

## GEOCRONITE

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### ABSTRACT

X-ray examination of geocronite from several localities shows that it is monoclinic, probable space group  $C_{2h}^2-P2_1/m$ , with cell dimensions varying slightly near  $a_0$  9.0,  $b_0$  31.9,  $c_0$  8.5,  $\beta$  118°. Geocronite is isostructural with jordanite and presumably constitutes the intermediate member of a series with varying proportions of antimony and arsenic, and possibly other compositional variation. Jordanite is the arsenic end-member of this series, the antimony end-member not being certainly known. As with jordanite there is uncertainty as to the cell content of geocronite and no simple formula can be assigned with assurance. Polished-surface observations indicate that geocronite, jordanite, and boulangerite are not distinguishable from one another with certainty by these methods alone and suggest that in a number of respects previous descriptions may be unreliable.

### HISTORY

Geocronite was named by Svanberg (1841). It has usually been assigned the formula  $Pb_5(Sb, As)_2S_8$ . Goniometric measurements have been reported by Kerndt (1845) and by D'Achiardi (1901) who considered it to be orthorhombic. Lamellar twinning has been repeatedly noted, D'Achiardi (1901), Ramdohr (1950) and Schröder (1941). Geocronite has been recognized as monoclinic by Hiller (1938), by Ramdohr and Ödman (1939) and by Ramdohr (1950). The powder x-ray diffraction pattern of geocronite has been reported by Hiller (1938) and by Harcourt (1942), these authors being substantially in agreement. No single-crystal x-ray study on geocronite is known to the writers. The close relationship of geocronite to jordanite was recognized by Solly (1900) from the morphology, especially the twin lamellae, and by Ramdohr and Ödman (1939) who stated that Hiller was to show the structural similarity by x-ray investigation.

### MATERIAL AND ACKNOWLEDGMENTS

The present study arose from the examination of a specimen of a sulfosalt from the 600 level of the Silver King mine, Park City, Utah, sent to the senior author (A.P.) for identification, by Mr. Rodney B. Sprague in 1950. Another specimen from this locality showing a small amount of the same mineral was later received from Mr. Everett O. Bracken. The sulfosalt, which was finally shown to be geocronite, occurs in the first and richer specimen as coatings of striated lead-gray crystals on galena,

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associated with quartz and a bit of pyrite. The galena crystals are in clusters with individual crystals over half a centimeter in diameter. The geocronite crusts reach a thickness of three millimeters or more in places. In the later stages of the study, specimens of geocronite from other localities, including material from the type locality, Sala, Sweden, and jordanite were obtained for comparison. Dr. George Switzer kindly lent 4 specimens from the collections of the United States National Museum and Mr. John B. Jago of San Francisco lent 2 specimens from his personal collection.

Altogether a dozen or more different specimens of geocronite, of supposed geocronite, or of jordanite from ten localities, were examined. Among these the following are of special interest:

1. Geocronite, 600 level, Silver King mine, Park City, Utah, gift of Mr. Rodney B. Sprague and Mr. Everett O. Bracken;
2. Geocronite, Sala, Sweden, *U.S.N.M. C 830*;
3. Geocronite, Custer Co., Idaho, *U.S.N.M. 106120*;
4. Boulangerite and galena, labelled "Geocronite, Sala, studied by Max Short," *U.S.N.M. 84328*;
5. Geocronite, labelled "boulangerite," Defiance mine, Cerro Gordo, California, *UC spec. No. 100*, gift of Dr. H. W. Gould;
6. Geocronite, 2800' level, Livingston mine, Mackay, Idaho, gift of Anaconda Copper Mining Company;
7. "Jordanite," Hope mine, Bonner County, Idaho, from J. B. Nichols Collection, purchased from Minerals Unlimited;
8. Jordanite with sphalerite and pyrite, Wiesloch, Baden, Germany, purchased from Ward's.

As suggested by this list, boulangerite and geocronite may readily be mistaken for each other though their  $x$ -ray diffraction patterns are distinctive. In addition to the case listed above another specimen in the collections of the University of California labelled geocronite was found to be boulangerite and Berry (1940) has reported a similar mislabelling of material from near Deer Lodge, Montana.

Funds for the analysis of geocronite, which was carried out by Dr. R. Klemen of Vienna, and for the spectrographic examinations were provided by a grant from the Committee on Research of the University of California. Professor Leonard G. Berry of Queen's University has critically examined the manuscript, and Professor Charles Meyer of the University of California has examined the section on polished-surface observations. The writers are most grateful to all who have given or lent materials and to those who have aided our work in various ways.

#### UNIT CELL AND SPACE GROUP

Specimens from Park City, Utah, Custer Co., Idaho, and from Sala, Sweden, numbers 1 to 3 in the list above, were studied by means of single-

crystal diffraction patterns using the rotation, Laue, Weissenberg and precession methods. Over 50 exposures were made. Geocronite proves to be monoclinic with cell dimensions very close to those of jordanite.

The cell dimensions of the three geocronites are set forth in Table 1. These are such that there also exists another monoclinic cell of nearly the same dimensions, as well as a pseudo-orthorhombic cell of double the

TABLE 1. CELL DIMENSIONS OF GEOCRONITE AND JORDANITE

	Geocronite Park City, Utah	Geocronite Sala, Sweden <i>USNM C830</i>	Geocronite Custer County, Idaho <i>USNM 106120</i>	Jordanite Binnenthal, Switzerland (Berry, 1940)
Dimensions of cell with smallest possible $a_0$ and $c_0$ :				
$a_0$	8.96±0.03 Å	9.00±0.02	8.96±0.03	8.87*
$b_0$	31.85±0.05	31.94±0.03	31.92±0.06	31.65±0.03 (kX)†
$c_0$	8.48±0.03	8.52±0.02	8.48±0.02	8.40±0.02†
$\beta$	118°00'±10'	118°00'±10'	118°00'±10'	118°6'*
( $\bar{1}02 \wedge 100$ )	90°14'	90°27'	90°14'	90°5'*
Dimensions of cell with same $c_0$ and $b_0$ as above and slightly longer $a_0$ :				
$a_0$ (alt.)	8.99	9.04	8.99	8.89±0.03†
	118°23'	118°31'	118°23'	118°21'±30'†
Angle for cell with smallest possible $a_0$ and $c_0$ corresponding to pseudo-cell which is strictly orthorhombic metrically, i.e., with ( $\bar{1}02 \wedge 100$ )=90°00'.				
	118°15'	118°15'	118°15'	118°16'

\* Values calculated from Berry's figures.

