

# THE MINERALS OF THE PHOSPHATE NODULES FROM NEAR FAIRFIELD, UTAH<sup>1</sup>

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## INTRODUCTION

In 1894, Mr. F. T. Millis of Lehi, Utah, sent to the United States National Museum a nodule about seven inches across that was made up mostly of a yellow material in which are embedded several small nodules of green variscite. The green variscite and yellow mineral are separated by a narrow layer of a white powdery material. R. I. Packard<sup>2</sup> made partial analysis of all three of the materials.

Later a considerable number of these nodules were secured by Ward's Natural Science Establishment and Dennison<sup>3</sup> analyzed and gave the name of wardite to the light green to bluish green mineral of concretionary habit which he found in many of the nodules.

In the early spring of 1923 the authors undertook to study again these nodules and the present paper is the result. The specimens in the United States National Museum were first studied and later those at Harvard University and a large collection kindly lent us by Ward's Natural Science Establishment. We take this occasion to thank Mr. George L. English and the Ward's Natural Science Establishment for their generosity in placing their whole collection of the nodules at our disposal.

Our study was rather intensive but not exhaustive. Calcite, variscite, and wardite are present in most of the nodules and eight new minerals were segregated, studied optically and physically, and analyzed, and some others were studied optically but were not segregated for analysis. Others are no doubt present and any trained mineralogist aspiring to describe and name a new mineral can probably find one in these nodules by careful search. The original deposit, if it should ever be opened up again, will

<sup>1</sup> Published with the permission of the Director of the U. S. Geological Survey and the Secretary of the Smithsonian Institute.

<sup>2</sup> Packard, R. I. Variscite from Utah, *Am. J. Sc.*, [III], 47, p. 297, 1894.

<sup>3</sup> Dennison, J. M. Wardite, a new basic phosphate of alumina, *Am. J. Sci.*, [IV], 2, p. 154, 1896.

be a most interesting mineral locality and should yield many new species.

In the summer of 1927, Larsen made a short visit to the wardite locality and collected a few poor specimens from the dump. The deposit is located a short distance north of the north fork of the south fork of Clay Canyon, about three-quarters of a mile above the road and clay pit, 2.8 miles from Fairfield South, and  $5\frac{1}{2}$  miles west of Fairfield, Utah. It was prospected by a short tunnel and drift. The phosphate nodules occur along thin discontinuous veinlets in gray limestones. One outcrop is 20 feet above the tunnel and a second is said to be covered by the dump. Very little of the phosphates are now exposed.

#### DESCRIPTION OF THE HAND SPECIMENS

Most of the minerals described in the following paper are new species. A list of the species, their chemical composition, optical and other properties are given in table 12, near the end of this paper.

The nodules are ellipsoidal or discoidal in shape and vary in size from a fraction of an inch to 8 inches. They are imbedded in a matrix of quartz and calcite. The phosphate nodules are sharply separated from the quartz-calcite matrix. Most of the smaller nodules are made up almost entirely of a compact sulphur yellow material with a little coarsely crystalline calcite, and have a central cavity with rough walls. The yellow material is in concentric layers of slightly differing color and density and resembles a metacolloid. It is made up chiefly of pseudowavellite.

Some of the large nodules are very similar but most of them have a number of minerals, arranged more or less in concentric layers or in part lining or filling cavities. The whole mass has the appearance commonly ascribed to a metacolloid, with concentric layering, shrinkage cracks, etc.

Some of the nodules have an outer shell, rarely as much as a millimeter thick which is gray to nearly colorless and vitreous. Veinlets of this material also cut across the yellow. It is an intimate mixture of pseudowavellite and deltaite. Other nodules made up largely of the yellow pseudowavellite have lenses or less regular cavities lined with calcite or with white fibrous or spherulitic crusts. These are dennisonite, lehiite, or an undetermined mineral. In some the original cavity is entirely filled. In a few cavities are perched plumes made up of small white hexagonal

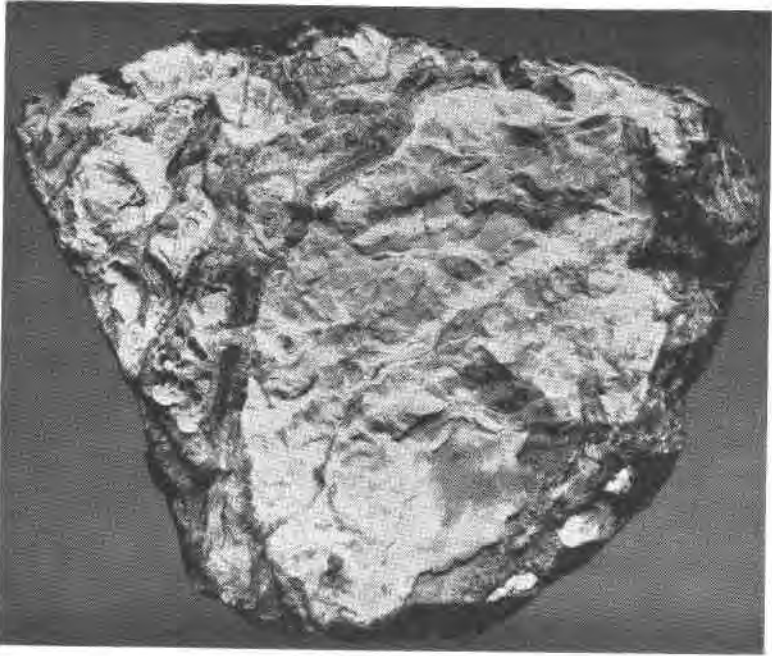


PLATE I. Phosphate nodule in the collections of the National Museum.



PLATE II. Polished phosphate nodule in the collections of the National Museum.

needles of dehrnite or lewistonite. Some of the yellow nodules have cores of bright green variscite. Rare nodules have a core of variscite, surrounded by a layer a millimeter or so thick, of white, powdery or chalky pseudowavellite (?), outside of which is a layer about a centimeter thick of dense, banded deltaite that looks like chert and has some thin colorless layers. Beyond this and sharply separated from it is an outer crust about a centimeter thick of cream color and made up of oölites a millimeter across in a scant matrix. They are intergrowths of pseudowavellite and deltaite.

Many of the nodules have irregular layers, mostly less than a millimeter across, of clear vitreous light green granular wardite. This is closely associated with vitreous, thinly banded white crusts of millisite resembling banded chalcedony. In places these two crusts were clearly deposited on the yellow pseudowavellite or on the variscite and the millisite was first deposited. This relationship is especially well shown where spherulites of these minerals are attached to the pseudowavellite or penetrate the variscite. The white millisite in all cases forms the center of the spherulites and the pale green wardite forms the outer crust. In a few specimens layers of the two kinds alternate in the spherulites. In a few specimens the light green wardite forms rude crystals, half a millimeter across, in the more porous parts.

In a few of the nodules, crusts, rarely much over a millimeter thick, of a clear, glassy, cleavable mineral (gordonite), separate the variscite from the other minerals. In some specimens this crust completely encrusts the variscite, in others it forms a lens on one side of the variscite. In cavities some good crystals of this cleavable mineral can be found.

In a very few nodules, crusts very much like those described in the preceding paragraph and occupying the same position, are made up of a mineral with a somewhat more platy curved micaceous cleavage (englishite).

#### METHODS OF STUDY

In the study of minerals that are so finely crystalline, so intimately intergrown, in such small masses, and so similar in their physical, optical, and chemical properties, the petrographic microscope and the immersion method are well-nigh indispensable. Heavy solution separations are necessary and for the micaceous

mineral, tapping on a sheet of paper was the only means found of cleaning it from variscite. The electromagnet was of no use as all of the minerals were found to be nonmagnetic, even to a strong electromagnet. Hand picking was found useful for preliminary separation and for getting rid of the bulk of a colored mineral like variscite. At every step in the process of preparing the samples for analysis the products were checked with the immersion method and the microscope and the next step largely depended on the result of this examination. Patience and no little thought and ingenuity were required even for what seemed to be a simple heavy solution separation, as the results were rarely just what one expected and still more rarely what one wanted. It is usually necessary to pass the sample through several liquids with different gravities.



