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Some minerals from the leucite-rich rocks of the West Kimberley area, Western Australia.

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IN the investigation of a suite of leucite-lamproites from the West Kimberley area of Western Australia, carried out in the Department of Mineralogy and Petrology, Cambridge, during the period 1937-38, a number of unusual minerals were noted. Three of these were isolated and analysed and two of them proved to be new species. The present paper deals mainly with the three minerals analysed. They are—

- (1) Magnophorite, a new amphibole allied to katophorite.
- (2) Wadeite, a new potassium-zirconium silicate.
- (3) Titaniferous phlogopite.

Field occurrence.

The leucite-bearing rocks occur at a number of isolated volcanic vents, nineteen of which have been examined and mapped by Dr. A. Wade. They have in every instance broken through sedimentary deposits of Permian age. Considerable diversity is to be seen in the rock types developed, but they are all characterized by high potash, magnesia, and titania, with low alumina and soda. Analyses of some types which indicate the general chemical character of these rocks are given in table I.

The minerals noted in this suite of rocks were leucite, phlogopite, diopside, katophoritic amphibole, rutile, and (?) nontronite (pseudomorphous after olivine), with wadeite, perovskite, and apatite as minor accessories, and serpentine, calcite, baryte, chalcedony, and various zeolites as secondary minerals and amygdales. A full account of the petrography and petrogenesis of this very unusual suite of rocks will be

published shortly (Wade and Prider, 1939). In the present paper the unusual minerals mentioned above will be described.

TABLE I. Chemical analyses of some leucite-lamproites from the West Kimberley area, Western Australia.

	I.	II.	III.
SiO ₂	45.82	52.45	54.48
TiO ₂	7.34	5.85	5.57
Al ₂ O ₃	6.86	8.64	9.87
Fe ₂ O ₃	6.07	5.48	4.89
FeO	1.98	0.94	1.70
MnO	0.10	0.13	0.09
MgO	10.90	6.42	5.35
CaO	4.70	2.01	1.89
Na ₂ O	0.84	0.38	0.88
K ₂ O	8.82	10.42	11.06
H ₂ O+	0.75	1.99	1.36
H ₂ O-	2.40	2.89	0.89
CO ₂	0.08	nil	nil
P ₂ O ₅	1.83	1.58	0.40
BaO	1.27	1.19	0.64
SrO	n.d.	n.d.	0.16
ZrO ₂	n.d.	n.d.	0.07
SO ₃	n.d.	nil	0.10
FeS ₂	0.07	n.d.	0.20
Cr ₂ O ₃	0.07	n.d.	trace
V ₂ O ₃	0.03	n.d.	n.d.
F	present	n.d.	0.09
	99.93	100.37	99.69
Less O=F ...	—	—	0.04
			99.65

I. Diopside-phlogopite-magnophorite-leucite-lamproite. Analyst, C. R. Le Mesurier.

II. Phlogopite-leucite-lamproite. Analyst, D. G. Murray (E. S. Simpson, 1926, p. 59.).

III. Magnophorite-leucite-lamproite. Analyst, R. T. Prider.

Magnophorite, a new amphibole allied to katophorite.

This mineral occurs as an essential and abundant constituent of most of the lamproites examined. It has invariably been the last essential mineral to separate and usually has a poikilitic structure enclosing euhedra of leucite and diopside (fig. 1). In one specimen from the Wolgidee Hills locality the amphibole is comparatively free from inclusions, except for calcite which frequently occurs as a coating on the cleavages. In this specimen the amphibole is idiomorphic towards a carbonated serpentinous groundmass and the forms developed are (110) and (010). The characteristic amphibole cleavages are well developed.

By fine crushing, treatment in acetic acid, and centrifuging in heavy liquids, followed by a separation with the electromagnet, it was possible to obtain a pure product for analysis. The analysis together with the calculation of the structural formula on a basis of $24(\text{O},\text{OH},\text{F})$ (Warren, 1930, p. 493) appears in table II.