† Values given by Berry in Peacock and Berry (1940), presumably in kX units.

volume. The relations are shown in Fig. 1. The lattice is also not far from being pseudo-hexagonal. Were the  $\beta$  angles closer to 120° there would exist three possible monoclinic cells of nearly the same dimensions. Table 1 includes the constants of the monoclinic cells with slightly larger  $a_0$  and also the angle ( $100 \wedge \bar{1}02$ ) whose difference from 90° is a measure of the departure of the pseudo-orthorhombic cell from orthogonality.

The only systematic extinction observed in the x-ray patterns is the absence of  $0k0$  with  $k$  odd. This would allow the space groups  $C_{2h}^2 - P2_1/m$  or  $C_2^2 - P2_1$ . We incline towards the former group as more probable in view of the relations of geocronite to jordanite and what seems to us the lack of conclusive evidence of polarity of the 2-fold axis. (See discussion of morphology.)

Table 1 also lists data for jordanite obtained by Berry (Peacock and

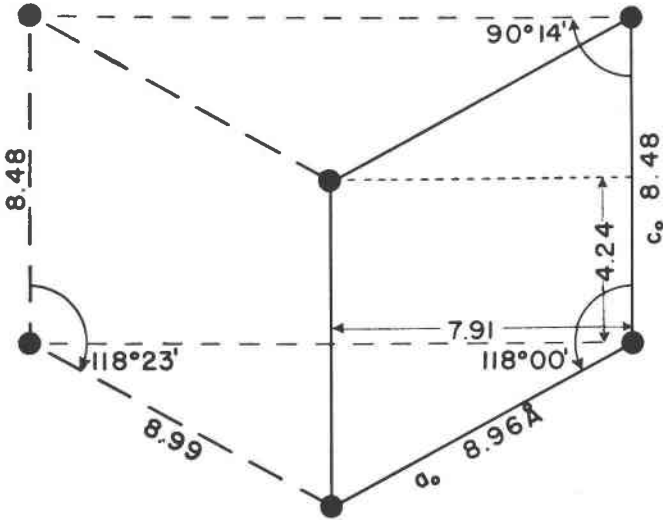


FIG. 1. A portion of the  $x_0z$  plane of the direct lattice of geocronite showing the relations of several choices of unit cell.

Berry, 1940). It appears that the cell which he chose is not that with shortest possible  $a_0$ . The axial elements of the two similar cells for jordanite may be compared with the axial elements given for this mineral by Baumhauer (1891) as transformed by Berry:

$$\begin{aligned}
 a_0 : b_0 : c_0 & 0.281 : 1 : 0.265 \quad 118^\circ 21' \quad (\text{Berry}) \\
 a : b : c & 0.2795 : 1 : 0.2655 \quad 117^\circ 49\frac{1}{2}' \quad (\text{Baumhauer-Berry}) \\
 a_0 : b_0 : c_0 & 0.280 : 1 : 0.2655 \quad 118^\circ \quad 6\frac{1}{2}' \quad (\text{alternative})
 \end{aligned}$$

It seems reasonable to suppose that jordanite and geocronite are isostructural. Substitution within the series is attended by changes in cell dimensions. These may be such that a direction chosen as  $a_0$ , the next to the shortest translation in the  $ac$  plane, for one member of the series is structurally equivalent to a translation direction in another member of the series which is not the next to the shortest in the  $ac$  plane. Accordingly it may be that Berry's  $a_0$  is equivalent to our  $a_0$  even though Berry's is not the next to the shortest translation in the  $ac$  plane.

Without reference to the structure or to suitable single-crystal patterns of Binnenthal jordanite, this point cannot be resolved. We have, however, assured ourselves that the orientations chosen for the three geocronites described in Table 1 are equivalent. Geocronite is not only metrically but also symmetrically pseudo-orthorhombic. All the principal spots in an  $h0l$  pattern show intensities conforming to the plane point group  $2l$ . Among the weaker spots, however, it is possible to discern that

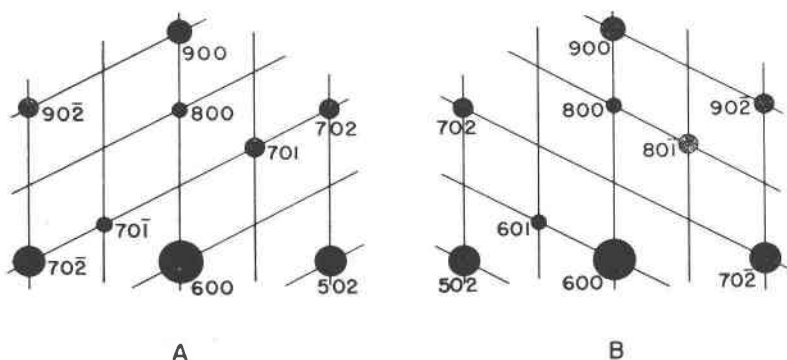


Fig. 2. A portion of the reciprocal lattice of geocronite. *A*. Indexed according to the cell with shortest possible  $a_0$  and  $c_0$ . *B*. Indexed according to a cell with slightly longer  $a_0$  as shown in Fig. 1. Sizes of circles are intended to suggest different intensities.

the symmetry is only 2 regardless of the closeness of approach of the pseudo-orthorhombic lattice to orthogonality. In order to tie the orientation chosen for geocronite to structural features as expressed in the diffraction pattern, a portion of the reciprocal lattice plane  $h0l$  is shown in Fig. 2. Fig. 2*A* shows the indexing of a group of points in accord with the cell bounded by the smallest possible  $a_0$  and  $c_0$ . Fig. 2*B* shows the indexing of the same points in accord with the same  $c_0$  but with another  $a_0$  only slightly different in length. It may be seen that the indexing of pairs of points similarly situated on opposite side of the  $a^*$  line is interchanged in these two settings so that these points offer no means of discriminating between them. There are points, 701 and  $70\bar{1}$  of Fig. 2*A*, whose indexing is peculiar to a certain setting and can be used to define the same.