FIG. 1. Separatory funnel.

Carbon tetrachloride (gravity = 1.60), bromoform ( $g. = 2.90$ ) and methylene iodide ( $g. = 3.32$ ) were used as heavy solutions. They can be mixed to form a solution of any desired gravity.

Most of the samples were small and on account of the inevitable loss of material in removing the last few per cent of impurities most of the samples analyzed contained some impurities. These impurities were determined under the microscope and the proportion estimated by counting the grains. A correction was then made in the analysis.

The separating funnels found most satisfactory have straight, steep sides and an open top as shown in figure 1. The hole in the stopcock should be large enough to allow the coarsest particles used to pass through easily but not so large as to allow the liquid

to flood through too quickly when the stopcock is opened wide. A diameter of about 3 millimeters for the opening is found satisfactory but it can be larger for a large funnel. It is very necessary that the slope of the funnel continue regularly to the opening in the stopcock as a shoulder above the stopcock will prevent some of the settled sand from coming through the stopcock readily. The upper lip of the funnel is ground and a cover of ground glass or a watch glass can be used.

The sample to be separated with heavy solutions is ground only so fine as is necessary to separate the different minerals as a coarse powder can be separated more quickly with a cleaner product than a fine one. Twenty mesh is very readily handled but for most of the minerals of the phosphate nodules finer grinding was required. Anything that will hold on a 200 mesh screen can be readily separated, and even finer material can be used but with much more difficulty. The grinding should be done in stages so as to produce the minimum amount of fines—grind a little, then screen, regrind the part that is still too coarse, and repeat until all passes the screen. Sizing before attempting to separate is helpful if the sample is large but is less necessary if the sample is small. Where material finer than 200 mesh is present the sample may have to settle over night or even longer before the liquid is clear, and the settling complete. Where much fine material is present the powder must be passed through the liquid repeatedly to get a clean product. A centrifuge is necessary for very fine material.

Before attempting a separation the powder is examined under the microscope to determine the minerals present, to see if the grains are made up of one mineral, as far as possible, and to recognize alteration products, gas inclusions, inhomogeneity, etc.

If the specific gravity of the minerals is known, a liquid is chosen that is between the minerals to be separated and preferably near that of the mineral it is desired to get in a pure state, so as to eliminate mixed and doubtful grains. If the specific gravity of the minerals is not known they may be roughly estimated from their mean index of refraction or a liquid can be prepared by immersing small grains of the minerals. Finally, the powder can be put into any liquid and the gravity of the liquid changed by adding a liquid with higher or lower gravity, as desired until a liquid is found that will give a satisfactory separation.

The funnel is about half filled with the liquid, the powder added,

and more liquid to wash down and mix with the powder. It may be stirred with a stirring rod. Any mineral on the sides of the funnel should be washed down. After the minerals have settled, if the light mineral is wanted, and no great economy of material is necessary, the heavy part is allowed to pass through the stopcock on to a coarse filter paper. It is washed with alcohol and the washings saved to recover the heavy solution by washing out the alcohol with water.

The light part is stirred into the solution again and the sides washed down with more liquid. By repeating this several times all of the heavy material is separated out and the light part is filtered from the liquid, washed with alcohol, dried, and examined with the microscope to determine what must be done next. The heavy part is also examined. By using a lighter liquid a cleaner product may be had by sacrificing some of the mineral.

The next step will depend on the results of the first trial. With fine grained, unknown minerals one trial is rarely sufficient and several are usually required.

If it is desired to get a clean product of the heavy part, it is run into a second separatory funnel that is two-thirds full of solution and allowed to settle through this liquid. Three separations are usually sufficient unless the powder is very fine or a large amount is used.

The gravity of any liquid can be changed in the funnel by adding a liquid of different gravity.

It was found impossible to separate the englishite from the variscite with a heavy solution. The micaceous nature of the englishite was therefore taken advantage of and the fine powder, made up of about equal amounts of each mineral, was placed on a sheet of paper or a filing card and by gently shaking and tapping, the rounded grains of variscite rolled off the card while the flakes of englishite remained behind. A piece of soft filter paper or japanese lens paper was found to hold the coarser flakes better than ordinary paper. By repeated cleaning in this way a product with less than 10% of variscite was procured. It was found best to retain only a little of the englishite at each operation, and to recover from the tailings repeatedly. Unless great care is taken much of the sample, and chiefly the platy mineral, will be lost by floating in the air.

In the microscopic study thin sections gave chiefly the relation

of the different minerals and crusts to each other while the immersed powders were found most valuable. In studying the powders all the optical properties of the minerals were determined. Interference figures were necessary with these minerals more than is commonly the case as several of the commonest minerals of the nodules have indices of refraction that are somewhat variable and between 1.59 and 1.64, and the birefringence of most of the minerals is near 0.01. The habit, form, extinction angles, elongation, etc., are variable and only partially characteristic. Until considerable familiarity with all the minerals was had, it was necessary to get all the properties of a mineral before it could be identified with assurance.

In the course of the heavy solution separations many immersions were made—probably over a hundred for some of the separations. This involves less time than might be thought as a powder with only a few minerals, all of whose properties are known, can be examined and rough estimates of the proportions of each of the constituents made in a few minutes.

The specific gravity was determined by floating in heavy solutions or in part by noting the specific gravities of the liquids that just settled and just floated the mineral in the course of the heavy solution separation. Most minerals settle over a moderate range of specific gravities due to included gas pores or other inclusions. The clearest crystals are the heaviest and the specific gravity of the mineral is not far from that of the liquid in which a few of the purest mineral grains just settle.

The study began with a careful examination of the hand specimens in the National Museum collections. Each crust or layer was then studied with the microscope by breaking or scraping with a knife or file enough material for a few immersions. The properties of all the minerals in the powder and their relations to each other were determined, their proportions roughly estimated and the suitability of the material for yielding samples of any of the minerals considered.

The crust or lens that was selected to yield the powder to be analyzed for a particular mineral was then broken out or scraped off with a sharp tool or filed off with a file and the mineral purified as described in the preceding pages. Most of the minerals are too hard to scrape off easily with a knife but a file worked well through it yielded a rather fine powder. Hand picking was resorted



to where necessary and possible and in most cases it was found expedient to remove some of the larger pieces of impurities by hand picking.

#### METHODS OF ANALYSIS

The samples which were available for analysis were of small size and had, in every case, been prepared at very great cost of time and labor. In few cases was it possible to use portions of more than 100 milligrams of any of the minerals for the analytical procedure. This made it necessary to follow a routine of methods which was simplified as far as possible to avoid the use of excessive quantities of reagents. Certain preliminary conditions proved fortunate. First, the minerals concerned, with few exceptions, were free from volatile substances other than water and contained no oxidizable elements so that a fairly exact estimation of the water content could be secured by weighing the loss on ignition. Further, after ignition, all were completely soluble on digestion in warm 1:1 hydrochloric acid. Qualitative tests showed them to be free from more than a trace of iron.

For the analyses (made by Shannon) the samples were placed in a small platinum crucible, heated for two hours at 110° C. and weighed, then heated slowly to a full red heat. After the second weighing the mineral was dissolved in warm 1:1 hydrochloric acid and the undissolved portion filtered off.

To the chloride solution there next was added a known amount of iron in the form of ferric chloride. This was prepared by dissolving an amount of very pure iron wire, approximately equal to the weight of the sample taken, in a small amount of hydrochloric acid to which a few drops of nitric acid had been added. The solution was then thrice precipitated with ammonia in the presence of an excess of ammonium chloride, the volume of both solutions and reagents being kept small.

