Lusakite, a cobalt-bearing silicate from Northern Rhodesia.

(With Plate XXIV.)

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Discovery and Occurrence.

THIS interesting new mineral was discovered by the first author in February 1933 whilst in the employment of the British South Africa Company Limited as a field geologist to the Rhodesia Minerals Concession Limited under the direction of Dr. J. Austen Bancroft. The locality, longitude 29° 29′ E. and latitude 15° 27′ S., is about eighty miles east of Lusaka, the new capital of Northern Rhodesia, after which the mineral is named. The central African plateau has here been cut back from the northern escarpment of the Zambezi rift valley, about 10 miles to the south, producing a rugged topography varying from 1,000 feet to 4,000 feet in altitude.

The general geological setting consists largely of granite-gneisses and amphibolites, with subsidiary epidosites, mica-schists, banded ironstones, and quartzites. There is a widespread mineralization of quartz-pyrite and quartz-tourmaline veins carrying low values in gold. The suite of rocks makes an interesting study in petrogenesis which it is hoped to describe elsewhere. The new mineral occurs in a rock of gneissoid appearance in which it is intimately associated with quartz, kyanite, and magnetite (pl. XXIV, fig. 1). The average approximate proportions of these minerals by weight and their quantity variations are as follows:

Lusakite	...	5−40%	...	average 30%
Quartz	...	10−25	...	„ 12
Kyanite	...	0−10	...	„ 3
Magnetite	...	40−65	...	„ 55

Parallel to the foliation of the rock are vuggy streaks in which well-developed crystals are found. This quartz-magnetite-lusakite-rock was found on a hillside as a few well-jointed float boulders obviously representing a broken down outcrop and indicating a vein or bed a few inches in thickness and extending possibly for thirty yards along the strike. Associated with these boulders were found larger pieces of a very interesting cordierite-anthophyllite-rock thought to be genetically connected with the lusakite-rock.

The average grain size of the mineral is about $2 \times 1 \times \frac{1}{2}$ mm. and individual crystals range from microscopic dimensions to 5 mm. long. In hand-specimens the colour is black, but minute crystals are deep cobalt-blue by transmitted light. The mineral gives a light blue streak, so that hand-specimens of the lusakite-bearing rock often show blue patches due to impact and abrasion. It is brittle, with subconchoidal fracture; the hardness is $7\frac{1}{2}$ and the lustre vitreous.

Microscopic Characters.—When viewed in thin sections the mineral has a vivid cobalt-blue colour in ordinary light, probably the most intense blue yet observed in a thin section of any mineral. It rarely shows crystal boundaries unless the section includes one of the vuggy portions of the rock referred to above (fig. 2). There is a distinct cleavage parallel to (010) and a less distinct one parallel to (100). No twinning has been observed. The refractive index is high, about 1·74, giving a marked relief in thin section. The deep body-colour somewhat masks the birefringence, but all sections show straight extinction parallel to cleavage cracks. Lusakite is strongly pleochroic in tints varying from light cobalt-blue to violet and even dark wine-red in thick sections; $\alpha[010]$ cobalt-blue, $\beta[100]$ violet-blue, $\gamma[001]$ violet. A biaxial interference-figure has been observed in an accurately orientated basal section, but 'eyes' lie outside the field suggesting a large value of 2V, whilst sections at right angles to an optic axis show a 'compass needle' isogyre, also indicating the closeness of 2V to 90°.

Under a high power blebs of 'myrmekitic' quartz of various shapes can frequently be observed sometimes arranged in fan-like aggregates (fig. 3). Two other minerals which are present in minor amounts are rutile, which occurs as inclusions in the kyanite, and fibrolite, seen as minute radiating clusters at the edges of the patches of quartz.