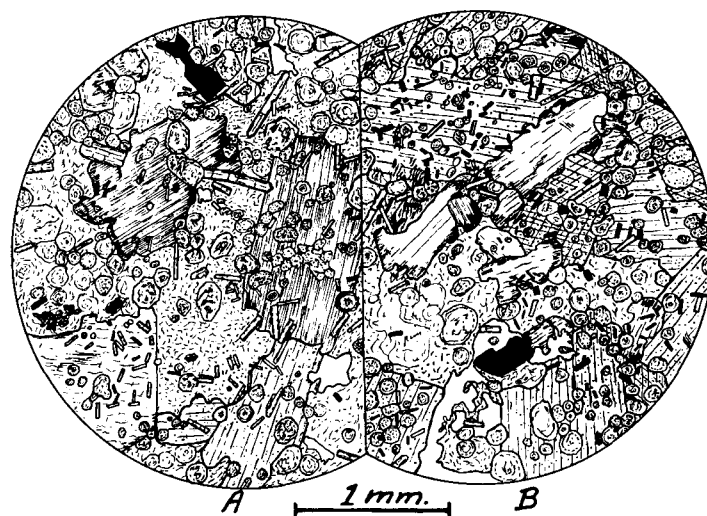


FIG. 1A. Lamproite (specimen no. 116a) from Moulamen Hill. Showing poikilitic inclusions of diopside and leucite in katophoritic amphibole (good prismatic cleavage; dotted) and phlogopite, the latter showing a dark resorption border. In lower left a well-shaped phlogopite plate is somewhat corroded. The groundmass is mainly greenish serpentine. Rutile as opaque rods and prisms.

FIG. 1B. Lamproite (specimen no. 456a) from Mt. North. Showing phlogopite (with dark resorption border) free from inclusions, and katophoritic amphibole (forming the greater part of the field) with poikilitic inclusions of diopside, leucite, and rutile. The groundmass is of serpentine. Irregular clear skeletal areas of zeolite.

The characteristics of this mineral are:

Specific gravity 3.12. Colour, pale reddish-brown.

Pleochroism: α colourless to pale yellow; β reddish, like α in hypersthene and increasing rapidly in intensity with increasing thickness; γ pale to bright yellow, occasionally slightly greenish. Absorption $\beta > \gamma > \alpha$.

Optic axial plane (010), $\beta = b$, $\gamma:c = 26^\circ$, $2V = 70^\circ$. Dispersion rather strong, $r < v$.

Refractive indices: α 1.616, γ 1.632, $\gamma - \alpha$ 0.016.

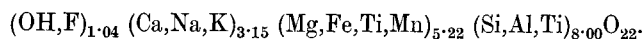
The absorption and pleochroism are indicative of a member of the katophorite group, but the analysis shows that the FeO and Fe₂O₃ of the normal katophorite have been replaced almost entirely by MgO. Another notable feature of this amphibole is the marked dominance of

TABLE II. Chemical analysis and calculation of katophoritic amphibole from specimen no. 242a, Wolgidee Hills, West Kimberley, Western Australia.

Analyst, H. C. G. Vincent.

	Wt. %	Molecular proportions.	No. of metal atoms on basis of 24(O,OH,F).	
SiO ₂ ...	52.67	0.878	7.582	} 8.000
Al ₂ O ₃ ...	1.72	0.017	0.294	
TiO ₂ ...	3.53	0.044	0.380	} 0.124 } 0.256
Fe ₂ O ₃ ...	0.58	0.004	0.069	
FeO ...	2.41	0.033	0.285	} 5.222
MnO ...	0.06	0.001	0.009	
MgO ...	21.32	0.533	4.603	} ... 3.152
CaO ...	6.95	0.124	1.071	
SrO ...	0.15	0.001	0.009	} ... 1.036
BaO ...	nil	—	—	
Na ₂ O ...	3.64	0.059	1.019	} ... 1.036
K ₂ O ...	5.70	0.061	1.053	
Li ₂ O ...	n.d.	—	—	
ZrO ₂ ...	nil	—	—	
H ₂ O— ...	nil	—	—	
H ₂ O+ ...	0.46	0.026	0.449	} ... 1.036
F ...	1.29	0.034	0.587	
	100.48			
Less O = F	0.54			
	99.94			

K₂O over Na₂O. The above calculation in table II shows that the structural formula of the mineral is:



This agrees fairly well with the typical amphibole structural formula, the main points of difference being the low value of 1.04 for (OH,F) and the high value of 3.15 for (Ca,Na,K).

