 2θ measurable: 7.0° (12.6 A).

TABLE 24.—*X-ray powder data for gaylussite,* $Na_2Ca(CO_3)_2 \cdot 5H_2O$, *from the John Hay, Jr., well 1, Sweetwater County, Wyo.*

[Monoclinic, $I2/a$—C^6_{2h}; $a = 11.57 \pm 0.01$ A, $b = 7.765 \pm 0.005$, $c = 11.20 \pm 0.01$, $\beta = 102°00' \pm 05'$]

| ASTM (Card 2-0122) [2] | | ASTM (Card 2-0528) [2] | | Mrose (unpublished data) [3] | | | |
| Measured | | Measured | | Measured (film 14651) | | Calculated | |
I	d_{hkl}	I	d_{hkl}	I	d_{hkl}	d_{hkl}	hkl
100	6.41	60	6.40	100	6.403	6.402	110
						6.333	011
50	5.57			18	5.662	5.659	200
				13	5.471	5.476	002
				25	4.495	4.496	$\bar{2}11$
70	4.45	40	4.45	35	4.428	4.429	112

TABLE 24.—*X-ray powder data for gaylussite,* $Na_2Ca(CO_3)_2 \cdot 5H_2O$, *from the John Hay, Jr., well 1, Sweetwater County, Wyo.*—Continued

| ASTM (Card 2-0122) [2] | | ASTM (Card 2-0528) [2] | | Mrose (unpublished data) [3] | | | |
| Measured | | Measured | | Measured (film 14651) | | Calculated | |
I	d_{hkl}	I	d_{hkl}	I	d_{hkl}	d_{hkl}	hkl
						4.421	$\bar{2}02$
				13	3.943	3.989	211
						3.939	112
50	3.90					3.882	020
						3.582	202
30	3.56			9	3.555	3.555	$\bar{1}21$
				9	3.417	3.413	121
						3.393	310
				25	3.308	3.305	013
80	3.18	100	3.19	100	3.203	3.202	220
						3.168	022
				9	3.159	3.161	$\bar{3}12$
				3	3 121	3.120	$\bar{2}13$
40	3.02						
40	2.91			18	2.921	2.917	$\bar{2}22$
				3	2.831	2.829	400
						2.759	$\bar{4}02$
						2.739	004
		40	2.71	80	2.726	2.723	321
						2.708	$\bar{4}11$
80	2.70			35	2.692	2.695	$\bar{2}04$
						2.682	$\bar{1}23$
						2.670	312
						2.646	213
80	2.61	80	2.63	80	2.635	{ 2.632	222
						2.632	$\bar{1}14$
						2.540	321
						2.523	130
70	2.49	20	2.50	50	2.515	2.519	031
						2.506	123
				2	2.478	2.475	411
40	2.40	10	2.40	13	2.420	2.418	114
				2	2.386	2.383	$\bar{4}13$
				6	2.356	2.357	$\bar{3}14$
						2.348	$\bar{3}23$
						2.344	231
50	2.32	10	2.32	18	2.330	{ 2.333	$\bar{1}32$
						2.325	402
				9	2.290	{ 2.287	420
						2.286	204
40	2.26			13	2.259	2.261	231
						2.253	132
						2.249	$\bar{4}22$
						2.238	024
40	2.19	20	2.20	18	2.212	{ 2.213	$\bar{2}24$
						2.210	404
				9	2.176	2.173	510
30	2.15			13	2.137	2.134	330
40	2.12	25	2.12			2.120	$\bar{2}15$
				3	2.113	2.111	033
						2.109	015
				3	2.065	{ 2.073	$\bar{3}32$
						2.061	$\bar{2}33$
10	2.02			9	2.030	2.034	323
70	1.98	35	1.99	25	1.994		
80	1.91	40	1.92	35	1.920		
				18	1.895		
				5	1.873		
20	1.85	15	1.85	9	1.855		
				5	1.841		
		15	1.83	18	1.824		
60	1.81			2	1.812		
30	1.78			9	1.787		
				5	1.752		
				13	1.729		
60	1.71	20	1.72	13	1.720		
				5	1.701		
				18	1.677		
60	1.67	20	1.67	18	1.675		
				3	1.652		
				3	1.610		
40D	1.60			2	1.590		
				2	1.583		
				2	1.562		
				9	1.540		
40	1.53			6	1.512		
40	1.50			6	1.491		
				3	1.477		
				3	1.447		
				3	1.438		
				3	1.417		
				3	1.366		
				3	1.358		
				3	1.348		
				3	1.332		
				6	1.297		

See footnotes at end of table.

TABLE 24.—*X-ray powder data for gaylussite*, $Na_2Ca(CO_3)_2 \cdot 5H_2O$, *from the John Hay, Jr., well 1, Sweetwater County, Wyo.*—Continued

ASTM (Card No. 2-0122)[2]		ASTM (Card No. 2-0528)[2]		Mrose (unpublished data)[3]			
Measured		Measured		Measured (film 14651)		Calculated	
I	d_{hkl}	I	d_{hkl}	I	d_{hkl}	d_{hkl}	hkl
				3	1.281		
				3	1.261		
				2	1.248		
				2	1.238		
				3	1.218		
				2	1.202		
				3	1.179		
				3	1.166		
				5	1.152		
				3	1.130		
				2	1.112		
				2	1.095		
				3	1.074		
				2	1.065		
				2	1.060		
				2	1.046		
				2	1.034		
				2	1.024		
				2	1.011		
				2	.9969		

[1] X-ray crystallographic data obtained by Mrose (unpublished data) by the Buerger precession method on crystal of gaylussite from the Green River formation, Westvaco mine, Sweetwater County, Wyo.
[2] Powder diffraction data for laboratory prepared materials. Camera diameter not indicated. Molybdenum radiation ($\lambda = 0.709$ A).
[3] Film shrinkage negligible. Camera diameter, 114.59 mm. Copper radiation, nickel filter ($\lambda = 1.5418$ A). Lower limit 2θ measurable: 7.0° (12.6 A).

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