Yet another feature of the lattice of geocronite merits mention. In the pseudo-orthorhombic reciprocal lattice all planes in the series  $1kl$ ,  $2kl$ , etc., with  $h$  even and those in the series  $hk1$ ,  $hk2$ , etc., with  $l$  even show the symmetry  $2l$ . Only the odd-numbered planes in these series show the lower symmetry  $l$  proper to a monoclinic crystal. Moreover these odd-numbered planes contain only very weak spots. The effect of these relations is apparent in the fragment of the reciprocal lattice shown in Fig. 2. There is then a pseudo-orthorhombic sub-cell (indicated in Fig. 1) having half the  $a$  and  $c$  dimensions of the B-centered pseudo-orthorhombic cell mentioned above and having orthorhombic symmetry. This would have half the volume of the correct monoclinic cell.\*

\* The true cell and various pseudocells of geocronite are analogous to those described for boulangerite by Berry (1940). Berry took the "orthorhombic" pseudocell to be orthogonal leaving a choice of two dimensionally identical monoclinic cells. He did not consider the problem of discriminating between these two.

An atomic arrangement in an orthorhombic space group with a cell of these dimensions ( $a_0$  7.91,  $b_0$  31.85,  $c_0$  4.24 for the Utah geocronite, for example) would represent the structure of geocronite to a first approximation. The case is somewhat similar to that of pyrrhotite, or at least of certain pyrrhotites, in which the commonly accepted structure is that of an hexagonal subcell, the true structure requiring a larger monoclinic cell for its description. Bertaut (1953) has shown that this larger cell is connected with a systematic distribution of vacancies in Fe positions. Though the structure of geocronite probably also involves vacancies in atomic positions (see discussion of cell content) it is not suggested that these necessarily determine differences between the true structure and an approximate structure conforming to the higher symmetry of the orthorhombic subcell.

## COMPOSITION AND CELL CONTENT

All of the geocronites and jordanites studied except specimens 2 and 6 (geocronite from Sala, *USNM C-830* and geocronite from Mackay, Idaho) were examined spectrographically by Mr. George M. Gordon in the Division of Mineral Technology, University of California, Berkeley. In all cases antimony and arsenic were found to be the only important metals, in addition to lead. The jordanite from Wiesloch showed the expected preponderance of arsenic over antimony, though the latter was

TABLE 2. SOME ANALYSES OF GEOCRONITE AND JORDANITE

	A	B	C
Pb	67.52 wt.%	68.90	68.72
As	3.65	4.54	12.39
Sb	11.48	9.27	
S	17.45	17.13	18.31
Total	100.10	99.84	99.42
Density	6.46±0.05		6.44

A. Geocronite, Silver King mine, Park City, Utah. Dr. R. Klemen, *analyst*. Density by Berman balance.

B. Geocronite, Sala, Sweden. C. Guillemain, *analyst*. Guillemain (1900).

C. Jordanite, Binnenthal, Switzerland. H. Jackson, *analyst*. Solly (1900). Density from Berry in Peacock and Berry (1940).

The figures given are in each case the means of two closely agreeing analyses, except for sulfur in A for which only a single determination was reported. One of the pair of jordanite analyses reported by Guillemain was used as the basis for cell content estimates by Richmond (Palache, Richmond and Winchell, 1938), whereas the average for the two given above was used by Palache and Fisher (1940) and both were used by Fisher (1940).

estimated to be present to the extent of several per cent so that this would probably be a more highly antimonian jordanite than any for which analyses are recorded by Doelter or Dana. The geocronites examined were all found to have about 10% Sb and 3–5% As, corresponding to the composition of most geocronites hitherto analyzed. Specimen 7, labelled jordanite, from the Hope mine, Bonner County, Idaho, was found to have about the same proportions of Sb and As as the geocronites. (The relations of these materials will again be referred to in the discussion of the powder patterns.)

A chemical analysis of the geocronite from the Silver King mine, Park City, Utah, was kindly carried out by Dr. R. Klemen of Vienna, on about one and a quarter grams of carefully purified material. The results of this analysis together with an analysis of geocronite from the type locality and one of jordanite are given in Table 2. The antimony content of the newly analyzed geocronite from Park City, Utah, is substantially higher than that previously found for any geocronite in which arsenic was also reported. According to *The System of Mineralogy* (1944) "the validity of [an arsenic-free variety]—is not yet established."

TABLE 3. CELL CONTENTS OF GEOCRONITE AND JORDANITE

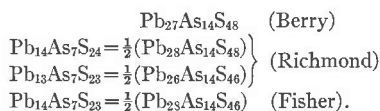
	<i>A</i> Geocronite Park City, Utah	<i>B</i> Geocronite Sala, Sweden	<i>C</i> Jordanite Binnenthal, Switzerland
$a_0$	8.96 Å	9.00	8.908*
$b_0$	31.85	31.94	31.714
$c_0$	8.48	8.52	8.417
$\beta$	118°00'	118°00'	118°21'
Density	6.46	6.45 (assumed)	6.44
Cell Vol.	2,136.73 Å <sup>3</sup>	2,162.48	2,092.67
Cell wt.	13,803.27 × 10 <sup>-24</sup> grs.	13,948.03	13,476.78
Number of atoms in cell corresponding to analyses in table 2. †			
Pb	27.09	27.94	26.92
As	4.05	5.09	13.42
Sb	7.84	6.40	
S	45.25	44.89	46.36

\* Berry's cell dimensions, presumably in kX units, have been converted to Å units by multiplying by 1.00202. The values given have been carried to one more decimal place than our own figures because it seemed best to avoid possibly excessive "rounding" on the data of others.

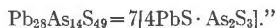
† Using atomic weights for 1942, Pb 207.21, As 74.91, Sb 121.76 and S 32.06, and weight of the unit of atomic weight  $1.6602 \times 10^{-24}$  grs. for consistency with dimensions in Ångstrom units.

In Table 3 are presented the results of cell content calculations for the geocronites and jordanite whose analyses are given in Table 2. Unfortunately Guillemin failed to state the density of the geocronite from Sala which he analyzed. The density 6.45 has been assumed for this material because nearly all good density determinations on geocronite are near this figure and it seems reasonable in view of the densities for the other minerals included in Table 2.