In table III are set down the analyses and optical properties of various amphiboles which show some affinities to that described above. From this table it will be seen that, optically, the Western Australian amphibole appears to be a katophorite; chemically, however, the closest relatives are imerinite, szechenyite, and richterite. The two former amphiboles differ from the Western Australian mineral in having a considerable Na₂O content and very little K₂O. Richterite, the manganese-rich

metamorphic amphibole, differs only in having a considerable amount of MnO and no TiO₂. The normal katophorite and anophorite have a high iron content, which in the Western Australian mineral has been replaced

TABLE III. Chemical analyses and optical data of various alkalic amphiboles showing affinities to the Western Australian amphibole.

	I.	II.	III.	IV.	V.	VI.	VII.	VIII.
SiO ₂	52.67	46.87	41.53	53.73	55.02	49.79	55.64	54.15
TiO ₂	3.53	1.03	1.12	0.41	—	5.37	nil	—
Al ₂ O ₃	1.72	7.97	10.27	2.72	4.53	1.98	1.08	0.52
Fe ₂ O ₃	0.58	5.52	} 25.02 {	4.72	1.04	7.54	—	1.77
FeO	2.41	8.57		4.70	3.28	9.18	6.35	2.80
MnO	0.06	1.18	—	—	—	0.36	0.77	5.09
MgO	21.32	13.22	6.32	20.60	20.36	11.59	22.09	20.18
CaO	6.95	7.69	9.34	2.73	8.00	3.16	7.64	6.06
SrO	0.15	—	—	—	—	trace	—	—
BaO	nil	—	—	—	—	—	nil	—
Na ₂ O	3.64	4.46	3.62	7.42	6.71	7.92	2.89	2.77
K ₂ O	5.70	1.75	1.21	1.82	1.52	1.85	0.98	6.37
H ₂ O+	0.46	1.87	1.65	0.85	0.51	1.52	2.95	0.12
F ...	1.29	—	—	0.92	—	—	nil	—
	100.48	'100.33'	100.08	100.62	100.97	100.26	100.39	99.83

Sp. gr.	3-12	3-201	3-408	3-02	3-033	3-166	3-0	—
α	1.616	1.655	—	—	—	—	—	—
γ	1.632	1.662	—	—	—	—	—	—
γ-α	0.016	0.007	—	—	—	—	0.020-0.030	—
Extinction	γ : c 26°	α : c 56°	α : c 66°	γ : c 50°	16°16'	β : c 20-28°	α : c 16-70°	—
2V	70°	small	—	small	—	2E 33-40°	—	—
Dispersion	{ strong r < v	—	—	strong	—	strong r > v	—	—

Pleochroism.

	α	β	γ	Absorption.
I. pale yellow		reddish	yellow	β > γ > α
III. clear green		brownish-red	reddish-yellow	β > γ > α
IV. pale yellowish-green		bluish-violet	pale bluish-green	β > γ = α
VI. pale yellow		greenish	reddish-brown	γ > β < α
VII. pinkish-lilac		paler lilac	blue	—

- I. Amphibole from lamproite specimen no. 242a, Wolgidee Hills, West Kimberley area, Western Australia.
- II. Katophorite, Khibina, Kola Peninsula, Russia. (Kunitz, 1930, pp. 219, 245.)
- III. Katophorite, Grouvslletten, Norway. (Kunitz, 1930, pp. 219, 245.)
- IV. Imerinite, Madagascar. (Lacroix, 1910, p. 787; 1922, p. 538.)
- V. Szechenyiite, Burma. (Krenner, 1899, p. 503.)
- VI. Anophorite, Katzenbuckel, Odenwald, Germany. (Freudenberg, 1908, p. 76; Rosenbusch, 1910, p. 201.)
- VII. Winchite, Jhabua State, Central India. (Fermor, 1909, p. 149.)
- VIII. Richterite, Långban, Sweden. (Magnusson, 1930, p. 45.)

almost entirely by MgO. Also the katophorite has much of its SiO_2 replaced by Al_2O_3 . The alkalis in the Western Australian mineral differ considerably from those of katophorite and anophorite, which both have soda dominant over potash. The richterite from Långban is the only amphibole in the above table which has a similar content and relative proportion of soda and potash to the Western Australian mineral.

This mineral is therefore best described as a kali-magnesio-katophorite, and as it differs considerably from the normal katophorite in chemical composition it appears to warrant a new name. In an earlier summary report (Wade and Prider, 1938; Prider, 1939) on these leucite-rocks the name simpsonite was proposed for this mineral. Almost simultaneously the name simpsonite was proposed by H. Bowley for a new hydrous tantalate of calcium and aluminium from Tappa Tappa, Western Australia (Bowley, 1938, 1939), so the name *magnophorite* is now suggested for this mineral.

