THE AMERICAN MINERALOGIST
JOURNAL OF THE MINERALOGICAL SOCIETY OF AMERICA

Vol. 22 SEPTEMBER, 1937 No. 9

WOODHOUSEITE, A NEW MINERAL OF THE BEUDANTITE GROUP

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SUMMARY OF PROPERTIES

Formula: $2CaO \cdot 3Al_2O_3 \cdot P_2O_5 \cdot 2SO_3 \cdot 6H_2O$.
Crystal system: hexagonal (rhombohedral subsystem).
Axial ratio: $a:c = 1:1.170$ ($\alpha = 91°42'$).
Sp. gr.: 3.012.
H.: $4\frac{1}{2}$.
Color: colorless to flesh-colored; transparent or translucent.
Luster: vitreous; pearly on $c\{0001\}$ and cleavage.
Cleavage: excellent basal (0001).
Optical character: uniaxial positive; also biaxial.
Indices: $n_\gamma(\epsilon) = 1.647$, $n_\alpha(\omega) = 1.636$ (± 0.003).
Birefringence: $n_\gamma(\epsilon) - n_\alpha(\omega) = 0.011$.

Woodhouseite is a new sulfate-phosphate member of the beudantite group. It is found in small quantities in quartz veins that adjoin and penetrate the commercial andalusite deposits[1] located on the west slope of White Mountain in the Northern Inyo Range, Mono County, California. The andalusite deposits occur in pre-Cambrian meta-quartzite,[2] and have been formed by intrusion of late Jurassic granitic rocks that are offshoots of the Inyo Batholith.

The name woodhouseite is proposed in honor of Mr. C. D. Woodhouse, General Manager, Champion Sillimanite, Inc., and well known as an enthusiastic and able mineral collector.

PHYSICAL PROPERTIES

Woodhouseite occurs in euhedral crystals which are colorless and transparent, or may be white or flesh-colored and translucent. Luster is vitreous, but is pearly on $c\{0001\}$. The specific gravity has been determined to be 3.012 at room temperature by the pycnometer method, 3.580 grams of material being used. Cleavage is excellent in one direction parallel to $c\{0001\}$.

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[1] Kerr, P. F., The occurrence of andalusite and related minerals at White Mountain, California: *Econ. Geol.*, vol. **27**, pp. 614–642, 1932.

[2] Lemmon, Dwight M., Geology of the andalusite deposits in the Northern Inyo Range, California: *Ph.D. Dissertation, Stanford University*, **1937.**

The optical character is uniaxial positive, but basal sections of the larger, striated crystals are composed of six radial biaxial segments, sixty degrees apart. The centers of some of these crystals are uniaxial, and cleavage fragments of small, undistorted crystals appear uniaxial. The axial angle 2V is about 20° maximum, and the axial plane is oriented in each segment approximately at right angles to the adjoining edge of the hexagonal crystal outline (average measured angle is 87°). Similar anomalies have been noted for certain other members of the alunite-beudantite group.

The birefringence of woodhouseite is 0.011, measured in oriented thin section by comparing the interference color with that of quartz mounted in the same section. Indices of refraction are

$$n_\alpha = 1.636, \quad n_\beta = 1.638, \quad n_\gamma = 1.647 \quad (\pm 0.003).$$

Determination of n_α and n_γ has been made by the oil-immersion method using an E-22 filter, fragments that are completely dark between crossed nicols being used to find n_α. The third index, n_β, has been estimated from the interference colors in an oriented thin section that gives a biaxial figure. The biaxial segments are not completely dark between crossed nicols, but give gray interference colors; a zonal banding is sometimes shown, different bands showing slightly different colors.