From the weight of  $P_2O_5$ ,  $Fe_2O_3$  and  $Al_2O_3$  obtained from the weighted and ignited precipitate, the calculated weight of  $Fe_2O_3$  added was deducted, the weight of  $P_2O_5 + Al_2O_3$  in the mineral thus being obtained. The precipitate was then carefully mixed with a large excess of sodium carbonate and cautiously brought to full fusion and thoroughly fused over the blast. After cooling this was brought into solution with 1:1 nitric acid and when the solution had become clear, it was heated to boiling and treated

with 60 cc. of ammonium molybdate. The precipitate of ammonium phospho-molybdate was filtered on a small tared gooch crucible. This was dried at 110° C. for one hour and then placed in a small air bath and the temperature held at 450–500° C. for one hour. It was then weighed as  $\text{MoO}_3 \cdot 24\text{P}_2\text{O}_5 = 0.03946 \text{ P}_2\text{O}_5$ .

In the combined filtrates the lime is precipitated as oxalate and weighed as CaO.

Gonyer's procedure differed from Shannon's in that the  $\text{P}_2\text{O}_5$  was precipitated with ammonium molybdate immediately after dissolving the sample. The precipitate was then dissolved in ammonium hydroxide and reprecipitated with magnesia mixture. The excess molybdenum was removed from the solution containing the sample and the analysis completed by the usual methods.

When material was available a separate sample was taken for alkalis.

#### *Wardite*

Dennison<sup>4</sup> gave the name of wardite to the light green to bluish green mineral of concretionary habit in the cavities of the nodules from Lewiston, Utah. Wardite has not been accepted as a species but our study shows it to be a definite well-defined mineral and entitled to species rank.

Wardite was found chiefly as pale green granular layers or spherulites but also as nearly colorless thin layers within or on the outside of some of the dirty gray, chalcedonic nodules of millisite and in scattered crystals and thin crusts within the yellow pseudowavellite. It is nearly always distinctly crystalline and granular with individual grains as much as a millimeter across. In a few specimens it forms poorly developed, drusy crystal aggregates in the porous parts but no good crystals were found. Some fairly well formed crystals are embedded in the pseudowavellite and millisite and appear to have an octahedral or similar habit. A few basal sections are eight sided and the mineral is probably tetragonal. It has a perfect basal cleavage.

Wardite has a hardness of 5 and a specific gravity of 2.81. (2.77 Dennison.) It is fusible at 3 with intumescence to a blebby glass. It is difficultly but completely soluble in acid.

It is uniaxial positive and its indices of refraction vary slightly ( $\pm 0.005$ ). Those of the analyzed powder are,  $\omega = 1.590$ ,  $\epsilon = 1.599$ .

<sup>4</sup> Dennison, J. W. *Loc. cit.*

Some of the green layer was carefully picked out of the specimens and purified with heavy solution. A product weighing two grams was thus obtained for analysis which contained about 8% of millisite.

The analysis by Shannon and the ratios are shown in Table 1, together with the older analyses by Dennison and the theoretical composition.

TABLE 1.  
ANALYSIS AND RATIOS OF WARDITE

	1. Analysis Dennison	2. Analysis Shannon	2a. Corrected for Impurities	2b. Ratios	Theoretical $2\text{Na}_2\text{O} \cdot \text{CaO} \cdot$ $6\text{Al}_2\text{O}_3 \cdot 4\text{P}_2\text{O}_5 \cdot$ $17\text{H}_2\text{O}$
$\text{Al}_2\text{O}_3$	38.25 <sup>a</sup>	36.54	36.6	.359 = 60 x 6	36.77
FeO	0.76				
CaO		3.30	3.0	.054 = 54 x 1	3.36
MgO	2.40				
CuO	0.04				
$\text{Na}_2\text{O}$	5.98	6.68	7.0	.113 = 60 x 2	7.44
$\text{K}_2\text{O}$	0.24	0.73	0.6	.007	
$\text{P}_2\text{O}_5$	34.46	34.76	34.9	.245 = 61 x 4	34.08
$\text{H}_2\text{O}$	17.87	17.85	17.9	.999 = 58 x 17	18.35
	100.00	99.86	100.0		100.00

<sup>a</sup> By difference.

The analysis of Shannon corresponds very closely to the formula  $2\text{Na}_2\text{O} \cdot \text{CaO} \cdot 6\text{Al}_2\text{O}_3 \cdot 4\text{P}_2\text{O}_5 \cdot 17\text{H}_2\text{O}$ . That of Dennison is very similar but was probably made on a less pure sample.

#### *The Identity of Soumansite with Wardite*

In 1910, Lacroix<sup>5</sup> gave the name of soumansite to a mineral that he found in specimens from Montebbras. Soumansite occurred as tetragonal crystals of pyramidal habit implanted on amblygonite. It has a hardness of  $4\frac{1}{2}$  and a specific gravity of 2.87. It is optically positive and in part uniaxial, in part divided into four biaxial segments. A specimen kindly furnished the authors by Professor Lacroix has a small axial angle and fragments tend

<sup>5</sup> Lacroix, A. *Min. de la France*, 4, 451, 1910.

to be normal to the acute bisectrix, indicating a perfect basal cleavage.  $\alpha=1.586$ ,  $\beta=1.586$ ,  $\gamma=1.595$ .

A partial analysis by Pisani gave:  $P_2O_5=31.5$ ,  $Al_2O_3=36.5$ , and blowpipe tests indicated considerable  $H_2O$ ,  $Na_2O$ , and F.

The chemical composition of soumansite as far as it has been determined, is, therefore, essentially the same as that of wardite and, as the crystal form and the optical properties are almost identical, the two minerals are without doubt identical. As the name wardite has priority, it should be retained for the species.

#### *Pseudowavellite*

A mineral that agrees with pseudowavellite, recently described by Laubmann<sup>6</sup> is one of the chief minerals of most of the nodules examined by us. It constitutes most of the yellow crusts. It is rather dense and is made up of successive concentric layers of somewhat different color and texture. For the most part it shows no distinct crystalline texture megascopically. The microscope shows that it is composed of crusts of subparallel fibers or of matted fibers which are rather coarse in some layers and extremely fine in others. The fibers in the more coarsely crystalline layers tend to grow normal to the walls. The fibers have a negative elongation and the coarsest give a positive uniaxial interference figure. The indices of refraction vary from  $\omega=1.59$  to 1.625 probably due to admixtures. The coarsest and best grains have  $\omega$  near 1.620.

A sample of the yellow crusts made up of very finely fibrous material was cleaned and made as homogeneous as possible by heavy solutions and analyzed. The average indices of refraction of the analyzed material are  $\omega=1.618$ ,  $\epsilon=1.623$ . It has a specific gravity of 2.92 and a hardness of 5. It fuses at  $2\frac{1}{2}$  to a white bead. Nearly two grams of the mineral were separated as usual for analysis and were found to contain about 6 per cent of fibers of dennisonite and to have indices of refraction that vary only 0.01 from the average of the material. The analyses by Shannon and the ratios are shown in table 2 column 1.

A few of the nodules have a thick yellow layer outside of and sharply separated from a layer of gray, chalcedony-like material that is made up mostly of oölites about a millimeter across with some irregular bodies of compact vitreous yellow material. Both

<sup>6</sup> Laubmann, H. Die Phosphat-Mineralien und Edelerden des Amberg-Auerbacher Erzkörpers, *Geogn. Jahres.*, XXXV, 202-3, 1922.

the oörites and the vitreous parts are made up of two minerals intimately intergrown. Similar vitreous material, partly yellow but mostly gray is very common in the nodules and is commonly associated with the yellow fibrous pseudowavellite. In part it forms an outside shell to the nodules and in part is present as veinlike bodies cutting the pseudowavellite. The spherulites are formed of rather coarse fibers radiating from the center in four bundles or sheaves of fibers in the four quadrants. The vitreous crusts and veinlets are granular in texture. Both kinds are made up of two minerals the chief of which is in relatively coarse crystals and the other has a higher index of refraction, and is embedded in the first as fibers, rods, or prisms. The two extinguish together, have the same birefringence, and orientation so that the mixture looks homogeneous between crossed nicols. They are sharply distinct without gradation and stand out prominently when the powder is immersed in a liquid with an index of refraction between that of the two minerals, and the index test made by lowering the condenser or shading one side of the field.