Chemical Composition.—Lusakite is essentially an aluminium silicate carrying cobalt, iron, nickel, and magnesium, and is unique amongst the silicates in its content of cobalt. A preliminary qualitative

analysis was made using a quartz-wedge spectrograph which facilitated the quantitative analysis carried out by Dr. A. W. Groves on two separate samples. The first sample was obtained by crushing the rock and hand-picking the fragments of lusakite, which, however, carried a certain amount of magnetite and quartz as inclusions. A preliminary determination of the specific gravity of this material, using an ordinary pyknometer and also a Jolly balance, gave 3.76 ± 0.05. The second sample was obtained by powdering rock containing lusakite but not kyanite, abstracting magnetite with a magnet and then boiling repeatedly with hydrochloric acid to dissolve the remaining magnetite; the mineral was then separated from quartz by scattering the powder over the surface of bromoform contained in a large funnel and repeating the operation several times. The specific gravity of this pure powder was determined more accurately by the Ellsworth silica pyknometer using carbon tetrachloride and leaving the mineral immersed under reduced pressure for twelve hours before weighing; the value obtained was 3.767 ± 0.005.

The chemical stability of lusakite is illustrated by the absence of alteration under tropical conditions of weathering; in the laboratory all acids including hydrofluoric acid are without effect upon it. It is infusible in the Bunsen flame but yields a black bead in an electric arc. Decomposition and solution can be brought about, however, by fusion with sodium carbonate before a strong blowpipe flame followed by extraction with hydrochloric acid.

The determination of ferrous iron proved extremely difficult on account of the chemical resistance of lusakite even to a mixture of hydrofluoric and sulphuric acids. Leaching with such a mixture three times in succession yielded values that must be considered as only approximate. Since the mineral is not taken into solution it is probable that only the outer portion of each particle of the powder is acted on and freed of its ferrous iron.

Table 1 shows the results of chemical analysis of the two samples. The second analysis, made on the more carefully prepared sample, leads approximately to the formula

$$H_2O.2(Co,Ni)O.FeO.MgO.9(Al,Fe)_2O_3.8SiO_2$$
$$\text{or}\quad H_2O.4R^{II}O.9Al_2O_3.8SiO_2 = H_2R_4^{II}Al_{18}Si_8O_{48}.$$
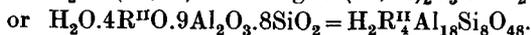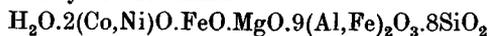
This corresponds with the formula $H_2O.4FeO.9Al_2O_3.8SiO_2$ deduced by F. Hörner[1] for staurolite.

[1] F. Hörner, Beiträge zur Kenntnis des Stauroliths. Inaug-Diss. Heidelberg, 1915. [Min. Abstr., vol. 1, p. 395.]

TABLE 1. *Chemical analyses of lusakite.*

	I.	Mol. ratios.			II.	Mol. ratios.		
SiO_2 ...	27·07	0·451 ⎫	0·461	9·75	...27·23	0·453 ⎫	0·459	7·75
TiO_2 ...	0·80	0·010 ⎭			... 0·50	0·006 ⎭		
Al_2O_3 ...	48·15	0·472 ⎫			...50·72	0·497 ⎫		
Cr_2O_3 ...	trace	— ⎬	0·540	11·34	... n.d.	— ⎬	0·528	8·905
Fe_2O_3 ...	10·83	0·068 ⎭			... 4·96	0·031 ⎭		
FeO ...	2·22	0·031 ⎫			... 3·42	0·048 ⎫		
NiO ...	0·53	0·007 ⎪			... 0·89	0·012 ⎪		
CoO ...	6·79	0·091 ⎬	0·189	4·00	... 8·48	0·113 ⎬	0·237	4·00
MnO ...	trace	— ⎪			... 0·08	0·001 ⎪		
MgO ...	2·44	0·060 ⎭			... 2·56	0·063 ⎭		
CaO ...	nil	—			... nil	—		
$H_2O+110°$	1·00	0·056	0·056	1·17	... 1·19	0·066	0·066	1·11
$H_2O-110°$	0·35	—			... nil			
S ...	0·07				... —			
	100·25				100·03			
Sp. gr. ...	3·76				3·767			

