

HEDLEYITE, A NEW BISMUTH TELLURIDE FROM
BRITISH COLUMBIA, WITH NOTES ON WEHRLITE
AND SOME BISMUTH-TELLURIUM ALLOYS

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and

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THE mineral described in this paper is a foliated bismuth telluride, resembling joseite, which was first noted on two small specimens showing visible gold, from the Good Hope mineral claim, about four miles south-east of the town of Hedley, Osoyoos mining division, B.C. These two specimens were received by one of us (H.V.W.) from Mr. W. R. Wheeler in the spring of 1943, about the time when gold was found on the Good Hope claim. Later in the year Mr. Wheeler kindly furnished further specimens of the telluride; these, together with a sample contributed by Dr. W. E. Cockfield, provided the material for the present work.

A preliminary study of the bismuth telluride was made in Vancouver with the assistance of Mr. R. M. Thompson, who made the many specific gravity measurements needed to prepare material for analysis, and Mr. G. S. Eldridge, who kindly undertook the analyses. The mineral was further examined in Toronto with the assistance of Dr. E. W. Nuffield, who determined the specific gravity and etch-reactions of typical material. When the work in Toronto finally showed that the mineral cannot be properly identified with any described bismuth telluride, we named it hedleyite after the mining town near which it was found.

OCCURRENCE AND GENERAL DESCRIPTION

(H.V.W.)

The geology and ore deposits of the Hedley district (Osoyoos mining division) have been described and mapped by Camsell (1910), Bostock (1930), Bostock & McNaughton (1940), and others. Dr. V. Dolmage, now in charge of development on the Good Hope claim, kindly furnished further geological information. From these sources it may be briefly stated that the region is occupied by inclined sedimentary rocks of Triassic age, intruded by granitic bodies of

late Mesozoic or Tertiary age. At the Good Hope claim the country rock is a skarn composed mainly of garnet, epidote, and pyroxene cut by irregular veins and stringers of quartz. Most of the hedleyite samples were obtained from these quartz bodies, but the mineral was also noted in the skarn. Some of the best samples were got by panning disintegrated rock in the vicinity of the mineral showing.

Hedleyite is associated with native bismuth, joseite, pyrrhotite, arsenopyrite, calcite, and gold. Bismuth is conspicuous in some samples but joseite cannot be distinguished from hedleyite by inspection. Pyrrhotite and arsenopyrite in small amounts occur in the skarn near the quartz veins. Calcite is sporadically scattered through the veins and stringers. Visible gold occurs close to the bismuth minerals, sometimes as films in the foliated tellurides. The ore minerals are notably poor in sulphur and thus it is evident that the mineralizing solution was deficient in sulphur. The presence of occasional quartz crystals projecting into cavities in the gangue indicate that the temperature of mineralization was low to moderate.

The presence of two bismuth tellurides on the material from Hedley was first suggested by the large variation shown by specific gravity measurements. A few plates gave 8.1, a normal value for joseite (Peacock, 1941, p. 87); but many others gave much higher and somewhat variable values, for example 8.68—8.89 (on 8 plates), 8.76—8.93 (on another 8 plates), measured on the Berman balance.

To obtain samples of the heavy telluride for analysis clean flakes were broken from the hand specimens or selected from pan concentrates. These were trimmed and cleaved if necessary to a weight of about 50 mg. The specific gravity of each flake was then determined and the flake was retained if it came within the range of the higher specific gravities. In this process a black film was frequently revealed in the cleavage planes. This was considered to be an alteration product since it appeared mainly in material obtained by panning disintegrated rock. Much of the mineral obtained directly from the veins appeared to be free from this film.

Two samples of the heavy bismuth telluride were analysed by Mr. G. S. Eldridge, with the results shown under 1 and 2. A spectrographic analysis of the material represented by analysis 1 gave the additional approximate percentages: Sb 0.05, Pb 0.01, Cu 0.01.

The simple rational formula which has the calculated

Bi.....
Te.....
S.....

Joseite from Glacier G (Warren & Davis, 1940; F be considered to be a sulphur as tellurbismuth (Bi_2Te_3). the x-ray work described in idea; it appears rather than whose composition may be expressed by a simple ratio

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The material received of the new mineral, up straight edges or bevelled white colour and heavy easy cleavage parallel readily separated into fine needle, giving cle warped and frequent hardness is 2, and the

In a polished section the plate surface, thin of silver and that of to dark grey). The standard etch-reagent and quickly turns HCl, negative. K iridescent. KOH other bismuth telluride

The simple rational formula which best fits the analyses is Bi_5Te_2 which has the calculated composition under A.

	1	2	A
Bi.....	80.60	81.55	80.4
Te.....	18.52	17.60	19.6
S.....	0.12	0.04
	<u>99.24</u>	<u>99.19</u>	<u>100.0</u>

Joseite from Glacier Gulch, B.C., has the composition Bi_4TeS_2 (Warren & Davis, 1940; Peacock, 1941), and thus hedleyite might be considered to be a sulphur-free joseite, related to joseite somewhat as tellurbismuth (Bi_2Te_3) is to tetradymite ($\text{Bi}_2\text{Te}_2\text{S}$). However, the x-ray work described in the following pages does not support this idea; it appears rather that hedleyite is a bismuth-tellurium alloy whose composition may vary and cannot, therefore, be properly expressed by a simple rational formula.