The two minerals are distinct without any gradation and have uniform properties in all the specimens whether in the yellow pisolites, the green pisolites, the yellow or gray massive material, or the gray vitreous borders and veinlets in the yellow, fibrous pseudowavellite. The mineral that forms the greater part of the material and is the host is pseudowavellite. It makes up about three-fourths of most of the mixture. It is in grains up to one-half millimeter across. It has a hardness of about 5 and a specific gravity of 2.88. It fuses at  $2\frac{1}{2}$  to a white enamel. It is uniaxial positive and  $\omega=1.622$ ,  $\epsilon=1.631$ . It probably has a perfect basal cleavage. It may belong to the same crystal system as deltaite, which is trigonal. Its properties were very uniform throughout the numerous specimens examined.

Considerable difficulty was experienced in separating the two minerals but after grinding to pass a 200 mesh sieve and repeated separations, and discarding mixed grains, a sample of the pseudowavellite was prepared that weighed 0.5 grams and was estimated to carry only 10 per cent of deltaite. This sample was analyzed by Gonyer. The analysis is shown in column 2, table 2, the analysis corrected for the admixed deltaite and the ratios follow.

The analyses and ratios of the yellow crusts and of material in the oörites separated from deltaite from Lewiston, Utah,

TABLE 2.  
ANALYSES AND RATIOS OF PSEUDOWAVELLITE

	1. Yellow crusts		2. Oolites		3. Auerbach	4. Theoretical
	Anal.	Corrected	Anal.	Corrected		
Al <sub>2</sub> O <sub>3</sub>	34.15	35.3	35.92	36.8	28.18	34.34
Fe <sub>2</sub> O <sub>3</sub>						
Rare earths					5.79	
CaO	15.30	13.2	14.74	13.8	1.02	15.69
MgO	2.06	2.1	0.72	0.7	16.86	
Na <sub>2</sub> O			0.33	0.3	BaO=0.67	
K <sub>2</sub> O			0.13	0.1		
P <sub>2</sub> O <sub>6</sub>	32.23	31.7	30.53	30.3	30.10	31.82
H <sub>2</sub> O <sup>+</sup>	17.50	17.7	17.39	18.0	18.76	18.15
H <sub>2</sub> O <sup>-</sup>						
	101.24	100.0	99.76		101.38	100.00

Ratios = 7 x 51 or 6 x 60  
 .360 = 7 x 51 or 6 x 60  
 .246 } = 5 x 54  
 .017 }  
 .005  
 .001  
 .213 = 4 x 53  
 .999 = 18 x 56

are shown in columns 1 and 2 of table 2, the analyses by Kieffer of the Auerbach, Bavaria, mineral in column 3, and the theoretical composition in column 4. The agreement is reasonably close. The Utah mineral has some of the CaO replaced by MgO, while the Auerbach mineral has some of the Al<sub>2</sub>O<sub>3</sub> replaced by Fe<sub>2</sub>O<sub>3</sub>, and carries some BaO and rare earths. The mineral from Auerbach, according to Laubmann, is in trigonal prisms, is uniaxial positive, has a perfect basal cleavage, indices of refraction between 1.627, and 1.655 and a birefringence of 0.015. It is soluble only in hot concentrated H<sub>2</sub>SO<sub>4</sub>. It occurs on wavellite in iron ores. Both the chemical compositions and the optical and other physical properties show the identity of the Utah mineral with the pseudowavellite. The formula 5CaO·6Al<sub>2</sub>O<sub>3</sub>·4P<sub>2</sub>O<sub>5</sub>·18H<sub>2</sub>O seems to fit the analyses.

TABLE 3. ANALYSIS AND RATIOS OF PSEUDOWAVELLITE(?) BY SHANNON

	1 Analysis	2 Corrected for Impurities	Ratios	Theoretical 3CaO·6Al <sub>2</sub> O <sub>3</sub> · 4P <sub>2</sub> O <sub>5</sub> ·17H <sub>2</sub> O
Al <sub>2</sub> O <sub>3</sub>	36.40	37.5	.367 = 6 x 61	37.00
CaO	11.80	10.4	.185	10.16
Na <sub>2</sub> O	1.40	1.4	.023	
K <sub>2</sub> O	0.54	0.5	.005	
P <sub>2</sub> O <sub>5</sub>	31.68	32.6	.230 = 4 x 58	34.34
H <sub>2</sub> O	18.40	17.6	.978 = 17 x 58	18.50
CO <sub>2</sub>				
	100.22	100.0		100.00

The nearly white chalky crusts, less than a millimeter thick, that line cavities mostly next or near the variscite, is made up chiefly of a mineral in minute hexagonal plates, in part very finely crystalline. It is intimately mixed with calcite and variscite, both in minute crystals. It is uniaxial positive with  $\omega = 1.619$  and  $\epsilon = 1.627$ . In the numerous specimens examined the optical properties of the distinctly crystalline part are about the same. Some of the material is indistinctly crystalline to amorphous and has a mean index of refraction as low as 1.59.

A sample weighing 0.2 grams of the best material available was carefully scraped from a specimen and used for the analysis. It

was estimated to have about 3 per cent of calcite as impurities and was uniform in its optical properties. The analysis, as made and as corrected for impurities, is given in table 3, column 1. It agrees fairly well with the theoretical composition given in column 3. The analysis agrees closely with the formula  $3\text{CaO} \cdot 6\text{Al}_2\text{O}_3 \cdot 4\text{P}_2\text{O}_5 \cdot 17\text{H}_2\text{O}$  which is similar to that of wardite with the soda replaced by lime. Crystallographically wardite appears to be tetragonal while this mineral is in hexagonal plates.

Until better evidence is available, it seems best to consider these hexagonal plates a variety of pseudowavellite.

#### *Deltaite, A New Mineral*

The mineral intergrown with pseudowavellite in the oölites as described in the section on pseudowavellite has a characteristic  $\Delta$  form like the Greek letter delta and the name deltaite is proposed for it. It constitutes only about one-fourth of the mixture. The individual crystals are rarely as much as 0.05 millimeters in cross section. The deltaite is partly in fibers but much of it is in rather stout prisms with triangular cross section. Some of these prisms taper at one end and are terminated by well formed, rather steep rhombohedrons at the other. In some grains the cross sections show two triangles of deltaite with the sides parallel but with apices pointed toward each other and nearly touching, giving an hourglass structure. In others four such triangles point toward a center with a thin layer of pseudowavellite between. Deltaite shows a marked tendency to develop crystal boundaries and in nearly every specimen it has the characteristic triangular cross section.

Deltaite has a specific gravity of about 2.95 and a hardness near 5. It is optically positive, and probably uniaxial,  $\omega = 1.641$ ,  $\epsilon = 1.650$ .

A sample of the deltaite weighing 0.5 grams, that contained 20 per cent of pseudowavellite was prepared. The analysis made by Gonyer is shown in column 1 table 4 and the corrected analysis and ratios follow.

One of the commonest types of crust about the variscite is a dirty gray, dense, cherty-looking layer which is commonly between the yellow oölitic layer and the variscite. A thin layer of chalky material separates it from the variscite and it commonly carries within it isolated crystals or thin white layers of wardite and



lenses and layers of dennisonite. Some of the crusts are as much as one centimeter across but most are thinner. These gray crusts are made up of matted fibers of a single mineral which appears to be identical with deltaite. This deltaite is tough and has a hardness of 5 and a specific gravity of 2.93. It fused at 2 with intumescence to a white opaque bead. The microscope shows that it is composed of matted fibers with negative elongation. The indices of refraction are:  $\alpha=1.630$ ,  $\gamma=1.640$ . A sample of this material weighing 2 grams was prepared. It contained no appreciable amount of visible impurities. An analysis of this sample made by Gonyer on 0.500 grams is shown in column 2 table 4.