From the analyses of the leucite-rocks which contain magnophorite (analyses I and III in table I) it will be seen that this mineral, which has been invariably the last to crystallize, has separated from a residuum (after crystallization of the earlier phlogopite, diopside, and leucite) which was rich in potash, magnesia, titania, and silica, and which contained very little alumina.

A similar mineral to the above has been recorded from two localities. Osann (1906, p. 295) has described an amphibole with similar pleochroism and absorption from the jumillites of Murcia, Spain, and Cross (1897, p. 125) records the presence of a similar amphibole in the rock orendite from the Leucite Hills, Wyoming. In both instances the mineral was considered to be katophorite, but in neither case was the mineral examined chemically. With regard to the amphibole occurring in the orendite of the Leucite Hills, Cross (1897, p. 126) states: extinction seems to be always parallel to the length axis; $\alpha = a$, pale yellow; $\beta = b$, red similar to hypersthene; $\gamma = c$, bright yellow; absorption $\beta > \gamma > \alpha$; almost uniaxial with the arms barely separating in the 45° position.

An examination of the amphibole in the orendite specimen in the Petrology Museum at Cambridge shows that this mineral is often zoned, with extinction-angles $\gamma:c = 5^\circ$ for the periphery and 17° for the centre. Extinction is rarely straight (as stated by Cross) and frequently is as much as 25° . The mineral has the same pleochroism, absorption, and strong dispersion as noted in the mineral described above as magnophorite, but has slightly higher refringence, β measured on several minute prisms being 1.643. This mineral, therefore, is essentially the

same as magnophorite. Its paragenesis is the same as for the Western Australian mineral, as it is associated with diopside, phlogopite, and leucite, and has separated from a potash-silica-rich and alumina-poor residuum after the formation of diopside, phlogopite, and leucite.

Cross (1897, p. 131) suggests, in view of the considerable zirconia content (0.22 %) of the orendites, 'that the peculiar amphibole of orendite is perhaps zirconia-bearing, analogous to lavenite, wöhlerite, and hiortdahlite'. Acting on this suggestion I determined zirconia on a slightly impure sample of magnophorite (containing not more than 5% impurity) and found this constituent to be absent.

Wadeite, a new potassium-zirconium silicate.

This new mineral was found in the rocks from the Wolgidee Hills, and amongst all the specimens examined it has only been noted from this locality. The material analysed was separated from the same specimen as the magnophorite described above, viz. no. 242a. In this rock the wadeite is present to the extent of about 1 or 2%, occurring as highly birefringent prisms up to 1 mm. in length and as hexagonal-shaped basal sections. It has crystallized before the magnophorite and is invariably idiomorphic towards it, but its relations with the diopside are not visible in any of my slices. It is invariably replaced in part (especially along the poor pyramidal cleavages) by calcite.

It appears to be hexagonal and is usually as well-shaped crystals flattened on the base, the sections then appearing to have elongation of a negative character. The faces developed are the base, prism, and occasionally a pyramid. Poor pyramidal cleavages intersecting at angles of nearly 90° are present in some crystals and are rendered visible because of the presence of secondary calcite which has entered along these directions. Typical sections of the mineral are shown in fig. 2.

The mineral is colourless, uniaxial, optically positive, and has ϵ 1.655, ω 1.625, $\epsilon - \omega$ 0.030.

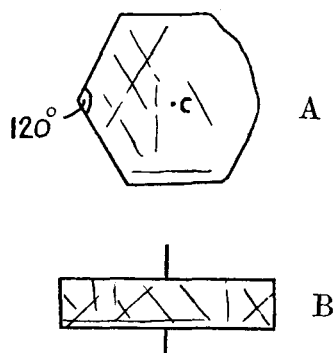


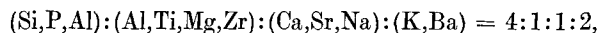
FIG. 2. Wadeite, showing forms developed.

A. Basal section showing imperfect (?) prism cleavages.

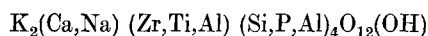
B. Section parallel to the *c*-axis, showing poor pyramidal cleavages intersecting at approximately 90° . A poor basal and prismatic cleavage also present.

It has a specific gravity of 3.10, is non-magnetic and insoluble in hot acids.