FURTHER OBSERVATIONS

(M.A.P.)

HEDLEYITE

The material received for study consisted of several clean plates of the new mineral, up to 6 mm. wide and 1 mm. thick, showing no straight edges or bevelling planes. These plates have the usual tin-white colour and heavy metallic lustre of bismuth tellurides and easy cleavage parallel to the plane of the plates. A single plate is readily separated into thin, somewhat flexible leaves by means of a fine needle, giving cleavage surfaces which are always more or less warped and frequently filmed with an iron black tarnish. The hardness is 2, and the specific gravity is 8.91 (Nuffield).

In a polished section of the largest plate, cut nearly parallel to the plate surface, the white colour in reflected light is between that of silver and that of galena. The anisotropism is slight (light grey to dark grey). The hardness is B (galena), and the reactions to the standard etch-reagents are as follows: HNO_3 , effervesces vigorously and quickly turns grey; the fumes give a brown iridescent tarnish. HCl , negative. KCN , negative. FeCl_3 , stains brown, in places iridescent. KOH , negative. HgCl_2 , negative. As compared to other bismuth tellurides hedleyite is clearly distinguished by only

one of its physical properties, namely the specific gravity which is substantially higher than that of any of the species in question.

X-ray powder photographs of hedleyite gave a rather simple pattern (Fig. 4) which resembles the patterns of joseite (Peacock, 1941) and first suggested that hedleyite is a sulphur-free joseite. However, an attempt to index the pattern with reference to a joseite lattice did not succeed. On the other hand, it was found that all the lines, except two weak ones, correspond to a rhombohedral lattice with the dimensions:¹

$$a_{\text{hex}} = 4.46 \text{ \AA}, c = 5.94 \text{ \AA}; a_{\text{rh}} = 3.248 \text{ \AA}, \alpha = 86^\circ 42\frac{1}{2}'$$

Table 1 gives the observed powder intensities, glancing angles, measured spacings, hexagonal and rhombohedral indices, and calculated spacings.

TABLE 1
HEDLEYITE: X-RAY POWDER SPECTRUM
Hexagonal, *R*

$$a_{\text{hex}} = 4.46 \text{ \AA}, c = 5.94 \text{ \AA}; a_{\text{rh}} = 3.248 \text{ \AA}, \alpha = 86^\circ 42\frac{1}{2}'$$

<i>I</i>	$\vartheta(\text{Cu})$	<i>d</i> (meas.)	(<i>hkil</i>) (<i>hkl</i>)	<i>d</i> (calc.)
1	10.1°	4.38 Å	
$\frac{1}{2}$	12.3 β	3.26 } 3.25 }	(10 $\bar{1}$ 1) (100)	3.238 Å
10	13.7 α			
5	19.0	2.36	(01 $\bar{1}$ 2) (110)	2.354
4	20.15	2.23	(11 $\bar{2}$ 0) (10 $\bar{1}$)	2.230
1	21.4	2.11	
3	22.8	1.984	(0003) (111)	1.980
3	24.7	1.840	(02 $\bar{2}$ 1) (11 $\bar{1}$)	1.836
4	28.3	1.621	(20 $\bar{2}$ 2) (200)	1.619
4	31.3	1.480	(11 $\bar{2}$ 3) (210)	1.481
3	32.8	1.419	(21 $\bar{3}$ 1) (20 $\bar{1}$)	1.418
2	33.6	1.389	(10 $\bar{1}$ 4) (211)	1.386
2	36.0	1.308	(12 $\bar{3}$ 2) (21 $\bar{1}$)	1.310
1	36.65	1.288	(30 $\bar{3}$ 0) (21 $\bar{1}$)	1.287

To explain the two lines which are not referable to the above rhombohedral lattice, basal diffractions were recorded by prolonged zero-Weissenberg resolutions on small practically plane cleavage plates rotated about random axes in the cleavage plane.

¹All the conjugate hexagonal and rhombohedral cell dimensions given in this paper rest on measured dimensions of the hexagonal cells, from which the rhombohedral dimensions have been calculated and checked by verifying the fact that the rhombohedral cell volume is one-third of the hexagonal cell volume.

The result was a complicated superlattice with $c' = 20c/11$. The lattice with $c'' = 20c = 118$ Å have the same value of a_{hex} . The superlattice elements are:

$$a_{\text{hex}} = 4.46 \text{ \AA}, c' = 118 \text{ \AA} \\ a_{\text{hex}} = 4.46 \text{ \AA}, c'' = 236 \text{ \AA}$$

The two extra lines in the pattern follow:

<i>I</i>	$\vartheta(\text{Cu})$	<i>d</i> (meas.)
1	10.1°	4.38 Å
1	21.4	2.11

The volumes of the alternate cells are 11 times the volume of the simple rhombohedral cell. To determine a choice between the two cells we may arbitrarily choose the simple cell with c'' to account for all the other lines.