The chalky layer between the variscite and the gray cherty deltaite appears to be made up of one mineral. It is very finely crystalline to submicroscopic and the larger crystals are uniaxial positive, with  $\omega=1.621$ , and  $\epsilon=1.629$ . About 100 milligrams of this material was separated by Larsen and analyzed by F. A. Gonyer. The results are shown in column 3 table 4. Carbon dioxide was present in considerable amount, probably several per cent, but sufficient material was not available for its determination. No calcite could be found in the sample although the mineral is clouded with submicroscopic inclusions, mostly gas pores. The chalky crust has less  $\text{Al}_2\text{O}_3$  and  $\text{P}_2\text{O}_5$  and more  $\text{CaO}$ ,  $\text{MgO}$ ,  $\text{CO}_2$  and  $\text{K}_2\text{O}$  than the other deltaites. However, it is believed to be deltaite though later work may show it to be different.

The formula of deltaite may be taken as  $8 \text{CaO} \cdot 5 \text{Al}_2\text{O}_3 \cdot 4 \text{P}_2\text{O}_5 \cdot 14 \text{H}_2\text{O}$ .

#### *Dennisonite, a New Mineral*

Many of the specimens especially the parts made up chiefly of the yellow pseudowavellite have scattered thin white crusts, mostly less than 1 mm. across, lining cavities. These crusts have botryoidal to spherulitic surfaces and are made up of rather coarse fibers of a single mineral. The cavities are mostly only a few millimeters long and less than a millimeter in thickness. They are also scattered through the dense gray deltaite. The name dennisonite is proposed for this mineral after J. M. Dennison who first described and analyzed wardite.

Dennisonite is softer than most of the associated minerals and has a hardness of  $4\frac{1}{2}$ . It has a specific gravity of 2.85.

Dennisonite is in stout fibers that have a negative elongation. Cross sections appear to be hexagonal and to show a perfect basal

TABLE 4.  
ANALYSES AND RATIOS OF DELTAITE BY GONYER

	1. Separated from Öolites		2. Gray Cherty Crusts		3. Chalky Layer		4. Theoretical
	Analyses	Corrected for Impurities	Ratios	Analyses	Ratios	Analyses	
Al <sub>2</sub> O <sub>3</sub>	30.06	28.0	.274 = 5 x 55	29.36	.287 = 5 x 57	26.87	.2630 = 4 x 66
FeO				tr.			
CaO	21.66	24.0	.428	22.95	.409 = 7 x 58	24.37	.435
MgO	0.91	0.9	.022			3.40	.084
Na <sub>2</sub> O	0.60	0.5	.008			0.33	.005
K <sub>2</sub> O	0.15	0.1	.001			1.13	.012
H <sub>2</sub> O+	14.23	13.1	.727 = 14 x 52	14.22	.792 = 14 x 57	14.29	.793 = 12 x 66
H <sub>2</sub> O-				0.04			
CO <sub>2</sub>						some	?
P <sub>2</sub> O <sub>5</sub>	32.72	33.4	.235 = 4 x 59	32.84	.231 = 4 x 58	27.60	.194 = 3 x 65
Insol.						0.60	
	100.33			99.41		98.59	



cleavage. The mineral is negative and sensibly uniaxial. The indices of refraction are:  $\omega = 1.601$  and  $\epsilon = 1.591$ .

TABLE 5.  
ANALYSIS, RATIOS, AND THEORETICAL COMPOSITION OF DENNISONITE

	Analysis	Corrected for Impurities	Ratios	$6\text{CaO} \cdot \text{Al}_2\text{O}_3 \cdot$ $2\text{P}_2\text{O}_5 \cdot 5\text{H}_2\text{O}$
$\text{Al}_2\text{O}_3$	12.90	11.82	.116 = 116 x 1	12.56
CaO	39.00	40.30	.718	106 x 6
MgO	1.41	1.38	.035	
$\text{P}_2\text{O}_5$	33.00	33.10	.233 = 116 x 2	34.97
$\text{H}_2\text{O}_+$	11.10	11.60	.644 = 129 x 5	11.08
$\text{H}_2\text{O}_-$	0.80			
	98.21			100.00

A sample weighing a little over 0.1 grams was prepared for analysis and was found to contain only a few per cent of the yellow pseudowavellite. The analyses, ratios, and theoretical composition are shown in table 5. Material was not available for a determination of the alkalis or for a check analysis. The analysis agrees rather closely with the formula  $6\text{CaO} \cdot \text{Al}_2\text{O}_3 \cdot 2\text{P}_2\text{O}_5 \cdot 5\text{H}_2\text{O}$ .

#### *Dehrnite*

Small, clear hexagonal crystals present in small amount in cavities in yellow pseudowavellite proved to be dehrnite. Under the microscope these crystals commonly show a core that is sensibly uniaxial and a narrow border that is sharply separated from the core by hexagonal crystal faces and that is divided into six biaxial segments. In all parts the mineral is optically negative. The uniaxial core has  $\omega = 1.640$ ,  $\epsilon = 1.633$  and the border, which is clouded with peg-like inclusions and makes up about a third of the crystals, has  $\alpha = 1.585$ ,  $\gamma = 1.600$ . It has a rather small axial angle. A sketch of the optical orientation is shown in figure 2.

An analysis by Shannon made on about 100 milligrams of these crystals is shown in table 6. The analyzed sample contained very little calcite. It had a specific gravity of 3.09.

Botryoidal crusts of dehrnite about a millimeter thick line cavities and cement fragments of pseudowavellite and deltaite

in a few specimens. These crusts are coarsely crystalline and show slight zoning and a tendency to divide into segments. They have a perfect basal cleavage. The specific gravity is 3.07. They

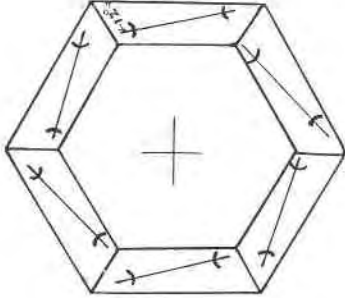


FIG. 2. Optical orientation of dehrnite on the base.

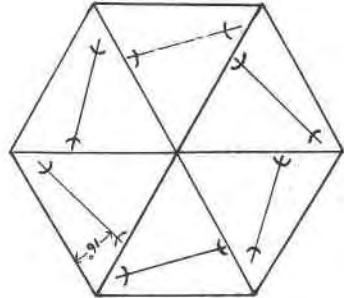


FIG. 3. Optical orientation of lewis-tonite on the base.

are biaxial with a small axial angle and are optically negative.  $\alpha = 1.610$ ,  $\beta = 1.619$ ,  $\gamma = 1.620$ . An analysis by Gonyer of these crusts is shown in table 6, column 2.

TABLE 6.  
ANALYSES OF DEHRNITE

	1. Zoned Crystals	Mol. ratios	2. Crusts	Mol. ratios
Al <sub>2</sub> O <sub>3</sub>	1.00		0.65	
CaO	47.65	.850	54.86	.978 = 15 x 65
MgO	0.85	.012		
K <sub>2</sub> O	5.90	.063	0.30	.003
Na <sub>2</sub> O	4.36	.070	3.70	.060 = 1 x 63
H <sub>2</sub> O	1.91	.106	3.02	.168 = 3 x 65
CO <sub>2</sub>	3.30	.075	1.22	.028
P <sub>2</sub> O <sub>5</sub>	35.68	.251 = 4 x 63	36.66	.258 = 4 x 64½
	100.65		100.41	
	14CaO · K <sub>2</sub> O · Na <sub>2</sub> O · 4P <sub>2</sub> O <sub>5</sub> · 2H <sub>2</sub> O · CO <sub>2</sub>		15CaO · Na <sub>2</sub> O · 4P <sub>2</sub> O <sub>5</sub> · 3H <sub>2</sub> O	

The formulae derived from the two analyses are given below the analyses. The formula derived from dehrnite from Dehrn is 14CaO · 2Na<sub>2</sub>O · 4P<sub>2</sub>O<sub>5</sub> · 2H<sub>2</sub>O. The three analyses are very close together and the formula for dehrnite may be taken as: 14CaO ·

$2(\text{Na},\text{K})_2\text{O}\cdot 4\text{P}_2\text{O}_5\cdot 3(\text{H}_2\text{O}, \text{CO}_2)$ , in which some of the alkalis may be replaced by lime. Dehrnite may be a member of the apatite group.