There has been much uncertainty as to the proper formulas for geocronite and jordanite. In later years several attempts have been made to idealize the cell content of jordanite in formulas. These have been summarized by Berry (Peacock and Berry, 1940) as follows:



Berry also pointed out that "in terms of the generally accepted formula the cell content is nearly given by:



In *The System of Mineralogy* (1944) the formula of geocronite is written  $\text{Pb}_5(\text{Sb}, \text{As})_2\text{S}_8$ , which might be taken to correspond to an ideal cell content  $\text{Pb}_{30}(\text{Sb}, \text{As})_{12}\text{S}_{48}$ , with integral subscripts close to those of the jordanite formulations just quoted.

This confused picture is not clarified by consideration of the new analysis or the results of calculations presented in Table 3. To the extent that the cell content calculations yield values less than those required by the formulas, one might ascribe the discrepancies to low determinations of density. Thus assumption of a density of 6.66 for Binnenthal jordanite would raise the calculated cell content to Pb 27.84, As 13.88, S 48.05, very close to the values chosen in the first of Richmond's formulations. Tempting though such manipulation may be, it seems unwarranted in the present case. It appears certain that geocronite and jordanite are isostructural. Referred to any of the formulas for jordanite given above, the geocronites are highly deficient in sulfur, whereas the lead content of one fits nicely the formula of Berry and that of the other the formula of Fisher. Berry (letter to Pabst, Dec. 2, 1953) points out that the "new analysis strongly suggests  $27\text{PbS} \cdot 6(\text{Sb}, \text{As})_2\text{S}_3$  for geocronite." This would necessitate a defect structure since neither of the permitted space groups for geocronite offer odd-fold positions. It may be that the numbers of positions for each kind of atom provided by the structure differ from those corresponding to any formula yet proposed.



TABLE 4. INDEXED POWDER PATTERN OF GEOCRONITE, SPECIMEN 1,  
SILVER KING MINE, PARK CITY, UTAH

<i>hkl</i>	<i>d</i> <sub>calc.</sub>	<i>d</i> <sub>obs.</sub>	<i>I</i>	<i>hkl</i>	<i>d</i> <sub>calc.</sub>	<i>d</i> <sub>obs.</sub>	<i>I</i>
120	7.08	6.91	1d	240	3.54	3.54	10
021	6.77	6.74	1	032	3.53		
121	6.75			232	3.52		
130	6.34	6.36	2-	042	3.38	3.39	8
031	6.12	6.12	2-	242	3.38		
131	6.10			052	3.23		
041	5.45	5.49	2+	252	3.22	3.18	8B
141	5.44			0·10·0	3.18		
150	4.96	4.95	1-d	260	3.17	3.06	9
151	4.84	4.84	1d	062	3.059		
101	4.48	4.46	4	262	3.052	2.98	7
201	4.46			270	2.985		
111	4.44	4.33	1-?	072	2.891	2.89	9
061	4.33			272	2.884		
161	4.32	4.33	1-?	280	2.806	2.80	5d
112	4.20	4.21	1+	132	2.796		
131	4.13	4.13	1+	332	2.784	2.72	5
231	4.12			191	2.779		
200	3.95	3.93	2-	082	2.727	2.72	5
170	3.94			142	2.723		
210	3.92	3.93	2-	282	2.722	2.63	2
071	3.89	3.89	4-	342	2.712		
220	3.84	3.83	4-	152	2.638	2.63	2
012	3.72	3.71	6	300	2.637		
230	3.71			352	2.628		
212	3.70	3.71	6	310	2.628		
022	3.64	3.64	2				
222							

## POWDER PATTERN

Powder patterns of all the geocronites examined proved to be nearly identical. By calculating the first 134 lines compatible with the space group it is possible to account for the first 24 lines of the powder pattern of Utah geocronite. Table 4 shows the indexing of all lines in a pattern of Utah geocronite corresponding to a spacing of 2.53 Å or more. Only those calculated lines considered to correspond to observed lines are included. Coincidences are numerous due to the large cell and indexing was assured only by comparison with fully indexed single-crystal patterns. Under these circumstances more extended indexing of the powder patterns was not attempted.

In Table 5 a more extended portion of the powder pattern of the Utah

TABLE 5. COMPARISON OF POWDER PATTERNS OF GEOCRONITE AND JORDANITE

Specimen 1 Geocronite Park City, Utah		Specimen 7 "Jordanite" Hope mine, Idaho		Specimen 8 Jordanite Wiesloch, Baden		Geocronite Falun, Sweden (Hiller, 1938)		Jordanite Silesia (Harcourt, 1942)	
<i>I</i>	<i>d</i>	<i>I</i>	<i>d</i>	<i>I</i>	<i>d</i>	<i>I</i>	<i>d</i>	<i>I</i>	<i>d</i>
1d	6.91 Å	1d	7.05 Å	1-	7.25 Å				
1	6.74			1+	6.71				
2-	6.36	1	6.30						
2-	6.12			1	6.03				
2+	5.49								
{1-d	4.95			1d	4.87				
{1d	4.84								
4	4.46	2-	4.42	2	4.40				
1-?	4.33								
{1+	4.21			2	4.17				
{1+	4.13			1	4.01				
2-	3.93	1	3.90			m	3.89		
4-	3.83	2	3.84						
				3	3.78				
6	3.71	5	3.70	4	3.65	m	3.71		
2	3.64			1	3.58				
10	3.54	8	3.53	6	3.47	m-st	3.54	1.0	3.49
8	3.39	7B	3.39	7	3.34	m-st	3.40	1.0	3.31
8B	3.18	10	3.19	8	3.15	st	3.19	1.0	3.15
		5	3.12						
9	3.06	5	3.05	8	3.06	m	3.07	1.0	3.01
7	2.98	{5-	2.98	9	2.97	m	2.99		
		{5+	2.96						
9	2.89	7	2.89	4-	2.87	st	2.90	1.0	2.87
5d	2.80	3d	2.80	5	2.78	m	2.84	0.5	2.75
5	2.72	4	2.72			m	2.74		
2	2.63	1d	2.64	1	2.63	v w	2.64		
1	2.59								
1-	2.55								
2-B	2.49	1+	2.49			m	2.46	0.3	2.48
1	2.44								
3-	2.39	3	2.39	3+	2.39			0.3	2.36
1+	2.33								
1-	2.29								
9	2.235	10	2.245	10	2.238	v st	2.24	3.0	2.22
6	2.122	4+	2.122	6	2.110	m	2.12	2.0	2.10
3	2.086	4+	2.094			w	2.087		
4+	2.052	3d	2.047						
4-	2.030			3	2.025	m	2.033		
				1	1.999			0.5	2.01
3+	1.973	2-	1.981			m	1.971		
5	1.984	3	1.949			m-st	1.947	0.5	1.93
2	1.918	6-	1.908	4	1.912	v w	1.910		
4	1.889					v w	1.886		
				4	1.870				
{3	1.850	9B	1.836						
{8	1.831			8	1.829	st	1.830	2.0	1.815
1	1.791	4	1.786	2	1.784				
7	1.765	6	1.765	5	1.755	sr	1.763	1.0	1.745
4	1.744	3	1.729	1	1.735	m-st	1.730		
3	1.694	2d	1.705	3	1.705	m	1.696		
2	1.677			2	1.681	v w	1.677		
2	1.651	5	1.627						
1	1.618								
3	1.597	2+	1.598			v w	1.595		
1d	1.565			3d	1.575				
				1	1.497				
3	1.489					w	1.485		
4d	1.469	4B	1.481	3	1.477				
				3+	1.462	w	1.467		
4	1.448	3-	1.447	2+	1.440	w	1.448		
2	1.428	1	1.433	2d	1.417	w	1.428		
4	1.409	3-	1.410	2d	1.403	w	1.408		

