On Tapiolite in the Pilbara goldfield, Western Australia.[1]

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THE Pilbara goldfield lies in the north-west division of Western Australia within the tropics, and has been described in considerable detail by A. Gibb Maitland in Bulletin 40 of the Geological Survey of Western Australia. Though the chief mineral product at present is gold, the district abounds in other economic minerals, notably ores of copper and tin, and has already become famous as being by far the most important producer of tantalum in the world, the chief source of supply of this metal being the manganotantalite of Wodgina.

The north-western portion of the Pilbara goldfield adjacent to th coast, and covering an area of about 100 miles (east and west) by 70 miles (north and south), is shown by A. Gibb Maitland's map to be occupied by an immense mass of granite, flanked and intruded by ancient greenstones. This area embraces the Wodgina mining centre and a number of other localities in which tantalum minerals have been found. These minerals are usually associated with detrital tin-ore, the source of both being traceable to pegmatite veins in which albite is frequently the preponderating constituent. The species and localities already recorded by the author[2] are:

Ferrotantalite: Greens Well.

Manganotantalite: Wodgina, Moolyella, Greens Well, Mt. Francisco, and probably Cooglegong.

Ferrocolumbite: Greens Well.

Manganocolumbite: Moolyella, Mt. Francisco, Cooglegong, Lalla Rookh (ferrocolumbite ?).

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[1] Published by permission of A. Gibb Maitland, Government Geologist.

[2] Bulletins and Annual Reports of the Geological Survey of Western Australia, and Transactions of Aust. Assoc. Adv. Science.

Ixiolite: Wodgina.
Microlite: Greens Well.
Mineral related to Fergusonite: Cooglegong.
Euxenite: Cooglegong.

To this list must now be added tapiolite, which has been discovered at Greens Well and Tabba-Tabba Creek.

The natural compounds of tantalic and niobic acids with iron and manganese are all metatantalates and metaniobates of the general form $(FeTa_2O_6)_n$. On crystallographic grounds they are divided into two groups, the tantalite group which is orthorhombic, and the tapiolite group which is tetragonal and isomorphous with the rutile group.

The chief members of the series are:

Tantalite Group:

Ferrotantalite, $(FeTa_2O_6)_n$
Manganotantalite, $(MnTa_2O_6)_n$
Ferrocolumbite, $(FeNb_2O_6)_n$
Manganocolumbite, $(MnNb_2O_6)_n$

Tapiolite Group[1]:

Tapiolite, $(FeTa_2O_6)_m$
Ixiolite, $(MnTa_2O_6)_m$
Mossite, $(FeNb_2O_6)_m$
$(MnNb_2O_6)_m$ and $(CaTa_2O_6)_m$, unknown as independent minerals, but found in minor amount in isomorphous mixture with the other members of the group.
Rutile, $(TiTi_2O_6)_m$
Cassiterite, $(SnSn_2O_6)_m$, &c.

To these must be added two important sub-species:

Strüverite, $4(FeTa_2O_6)_m + (TiTi_2O_6)_m$ to $(FeTa_2O_6)_m + 4(TiTi_2O_6)_m$
Ilmenorutile, $4(FeNb_2O_6)_m + (TiTi_2O_6)_m$ to $(FeNb_2O_6)_m + 4(TiTi_2O_6)_m$

Of the two localities in the Pilbara goldfield where tapiolite has been found, viz., Tabba-Tabba Creek close to the railway crossing, and Greens Well, the latter is about thirty miles due south of the former. Both centres lie within the same large area of granite, which is intersected by pegmatite veins and greenstone dykes and bosses.

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[1] The names and formulae ascribed to these minerals are dealt with fully in a paper on the tapiolite group now in course of preparation.

TABBA-TABBA CREEK.

Tabba-Tabba Creek runs almost due north into the Indian Ocean in long. 118° 55′ E. Alluvial tin claims have recently been taken up at two points on it about ten miles apart, the more northerly being known locally as Tabba-Tabba North, the other centre simply as Tabba-Tabba. It is in association with alluvial tin-ore from the former spot that tapiolite has been recognized.