Using the measured spacings of the two rhombohedral cells, the following values were obtained. With these values the following atomic cell contents were calculated:

	Anal. 1	simple cell
Bi.....	80.60	0.7
Te.....	18.52	0.2
S.....	0.12	0.0
	99.24	0.9

The two cells contain nearly equal numbers of atoms and in view of the alloy-character of the material, integral numbers of atoms are preferred. The empirical content of the lattice is Bi_{0.7}Te_{0.2}S_{0.0}. The calculated specific gravity is 8.91. If the measured value 8.91 is expressed by a rational formula

The result was a complicated series of spots indicating an hexagonal superlattice with $c' = 20c/3 = 39.60 \text{ \AA}$, or a rhombohedral superlattice with $c'' = 20c = 118.8 \text{ \AA}$. Assuming that these superlattices have the same value of a_{hex} as the principal lattice, the alternative superlattice elements are:

$$a_{\text{hex}} = 4.46 \text{ \AA}, c' = 39.60 \text{ \AA};$$

$$a_{\text{hex}} = 4.46 \text{ \AA}, c'' = 118.8 \text{ \AA}; a_{\text{rh}} = 39.68 \text{ \AA}, \alpha = 6^\circ 26\frac{1}{2}'$$

The two extra lines in the powder spectrum can then be indexed as follows:

<i>I</i>	$\vartheta(\text{Cu})$	<i>d</i> (meas.)	$(hk\bar{l})c'$	$(hk\bar{l}) (hkl)c''$	<i>d</i> (calc.)
1	10.1°	4.38 Å	(0009)	(0.0.0.27) (999)	4.400 Å
1	21.4	2.11	(11 $\bar{2}$ 6)	(1.1. $\bar{2}$.18) (765)	2.113

The volumes of the alternative superlattice cells are both twenty times the volume of the small rhombohedral cell. There is nothing to determine a choice between the two superlattices, and therefore we may arbitrarily choose the rhombohedral cell corresponding to c'' to account for all the observed diffractions.

Using the measured specific gravity 8.91 the molecular weights of the two rhombohedral cell contents are 184.2 and 3684 respectively. With these values the two analyses of hedleyite give the following atomic cell contents:

	Anal. 1	Atoms in		Anal. 2	Atoms in	
		small cell	large cell		small cell	large cell
Bi.....	80.60	0.716	14.32	81.55	0.725	14.49
Te.....	18.52	0.270	5.39	17.60	0.257	5.13
S.....	0.12	0.008	0.15	0.04	0.003	0.05
	99.24	0.994	19.86	99.19	0.985	19.67

The two cells contain nearly 1 atom and 20 atoms, respectively; and in view of the alloy-character of the mineral we need not expect integral numbers of atoms of Bi and Te in the larger cell. The empirical content of the larger cell is roughly $\text{Bi}_{14}\text{Te}_6$, which gives the calculated specific gravity 8.93, in good agreement with the measured value 8.91. If the composition of the mineral is to be expressed by a rational formula, Bi_7Te_3 (79.3 per cent Bi) is pre-

ferable to Bi_5Te_2 even though the analyses come closer to the latter formula.

Comparing hedleyite and joseite, which has a rhombohedral unit cell containing 7 atoms— Bi_4TeS_2 , or more generally $\text{Bi}_{4+x}(\text{Te}, \text{S})_{3-x}$ (Peacock, 1941)—we note a similarity in the hexagonal lattice dimensions:

Hedleyite:	$a_{\text{hex}} = 4.46 \text{ \AA}$,	$c'' = 3(39.60) \text{ \AA}$
Joseite:	$a_{\text{hex}} = 4.24$	$c = 39.69$
	4.33	40.75

However, if hedleyite has the character of a 3-storey joseite structure, the larger cell of hedleyite would contain 21 atoms, not 20. For this reason, and the fact that S is an essential constituent of joseite, amounting to 1 or 2 atoms in the 7-atom cell, hedleyite does not appear to be a variety of joseite.

This leaves one described bismuth telluride to which we might compare hedleyite, namely the mineral from Deutsch-Pilsen, Hungary, called wehrlite. Although we have not been able to obtain a specimen of this mineral either in Canada or the United States, a consideration of its described properties permits some useful conclusions regarding its character and its relation to hedleyite.

WEHLITE

A bismuth telluride was known from Deutsch-Pilsen, Hungary, already in the eighteenth century. Originally supposed to be a compound of silver and molybdenum (*argent molybdique* de Born) the mineral was soon found to be a compound of bismuth (*Wismuthglanz* Klaproth). The approximate quantitative composition of the mineral was first established by an incomplete analysis by Wehrle in 1831 (Table 3), and the mineral was therefore named wehrlite²

²The name wehrlite has fallen into some confusion. It was originally given by von Kobell in 1838 to a silicate which was soon identified with ilvaite, or a mixture, and subsequently the name was used to denote an ultrabasic rock-type. In spite of the recommendation of the Committee on British Petrographic Nomenclature (1921) that wehrlite be dropped as an unnecessary petrological term *Mineralogical Abstracts*, vols. 1-8 (1920-1943), show that wehrlite continues to be used both as a rock-name and as the name of the Hungarian ore mineral. One is tempted to recommend the revival of Kenngott's *pilsenite* for the ore mineral; but since pilsenite has long been dismissed as a synonym of wehrlite it will be more practical to urge again that wehrlite be restricted to the bismuth telluride from Deutsch-Pilsen.

by Huot in 1841. Later S... of which was made on exc... that more than one specie... Pilsen, as is the case in oth... lent material, seems to be... sent the original silver-bea...

WEHLITE FROM

Ag.....
Bi.....
Te.....
S.....