plus about 20 more lines in each pattern.

plus 16 more lines.

geocronite is tabulated together with earlier published patterns of geocronite and jordanite and with patterns obtained from the two specimens labelled jordanite which were examined in the course of this study. As may be seen from the table these do differ from the geocronite pattern but are not identical to each other. Hiller (1938) gave his powder-pattern results for geocronite in terms of angle and  $\sin^2$  values for Fe radiation. These have been converted to spacings for presentation in Table 5. *ASTM* card 2-1144 gives a composite record of Hiller's geocronite pattern and one reported by Harcourt (1942). In Table 5 lines are tabulated only to  $d$  1.41, the limit of this card. Harcourt's jordanite pattern is recorded on *ASTM* card 2-1149.

## MORPHOLOGY

Goniometric measurements on geocronite have been published only by Kerndt (1845) and by D'Achiardi (1901). Both measured crystals from Val di Castello, near Pietrasanta, Tuscany. The measurements

TABLE 6. SUMMARY OF SOME GEOCRONITE SETTINGS BASED ON ANGLES REPORTED BY KERNDT

Author	Year	Indices			
		pinacoid	prism	dipyramid	$a:b:c$
Kerndt* as corrected by Goldschmidt	1845	{100}	{120}	{111}	0.290 :1:0.503
	1890				
Goldschmidt Goldschmidt	1890	{001}	{011}	{212}	1.006 :1:0.58
	1897				
Groth†	1882				0.58 :1:0.48 circa
Dana	1892	{100}	{110}	{211}	0.5805:1:0.5028

\* The axial ratios given by Kerndt, " $a:b:c=1:0.269197:0.468949$ ," are difficult to interpret and probably in error.

† Probably a slightly erroneous statement of ratios corresponding to the setting later used by Dana.

The transformations for the settings given above are:

	Kerndt (Gdt. 1890)	Goldschmidt 1890	Dana 1892
Kerndt		002/010/200	200/010/001
Goldschmidt	00½/010/½00		001/010/½00
Dana	½00/010/001	002/010/100	

of Kerndt were the basis of crystallographic descriptions of geocronite in many well-known texts. The work of Kerndt is subject to several uncertainties which were discussed by Goldschmidt (1890). The results of Kerndt and the more important descriptions based thereon are summarized and correlated in Table 6.

Whereas Kerndt reported only three forms D'Achiardi found a great number. Inspection of the drawings published by these authors leaves no doubt that D'Achiardi used a setting corresponding to that adopted by Goldschmidt (1890 and 1897). It is not possible, however, to give a transformation between the setting of D'Achiardi and previous settings.

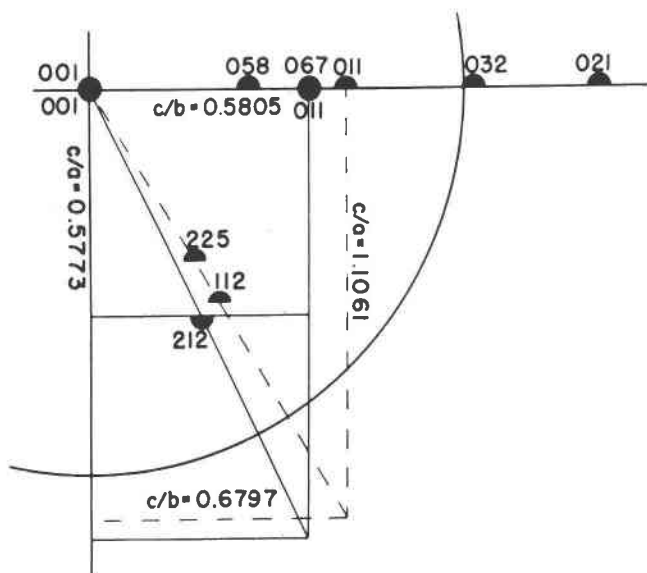


FIG. 3. One quadrant of a gnomonic projection of geocronite. Upper semicircles and projection elements written above dashed lines according to D'Achiardi (1900). Lower semicircles and projection elements written below full lines according to Goldschmidt (1890, 1897) from angles of Kerndt (1845).

Though  $\rho_{067}$  of D'Achiardi,  $30^{\circ} 12'$ , is close to  $\rho_{011}$  of Goldschmidt,  $30^{\circ} 07'$ , this is insufficient to establish a transformation since no certain correlation can be found between the "pyramidal" forms reported by D'Achiardi and the single such form reported by Kerndt. This is illustrated in Fig. 3 by superposition of gnomonic projections corresponding to the Kerndt-Goldschmidt and the D'Achiardi settings.