The mineral was separated as follows: In the case of the finer grained ore in fragments up to one centimetre in diameter the mixture was treated in a zinc tray with dilute hydrochloric acid for a few minutes, the acid then washed off with clean water, and the fragments of cassiterite, now coated with bright metallic tin, were picked out and rejected. In the case of larger fragments, small chips were taken off each and treated on zinc with hydrochloric acid. Though many fragments of the tantalum minerals thus selected were either not crystallized, or too imperfectly so for their crystalline system to be determined, a fair number of well-crystallized fragments were obtained, measurements of which left no doubt as to their tetragonal form, whilst their high specific gravity distinguished them from rutile, &c.

At first sight the crystals of tapiolite from this locality would appear to be monoclinic, several having a distinct resemblance in form to orthoclase. Since the form, however, in no wise recalled that of the orthorhombic ferrotantalite series, and in view of the recorded distortions of form already noted in cassiterite,[1] rutile,[2] tapiolite,[3] and strüverite,[4] their true nature was early suspected and subsequently confirmed by angular measurements supported by specific gravity determinations and an analysis. The distorted form and almost invariable twinning caused considerable difficulty in some cases in establishing the correct orientation of the crystals. For this purpose the most useful measurements were found to be:[5]

	°	′		°	′
$a^1a^2 =$	90	0	$a^1r^1 =$	33	41
$a^1a^3 =$	180	0	$a^2(a^4) =$	65	46
$a^1(a^1) =$	180	0	$s^1s^2 =$	57	0

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[1] W. G. Woolnough, Proc. R. Soc. N. S. W., 1901, vol. xxxv, p. 332.

[2] W. P. Headden and L. V. Pirsson, Amer. Journ. Sci., 1891, vol. xli, p. 249.

[3] C. H. Warren, Amer. Journ. Sci., 1898, vol. vi, p. 121.

[4] A. Lacroix, Bull. Soc. franç. Min., 1912, vol. xxxv, pp. 187-191.

[5] The faces of the rotated half of the twin are bracketed.

Two other common angles, however, approximated closely to s^1s^2, and were at times the cause of some confusion. These were

$$a^1r^3 = 56^\circ\ 19' \qquad a^1e^1 = 57^\circ\ 7'$$

The recognizable crystals ranged in weight from about one gram to 120 grams, and were with one possible exception unsuited for exact measurement owing to the corroded and often slightly weathered surfaces. The one exception has been reserved for measurement with a theodolite-goniometer, whilst the others have been measured with a contact goniometer.

The axial ratios ($a:c$) recorded for four of the five tantalum-niobium minerals of the tetragonal group are:

	c.	
Tapiolite	0·6464	(Nordenskiöld).
„	0·6525	(Brögger).
Mossite	0·6438	(Brögger).
Strüverite	0·6456	(Zambonini).
„	0·6469	(Ungemach).
Ilmenorutile	0·6436	(Eremyeev).

Nordenskiöld's value was used in calculating the theoretical angles, against which the measurements were checked.

The common minerals of the group, viz. rutile, cassiterite, and zircon, have yielded a large number of forms, but, except in the case of ilmenorutile, the already recorded forms for the tantalum and niobium minerals are comparatively few. The complete list is:

Anglo-American notation.	French notation.[1]	Symbol.	Mineral.
a	h^1	100	T, M, S, I.
c	*p*	001	T, M, I.
m	*m*	110	T, M, S, I.
Q	h^4	530	S.
r	h^6	320	T, I.
l	h^2	310	I.
x	$h^5/_3$	410	I.
s (*p*)	$b^{\frac{1}{2}}$	111	T, M, S, I.
ϕ	$b^1/_3\ b^1/_{12}\ h^1/_{10}$	6·9·10	M.

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[1] For comparison of Ungemach's and Lacroix's figures with those in the present paper.

μ	$b^4/_9$	998	I.
t	$b\frac{1}{2}\ b^1/_4\ h^1/_3$	313	I.
f	z	323	S, I.
z	$b^1\ b^1/_5\ h^1$	321	I.
ρ	$b^1/_4$	221	I.
e	a^1	101	T, M, S, I.
y	$a^5/_3$	305	M.
v	$a^1/_3$	301	T, M.
w	$a^1/_5$	501	I.

Of these forms *e* has been recognized as a common twinning-plane.