GEOMETRICAL CRYSTALLOGRAPHY

Woodhouseite occurs in rhombohedral crystals of variable habit. The optical characteristics show that the large, striated crystals are only pseudo-rhombohedral. Forms observed are $c\{0001\} = \{111\}$, $r\{10\bar{1}1\} = \{100\}$, $t\{40\bar{4}1\} = \{3\bar{1}\bar{1}\}$, $u\{50\bar{5}1\} = \{11.\bar{4}.\bar{4}\}$, and $s\{02\bar{2}1\} = \{11\bar{1}\}$. Crystal faces are frequently curved, striated, or etched, and give poor reflection signals. Twelve good crystals, ranging in size from $\frac{1}{3}$ mm. to 1 mm. and suitable for measurement, have been discovered after careful search. The acceptable measurements from these crystals are given in Table 1:

TABLE 1

	Number of observations	Measured mean	Calculated	Measured range
cr	32	53°30′	—	53°12′–53°41′
rr′	12	88 18	88°15′	88 09 –88 33
ct	18	79 26	79 31	78 47 –80 11
cu	2	81 35	81 35	81 28 –81 43
cs	3	69 47	69 42	69 09 –70 20

Unreliable reflections have also been observed from the following doubtful forms: $\{10\bar{1}2\}=\{411\}$, $\{30\bar{3}1\}=\{7\bar{2}\bar{2}\}$, $\{50\bar{5}4\}=\{14.\bar{1}.\bar{1}\}$, $\{0\bar{7}74\}=\{11.11.\overline{10}\}$, $\{05\bar{5}2\}=\{77\bar{8}\}$. These doubtful forms have given reflections from line faces in curved portions of a few crystals.

Character of faces. The faces of *c* are commonly rough and pitted because of surface alteration, but are never curved. The faces of *r* are always brilliant, but are frequently striated horizontally and slightly curved. The faces of *t* are usually narrow, and are rarely plane, curvature sometimes extending from *r* through *t* and *u*. The form *u* is not common and its faces are very small. The faces of *s* are small; they are usually dull or pitted and give poor signals, but are present on a number of crystals.

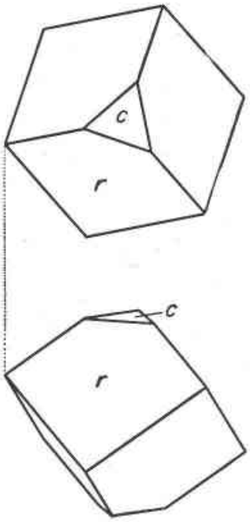

FIG. 1

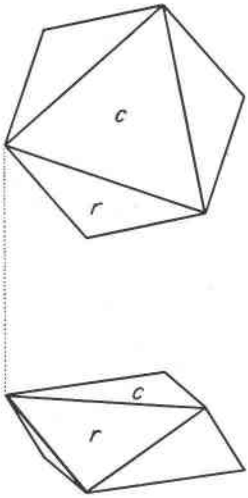

FIG. 2

The faces of the forms *c* and *r* are best developed and give the most reliable signals. The axial ratio $a:c=1:1.170$ ($\alpha=91°42'$) has been calculated from the fundamental measured angle *cr*. Computed values for other interfacial angles, using this ratio, compare favorably with the measured angles, and the best measurements are in close agreement with the axial ratio.

Habit. The commonest habit is pseudo-cubic with the single form $r\{10\bar{1}1\}$; the sides of the largest observed crystals of this type are one centimeter in size, and range downward to one-tenth millimeter or less.

Frequently the basal pinacoid *c* modifies the pseudo-cubic habit (Fig. 1) The modifying rhombohedrons *t*, *u*, and *s* (Fig. 4) occur less commonly, and to casual inspection simulate faces of a hexagonal prism, a form that has not been identified upon measured crystals. Equal development of *c* and *r* results in wedge shaped crystals (Fig. 2). Very thin plates (Fig. 3) caused by the dominance of *c* have been found in a few specimens; the maximum diameter of these platy crystals is about five millimeters. Similar crystal habits and forms have been described for various other members of the alunite-beudantite group.