1. Anal. Wehrle (1831, in I...)
2. Anal. Sipöcz (1885), on... with hardness 2, sp. grav. 8.368... a collection in Budapest. Com...
3. Anal. Sipöcz (1885), on... Composition Bi_3Te_2 , excluding...

A valuable addition to... powder pattern obtained... from Deutsch-Pilsen, the... ings and intensities for w... hedleyite and consequentl... hedral elements similar to... namely:

$$a_{\text{hex}} = 4.42 \text{ \AA}, c =$$

Table 3 gives the observed... above elements. The ag...

³Dr. G. A. Harcourt (Copp... of his observations on this mi... sheet of the specimen, and all... weak. A semi-quantitative sp... the polished section of the sam... intensities 12, 10, 1, respectiv... substantial amount of Ag, in k... sidered to be the most reliable...

by Huot in 1841. Later Sipöcz (1885) added two analyses the first of which was made on excellent material. These analyses suggest that more than one species of bismuth telluride occur at Deutsch-Pilsen, as is the case in other localities. Analysis 2, made on excellent material, seems to be the most reliable, and it may best represent the original silver-bearing mineral.

TABLE 2
WEHLITE FROM DEUTSCH-PILSEN: ANALYSES

	1	2	3
Ag.....	2.07	4.37	0.48
Bi.....	61.15	59.47	70.02
Te.....	29.74	35.47	28.52
S.....	2.33	1.33
	<u>95.29</u>	<u>99.31</u>	<u>100.35</u>

1. Anal. Wehrle (1831, in Dana, 1892, p. 41); sp. grav. 8.44.

2. Anal. Sipöcz (1885), on very clean, thin, broad, flexible and elastic plates, with hardness 2, sp. grav. 8.368 (mean of three pycnometric measurements), from a collection in Budapest. Composition, AgBi_7Te_7 .

3. Anal. Sipöcz (1885), on scanty material from a collection in Vienna. Composition Bi_3Te_2 , excluding Ag_2S and Bi_2S_3 as assumed impurities.

A valuable addition to the knowledge of wehlite is the x -ray powder pattern obtained by Harcourt (1942, p. 103) on a specimen from Deutsch-Pilsen, the type locality.³ Harcourt's observed spacings and intensities for wehlite resemble our observed data for hedleyite and consequently the wehlite pattern leads to rhombohedral elements similar to those of the smaller cell of hedleyite, namely:

$$a_{\text{hex}} = 4.42 \text{ \AA}, c = 5.97 \text{ \AA}; a_{\text{rh}} = 3.236 \text{ \AA}, \alpha = 86^\circ 08\frac{1}{2}'$$

Table 3 gives the observed spacings and those calculated from the above elements. The agreement is unusually good, and the two

³Dr. G. A. Harcourt (Copper Cliff, Ontario) has kindly sent us further details of his observations on this mineral. The x -ray sample was taken from a thin sheet of the specimen, and all the powder lines beyond $d = 1.140 \text{ \AA}$ were very weak. A semi-quantitative spectrographic analysis was made on a sample from the polished section of the same material. Only Bi, Ag, Te, were noted, with intensities 12, 10, 1, respectively. This shows that the mineral contained a substantial amount of Ag, in keeping with analysis 2 in Table 2, which we considered to be the most reliable.

very faint lines which cannot be indexed can perhaps be neglected as extraneous.

Assuming that Harcourt's pattern corresponds to the specific gravity and preferred analysis by Sipöcz, the cell content of wehrlite is Ag 0.07, Bi 0.49, Te 0.48 = 1.04 atoms, or roughly one atom in the unit cell. Conversely the specific gravity of wehrlite calculated from the analysis and a cell containing one atom, is 8.05, in rather poor agreement with the measured value 8.368. However, a cell containing $\frac{1}{2}[\text{BiTe}]$ has the calculated specific gravity 8.245 and silver has the specific gravity 10.50. Assuming that Ag is present in wehrlite as uncombined silver, and using the empirical formula AgBi_7Te_7 appropriate to the analysis, the calculated specific gravity is $14(8.245)/15 + (10.50)/15 = 8.40$, which agrees well with the