In this table T stands for tapiolite, M for mossite, S for strüverite, and I for ilmenorutile. The authorities are: for tapiolite, Nordenskiöld, quoted by Dana, and C. H. Warren[1]; for mossite, Brögger, quoted by Dana; for strüverite, Zambonini,[2] Lacroix,[3] and Ungemach[4]; for ilmenorutile, Eremyeev.[5]

Of the above forms the Tabba-Tabba tapiolite has yielded the common forms *a*, *c*, *s*, and *e*, whilst a further form *r* is frequently present. This form is known in cassiterite and rutile, and is present in ilmenorutile and Nordenskiöld's skogbölite (since proved to be tapiolite), in which through wrong orientation it was figured as *o* (211) and *p* (111). Twins on *e* are very abundant.

Figs. 1 to 4 illustrate typical crystals from Tabba-Tabba North, which exhibit the characteristic features of twinning on *e*, elongation parallel to the edge s^1s^2 (or other adjacent pair of unit pyramid-faces), and unequal development of the various faces of the one form.

Crystal I is unique in having a prismatic habit parallel to the vertical axis. The outline of the basal section is somewhat distorted owing to the irregular development of the faces; those present are: a^1, a^2, a^3, r^1, r^2, r^3, r^4, r^5, s_3, s_4, and one small face which is probably e^4, and a second which may be d^3 (058) or (a^4).[6] The angular measurements obtained are given in the table below. This fragmentary detrital crystal weighs 18½ grams, and has a density of 7·69 (compared with water at 4°).

Crystal II, illustrated in orthographic projection in fig. 1, is one of three parallel crystals forming a group which has been but little affected

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[1] C. H. Warren, Amer. Journ. Sci., 1898, vol. vi, p. 121.

[2] F. Zambonini, Mineralogical Magazine, 1908, vol. xv, p. 79.

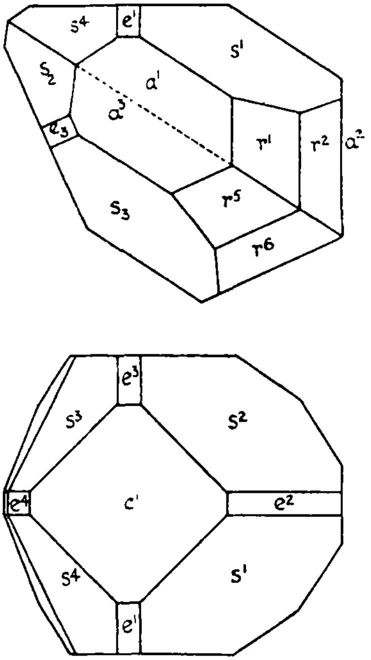
[3] A. Lacroix, Bull. Soc. franç. Min., 1912, vol. xxxv, p. 186.

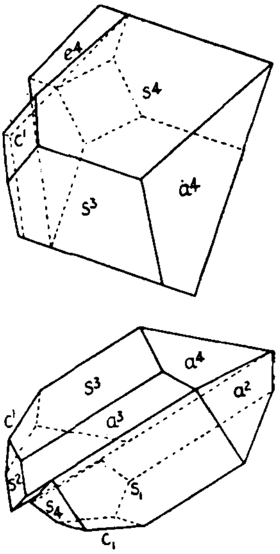
[4] H. Ungemach, ibid., 1916, vol. xxxix, p. 8.

[5] Quoted by Hintze, Handbuch d. Min., 1907, vol. i, p. 1611.

[6] $a^2d^3 = 68°\ 0'$; $a^2(a^4) = 65°\ 46'$.

by the destructive effects of stream action. It is only slightly fractured, and some quartz is still firmly attached to it in sheltered corners, accompanied by some small scales of mica. The group weighs 27 grams, and has a specific gravity of 7·26 inclusive of the quartz. It was received from Port Hedland, the nearest port to Tabba-Tabba, which is probably, though not certainly, its original locality.