Some of the best colorless needles from another specimen have a clouded core that is sensibly uniaxial,  $\omega = 1.623$ ,  $\epsilon = 1.613$ , and a clear border that is divided into six segments. On the basal sections each segment gives an extinction at  $12^\circ$  ( $Z$  to the trace of the hexagonal face). The axial angle of this outer zone is of moderate size and the mean index of refraction about 1.616. No analysis of this material was made.

#### *Lewistonite, a New Mineral*

Some of the hexagonal prisms which are very much like the dehrnite have less alkali and much more water. Chemically they are so different from dehrnite as to give them species rank and the name lewistonite is proposed after Lewiston, Utah.

Lewistonite was found as stout hexagonal prisms associated with the oölites of pseudowavellite and deltaite and as white, powdery crusts lining cavities in pseudowavellite and as amygdules filling the cavities.

The stout crystals associated with the oölites in large part show no central uniaxial core but some of them have a uniaxial core with  $\omega = 1.60$ . The main outer biaxial zone has an axial angle of about  $2V = 42^\circ$ . The optical orientation is like that shown in figure 3 and the extinction angle is about  $16^\circ$ .  $\alpha = 1.613$ ,  $\beta = 1.623$ ,  $\gamma = 1.624$ . The indices vary about  $\pm 0.005$ . The specific gravity of these crystals is about 3.06. A sample of little over 100 milligrams of these crystals, made up very largely of the biaxial type, was prepared for analysis. It contained about 7 per cent of pseudowavellite and 3 per cent of deltaite as impurities. The analysis by Shannon is shown in column 1, table 7.

One amygdule weighing 200 milligrams was nearly pure lewistonite. It is made up of stout fibers with negative elongation. It appears to be uniaxial and optically negative.  $\omega = 1.621$ ,  $\epsilon = 1.611$ . It has a hardness of about 4 and a specific gravity of 3.08. An analysis of this material by Gonyer is shown in column 2, table 7.

Lewistonite appears to have a perfect basal and probably also a perfect prismatic cleavage. It has a hardness of 5 and a specific gravity of about 3.06. It has a formula near  $15\text{CaO}\cdot (\text{K}, \text{Na})_2\text{O}\cdot 4\text{P}_2\text{O}_5\cdot 8\text{H}_2\text{O}$ .

TABLE 7.  
ANALYSES AND RATIOS OF LEWISTONITE

	1. Hexagonal Prisms		2. Amygdale		3.
	Analysis	Corrected for impurities	Ratios	Analysis	
SiO <sub>2</sub>	1.12				
Insol.	0.60	0.8	.008	2.53	
Al <sub>2</sub> O <sub>3</sub>	3.67	44.6	.742 = 13 x 57	46.78	
CaO	41.41	8.1	.200 = 4 x 50		
MgO	7.10	4.6	.049 = 1 x 57		
K <sub>2</sub> O	3.71	0.6	.008 = 8 x 57	1.36	.025
Na <sub>2</sub> O	0.47	8.2	.456 = 4 x 57	4.34	.834 = 7 x 119
H <sub>2</sub> O	8.60	33.1	.233 = 4 x 57	7.69	
P <sub>2</sub> O <sub>5</sub>	32.31			37.92	
	98.99			100.62	

Calculated formula 13CaO · 4MgO · K<sub>2</sub>O · 4P<sub>2</sub>O<sub>5</sub> · 8H<sub>2</sub>O

14CaO · 2Na<sub>2</sub>O · 4P<sub>2</sub>O<sub>5</sub> · 8H<sub>2</sub>O.

15CaO · Na<sub>2</sub>O · 4P<sub>2</sub>O<sub>5</sub> · 8H<sub>2</sub>O

52.06

3.85

8.92

35.17

*Englishite, a New Mineral*

Layers of a clear, glassy, cleavable mineral that resembles crusts of gordonite, and that occupy about the same position in the nodule as gordonite, were found on microscopic examination to be a different species and one that differed from any known mineral. The name englishite is proposed for this mineral after Mr. George L. English.

Englishite is found in layers up to a millimeter thick that lie next to or very near the variscite. It is white to colorless and has a very prominent cleavage. It differs from gordonite in the hand specimen chiefly in that it is more platy and its cleavage surfaces are broad and curved. It has a hardness of about 3 and a specific gravity of about 2.65.

TABLE 8.  
ANALYSIS AND RATIOS OF ENGLISHITE

	Analysis	Corrected for Impurities	Ratios	Theoretical $4\text{CaO} \cdot \text{K}_2\text{O} \cdot 4\text{Al}_2\text{O}_3 \cdot$ $4\text{P}_2\text{O}_5 \cdot 14\text{H}_2\text{O} \cdot$
Insol.	1.10			
$\text{Al}_2\text{O}_3$	25.21	24.7	.242 = 2 x 121	26.41
CaO	12.80	14.1	.251 = 2 x 126	14.50
MgO	tr.			
$\text{Na}_2\text{O}$	1.56	1.6	.026 } = $\frac{1}{2}$ x 166	6.08
$\text{K}_2\text{O}$	4.84	5.4		
$\text{H}_2\text{O}^+$	16.80	16.5	.916 = 7 x 131	16.29
$\text{H}_2\text{O}^-$	none			
$\text{P}_2\text{O}_5$	37.89	37.8	.266 = 2 x 133	36.73
	100.20			

It has a highly perfect cleavage and characteristic optical properties. The acute bisectrix is normal to the cleavage. The axial angle is small and the optical character is negative. The birefringence is very faint and the powdered mineral can easily be mistaken for an isotropic mineral. Its indices of refraction vary  $\pm 0.005$ ; the average values are:  $\alpha = 1.570, \gamma = 1.572$ . If the cleavage be taken as (001) the orientation is  $X = c$ . The mineral is probably orthorhombic.

About 180 milligrams of this mineral were prepared for the analysis and the analyzed powder contained about 91% englishite,

2% wardite, and 7% variscite. The analyses by Shannon, the ratios and theoretical composition are shown in table 8. The formula derived from the analysis is  $4\text{CaO} \cdot \text{K}_2\text{O} \cdot 4\text{Al}_2\text{O}_3 \cdot 4\text{P}_2\text{O}_5 \cdot 14\text{H}_2\text{O}$ .

*Millisite, a new Mineral*

Many of the phosphate nodules have layers or irregular crusts of a nearly white, banded material that looks like chalcedony, mostly associated with and interlayered with the green wardite. Many of the spherulites have a white central part of fibers of this mineral and an outer layer of green, granular wardite.

This white fibrous mineral proved to have a composition related to that of wardite but to be biaxial negative. The name millisite is proposed for the species after F. T. Millis who sent the original specimens to the U. S. National Museum.

Millisite has a hardness of  $5\frac{1}{2}$  and a specific gravity of 2.83. It fuses at  $3\frac{1}{2}$  with slight intumescence to a blebby glass.

The crusts of millisite are made up of successive layers of minute, matted fibers with a mean index of refraction varying from about 1.595 to 1.605. The fibers have negative elongation and are optically negative. The matted fibers appear to be uniaxial but coarser crystals prove to be biaxial with a moderate axial angle. For the analyzed powder the average value for the indices were  $\alpha$  about 1.584,  $\beta = 1.598$ ,  $\gamma = 1.602$ .