TABLE 3
WEHRLITE: X-RAY POWDER SPECTRUM
Hexagonal, *R*

<i>I</i>	$\vartheta(\text{Cu})$	<i>d</i> (meas.)	(<i>hkl</i>) (<i>hkl</i>)	<i>d</i> (calc.)
	$a_{\text{hex}} = 4.42 \text{ \AA}$, $c = 5.97 \text{ \AA}$; $a_{\text{rh}} = 3.236 \text{ \AA}$, $\alpha = 86^\circ 08\frac{1}{2}'$			
6.0	13.8°	3.22 Å	(10 $\bar{1}$ 1) (100)	3.222 Å
3.0	19.1	2.35	(01 $\bar{1}$ 2) (110)	2.354
3.0	20.35	2.21	(11 $\bar{2}$ 0) (10 $\bar{1}$)	2.210
1.0	22.7	1.99	(0003) (111)	1.990
1.0	25.0	1.82	(0221) (11 $\bar{1}$)	1.823
1.0	28.5	1.61	(20 $\bar{2}$ 2) (200)	1.611
1.0	31.35	1.478	(11 $\bar{2}$ 3) (210)	1.479
1.0	33.3	1.40	{(21 $\bar{3}$ 1) (20 $\bar{1}$)	1.406
			{(10 $\bar{1}$ 4) (211)	1.391
0.5	36.2	1.302	(12 $\bar{3}$ 2) (21 $\bar{1}$)	1.302
0.3	37.05	1.275	(30 $\bar{3}$ 0) (21 $\bar{1}$)	1.276
0.3	40.65	1.180	(02 $\bar{2}$ 4) (220)	1.177
0.3	42.4	1.140	(01 $\bar{1}$ 5) (221)	1.140
0.2	44.1	1.105	(2240) (202)	1.105
0.2	45.25	1.082
0.2	45.65	1.075	(30 $\bar{3}$ 3) (300)	1.074
0.2	47.65	1.040	(21 $\bar{3}$ 4) (310)	1.039
0.2	50.4	0.998	{(31 $\bar{4}$ 2) (30 $\bar{1}$)	1.000
			{(0006) (222)	0.995
0.2	51.45	0.983
0.2	54.7	0.942	(40 $\bar{4}$ 1) (31 $\bar{1}$)	0.945
0.2	56.5	0.922	(12 $\bar{3}$ 5) (320)	0.921

measured value. Ag may be combined silver, and wehrlite may be of composition BiTe .

From the foregoing it is evident that the structural similarity between wehrlite and other minerals differ so greatly that wehrlite, Bi_7Te_3 , $G = 8.9$; wehrlite may be usefully referred to a similar name. Some consideration of the structure and examination of sections tend to support the decision to use the name wehrlite.

The results of studies of wehrlite are summarized in Hansen (1936, p. 340, fig. 160), in which the system is extending from Bi to Bi_2Te_3 . It is noted that there is only one compound in the system (52.2 per cent Bi by weight).

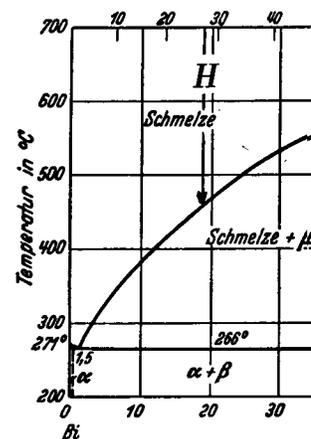


FIG. 1.—Bismuth-tellurium phase diagram (Hansen, p. 340, fig. 160), showing the reaction between bismuth (Bi_2Te_3).

measured value. Ag may therefore be present in wehrlite as uncombined silver, and wehrlite may then have substantially the composition BiTe.

From the foregoing it is clear that there is an underlying structural similarity between hedleyite and wehrlite. However, the two minerals differ so greatly in composition and specific gravity (hedleyite, Bi_7Te_3 , $G = 8.9$; wehrlite, BiTe , $G = 8.4$) that they cannot be usefully referred to a single name. As shown in the next section some consideration of the artificial system Bi-Te, and the preparation and examination of several alloys in the appropriate range, also tend to support the decision to distinguish these minerals by separate names.

SYNTHESES

The results of studies of the bismuth-tellurium system are summarized in Hansen (1936, p. 339) and represented in his phase diagram (Fig. 1), in which we are concerned only with the region extending from Bi to Bi_2Te_3 . The previous workers are agreed that there is only one compound in this system, namely Bi_2Te_3 (52.2 per cent Bi by weight), which corresponds to the now well-

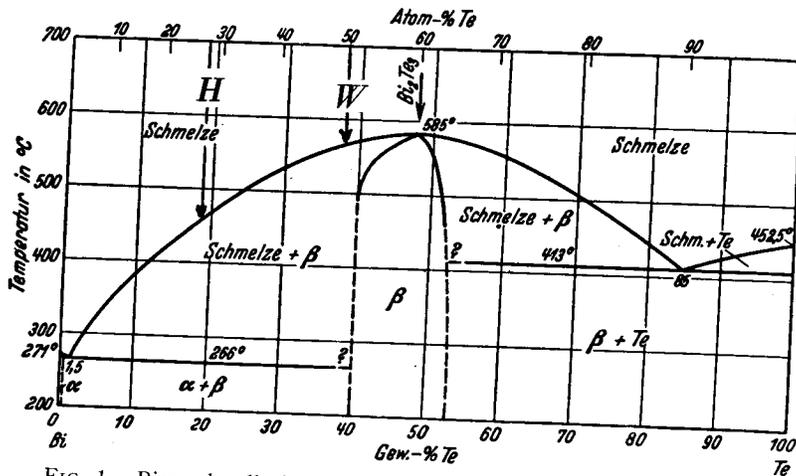


FIG. 1.—Bismuth-tellurium system: phase diagram from Hansen (1936, p. 340, fig. 160), showing the relations of hedleyite (H), wehrlite (W), and tellur-bismuth (Bi_2Te_3).

known mineral tellurbismuth (Warren, 1940, p. 109; Peacock & Berry, 1940, p. 67; Frondel, 1940). This compound takes Bi or Te into solid solution giving the β -phase with the approximate range, 60-47 per cent Bi. Bismuth will hold only about 1 per cent Te in solid solution (α -phase), and thus stable alloys with 99 to 60 per cent Bi are mixtures of the α - and β -phases. X-ray powder photographs were made of some of the Bi-Te alloys by Körber & Haschimoto (1930), but these were used only in a qualitative way.