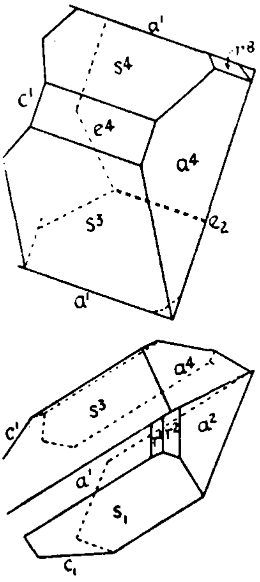


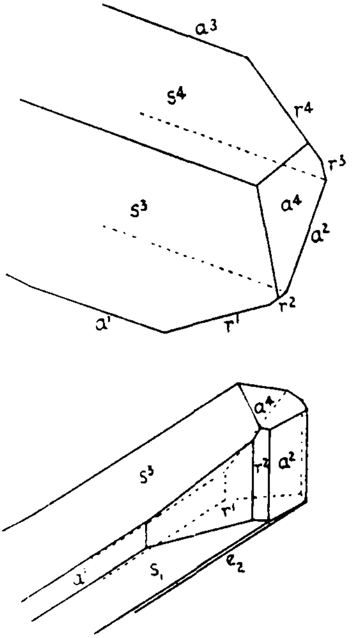
Tapiolite from Tabba-Tabba Creek, Western Australia.

FIG. 1.—Orthographic projections (somewhat idealized) of twinned crystal II from triple group. The original is an almost perfect reflection-twin on e^3 (011).

FIG. 2.—Plan and clinographic projection of twinned crystal III. Steps on a^3 and (a^4) omitted. The left-hand side of the crystal is imperfectly developed in the original. A dislocated twin on e^4 $(0\bar{1}1)$.

The crystals are twinned on *e*, and the various faces in the group are more regularly developed than in most cases, whilst the transverse axes of each part of the twin lie almost in the same vertical plane (parallel to 100), which was not the case with most of the twins from this locality. In this instance the twin was an almost perfect reflection-twin over the face (011). Though rotation about a normal to this plane would bring all the faces into normal crystallographic orientation, it would not yield a perfect crystal, since the outlines on either side of the composition-plane are quite different, there being no prism-faces on the left-hand side of the crystal. The faces have, however, been lettered as for a rotation-twin, as this appeared the method more suited to the other crystals here described.





Tapiolite from Tabba-Tabba Creek, Western Australia.

FIG. 3.—Plan and clinographic projection of twinned crystal IV. A dislocated twin with prism-faces unequally developed.

FIG. 4.—Plan and clinographic projection of twinned crystal V. A dislocated twin with undulating composition surface.

Crystals III and IV (figs. 2 and 3) illustrate the form of twin more commonly developed at Tabba-Tabba. This is still a twin on *e*, but is not a reflection-twin, and though rotation through 180° about a normal will bring all faces into uniform orientation, it will not lead to a perfect crystal. Very noticeable is the dislocation of the centre in the two halves along that one of the horizontal axes which lies in the twinning-plane, a condition prevailing to a greater or less degree in all the twins from this locality. The various faces of the same form in the prism-zone (100 and 320) are very unequally developed, pointing to a low order of symmetry in this mineral. A study of the figures shows that crystals III and IV may further be looked upon as right- and left-hand reciprocals. In both cases there is an elongation in the direction of the edge s^3s^4.

Crystal III (fig. 2) is large, weighing 79 grams, and has a specific gravity of 7·52. Though not fractured, the left-hand side is poorly developed owing to interference by other minerals of the pegmatite vein during growth. Faces a^2, (a^4) are stepped with small faces r^1 and (r^5) forming the junction; this is not shown in the figure.

Crystal IV (fig. 3) is a smaller, 7 grams, corroded, and imperfectly developed individual with a specific gravity of 7.44.

Crystal V (fig. 4) illustrates a somewhat different twin. This resembles the other crystals in its elongation parallel to the edge *ss* and in its twinning on *e*, and in the dislocation of the twinned half. The differences lie in a still further departure from the form of a reflection-twin, the shape of the upper and lower halves of the crystal being markedly different, and in the fact that the composition-surface is no longer a simple plane *e*, but an undulating surface, the faces r^1, r^2, r^3, r^4 rising above the plane *e* drawn through the edge $a^2(a^4)$, and the faces (s^3), (s^4) descending below it. This crystal weighs 4·7 grams, and has a specific gravity of 7·46.

The principal angles measured on these crystals with a contact goniometer are:

Angle.[1]	Calculated.	Crystal I.	Crystal II.	Crystal III.	Crystal IV.	Crystal V.
	° ′	°	°	°	°	°
$a^2(a^4)$	65 46	—	—	66	66	66
$a^2(a^3)$	90 0	—	—	90	90[2]	—
a^1a^2	90 0	90	—	90	90	90
a^1r^1	33 41	34	33½	34	34	—
a^1r^2	56 19	56	—	—	56	56
a^3c^1	90 0	—	90	91	90	—
$(a^4)(e^4)$	57 7	—	—	—	57	—
e^1c^1	32 53	—	33	—	32½	—
a^1s^1	61 30	61½	—	—	61	61
s^1s^2	57 0	57	57	57	57	57

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[1] Or corresponding pair of faces.