About 0.8 grams of the mineral was prepared for the analyses by hand picking and cleaning with heavy solutions. The sample contained about 5 per cent of wardite and 1 per cent of dennisonite. Two analyses of this material were made and are shown in table 9, together with the composition corrected for impurities, the ratios, and the theoretical composition for  $2\text{CaO} \cdot \text{Na}_2\text{O} \cdot 6\text{Al}_2\text{O}_3 \cdot 4\text{P}_2\text{O}_5 \cdot 17\text{H}_2\text{O}$ .

The agreement of the analysis with the theoretical composition is very close and the composition of millisite appears to be near that of wardite with half of the alkalies replaced by lime.

*Lehiite, a new Mineral*

Crusts that resemble those of millisite but lack the banding and have higher indices of refraction were found in only a few specimens.

A sample selected for analysis had a crust of this mineral up to 3 millimeters thick that is dense white, and without banding. It



TABLE 9.  
ANALYSES, RATIOS, AND THEORETICAL COMPOSITION OF MILLISITE, BY SHANNON

	Analyses	Average	Corrected for Impurities	Ratios	$2\text{CaO} \cdot \text{Na}_2\text{O} \cdot$ $6\text{Al}_2\text{O}_3 \cdot 4\text{P}_2\text{O}_5 \cdot$ $17\text{H}_2\text{O}$
$\text{Al}_2\text{O}_3$	36.33	36.03	36.3	.356 = 60 x 6	36.87
$\text{CaO}$	7.00	6.80	7.1	.131 = 63 x 2	6.75
$\text{MgO}$	0.33	0.22	0.2		
$\text{Na}_2\text{O}$	3.00	3.00	2.8	.045 = 63 x 1	3.73
$\text{K}_2\text{O}$	1.64	1.64	1.7	.018 = 60 x 4	34.22
$\text{P}_2\text{O}_5$	33.17	33.60	33.8	.238 = 59 x 17	18.42
$\text{H}_2\text{O}$	17.60	17.88	18.0		
		99.17	100.0		100.00

has a hardness of  $5\frac{1}{2}$  and a specific gravity of 2.89. It is in rather coarse fibers, has a very large axial angle and is optically, negative,  $\alpha = 1.600$ ,  $\beta = 1.615$ ,  $\gamma = 1.629$ . The fibers show a large extinction angle. An analysis by Gonyer of a sample of this material weighing 0.2 grams is shown in table 10.

The formula derived is  $5\text{CaO} \cdot (\text{Na}, \text{K})_2\text{O} \cdot 4\text{Al}_2\text{O}_3 \cdot 4\text{P}_2\text{O}_5 \cdot 12\text{H}_2\text{O}$ . This is similar to the formula for deltaite although it is lower in lime and higher in alkalis.

TABLE 10.  
ANALYSIS AND RATIOS OF LEHITTE

	Analysis	Ratios	$5\text{CaO} \cdot \text{Na}_2\text{O} \cdot 4\text{Al}_2\text{O}_3 \cdot 4\text{P}_2\text{O}_5 \cdot 12\text{H}_2\text{O}$
$\text{Al}_2\text{O}_3$	27.79	.2729 = 4 x 68	26.62
CaO	18.10	.3227 = 5 x 65	18.26
MgO	none		
$\text{Na}_2\text{O}$	3.08	.497 } = 1 x 74 .239 }	4.04
$\text{K}_2\text{O}$	2.25		
$\text{H}_2\text{O}$	14.19	.7876 = 12 x 66	14.07
$\text{P}_2\text{O}_5$	34.64	.2438 = 4 x 61	37.01
Insol.	0.58		
	100.63		

*Gordonite, a new Mineral*

Layers of clear, glassy, cleavable crystals, mostly less than a millimeter thick, are present encrusting, or very near, the variscite in a number of the nodules. It is one of the rarer but best crystallized of the minerals in the specimens. A study of this material showed it to be related to paravauxite with the iron replaced by magnesia and the name gordonite is proposed for the mineral after Mr. S. L. Gordon who first described paravauxite.

Good crystals of this material were not available. However, a careful search may be rewarded by better crystals than those found. The largest and most characteristic terminal face on gordonite corresponds rather well with the base of paravauxite, if the crystals are set up in the position of the latter, and are considered triclinic, as is paravauxite. The most prominent faces in the prism zone then correspond to the prominent forms of paravauxite.

Thus good signals are reflected from (010), and ( $\bar{1}\bar{1}0$ ). The front pinacoid (100) is a narrow line face. The form ( $\bar{4}\bar{9}0$ ) is not well developed. The data at present available are not sufficient for establishing an axial ratio, and not of first quality, therefore, only a comparison with paravauxite is here given. It is hoped that a careful search will yield better crystallographic material for a further study.

Forms	Symbols	Paravauxite		Gordonite	
		$\phi$	$\rho$	$\phi$	$\rho$
<i>c</i>	(001)	57° 20'	23° 49'	54° 20'	25° 1'
<i>b</i>	(010)	0°	90° 00'	0°	90° 00'
<i>a</i>	(100)	75° 15'	90° 00'	75° 24'	90° 00'
<i>M</i>	(110)	103° 2'	90° 00'	101° 51'	90° 00'
<i>O</i>	( $\bar{4}\bar{9}0$ )	130° 22'	90° 00'	130° 34'	90° 00'
<i>S</i>	( $\bar{2}11$ )	-85° 46'	68° 03'	-87° 16'	68° 47'

Gordonite has a hardness of  $3\frac{1}{2}$ , a specific gravity of 2.28 and a fusibility of 3. It is soluble in acids.

It is biaxial positive,  $2V$  is about  $73^\circ$ , and  $\rho < \nu$  is easily perceptible.  $\alpha = 1.534$ ,  $\beta = 1.543$ ,  $\gamma = 1.558$ . The best crystals are lath shaped and have a very perfect cleavage parallel to the length of the laths and about normal to the flat face. Crystals lying on the flat face and cleavage fragments turned on edge give an extinction angle ( $Z$  to trace of cleavage) of  $23^\circ$  in the acute angle  $\beta$ .  $X$  is about normal to the flat face. The optical symmetry might be mistaken for monoclinic but crystal measurements make the mineral triclinic. The cleavage would be (100).

By careful hand picking and later cleaning with heavy solution about 0.2 gram of material was secured for analysis. The analysis was made by Shannon on 0.1 gram of material and the check analysis was lost. No  $\text{CO}_2$ ,  $\text{SO}_3$ , or  $\text{NH}_3$  were found. The water in the closed tube was neutral.

The analyses, ratios and theoretical composition are shown in table 11.

The analysis agrees closely with the formula  $\text{MgO} \cdot \text{Al}_2\text{O}_3 \cdot \text{P}_2\text{O}_5 \cdot 9\text{H}_2\text{O}$ .

TABLE 11.  
ANALYSIS, RATIOS, AND THEORETICAL COMPOSITION OF GORDONITE

	Analysis	Ratios	MgO · Al <sub>2</sub> O <sub>3</sub> · P <sub>2</sub> O <sub>5</sub> · 9H <sub>2</sub> O
Al <sub>2</sub> O <sub>3</sub>	20.68	.203 = 203 x 1 .92 x 1	22.87
MgO	10.01	.225 = 225 x 1 102 x 1	8.97
P <sub>2</sub> O <sub>5</sub>	32.80	.231 = 231 x 1 105 x 1	31.84
H <sub>2</sub> O+	16.80	.1944 = 216 x 9 98 x 9	36.32
H <sub>2</sub> O-	18.20		
	98.49		100.00

*Variscite*

Variscite is found chiefly in the grass-green knots within the nodules and it was clearly the original mineral of the nodules from which the other minerals were derived. This green variscite is very finely crystalline.