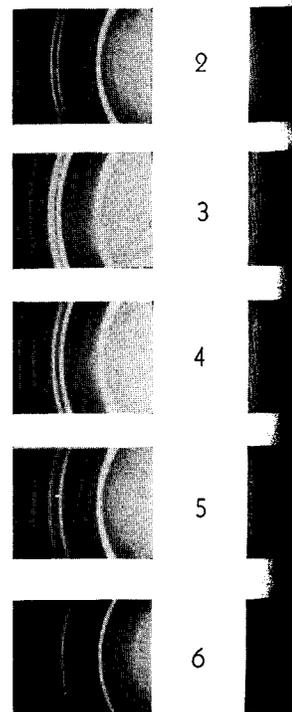
From the foregoing it seemed unlikely that hedleyite could be reproduced by fusing the elements. However, the attempt was made by fusing a charge of 1 gm. of powdered Bi and Te with the same composition as the mineral (81.2 per cent Bi) in an evacuated pyrex tube, and cooling in air. A polished section of the product showed white moderately anisotropic crystal plates in a ground that rapidly took on the familiar brown tarnish of bismuth and showed minute inclusions of the white platy crystals. According to the phase diagram this intergrowth consists of crystals of the β -phase at the limiting Bi-content (60 per cent) in a eutectic of the α -phase (99 per cent Bi) and the β -phase. The x-ray powder photograph (Fig. 3) showed a pattern which has the appearance of the hedleyite pattern (Fig. 4) with some of the hedleyite lines replaced by doublets. A plate of hedleyite was then fused and allowed to crystallize in an evacuated pyrex tube. The powder photograph showed the same double pattern with the same relative intensities of the two components.

The double pattern of these fusion products was completely indexed with reference to two rhombohedral lattices (α -phase and β -phase) which compare with the rhombohedral lattices of bismuth, hedleyite, and tellurbismuth, as shown below with hexagonal elements:

	a_{hex}	c
⁴ Bismuth.....	4.55 Å	2(5.925) Å
α -phase in fused hedleyite.....	4.52	2(5.90)
Hedleyite.....	4.46	20(5.94)
β -phase in fused hedleyite.....	4.42	5.93
⁵ Tellurbismuth.....	4.375	5(6.08)

⁴Strukturbericht, vol. 1, p. 58.

⁵Peacock, in Peacock & Berry (1940, p. 67).



FIGS. 2-6.—Bismuth radiation (Ni-filter); camera reproductions of contact

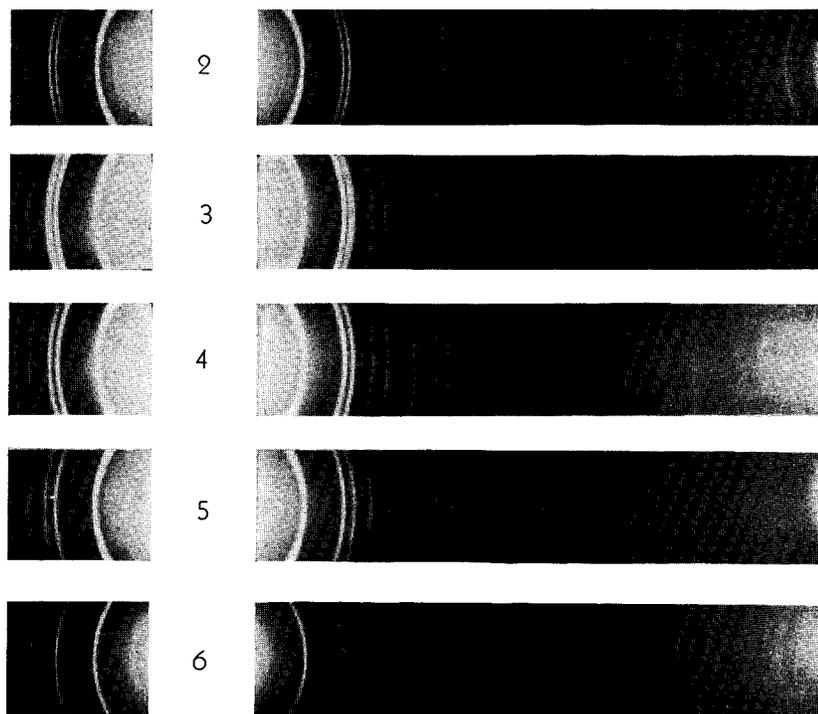
FIG. 2.—Pure bismuth

FIG. 3.—Bi 81.2-Te. of the α -phase (Bi) and the double pattern.

FIG. 4.—Hedleyite; position as the above. is visible in the print.

FIG. 5.—Bi 62.1-Te gives the same pattern.

FIG. 6.—Bi 52.2-Te pattern.



FIGS. 2-6.—Bismuth-tellurium alloys: x -ray powder photographs with Cu -radiation (Ni-filter); camera radius $90/\pi$ mm. (1 mm. on film = $1^\circ\vartheta$); full-size reproductions of contact prints.

FIG. 2.—Pure bismuth; α -phase.