[2] The angle $a^2(a^1)$.

In order to determine the composition of this mineral, a fractured and slightly weathered crystal was chosen which had been found associated with crystal III, and which had approximately the same density, viz. 7·45. This crystal weighed 35 grams, and about one-third of it was broken off and crushed. The results of the analysis of this portion are:

Tapiolite from Tabba-Tabba North.

	Per cent.	Molecular ratios.	
Ta_2O_5	82·55	186	191
Nb_2O_5	1·37	5	
TiO_2	0·18	2	
SnO_2	0·34	2	
Fe_2O_3	0·83	5	
FeO	10·69	149	207
MnO	1·49	21	
CaO	1·96	35	
MgO	0·10	2	
H_2O (over 105° C.)	0·31		
	99·82		

To make sure that the substance weighed as lime was really so,[1] its molecular weight was determined by conversion into sulphate. The result obtained was 56·05, which agrees with that calculated from the 1916 International Atomic Weights Table, viz. 56·07. The figures could not be correlated with any known rare earth sesquioxide, nor was the hydrate precipitated by ammonia. The small magnesia precipitate was tested colorimetrically for manganese, which was found to be absent from it. The analysis was made wholly in vessels of quartz and platinum, except for the preliminary fusion with caustic potash, which was made in a nickel crucible for the estimation of the acid oxides and in a silver crucible for the estimation of the strong bases. The purity of all reagents was proved before use.

The physical characteristics of the Tabba-Tabba tapiolite are as follow: Form, often well-crystallized, usually in twins on (101), and elongated parallel to the edge of adjacent unit pyramid-faces; at other times in rough fragments, water-worn to various degrees. Density, 7·36 to 7·69. Hardness, 6¼. Brittle, no cleavage. Colour on fresh fracture, pure

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[1] W. T. Schaller does not accept $CaTa_2O_6$ as isomorphous with $MnTa_2O_6$ and $FeTa_2O_6$. W. T. Schaller, 'The rutile group,' U. S. Geol. Survey, Bull. 509, 1912, pp. 10–18, 19–20.

black; colour of surface, black to dark brown, the brown tints being a sign of a thin surface weathering. Opaque, except in very fine powder (1/25 mm.), which is translucent under the microscope and dichroic, light to very dark brown. Birefringence, strong.

GREENS WELL (CHINGAMONG).

Some time ago a few small pure black crystals were collected in alluvium at Greens Well (sometimes known as Chingamong), about thirty miles south of Tabba-Tabba. On account of their high specific gravity, 7·84 to 7·91, these were suspected to be a tantalum mineral, and subsequent crystallographic examination proved their identity with tapiolite. The crystals are small, 2·1 to 3·5 grams, and broken, but such faces as are preserved are mostly but little corroded, and have a brilliant lustre, making them suitable for exact measurement, for which purpose they are being carefully preserved. A preliminary measurement of the angle *as* with a two-circle goniometer gave a reading of 61° 19′ as against 61° 30′ calculated from Nordenskiöld's value for *c*, viz. 0·6464.

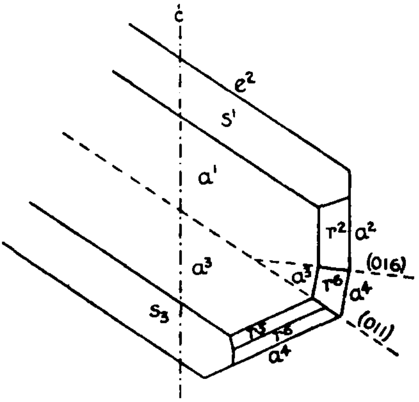

FIG. 5.—Tapiolite from Greens Well, Western Australia. Projection on (100) showing double twinning, viz. on (011) and (016).