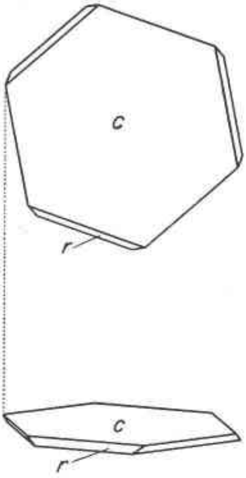

FIG. 3

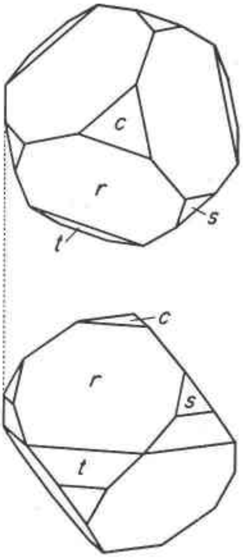

FIG. 4

CHEMICAL COMPOSITION

Woodhouseite is readily soluble in dilute acid after it has been heated in a closed tube to drive off the water. Calcium sulfate hemihydrate crystallizes from the HCl solution. Qualitative tests for aluminum and phosphate are excellent. The following analysis has been made by Mr. A. Rautenberg, Ceramic Division, Champion Spark Plug Company. The material analyzed consisted of crystals which were pried from vugs in quartz, then crushed to 20–40 mesh and sorted under a binocular microscope to separate all traces of rutile and limonite.

The molecular ratio is in good agreement with the formula $2CaO \cdot 3Al_2O_3 \cdot P_2O_5 \cdot 2SO_3 \cdot 6H_2O$, the theoretical composition of which is shown

TABLE 2. CHEMICAL ANALYSIS OF WOODHOUSEITE

	Analysis	Molecular ratios				Theoretical composition
P_2O_5	18.13%		.1276	1.07	1×1.07	17.15%
SiO_2	0.30		—	—	—	—
Al_2O_3	36.63		.3593	3.00	3×1.00	36.93
CaO	12.31	.2195	.2326	1.94	2×0.97	13.54
SrO	0.25	.0024				—
BaO	1.00	.0065				—
MgO	0.11	.0027				—
Na_2O	0.08	.0013				—
K_2O	0.02	.0002				—
SO_3	17.59		.2197	1.84	2×0.92	19.33
H_2O+105°C.	13.25		.7353	6.15	6×1.02	13.05
H_2O-105°C.	0.20		—	—	—	—
Total	99.87					100.00

in the last column. Inspection shows that the content of P_2O_5 is a little high, and SO_3 a trifle low. This deviation suggests the possibility of an isomorphous relationship between phosphate and sulfate with the formation of a mixed crystal. In the absence of more analyses, the variation from the theoretical values is insufficient to prove isomorphism.

OCCURRENCE

Woodhouseite is a late hydrothermal mineral lining vugs in quartz veins that cross the andalusite zones. Although not abundant, the mineral has been observed in both the upper and lower andalusite deposits, and appears to be widespread in small amounts. It is commonly associated with topaz, quartz, augelite, lazulite, tourmaline, barite, muscovite, and pyrophyllite, all of which formed previously to it. Small crystals frequently coat euhedral quartz and augelite.* A few interesting specimens have been found showing clear, pseudo-cubic woodhouseite crystals strung like beads upon hair-like crystals of colorless tourmaline (achroite). In the portions of veins that are open to supergene solutions, woodhouseite is usually coated with the supergene minerals jarosite and limonite, and sometimes with hyalite opal.

Woodhouseite is found only near masses of lazulite, which has probably provided some of the chemical components. No quantitative analysis of the lazulite has been made, but qualitative tests indicate the

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* The geometrical crystallography of augelite will be described in a later paper.

presence of calcium. T. L. Watson[3] has shown that the lazulite from Graves Mountain, Georgia, contains 3% CaO, and notes that lazulite from some other localities contains appreciable amounts of calcium. There are no other abundant calcium-bearing minerals associated with the andalusite deposits, although calcite is a constituent of the adjoining schistose porphyry.

Strontium-bearing natroalunite, which is also present in the andalusite deposits, is more abundant than woodhouseite. It usually occurs in coarsely granular masses or veins a foot or less in width, accompanied by muscovite and quartz. Small amounts of finely granular natroalunite have attacked the andalusite ores. Euhedral crystals, which are rough and wedge shaped, are not common. Natroalunite and woodhouseite have not been observed together. They can be distinguished by chemical tests, specific gravity, indices of refraction, or crystal habit. The natroalunite has the following properties: specific gravity, 2.90; SrO = 2.81%, $Na_2O:K_2O:SrO = 5:4:3$; $n_\epsilon = 1.608$, $n_\omega = 1.587$ (± 0.003).