The white, powdery layer that surrounds the green variscite in most of the nodules is made up chiefly of deltaite but it contains more or less variscite in considerably coarser crystals than in the green mass. Some of the white, powdery layers next the green variscite are made up almost entirely of white variscite in relatively coarse crystals.

All of the variscite is in minute tablets with rhombic outline and in some with a short pyramidal face as well. They are biaxial negative,  $2V$  is rather large,  $Y$  is normal to the plates and  $Z$  bisects the acute angle of the rhombs. The indices of refraction for the green part measured  $\alpha = 1.569$ ,  $\beta = 1.586$ ,  $\gamma = 1.594$ . For the white crystals  $\alpha = 1.572$ ,  $\beta = 1.592$ ,  $\gamma = 1.597$ .

*Unnamed Minerals or Varieties*

A considerable number of minerals that could not be identified by their optical properties were found. Only a few of the more conspicuous or common of these will be described; for none of them was material suitable for chemical analysis found.

1. In a few places a uniaxial negative mineral was found with indices of refraction about midway between those of dennisonite and dehrnite. It was found in the cavities as were dehrnite and dennisonite. It may be a variety of dehrnite which shows considerable variation in its indices of refraction.

2. Other crystals in the cavities resemble dehrnite but have an index of refraction  $\omega = 1.650$ .

3. Another mineral that was found in small amount in a number of specimens and that appears to replace lewistonite occurs in fibers with negative elongation, weak birefringence and an index of refraction of about 1.62.

4. Somewhat similar appearing fibers with weak birefringence, and partly negative, partly positive elongation, have an index of refraction of about 1.590.

5. Some minute spherulites in cavities have positive elongation and  $\alpha = 1.630$ ,  $\gamma = 1.640$ .

6. A biaxial form that has no similarity to any of the other forms was found in small amounts as a thin bluish white crust in one of the specimens in the Harvard collection. The crystals are biaxial positive, have a large axial angle and the indices of refraction,  $\alpha = 1.607$ ,  $\beta = 1.615$ ,  $\gamma = 1.623$ . The mineral is monoclinic and is twinned with (100) as the composition plane.  $X = b$ ,  $Y \wedge c = 8\frac{1}{2}^\circ$ .

7. A white, porcelain-like crust between variscite and a thick crust of dehrnite proved to be isotropic with  $n = 1.575$ . Some incipient spherulites are included in the isotropic mass.

8. On one specimen, made up chiefly of yellow pseudowavellite but with some nodules of variscite, a coating of clear glassy prismatic crystals was found surrounding the variscite, much as the gordonite and the lewistonite surround the variscite. These crystals have a hardness of about  $3\frac{1}{2}$ . They have a very large axial angle, and are optically negative. The indices of refraction are:  $\alpha = 1.567$ ,  $\beta = 1.574$ ,  $\gamma = 1.580$ . The crystals appear to have two perfect cleavages parallel to the length and give parallel extinction.  $Z$  is normal to the best cleavage and  $X$  is parallel to the elongation. This is different from any of the other minerals.

#### PARAGENESIS

The order of deposition of the minerals can be determined in considerable part. The variscite was the first mineral to form. The pseudowavellite and deltaite were derived in part and probably entirely from the variscite. The deltaite is in part later than the pseudowavellite as it occurs chiefly as border zones and veinlets cutting it. It is partly contemporaneous and intergrown with the pseudowavellite. The millisite and wardite are later than the

TABLE 12.  
THE COMPOSITIONS AND PROPERTIES OF THE MINERALS OF THE NODULES FROM NEAR FAIRFIELD, UTAH

Mineral	Crys. Sys.	CaO	(Na, K) <sub>2</sub> O	Al <sub>2</sub> O <sub>3</sub>	P <sub>2</sub> O <sub>5</sub>	H <sub>2</sub> O	Opt. Char.	$\alpha$	$\beta$	$\gamma$	2v	Sp. Gr.	H.	Cleav.
Wardite	Tet.	1	2	6	4	17	Un. +	1.590	1.599			2.81	5	(001)
Pseudowavellite	Trig.	5		6	4	18	Un. +	1.622	1.631			2.92	5	
Pseudowavellite	Hex.?	3		6	4	17	Un. +	1.619	1.627			2.92	5	
Deltaite	Trig.	8		5	4	14	Un. +	1.630	1.640			2.95	5	
Dennisonite	Hex.?	12		2	4	10	Un. -	1.591	1.601			2.85	4½	(0001)
Dehrnite	{Ps. hex.	14	2		4	3	{Un. -	1.633	1.640		0°	3.09		(0001)
	{Hex.						1.581	1.600	med.					
Lewistonite	{Ps. hex.	15	1		4	8	{Un. or	1.610	1.620		sm.	3.07		
	{Hex.						1.613	1.624	42° ±					
Millisite	Mon.?	2	1	6	4	17	Bi. -	1.584	1.598	1.602	med.	2.83	5½	(0001)
Lehite	Mon.?	5	1	4	4	12	Bi. -	1.602	1.616	1.629	large	2.89	5½	
Englishite	Orth.	4	1	4	4	14	Bi. -	1.570	1.572	1.572	sm.	2.65	3	(001)
Variscite	Orth.			4	4	16	Bi. -	1.569	1.586	1.594	{rather large	2.52	5	
?	Orth.						Bi. -	1.567	1.574	1.580			3½	
Gordonite	Mon.	MgO 1		1	1	9	Bi. +	1.534	1.543	1.558	large	2.28	3½	(100)
	Mon.?													

deltaite as they are found as crusts and spherulites in cavities and attached to it. The millisite in large part preceded the wardite but there was some alternation. This is especially well shown by the spherulites which have a central part of millisite and outer layers of wardite. The dehrnite, lewistonite, and dennisonite are later than the deltaite and probably later than the wardite. They occur as crystals or crusts lining cavities in the deltaite and pseudowavellite. The age of the gordonite and englishite are uncertain.

All of the minerals are high in phosphoric acid and water. The first minerals to form were high in alumina. Later minerals contained high lime as well as alumina. Still later alkalies took the place of some of the lime and the last minerals were low in alumina, very high in lime and moderate in alkalies. They were also lower in water than the other minerals.

#### CONCLUSION

The chemical compositions and properties of the minerals of the nodules are shown in table 12.

Wardite is a rather abundant mineral and it occurs as pale greenish or bluish green vitreous crystals and grains in layers associated with the white banded chalcedonic-looking millisite. It is found also in nearly colorless grains associated with deltaite.

Pseudowavellite is the most abundant mineral of the nodules and makes up most of the yellow, matted fibers and over half of the oölites.

Deltaite is next in abundance after pseudowavellite and is present in nearly every specimen. It is intimately associated with the pseudowavellite. It is present in the oölites and makes up most of the gray looking layers and veinlike streaks that cut the pseudowavellite. It also constitutes the white powdery crusts next to the pseudowavellite and dense deltaite and much of the rough yellow linings of the cavities in pseudowavellite.

Dennisonite occurs as white, botryoidal crusts made up of fibers that line cavities in the pseudowavellite.

Dehrnite was found only in very small amount as small hexagonal crystals in cavities in pseudowavellite. Some white botryoidal crusts that cement fragments of some of the nodules are dehrnite.

Lewistonite is also in very small amount. It was found in stout hexagonal prisms in cavities in the oölites and as a white amygdaloidal filling in pseudowavellite.

Millisite is a fairly abundant and rather conspicuous constituent in many of the nodules. It forms white banded chalcedonic-looking layers that are commonly associated with wardite.

Lehiite was found as a white lens or band that resembled millisite but lacked the banding.

Englishite is in very small amount but it is easily recognized where present. It was found only as thin layers next to variscite. Its very perfect, pearly, curved cleavage surfaces serve to identify it.

Gordonite is also in very small amount and it also was found in thin layers next to variscite. It is in glassy, tabular crystals, often in sub-parallel or radiating groups. Its optical properties complete its identification.