In one crystal, fig. 5, in addition to the usual twinning on *e* yielding a form similar to that of strüverite from Ampangabe, Madagascar, illustrated by Lacroix's fig. 10, page 190 of the Bulletin de la Société française de Minéralogie for 1912, there is further a small inset which is a twin on (106), previously not known as a face or twinning-plane in this series of minerals. An orthographic projection of this crystal on (100) is given in fig. 6. Pending final measurement, the faces present appear to be:

Upper half of twin: a^1, a^2, r^2, r^3, s^1, s^2, e^2.
Small inset: a^3, a^4, r^6, r^7.
Lower half of twin: a^3, a^4, a^1 ?, r^5, r^6, r^7, r^8, s_3.

Measurements on this crystal gave the following angular values:

Angle.	Measured. ° ′	Calculated Nordenskiöld. ° ′	Calculated Brögger. ° ′
$a^2((a^4))$	12 20	12 18	12 24
a^1a^2	90 0	90 0	90 0
ar^1	33 36	33 41	33 41
ar^2	56 39	56 19	56 19
ae	56 48	57 7	56 53½
as	61 19	61 30	61 21

From *ae* the length of the vertical axis is calculated to be 0·6543, and from *as*, 0·6535, the mean of which is 0·6539. Nordenskiöld gives 0·6464, and Brögger, 0·65215.

This crystal weighs 2½ grams, and has a specific gravity of 7·839.

A second crystal from the same locality, with a density of 7·907 and weighing 4 grams, is heart-shaped, with a small re-entrant angle of approximately 11°. This appears to be a twin on (301) somewhat resembling the rutile twin shown in fig. 9 of the 6th Edition of Dana's 'System of Mineralogy' (1892). Owing to imperfect development of faces and to fracturing, it is not suited for exact measurement. The calculated re-entrant angle is 11° 12′ (Nordenskiöld's parameter).

A third distorted and fractured crystal appears to exhibit the following faces: a^1, a^2, r^1, r^2, s^1, s_3, s_4. Of these the most prominent are s^1 and s_4, a^1 and r^2 being moderately large, the others quite small. This crystal weighs 2·7 grams, and has a specific gravity of 7·875.

In addition to the unusual habit exhibited by these crystals, interest centres on the density, which for the pure tetragonal compounds has not been definitely settled. Until this is done it is impossible to study in detail the constitution of strüverite and ilmenorutile, and probably nigrine.

The determination of the specific gravity of a heavy mineral by a Jolly or Walker balance is very unsatisfactory, since owing to the small relative loss of weight in water, an error ranging up to 3 in the first place of decimals may occur in the density. With a chemical balance results correct to units in the second place of decimals are obtained without difficulty, either by suspension, when the mineral fragment weighs not less than 3 or 4 grams, or by pycnometer for somewhat smaller amounts.

Dana quotes 7·8 to 8·0 as the specific gravity of skogbölite (tapiolite) and 7·85 for the 'nearly pure iron tantalate' from Skogböle having the following composition:

Ta_2O_5.	Nb_2O_5.	FeO.	MnO.	CaO.	CuO.	SnO_2.	Total.
84·44	?	13·41	0·96	0·15	0·14	1·26	100·36.

The figures 7·8 to 8·0 are evidently to be considered approximate and liable to an error of anything up to 0·3.

For the original tapiolite[1] from Sukula, Tammela, Finland, Nordenskiöld found a density of 7·36, and Rammelsberg 7·496, the mineral having the composition:

Ta_2O_5.	Nb_2O_5.	FeO.	MnO.	SnO_2.	Total.
73·91	11·22	14·47	0 ·81	0·48	100·89.

Warren[2] gives 7·66 to 7·87 for tapiolite from Topsham, Maine. Prior[3] in 1913, after quoting the above analyses, writes: 'The density of these tetragonal metaniobates and tantalates, however, appears to be greater than that of the orthorhombic minerals of similar composition.'

In dealing with strüverite, D'Achiardi[4] assumes the density of pure mossite ($FeNb_2O_6$) to be 6·45, a value based on the assumption that Brögger's mossite from Moss was pure $FeNb_2O_6$, which is very far from the truth. Crook and Johnstone[5] in discussing the constitution of strüverite from Perak assume 7·3 to be the 'specific gravity of a typical tapiolite, i. e. one containing only a few per cent. of niobic oxide'.