The difficulty just explained was circumvented in the 7th edition of *The System of Mineralogy*, 1944 (vol. 1, pages 395-396). The axial ratios given there,  $a:b:c=0.5028:1:0.5805$ , correspond to those in the

6th edition derived from Kerndt's measurements with  $a$  and  $c$  interchanged. A note contains the statement "Elements from Kerndt's angles, on Val di Castello crystals in the orientation of D'Achiardi (1901) with the unit of Dana (1892). The angles of D'Achiardi are not in close agreement with those of Kerndt. Transformation Kerndt to D'Achiardi 001/010/100." The transformation is misleading. It ought to result in correspondence of the newly transformed axial ratios given above with those of D'Achiardi, 0.6145:10.6797. The so-called "transformation" must be taken to indicate merely the correspondence of axial directions and not of unit distances. Possibly such a relation could be more appropriately symbolized by Z/Y/X.

D'Achiardi (1901) reported differences in the terminations at either end of the axis normal to the large face which he designated (001) and referred geocronite to the orthorhombic pyramidal class. The crystals we measured show a development obviously similar to that of Val di Castello crystals. Such crystals rarely show identical development at the positive and negative ends of the  $b$  axis normal to the large face because they are most frequently attached in such a way that only one of these faces is developed. Under these circumstances it is difficult to check on the polar character of this axis. Such observations as we have made indicate lack of complete correspondence between  $hkl$  and  $h\bar{k}l$  faces but no systematic variations. The minor departures from ideal  $2/m$  symmetry observed might well be attributed to accidents of growth. Since our work has shown that geocronite is isostructural with jordanite

TABLE 7. STANDARD ANGLE TABLE FOR GEOCRONITE BASED ON STRUCTURAL CELL DETERMINED FOR SPECIMEN 1

Monoclinic; prismatic— $2/m$

$a:b:c=0.2813:1:0.2662$ ;  $\beta$   $118^{\circ}00'$ ;  $p_0:q_0:r_0=0.9463:0.2350:1$

$r_2:p_2:q_2=4.2546:4.0257:1$ ;  $\mu$   $62^{\circ}00'$ ;  $p_0'$   $1.0717$ ,  $q_0'$   $0.2662$ ,  $x_0'$   $0.5317$

Forms:	$\phi$	$\rho$	$\phi_2$	$\rho_2=B$	C	A	
	001	$90^{\circ}00'$	$28^{\circ}00'$	$62^{\circ}00'$	$90^{\circ}00'$	—	$62^{\circ}00'$
$b$	010	0 00	90 00	—	0 00	$90^{\circ}00'$	90 00
$a$	100	90 00	90 00	0 00	90 00	62 00	—
	170	29 54	90 00	0 00	29 54	76 28	60 06
$\epsilon$	110	76 03	90 00	0 00	76 03	62 58	13 57
	101	$-90$ 00	28 22	118 22	90 00	56 22	118 22
	011	63 24	30 44	62 00	76 46	13 14	62 48
	111	$-63$ 26	31 07	118 22	76 49	57 23	62 27

(Letter designations are given for those forms surely corresponding to the similarly lettered forms in the angle table for jordanite in The System of Mineralogy, 7th ed. Vol. I, p. 398, 1944.)

which is recognized as having the symmetry  $2/m$ , we are inclined to consider that geocronite has this symmetry as well, and this has influenced our choice of probable space group.

An angle table calculated for geocronite with elements based on the structural cell is reproduced as Table 7. All forms listed in the angle table were observed, but numerous other forms were observed in each of the zones  $[001]$ ,  $[100]$  and  $[101]$  represented in the table. In certain parts

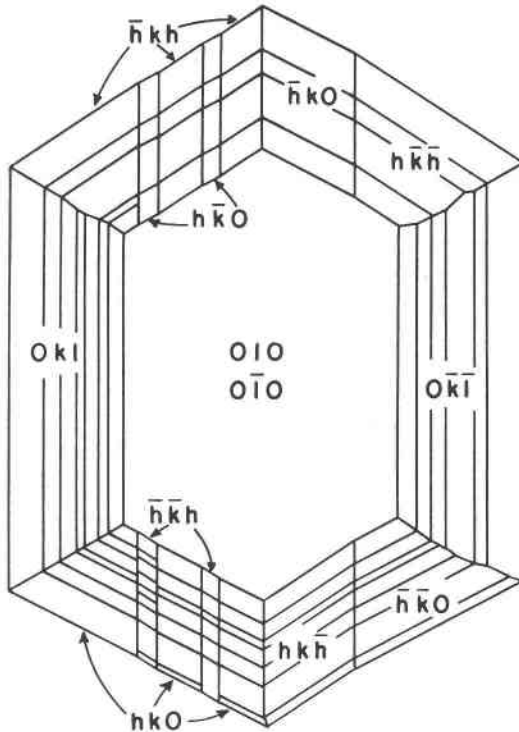


FIG. 4. Idealized sketch of a twinned crystal of geocronite.

of these zones faces may be so closely spaced that signals overlap on the reflecting goniometer and a continuum of reflections is seen. It is not possible to assign an order of prominence of the forms with any assurance but  $\{010\}$  which is common to the three zones mentioned is generally the most prominent form. The form  $\{170\}$  is included in the angle table only because its  $\rho_2$  value is close to that of D'Achiardi's  $\{067\}$  and of the single prismatic form  $\{g\}$  recorded by Kerndt.

The habit of geocronite corresponds closely to that of jordanite. The

similarity of the crystals is apparent in a comparison of the angle tables.\* An idealized drawing of one crystal of geocronite from Park City, Utah, is shown in Fig. 4. The over-all appearance is that of an orthorhombic crystal with pronounced development of one pinacoid, one series of cozonal prisms and one series of cozonal dipyrramids. Where twin boundaries traverse (010), which is in common for the two parts of the twin, they are not discernible and hence are not shown in the drawing. Though the material available to us lacks fully developed crystals a little variation in habit is discernible. In general {010} is a little less prominent than in the drawing and the development of the three zones having this form in common varies somewhat, the [001] zone being least conspicuous in some instances. One crystal, however, shows a large (010) face and prominent development of a zone of faces not traversed by twin striations as pictured by Kerndt (1845) and D'Achiardi (1901). Figure 4 gives the interpretation of such a crystal taking into account the monoclinic character and the twinning.