FIG. 3.—Bi 81.2-Te 18.8 wt. per cent; two-phase alloy showing the patterns of the α -phase (Bi) and the β -phase (Bi_2Te_3 , Bi). Fused hedleyite gives the same double pattern.

FIG. 4.—Hedleyite; essentially an unstable single phase with the same composition as the above. Only one faint line ($\vartheta = 21.4^\circ$) from the superstructure is visible in the print.

FIG. 5.—Bi 62.1-Te 37.9 (Bi : Te = 1 : 1); β -phase (Bi_2Te_3 , Bi). Wehrlite gives the same pattern.

FIG. 6.—Bi 52.2-Te 47.8 (compound Bi_2Te_3). Tellurbismuth gives the same pattern.

In keeping with the slight solid solubility of Te in Bi the lattice of the α -phase in fused hedleyite is a slightly contracted Bi-lattice. Owing to the greater solid solubility of Bi in Bi_2Te_3 the lattice of the β -phase shows more distortion as compared to the lattice of Bi_2Te_3 ; furthermore it is relatively simple since it shows none of the lines that require the $5c$ -axis which is characteristic of Bi_2Te_3 .

From these results, which are in agreement with the phase diagram of the Bi-Te system, it is clear that hedleyite is essentially an unstable solid solution of Bi in Bi_2Te_3 with Bi greatly in excess of the stable saturation limit. The composition of the analysed material may therefore be expressed approximately by the formula $\text{Bi}_2\text{Te}_3.\text{Bi}_5$; but the name hedleyite will be properly applied to any bismuth telluride, free from significant amounts of other elements, particularly sulphur, which is essentially a solid solution of Bi in Bi_2Te_3 with Bi largely in excess of 60 per cent by weight. At some undetermined composition between that of hedleyite and bismuth we may expect natural alloys which will give the Bi-pattern (α -phase); these would be properly regarded as varieties of bismuth and named tellurian bismuth.

Wehrlite, as we have seen, appears to be essentially an alloy with the composition BiTe (62.1 per cent Bi) which is practically the Bi-limit of the β -phase in the artificial system. It seemed possible, therefore, that the mineral might be reproduced by fusion of the elements, and an alloy of this composition was accordingly prepared. It proved to be a nearly homogeneous aggregate of warped crystal plates (β -phase) with sparse inclusions of a tarnished phase (α -phase). The x -ray powder photograph (Fig. 5) gave a simple pattern which agrees exactly with Harcourt's pattern for wehrlite, except for the absence of the two very faint lines which could not be indexed in Harcourt's pattern. The pattern of the alloy was fully indexed with reference to a rhombohedral lattice whose hexagonal dimensions compare with those of wehrlite and tellurbismuth as shown below:

	a_{hex}	c
Wehrlite	4.42 Å	5.97 Å
β -phase in Bi : Te = 1 : 1	4.42	5.99
Tellurbismuth	4.375	5(6.08)

The structural identity of wehrlite and the alloy Bi : Te = 1 : 1

confirms the earlier view that it is a solid solution of Bi in Bi_2Te_3 phase at about the composition expressed by writing $\text{Bi}_2\text{Te}_3.\text{Bi}_5$. This might suggest that the mineral is however, the fact that it is with Bi_2Te_3 , and not wehrlite. This should be found to form in nature.

At one stage in the investigation into the existence of wehrlite, it was overlooked in the search for a simple composition which would give wehrlite and the alloy which require the $5c$ -axis. The pattern of the powder was dispelled by a resolution experiment. A plate picked from the powder showed exactly with those of wehrlite. It was shown that the true pattern of wehrlite by the powder pattern method. Wehrlite might be reproduced by fusion of the elements, and an alloy of this composition was accordingly prepared. It proved to be a nearly homogeneous aggregate of warped crystal plates (β -phase) with sparse inclusions of a tarnished phase (α -phase). The x -ray powder photograph (Fig. 5) gave a simple pattern which agrees exactly with Harcourt's pattern for wehrlite, except for the absence of the two very faint lines which could not be indexed in Harcourt's pattern. The pattern of the alloy was fully indexed with reference to a rhombohedral lattice whose hexagonal dimensions compare with those of wehrlite and tellurbismuth as shown below:

Hedleyite is a bismuth telluride, a solid solution of Bi in Bi_2Te_3 with Bi in excess of the saturation limit (about 60 per cent). The specific properties are: color, black; luster, metallic; cleavage, rhombohedral; $a_{\text{rh}} = 39.68 \text{ \AA}$; $c = 5.97 \text{ \AA}$; the rhombohedral unit cell contains 6 atoms of Bi_2Te_3 ; substructure, rhombohedral (from $a_{\text{hex}} = 4.46 \text{ \AA}$, $c = 5.97 \text{ \AA}$); $d_{111} = 8.93 \text{ \AA}$; $d_{112} = 8.93 \text{ \AA}$; $d_{113} = 8.93 \text{ \AA}$; $d_{114} = 8.93 \text{ \AA}$; $d_{115} = 8.93 \text{ \AA}$; $d_{116} = 8.93 \text{ \AA}$; $d_{117} = 8.93 \text{ \AA}$; $d_{118} = 8.93 \text{ \AA}$; $d_{119} = 8.93 \text{ \AA}$; $d_{120} = 8.93 \text{ \AA}$; $d_{121} = 8.93 \text{ \AA}$; $d_{122} = 8.93 \text{ \AA}$; $d_{123} = 8.93 \text{ \AA}$; $d_{124} = 8.93 \text{ \AA}$; $d_{125} = 8.93 \text{ \AA}$; $d_{126} = 8.93 \text{ \AA}$; $d_{127} = 8.93 \text{ \AA}$; $d_{128} = 8.93 \text{ \AA}$; $d_{129} = 8.93 \text{ \AA}$; $d_{130} = 8.93 \text{ \AA}$; $d_{131} = 8.93 \text{ \AA}$; $d_{132} = 8.93 \text{ \AA}$; $d_{133} = 8.93 \text{ \AA}$; $d_{134} = 8.93 \text{ \AA}$; 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confirms the essential composition of the mineral and shows that it is a solid solution of Bi in Bi_2Te_3 corresponding to the β -phase at about the Bi-limit in the artificial system. This can be expressed by writing the composition of wehrlite as $\text{Bi}_2\text{Te}_3\cdot\text{Bi}$. This might suggest that wehrlite is merely a variety of tellurbismuth; however, the fact is that there are now ten analyses of tellurbismuth (Doelter, 1926, p. 858, 1-9; Warren, 1940, p. 110) which agree closely with Bi_2Te_3 , and none in the range between tellurbismuth and wehrlite. This shows that there is a marked tendency for this compound to form in nature without excess Bi.

At one stage in this work it seemed that the evidence was pointing to the existence of a distinct compound BiTe which had been overlooked in the artificial system. This was suggested by the simple composition of wehrlite and the fact that the patterns of wehrlite and the alloy $\text{Bi} : \text{Te} = 1 : 1$ lack the lines of tellurbismuth that require the $5c$ -axis and consequently differ in appearance from the pattern of the pure compound. However, this idea was finally dispelled by a resolution of the basal diffractions from a nearly flat plate picked from the crushed alloy. These diffractions agreed exactly with those given by a plate of the pure compound and showed that the true c -axis of the alloy is five times the value given by the powder pattern. A similar multiplication of the c -axis of wehrlite might be revealed by a resolution of the basal diffractions.

SUMMARY

Hedleyite is a bismuth-tellurium alloy which is essentially a solid solution of Bi in Bi_2Te_3 , with Bi greatly in excess of the saturation limit (about 60 per cent Bi) found in the artificial system. The specific properties of the type material are as follows: Rhombohedral; $a_{\text{rh}} = 39.68 \text{ \AA}$, $\alpha = 6^\circ 26\frac{1}{2}'$ (from $a_{\text{hex}} = 4.46 \text{ \AA}$, $c = 118.8 \text{ \AA}$); the rhombohedral unit cell contains 20 atoms or approximately $\text{Bi}_{14}\text{Te}_6$; substructure rhombohedral; $a_{\text{rh}} = 3.248 \text{ \AA}$, $\alpha = 86^\circ 42\frac{1}{2}'$ (from $a_{\text{hex}} = 4.46 \text{ \AA}$, $c = 5.94 \text{ \AA}$); this rhombohedral cell contains 1 atom. In plates with easy cleavage (111) giving flexible and slightly elastic folia. Hardness 2; specific gravity 8.68—8.93, 8.91 (meas.), 8.93 (calc.); lustre metallic; colour tin-white with iron-black tarnish; opaque. Polished section white, slightly anisotropic on section near

(111). Strongest x -ray powder lines: (10) 3.25, (5) 2.36, (4) 2.23 Å. Composition near $\text{Bi}_2\text{Te}_3\text{Bi}_5$. Analyses: Bi 80.60, 81.55; Te 18.52, 17.60; S 0.12, 0.04; totals 99.24, 99.19. Occurs with native bismuth, joseite, and gold, in quartz and skarn at Good Hope mineral claim, Hedley, B.C. Breaks down to Bi and a solid solution of Bi in Bi_2Te_3 (wehrlite) on fusion and recrystallization.

Wehrlite is a bismuth-tellurium alloy, with added silver, which is essentially a solid solution of Bi in Bi_2Te_3 with Bi approximately at the saturation limit (about 60 per cent Bi) found in the artificial system. Rhombohedral; $a_{\text{rh}} = 3.236$ Å, $\alpha = 86^\circ 08\frac{1}{2}'$ (from $a_{\text{hex}} = 4.42$ Å, $c = 5.97$ Å); the rhombohedral unit cell contains 1 atom or $\frac{1}{2}[\text{BiTe}]$. Basal diffractions may reveal a multiple c -axis. In foliated masses with perfect cleavage (111) giving flexible and slightly elastic folia. Hardness 1-2; specific gravity 8.37-8.44 (meas.), 8.40 (calc. for BiTe with Ag as intercalated silver); lustre bright metallic; colour tin-white to light steel-grey; opaque. Strongest x -ray powder lines (Harcourt): (6) 3.22, (3) 2.35, (3) 2.21 Å. Composition: $\text{Bi}_2\text{Te}_3\text{Bi} + \text{Ag}$. Analysis (Sipöcz): Bi 59.47, Te 35.47, Ag 4.37 = 99.31. Definitely known only from Deutsch-Pilsen, Hungary. The nearly homogeneous artificial alloy Bi : Te = 1 : 1 gives the x -ray powder pattern of wehrlite.

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