Schaller,[6] from the value 7·85 for tapiolite and 6·45 for type mossite with equal molecules of tantalate and niobate, calculates 5·05 to be the density of pure $FeNb_2O_6$, a value with which, however, he is not too well satisfied, and which he queries in his tabulation. From the same data the present author calculates a density of 5·14 for $FeNb_2O_6$, using the formula

$$\text{Density} = \frac{\text{Molecular weight}}{\text{Molecular volume}} = \frac{338{\cdot}84}{65{\cdot}9},$$

where 65·9 is the mean of the molecular volumes calculated from his data for tapiolite and 1 : 1 mossite, viz. 65·6 and 66·2. Schaller assumes

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[1] Dana's 'System of Mineralogy', 6th edit., 1892, p. 738.

[2] C. H. Warren, loc. cit.

[3] G. T. Prior, Doelter's Handbuch der Mineralchemie, 1913, vol. iii, p. 264.

[4] G. D'Achiardi, ibid., 1913, vol. iii, p. 27.

[5] T. Crook and S. J. Johnstone, Mineralogical Magazine, 1912, vol. xvi, p. 231.

[6] W. T. Schaller, U. S. Geol. Survey, Bull. 509, 1912, p. 11.

from very limited data a progressive increase in molecular volume in passing from tapiolite to mossite, the volume being taken as a linear function of the percentage composition of the mineral. His molecular volume for pure mossite, however, on this theory becomes 67·1, which is doubtful in view of the free crystalline intergrowth of $FeNb_2O_6$ with $TiTi_2O_6$, the latter having a molecular volume of at most 60·0, and is unsupported by density determinations of actual minerals. If anything, one would expect the molecular volume of $FeNb_2O_6$ to be less than that of $FeTa_2O_6$ and nearer that of $TiTi_2O_6$.

Assuming that the tetragonal isomorphous series consisting of the metaniobates and metatantalates of iron, manganese, and calcium have an identical molecular volume, the highest specific gravity will be found in the pure compound having the highest molecular weight, viz. $FeTa_2O_6$. The highest specific gravity recorded for any mineral of this group is that now given for a crystal from Greens Well, viz. 7·907, and in view of the somewhat lower densities obtained for but slightly impure iron tantalate from other localities, the error in assuming 7·90 to be the density of pure tapiolite ($FeTa_2O_6$) must be extremely small. From this figure the molecular volume of the various members of the series is calculated to be 65·2 and the densities of the various pure minerals as follow:

$FeTa_2O_6$ (Tapiolite)	7·90	$FeNb_2O_6$ (Mossite)	5·20
$MnTa_2O_6$ (Ixiolite)	7·88	$MnNb_2O_6$	5·18
$CaTa_2O_6$ [1]	7·65	$CaNb_2O_6$	4·95

Given these values, the density may be used as a check upon the analytical figures obtained, particularly upon those for Ta_2O_5 and Nb_2O_5, by means of the known hyperbolic (not linear as so often assumed in mineralogical literature) relationship between the percentage composition of a mixture and its density, viz.

$$P_h = \frac{100 D_h (D_m - D_l)}{D_m (D_h - D_l)},$$

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[1] W. T. Schaller, loc. cit., omits these proved calcium isomorphs from his list and fails to take the lime and magnesia into consideration in discussing my analysis of Wodgina ixiolite. On the other hand, he includes $FeTiO_3$, whose only claim to existence as a tetragonal compound, except the very doubtful 'iserite', are some analyses of rutile and nigrine in which neither Nb_2O_5 nor Ta_2O_5 nor V_2O_5 have been looked for, though all three are probably present, and lastly analyses of ilmenorutile and strüverite in which the relative figures for Ta_2O_5, Nb_2O_5, and TiO_2 are not absolutely above suspicion, and of which in any case a different interpretation, not involving $FeTiO_3$, is possible. The present author contends on theoretical grounds that $FeTiO_3$ cannot be isomorphous with the series of compounds here discussed.

where P_h is the percentage present of the compound with higher density,

D_h the density of the heavier compound,

D_l the density of the lighter compound,

D_m the experimentally determined density of the mineral.