Most of the crystals are twinned in such a way that nearly coincident zones appear in certain sectants.  $\phi_2$  differences measured for such pairs of zones were somewhat erratic, ranging from  $3\frac{1}{2}$  to  $6\frac{1}{2}$  degrees, usually close to 5 degrees. Such a development might arise from repeated twinning on either {001} or {101}, the ideal  $\phi_2$  differences being  $5^\circ 38'$  and  $5^\circ 16'$  respectively. From lattice dimensions either twinning seems probable. The index of the twin is unity in both cases and the obliquity  $3^\circ 49'$  and  $3^\circ 34'$  respectively (Donnay, 1940). Goniometric measurement will not distinguish the two cases with certainty or even eliminate the possibility that both kinds of twinning occur since the  $\rho_2$  angles in the zones [100] and [101] differ by only a few minutes. Fortunately it was possible to discern twinning in zero-layer Weissenberg patterns on the *b* axis for crystals from specimens 1, 2, and 3. In each case {001} twinning only was observed. This does not exclude the possibility of the occurrence of {101} twinning as well, or of a combination of the two. For jordanite twinning reported by Palache is described in the System of Mineralogy (1944) in terms of the cell found by Berry as "(a) On {001}, most common and often lamellar; (b) on  $\{201\}$ , common; (c) on  $\{\bar{1}01\}$ , rare; (d) on {101}, very rare." The correspondence of the {001} or  $\{\bar{1}01\}$  twinning of jordanite to {001} twinning in geocronite is subject to the uncertainty connected with the existence of two nearly identical line lattices in these minerals as set forth in the discussion of Table 1.

We have observed what appeared to be cleavage parallel to {100} and have checked its orientation by means of single-crystal patterns in frag-

\* Note: The values  $r_2$  and  $\beta_2$  in the angle table for jordanite in the System of Mineralogy, 7th edition, vol. I, p. 398, 1944, should be interchanged.

ments from specimens 1, 2 and 3. This is not at all conspicuous. It is uncertain whether it corresponds to the better cleavage reported by Kerndt (1845) and mentioned as “{011} distinct” in *The System of Mineralogy* (1944). In any case the lack of {010} cleavage in geocronite, whereas jordanite is reported to have “very perfect” {010} cleavage, furnishes one of the few sharp differences between these closely related minerals.

#### POLISHED-SURFACE OBSERVATIONS [R. M. D.]

Polished sections of specimens of geocronite, jordanite and boulangerite were studied using with few modifications the techniques set forth by Short (1940). Geocronite and jordanite were examined because of their close relation to each other, and boulangerite because of its frequently being mistaken for geocronite and vice versa. The identification of all specimens was confirmed by  $x$ -ray powder patterns, and numbers 1, 3, 5, 7 and 8 were examined spectrographically in addition.

In spite of uncertainty of identification of many of the materials described as one of these three minerals in the literature, the results of the present polished-surface study are in fairly good agreement with those descriptions with the notable exception of the behavior of these three minerals toward nitric acid. All of the authors cited below reported strongly positive reactions with this reagent whereas the tests are all reported herein as negative. This discrepancy is apparently due principally to the care with which the acid is applied to the surface rather than to misidentification of materials, although the latter might be partly responsible. If the drop is applied so as to avoid overlapping onto cracks or intergrown grains of other minerals, no reaction ensues; with many specimens this may necessitate very careful application of quite small drops. If such overlapping occurs rapid blackening accompanied by effervescence usually results. If this reaction is not too rapid it can be seen to originate at the cracks or inclusions, passing as a wave across the surface with iridescent concentric rings preceding the blackening and effervescence. Frequently the entire surface covered by the acid is thus affected, although occasionally the reaction may stop short. To demonstrate that failure to react is not due merely to an unclean surface (in spite of careful polishing) or to the relatively small area of the mineral in contact with the reagent, the surface may be scratched gently with a needle immediately prior to application of the drop. Moreover if a needle be introduced into the drop after application there results a “positive” reaction closely simulating that described above. These observations suggest that some extraneous electrolytic effect is responsible for the reported “positive” reactions with nitric acid, and further emphasize the necessity of great care in making and interpreting etch tests in general.



Although presence of lamellar twinning is suggestive of geocronite or possibly jordanite, and slightly stronger anisotropism is suggestive of boulangerite, it remains doubtful whether or not these three minerals can be distinguished with certainty by polished-surface observations alone.

**GEOCRONITE:** Murdoch (1916) performed etch tests on one specimen from one locality (not given) and considered the determination only "fairly reliable"; no confirmatory data as to the identification of the specimen are mentioned. Davy and Farnham (1920) gave no sources of data. Schneiderhöhn and Ramdohr (1931) and Ramdohr (1950) referred to Murdoch for etch behavior and gave no further sources of data. Short (1940) stated (p. 2) that "over 20 per cent of [Murdoch's] minerals were mislabelled"; furthermore a specimen labelled "geocronite, Sala, studied by Max Short" (no. 4 of this paper) was found in the present study to be a mixture of boulangerite and galena. Anderson (1946) based his identification solely on polished-surface observations as described by Short. Uytendogaardt (1951) referred to Murdoch, to Short and to Schneiderhöhn and Ramdohr.

Five specimens of geocronite were examined in the present study—numbers 1, 2, 3, 5 and 6.

*Hardness*—Talmage hardness  $\sim$ B, but harder than galena as indicated by lightly drawing a needle across geocronite-galena contacts (nos. 1, 2 & 3): the scratches are decidedly deeper and wider in galena. Difference in relief owing to difference in polishing hardness is not discernible by movement of "Becke-like" line. (This is contrary to Schneiderhöhn and Ramdohr, 1931, and to Ramdohr, 1950, who reported polishing hardness definitely lower than galena although variable. Uytendogaardt, 1951, gave " $H < \text{galena}$ " [after Schneiderhöhn and Ramdohr?].)

*Cleavage*—Not apparent in polished sections. (Short, 1940, stated that geocronite "has at least one good cleavage.")