The Beudantite Group

Woodhouseite belongs to the beudantite group, which includes the isomorphous minerals beudantite, corkite, svanbergite, and hinsdalite. The name of the group is derived from the first known representative, described by A. Levy in 1826, and named in honor of the French mineralogist, F. S. Beudant. Many of our mineral names were first applied by Beudant, who systemized much of the nomenclature.[4]

Properties of the members of the isomorphous group are compared in the following table, which includes chemical composition, axial ratio, rhombohedral angle α (for the three-axis method), specific gravity, and indices of refraction.

Table 3

		c	α	*Sp. gr.*	*Indices*	
					ω	ϵ
Beudantite	$2PbO \cdot 3Fe_2O_3 \cdot As_2O_5 \cdot 2SO_3 \cdot 6H_2O$	1.184	91°16′	4.1±	1.96	B.=mod.
Corkite	$2PbO \cdot 3Fe_2O_3 \cdot P_2O_5 \cdot 2SO_3 \cdot 6H_2O$			4.2±	1.93	B.=low
Woodhouseite	$2CaO \cdot 3Al_2O_3 \cdot P_2O_5 \cdot 2SO_3 \cdot 6H_2O$	1.170	91 42	3.01	1.636	1.647
Svanbergite	$2SrO \cdot 3Al_2O_3 \cdot P_2O_5 \cdot 2SO_3 \cdot 6H_2O$	1.206	90 34	3.30	1.626	1.640
Hinsdalite	$2PbO \cdot 3Al_2O_3 \cdot P_2O_5 \cdot 2SO_3 \cdot 6H_2O$	1.268	88 39	3.65	1.671	1.689

The optical properties for the four previously known members of the

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[3] Watson, T. L., Lazulite of Graves Mountain, Georgia, with notes on other occurrences in the United States: *Jour. Wash. Acad. Sci.*, vol. **11,** no. 16, pp. 386–391, 1921.

[4] Beudant, F. S., *Traité élémentaire de minéralogie.* Paris, **1824:** 2nd. ed., 2 vols., **1832.**

group have been taken from Larsen and Berman.[5] The iron members, beudantite and corkite, are optically negative; the aluminum members, positive. All members of the group, with the exception of svanbergite, which has not been investigated, show an anomalous biaxial character, basal sections being composed of six biaxial segments. The crystallographic axial ratio for beudantite and corkite is a combined average, necessitated by failure of early investigators to distinguish between the two minerals.[6] The axial ratio for hinsdalite[7] was computed from measurements made with a contact goniometer.

Svanbergite was first described as a calcium aluminum sulfate-phosphate (1854). G. T. Prior[8] proved that strontium, not calcium, was the dominant alkaline earth metal present in the original material. The only satisfactory complete analysis of svanbergite, in which the strontium was also erroneously given as calcium, was made for C. W. Blomstrand (1868) upon lead-bearing svanbergite (3.82% PbO) from Westanå, Sweden.

The following mineral associations have been observed for various members of the beudantite group:

Beudantite: quartz, bindheimite, mimetite, carminite, pyrolusite, limonite.
Corkite: pyromorphite, limonite.
Hinsdalite: quartz, barite, pyrite, galena, tetrahedrite, rhodochrosite.
Svanbergite: kyanite, lazulite, pyrophyllite, mica, quartz, hematite, rutile, augelite.

The mineral association reported for svanbergite is similar to that for woodhouseite. The members of the beudantite group have been formed by late hydrothermal solutions or by oxidation wherever they are found.

THE ALUNITE-BEUDANTITE GROUP

G. T. Prior noted the close relationship of the beudantite group to the goyazite (hamlinite) group and to the alunite group. Later, W. T. Schaller[9] discussed the three groups as subdivisions of a major alunite-beudantite group, and, taking alunite, goyazite, and corkite as type examples, showed the following chemical analogy:

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[5] Larsen, E. S., and Berman, H., *The Microscopic Determination of the Nonopaque Minerals*, 2nd edition: *U. S. Geol. Surv., Bull.* **848,** p. 219, 1934.