Having determined the densities of pure tapiolite and mossite, the relationship which strüverite and ilmenorutile bear to rutile, on the one hand, and to tapiolite and mossite, on the other hand, may be graphically

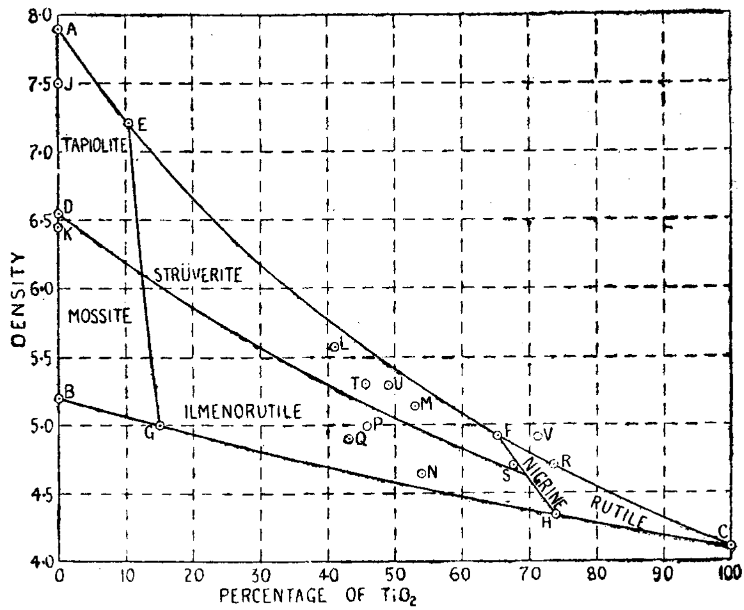

FIG. 6.—Graph showing relationship between tapiolite, mossite, rutile, strüverite, ilmenorutile, and nigrine.

A. Pure $FeTa_2O_6$, Tapiolite, Greens Well. D, 7·90.
B. Pure $FeNb_2O_6$. D, 5·20.
C. Pure $TiTi_2O_6$. D, 4·10.
D. $FeTa_2O_6 + FeNb_2O_6$. D, 6·55.
E. $4\ FeTa_2O_6 + TiTi_2O_6$.
F. $FeTa_2O_6 + 4\ TiTi_2O_6$.
G. $4\ FeNb_2O_6 + TiTi_2O_6$.
H. $FeNb_2O_6 + 4\ TiTi_2O_6$.
J. Type Tapiolite, Tammela.
K. Type Mossite, Moss.
L. Type Strüverite, Craveggia.
M. Type Ilmenorutile (Strüverite ?), Miask.
N. Typical Ilmenorutile, Iveland.
P. Ilmenorutile, Lake Monger, W. A.
Q. Ilmenorutile, Melville, W. A.
R. Ilmenorutile ?, Evje.
S. Ilmenorutile (Strüverite ?), Tvedestrand.
T. Strüverite, Perak.
U. Strüverite, Black Hills.
V. Strüverite ?, Ampangabe.

illustrated as is done in fig. 6. In this figure the equation for the curve AEFC, calculated from the foregoing general formula, is:

$$D = 852{\cdot}4 \div (107{\cdot}9 + R),$$

for the curve BGHC $D = 1938{\cdot}2 \div (372{\cdot}7 + R)$,

and for the curve DSC $D = 1095{\cdot}8 \div (167{\cdot}3 + R)$,

D in each case being the density of the mixed crystal, R the percentage by weight of rutile (TiO_2) present.

The ratio 4 : 1 taken as the limiting point between tapiolite and strüverite, &c., may appear to be arbitrary, as to some extent it undoubtedly is, but was not chosen without consideration, though other adjacent ratios such as 5 : 1 or 3 : 1 might be substituted.

The equivocal position of the type ilmenorutile from Miask on Prior's data[1] as to density and percentage of titanium oxide should be noted. The mineral from Iveland is unquestionably typical, as also apparently minerals found at Melville and Lake Monger in the Yalgoo goldfield of Western Australia, of which only preliminary data are at present available.

Perth, W. A.
September 11, 1916.

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[1] In the discussion following the reading of this paper, Dr. G. T. Prior remarked that since the publication of his own results (this Magazine, 1908, vol. xv, p. 80) he had realized that, with the small amounts of material at his disposal, the Marignac method for the separation of tantalic and niobic acids gave in all probability results much too low for tantalic acid. Until accurate methods or the separation of tantalic and niobic acids have been devised, the position in the strüverite-ilmenorutile series of the minerals he then analysed is best given by the density and percentage of titanium dioxide, the general accuracy of the data for which there is no reason to doubt.