*Color*—Galena white, but where in contact with galena (nos. 1, 2, & 3) a faint but definite greenish, bluish-green, or olive tinge is seen.

*Polarization*—Anisotropism, but color effects weak: light gray to dark gray, bluish gray, or steel blue; or creamy tan to brownish gray. (The polarization colors in any given section are subject to considerable variability depending especially on the angular departure from perpendicularity of the planes of polarization of the nicol prisms, and on the light source.) Reflection pleochroism weak. Fine lamellar twinning and rare coarser twinning on another law may be revealed under crossed nicols. Twinning in any given section is frequently not apparent, however, and thus lamellar twinning as a diagnostic (suggested by Schneiderhöhn and Ramdohr, 1931, and by Ramdohr, 1950) may be unreliable.

*Etch reactions*

$\text{HNO}_3$  (1 part concentrated nitric acid, sp. gr. 1.42:1 part water by volume)—Negative. (Descriptions in the literature give rapid blackening with effervescence—see opening discussion.)

$\text{HNO}_3$  conc.—Negative, although on long standing a very faint brown tarnish may remain which does not wash off.

$\text{HCl}$  (1 pt. conc. hydrochloric acid, sp. gr. 1.19:1 pt. water by vol.) and  $\text{HCl}$  conc.—Essentially negative, although on long standing a very faint tan tarnish may remain which does not wash off; fumes may tarnish also. (Short, 1940, classed the reaction with  $\text{HCl}$  (1:1), as positive. Murdoch, 1916, reported “instantly bright brown” with concentrated  $\text{HCl}$ .)

Aqua regia (3 pts. conc.  $\text{HCl}$ :1 pt. conc.  $\text{HNO}_3$  by vol.)—Fumes may tarnish light yellowish brown, not washing off; little or no effect under drop. (Murdoch, 1916, reported “rapidly tarnishes iridescent.”)

$\text{KCN}$  (20% by wt. in water),  $\text{FeCl}_3$  (20%),  $\text{KOH}$  (40%) and  $\text{HgCl}_2$  (5%)—Negative.

JORDANITE: Murdoch (1916) performed etch tests on one specimen from one locality (not given) and considered the determination “doubtful.” Davy and Farnham (1920) and Short (1940) described the mineral but gave no information as to reliability of identification of the specimens, the number examined, or their localities. Schneiderhöhn and Ramdohr (1931) and Ramdohr (1950) referred to Murdoch regarding etch behavior. Anderson (1946) based his identification solely on polished-surface observations as described by Short. Uytendogaardt (1951) referred to Anderson and to Schneiderhöhn and Ramdohr.

Two specimens of jordanite were examined in the present study—numbers 7 and 8 of this paper; number 7 is from the same locality as material described by Anderson (1946).

*Hardness*—Talmage hardness B to C. (Schneiderhöhn and Ramdohr, 1931, and Ramdohr, 1950, stated polishing hardness slightly greater than that of galena.)

*Cleavage*—Not apparent in polished section.

*Color*—Galena white.

*Polarization*—Anisotropism weak to moderate; colors from light to dark gray. (Anderson, 1946, reported “distinctive but rather weak anisotropism,” Schneiderhöhn and Ramdohr, 1931, and Ramdohr, 1950, strong anisotropism.) Twinning not apparent. (Schneiderhöhn and Ramdohr and Ramdohr reported both lamellar twinning and rarer, less well developed twinning on another law in material from Binnenthal.)

*Etch reactions*

$\text{HNO}_3$ —Negative. (Descriptions in the literature give reaction slow

in starting, then staining gray to brown; Short, 1940, reported reaction accompanied by slow effervescence—see opening discussion.)

HNO<sub>3</sub> conc., HCl and HCl conc.—Negative, or very faint brown stain may remain after rinsing.

Aqua regia—Negative or faint brown stain; fumes may tarnish also.

KCN, FeCl<sub>3</sub>, KOH and HgCl<sub>2</sub>—Negative.

**BOULANGERITE:** Murdoch (1916) performed etch tests on two specimens from two localities (not given), but gave no confirmatory data. Davy and Farnham (1920) and Short (1940) described the etch behavior but gave no information as to reliability of identification of the specimens, the number examined, or their localities. Schneiderhöhn and Ramdohr (1931) and Ramdohr (1950) referred to Murdoch regarding etch behavior. Berry (1940), Hawley (1941) and Chace (1948) confirmed the identification of the materials they examined by *x*-ray patterns and by density determinations. Anderson (1946) based his identification solely on polished-surface observations as described by Short. Uytenbogaardt (1951) referred to Short, to Berry, to Hawley, to Chace and to Schneiderhöhn and Ramdohr.

Six specimens of boulangerite were examined in the present study—number 4 of this paper (studied by Max Short as geocronite), two from Oberlahr, Germany (cf. Berry, 1940, numbers 5 and/or 19), one from Cleveland mine, Stevens County, Washington (cf. Berry number 11), and two from Lower California, Mexico (one of which was mislabelled “geocronite”).

*Hardness*—Talmage hardness B and C; harder than associated galena (no. 4) (by scratching across contact). (Schneiderhöhn and Ramdohr, 1931, and Ramdohr, 1950, stated hardness very similar to galena, a trace less.)

*Cleavage*—Not apparent in polished section.

*Color*—Galena white, but when in contact with galena (no. 4) shows a faint bluish-green tinge.

*Polarization*—Anisotropism moderate to strong; colors light tan or gray to steel blue. Twinning not apparent.

#### *Etch reactions*

HNO<sub>3</sub>—Negative. (Descriptions in the literature give blackening with effervescence—see opening discussion.)

HNO<sub>3</sub> conc., HCl and HCl conc.—Negative, or very faint brown stain may remain after rinsing.

Aqua regia—Fumes may tarnish light brown, not washing off. (Murdoch, 1916, reported blackening with effervescence.)

KCN, FeCl<sub>3</sub>, KOH and HgCl<sub>2</sub>—Negative. (Chace, 1948, reported

slight brown to iridescent stain with KOH. Hawley, 1941, reported negative or in some places possibly stains faint gray or brown with KOH and faint brown color at edge of drop with HgCl<sub>2</sub>. It is suspected that these observers have encountered the difficulty in using these reagents which is discussed by Short, 1940, p. 98).

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