The mineral was separated by centrifuging the fine-powdered, acid-treated rock in heavy liquids and later purified by separation with the electromagnet and finally by hand-picking. In all, only 0.5 gram was obtained and that included slight impurity (estimated at less than 5%). The analysis must therefore be regarded as correct only to the nearest whole number. Water above 110° C. was determined by loss on ignition on the main portion. The result of the analysis is shown in table IV. This table also shows the calculation of the analysis. In the third column the proportions of the groups of metal atoms has been worked out as shown and are found to be approximately:



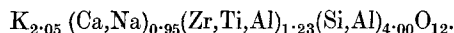
from which the formula (omitting the small amounts of Sr, Mg, and Ba) appears to be:



or ideally $\text{K}_2(\text{Ca,Na})\text{Zr}(\text{Si,Al})_4\text{O}_{12}(\text{OH})$.

In the fourth column the number of metal atoms on a basis of 13(O,OH) is given, and it will be seen that the values obtained closely approach the ideal proportions of 4:1:1:2:1.

Regarding the 'loss on ignition' assumed in the above to be water above 110° C., the mineral was heated to redness and then examined microscopically. It suffered no apparent change during the heating, no signs of incipient fusion were present and the mineral retained its clarity. It is doubtful, therefore, whether any water is present in the structure of the mineral. The analysis has been recalculated on a basis of 12(O) and the 1.30% loss on ignition disregarded. The results of this calculation are shown in table V. The formula of the mineral according to this calculation is:



Acting on the suggestion of Professor Tilley, attempts were made to synthesize the mineral. This work was conducted by Mr. H. C. G. Vincent to whom I am indebted for the following notes. An initial charge of K_2CO_3 1.382, CaCO_3 1.001, ZrO_2 1.232, SiO_2 2.402 grams was heated for $\frac{3}{4}$ hour in the electric furnace to drive off the CO_2 . After several attempts at heating in the Fletcher gas-furnace a pure glass was obtained. This was crushed and crystallized at a temperature of approximately 900° C. for 14 hours in the electric furnace, giving a crystalline

mass plus a little glass. Microscopical examination showed the crystals to be in sheaf-like masses with negative elongation, straight extinction, uniaxial of positive optical character with a refractive index slightly

TABLE IV. Chemical analysis and calculation of wadeite. Analyst, R. T. Prider.

	Wt. %	Molecular proportions.	No. of metal atoms × 1000.	No. of metal atoms on basis 13(O,OH).
SiO ₂	39.43	0.657	657	3.544
P ₂ O ₅	3.15	0.022	44	0.237
Al ₂ O ₃	5.98	0.059	118	0.636
(Ce,Yt) ₂ O ₃	nil	—	—	—
Fe ₂ O ₃	trace	—	—	—
TiO ₂	1.63	0.020	20	0.108
MgO	0.28	0.007	7	0.038
ZrO ₂	21.29	0.173	173	0.933
CaO	5.22	0.093	93	0.502
SrO	0.16	0.002	2	0.011
Na ₂ O	2.82	0.045	90	0.485
K ₂ O	18.40	0.196	392	2.114
BaO	1.20	0.008	8	0.043
H ₂ O—	nil	—	—	—
H ₂ O+	1.30	0.072	144	0.777
				100.86

TABLE V. Calculation of analysis of wadeite, assuming that no hydroxyl is present in the structure.

	Molecular proportions.	No. of oxygens.	No. of metal atoms on a basis of 12(O).
SiO ₂	0.657	1.314	3.372
P ₂ O ₅	0.022	0.110	0.226
Al ₂ O ₃	0.059	0.177	0.605
TiO ₂	0.020	0.040	0.103
MgO	0.007	0.007	0.036
ZrO ₂	0.173	0.346	0.888
CaO	0.093	0.093	0.477
SrO	0.002	0.002	0.010
Na ₂ O	0.045	0.045	0.462
K ₂ O	0.196	0.196	2.012
BaO	0.008	0.008	0.041
			2.338

greater than 1.608. This material appeared to resemble pseudo-wollastonite, but it was insoluble in HCl. (Note: the natural mineral is similar in its optics to pseudo-wollastonite). These crystals must have had a composition approaching K₂CaZrSi₄O₁₂, as there was very little glass left after crystallizing for 14 hours: optically they are similar (but with somewhat lower refractive indices and different habit) to the natural

mineral. Another sample of the glass was now crystallized at 1300° C. (i.e. above the transition-point of pseudo-wollastonite) and the result was a colourless prismatic mineral (very similar to that obtained at 900° C.) plus some very highly refracting and highly birefringent rounded granules plus some glass.