[6] Hintze, C., *Handbuch d. Mineralogie,* 46 lief., p. 724, **1931.**

[7] Larsen, E. S., and Schaller, W. T., Hinsdalite, a new mineral: *Am. Jour. Sci.,* 4th ser., vol. **32,** p. 251, 1911.

[8] Prior, G. T., Hamlinite, florencite, plumbogummite, beudantite, and svanbergite as members of a natural group of minerals: *Mineral. Mag.,* vol. **12,** pp. 249–254, 1900.

[9] Schaller, W. T., The alunite-beudantite group: *U. S. Geol. Surv., Bull.* **509,** pp. 70–76, 1912.

Alunite	$K_2O \cdot 3Al_2O_3 \cdot 4SO_3 \cdot 6H_2O$	*or*	$[Al(OH)_2]_6 \cdot [K_2] \cdot [SO_4]_2 \cdot [SO_4]_2$
Goyazite	$2SrO \cdot 3Al_2O_3 \cdot 2P_2O_5 \cdot 7H_2O$	*or*	$[Al(OH)_2]_6 \cdot [Sr] \cdot [HPO_4]_2 \cdot [Sr(PO_4)_2]$
Corkite	$2PbO \cdot 3Fe_2O_3 \cdot 2SO_3 \cdot P_2O_5 \cdot 6H_2O$	*or*	$[Fe(OH)_2]_6 \cdot [Pb] \cdot [SO_4]_2 \cdot [Pb(PO_4)_2]$

S. B. Hendricks[10] has obtained x-ray data for alunite, jarosite, natrojarosite, argentojarosite, ammoniojarosite, plumbojarosite, goyazite (hamlinite), karphosiderite, borgströmite, and the artificial compound $3Fe_2O_3 \cdot 4SO_3 \cdot 9H_2O$. He has derived the crystal structure from this study. The space lattice is rhombohedral; so three axes of reference should be used instead of four. X-ray data for karphosiderite, borgströmite, and goyazite (hamlinite) were obtained from material that had not been analyzed, and lattice dimensions were not determined. No mineral of the beudantite group was investigated.

Hendricks offers an explanation of the various types of isomorphous replacements on the basis of his structure determinations. The simple replacements include Na^+, K^+, Rb^+, Ag^+, NH_4^+; Ca^{++}, Ba^{++}, Sr^{++}, Pb^{++}; Al^{+++}, Fe^{+++}; and PO_4^{---}, AsO_4^{---}. In plumbojarosite, half the potassium atoms of jarosite are replaced by lead atoms, the other half of the positions remaining vacant, and the rest of the structure is practically undisturbed. In minerals of the beudantite group, this vacant position is filled by R'' atoms, and SO_4 is replaced by PO_4 or AsO_4. Replacements involving change in charge (e.g., Sr^{++} for K^+, or PO_4^{---} for SO_4^{--}) are balanced by corresponding replacement of an oppositely charged ion or by replacement of R^+ or OH^- by H_2O neutral. Schaller's concept of HPO_4^{--} replacing SO_4^{--} is abandoned.

The well-established members of the three allied mineral groups as they are now known consist of the minerals tabulated below. The year first described, the name, the chemical composition, the axial ratio c, and the rhombohedral angle α (for the three-axis method) are listed. The formulae are patterned upon those proposed by Hendricks.

Alunite Group

1824	Alunite	K	Al_3	(SO_4)	(SO_4)	$(OH)_5$	(OH)	1.252	89°10′
1902	Natroalunite	Na	Al_3	(SO_4)	(SO_4)	$(OH)_5$	(OH)	—	—
1852	Jarosite	K	Fe_3	(SO_4)	(SO_4)	$(OH)_5$	(OH)	1.249	89 15
1902	Natrojarosite	Na	Fe_3	(SO_4)	(SO_4)	$(OH)_5$	(OH)	1.104	93 50
1927	Ammoniojarosite	NH_4	Fe_3	(SO_4)	(SO_4)	$(OH)_5$	(OH)	1.18*	91 25
1923	Argentojarosite	Ag	Fe_3	(SO_4)	(SO_4)	$(OH)_5$	(OH)	1.106	93 42
1902	Plumbojarosite	Pb	$[Fe_3$	(SO_4)	(SO_4)	$(OH)_5$	$(OH)]_2$	1.216	90 18

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[10] Hendricks, S. B., The crystal structure of alunite and the jarosites: *Am. Mineral.*, vol. **22**, pp. 773–784, 1937.