A little of the natural mineral (slightly impure) was fused in a small platinum capsule in the Fletcher gas-furnace for $\frac{3}{4}$ hour. On quenching the melt the result was glass plus some very highly refringent granules (? similar to those obtained in crystallizing the artificial material at 1300° C.). The glass of the natural mineral melt was now crystallized at 1300° C. giving small prismatic crystals plus some glass.

The fusion experiment on the natural mineral appears to indicate that it melts incongruently to glass plus a very highly refringent material. Attempts at synthesizing the mineral gave at low temperatures of 900° C. a mineral very similar in optics but differing in habit. At higher temperatures of 1300° C. crystals plus highly refringent globules similar to those in the quenched melt of the natural mineral were obtained, thus supporting the suggestion that the natural mineral melts incongruently.

Returning to a consideration of the natural mineral, it is distinct from any previously described. Its closest relative is catapleiite from which it differs mainly in its low water and high potash content. The name proposed for this new mineral is *wadeite*, in honour of Dr. Arthur Wade, who was responsible for the collecting of this suite of rocks, and who discovered the new Wolgidee Hills intrusion where this mineral has been found.

Titaniferous Phlogopite.

This mineral occurs as a constant constituent of most of the leucite-bearing rocks. It appears to be fairly constant in character throughout the suite of rocks examined, except that in the more basic types it has a somewhat stronger absorption. One group of these rocks of wide-spread occurrence is made up entirely of this mineral plus leucite plus a very siliceous glassy groundmass. The phlogopite is usually phenocrystal, and the rocks appear to be surface flows as they usually show a flow orientation of the phlogopites or an elongation of the chalcedony-filled vesicles. The material for analysis was separated from an amygdaloidal phlogopite-leucite-lamproite from the Howe's Hill locality. The phlogopite in this rock is present as parallel alined, usually somewhat corroded, lath-shaped phenocrysts up to 2 mm. in length, which have crystallized earlier than the leucite and rutile which occurs as innumer-

able minute prisms in the glassy base. It is a deep reddish-brown colour, and is characterized by strong pleochroism after the scheme: α practically colourless to pale salmon-pink, β bright yellow, γ reddish-brown.

It has a comparatively large axial angle and always shows polysynthetic twinning parallel to the base, which, owing to the marked difference in absorption along β and γ , is visible without the aid of the analyser, as the alternate lamellae show different pleochroism, one set of lamellae from pale salmon-pink to bright yellow and the alternate lamellae from pale salmon-pink to deep reddish-brown.

TABLE VI. Chemical analysis and calculation of phlogopite from phlogopite-leucite-lamproite, Howe's Hill, Western Australia. Analyst, H. C. G. Vincent.

		Wt. %.	Molecular proportions.	No. of metal atoms on basis 12(O,OH,F).	
SiO ₂	...	40.78	0.680	2.986	} 4.000
Al ₂ O ₃	...	10.95	0.107	0.940	
TiO ₂	...	8.97	0.113	0.496	
Cr ₂ O ₃	...	trace	—	—	} 2.925
Fe ₂ O ₃	...	2.18	0.014	0.123	
FeO	...	3.73	0.051	0.224	
MnO	...	trace	—	—	
MgO	...	19.66	0.491	2.156	
CaO	...	0.11	0.002	0.009	} ... 1.028
SrO	...	trace	—	—	
BaO	...	0.35	0.002	0.009	
Na ₂ O	...	0.11	0.002	0.018	
K ₂ O	...	10.59	0.113	0.992	} ... 1.080
Li ₂ O	...	nil	—	—	
H ₂ O—	...	0.19	—	—	
H ₂ O+	...	1.87	0.106	0.931	
F	...	0.66	0.017	0.149	
		100.15			
—O = F		0.27			
		99.88			

The analysis of this mineral is shown in table VI and the optical properties are:

Colour, deep reddish-brown.

Pleochroism: α pale salmon-pink to practically colourless, β bright yellow, γ reddish-brown. Absorption $\alpha < \beta < \gamma$.

α 1.599, γ 1.643, $\gamma - \alpha$ 0.044; $\alpha : c$ to 5°.

2V 38°, negative; dispersion very strong, $r < v$.

The structural formula (calculated in table VI):