Beudantite Group

1826	Beudantite	Pb	Fe_3	(SO_4)	(AsO_4)	$(OH)_5$	(OH)	1.184	91 16
1869	Corkite	Pb	Fe_3	(SO_4)	(PO_4)	$(OH)_5$	(OH)		
1937	Woodhouseite	Ca	Al_3	(SO_4)	(PO_4)	$(OH)_5$	(OH)	1.170	91 42
1854	Svanbergite	Sr	Al_3	(SO_4)	(PO_4)	$(OH)_5$	(OH)	1.206	90 34
1911	Hinsdalite	Pb	Al_3	(SO_4)	(PO_4)	$(OH)_5$	(OH)	1.268	88 39

Goyazite (Hamlinite) Group

1884	Goyazite								
(1890	Hamlinite)	Sr	Al_3	(PO_4)	(PO_4)	$(OH)_5$	H_2O	1.185	91 15
1786	Plumbogummite	Pb	Al_3	(PO_4)	(PO_4)	$(OH)_5$	H_2O	—	—
1906	Gorceixite	Ba	Al_3	(PO_4)	(PO_4)	$(OH)_5$	H_2O	—	—
1902	Florencite	Ce	Al_3	(PO_4)	(PO_4)	$(OH)_5$	(OH)	1.190	91 04

* *X*-ray measurement by S. B. Hendricks.

The new minerals argentojarosite, ammoniojarosite, and woodhouseite have been added to those listed by Schaller (quoted by Hendricks), and the doubtful minerals karphosiderite and harttite have been omitted.

Karphosiderite was accepted by Schaller to include a number of similar or identical hydrous ferric sulfates with the probable composition $3Fe_2O_3 \cdot 4SO_3 \cdot 7H_2O$, analogous to jarosite. Many specimens of karphosiderite have been shown to be mixtures. The mineral borgströmite, which is probably identical with the artificial compound $3Fe_2O_3 \cdot 4SO_3 \cdot 9H_2O$ (or $H_2OFe_3(SO_4)_2(OH)_5H_2O$), may be a distinct mineral, or may possibly belong under the name karphosiderite. The status of the natural hydrous ferric sulfates remains undecided.

More information is required to establish harttite as a definite mineral. The name is based on a chemical analysis of a somewhat impure aggregate found in the Brazilian phosphate favas. Schaller interpreted the same analysis as an isomorphous mixture of about two parts of goyazite (hamlinite) with one part of strontium-alunite.

Schaller showed the probable identity of hamlinite and goyazite, and later acknowledged that goyazite has priority.[11]

The fact that more of the theoretically possible members of these three mineral groups have not been identified is probably explained by the difficulty of obtaining sufficiently pure material in large enough quantity for investigation. The lack of material also explains the missing data for many of the established minerals. Measurable euhedral crystals have never been found for natroalunite, ammoniojarosite, plumbo-

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[11] Loughlin, G. F., and Schaller, W. T., Crandallite, a new mineral: *Am. Jour. Sci.*, 4th series, vol. **43,** p. 69, 1917.

gummite, gorceixite, or harttite. Mixed crystals have been observed within limits, but the rarity of occurrences has prohibited discovery of many intermediate members, or in some cases of end members. The alunite-natroalunite series is most thoroughly known, although pure natroalunite has not yet been found.

ACKNOWLEDGMENTS

The writer is deeply indebted to Professor A. F. Rogers for suggestions and for criticism. Dr. J. A. Jeffery, Vice-President, Champion Spark Plug Company, has furnished the chemical analysis, which was made by Mr. A. Rautenberg. Mr. C. D. Woodhouse has permitted free use of material from his collection.