Crystallography. The crystals are generally tabular in habit, but some detached for goniometric and X-ray work were practically equidimensional prisms. The only forms observed with certainty are (010) and (110), the former usually predominating. Optical reflections from the faces are poor and there is vicinal plane development. Also some crystals show striated tabular (010) faces due to the alternation of (010) and (110). Accurate interfacial angles were therefore difficult to obtain, but so far as the prism-zone is concerned crystals of the mineral appear to possess a plane of symmetry parallel to (010). The average values obtained from three crystals for the angle (010) : (110) is 64° 37′ corresponding to an axial ratio $a : b = 0.474 : 1$. Owing to the absence of definite terminal faces the ratio $c : b$ could not be obtained by direct goniometric measurement.

X-ray investigation.—One of the smaller crystals used for goniometric measurements was used for X-ray work. Laue photographs along the three axes of the crystals show in each case two planes of symmetry at right angles. Rotation photographs about these three directions yield the dimensions a 7·86, b 16·62, c 5·65 Å. The limits of error for these measurements are ± 0.01 Å. for a and c and 0·03 Å. for b. The axial ratios calculated from the unit-cell dimensions are $a : b : c = 0.473 : 1 : 0.340$. The $a : b$ ratio is in satisfactory agreement with the goniometric value. A series of oscillation photographs about [100], [010], and [001] were indexed and the following halvings found : all (hkl) for $h + k$ odd and all $(0kl)$ for $k + l$ odd. A special

search was made for any weak spots on the equator of the photographs about the [100] axis which defied the latter halving. None could be found. Moreover, no weak layer-lines could be detected requiring the doubling of any of the unit-cell lengths. The space-group of the mineral is therefore V_h^{17}.

Crystal-structure.—The chemical analysis, the X-ray data, and the optical properties all show that lusakite is closely related to staurolite. The intensity differences of spots on rotation photographs of each mineral about the [001] axis are indeed very small so that we can be certain that the crystal-structures are also practically identical. Below are listed the known crystallographic and X-ray data for staurolite and lusakite.

Mineral.	Space-group.	Unit-cell dimensions			Calculated axial ratio.
		$a.$	$b.$	$c.$	
Lusakite ...	V_h^{17}	7·86	16·62	5·65	0·473 : 1 : 0·340
Staurolite [1] ...	V_h^{17}	7·81	16·59	5·64	0·471 : 1 : 0·339
Staurolite [2] ...	V_h^{17}	7·82	16·52	5·63	0·473 : 1 : 0·341

The axial ratio c of staurolite referred to the axes adopted by Dana has to be halved. The faces indexed according to those axes as (101) and (011) should be transformed to (201) and (021) respectively. The axial ratios based on the measurements of W. Phillips (1823) therefore become $a : b : c = 0.4734 : 1 : 0.3414$, and those on F. Hörner's measurements (1915) $a : b : c = 0.4734 : 1 : 0.3410$, both in very close agreement with the X-ray values. Náray-Szabó has proposed a sandwich type of crystal-structure for staurolite consisting of blocks of kyanite interleaved with layers of $Fe(OH)_2$. This structure is based upon an 'ideal' formula $H_2FeAl_4Si_2O_{12}$ which may be written $[Fe(OH)_2 + 2Al_2SiO_5]$. He rejected the formula of S. L. Penfield and J. H. Pratt [3] and also that of F. Hörner [4] as unsatisfactory. If, however, the actual chemical analyses and density data of Penfield and Pratt and of Hörner are used as a basis of calculation it is significant that the number of oxygen atoms per unit cell of staurolite is practically constant and equal to 48. From table 2 it is seen that the maximum variation in the oxygen figures for staurolite and lusa-

[1] G. M. Cardoso, Zeits. Krist., 1928, vol. 66, p. 485. [M.A. 3–529, 4–111.]

[2] S. Náray-Szabó, Zeits. Krist., 1929, vol. 71, p. 103. [M.A. 4–160.]

[3] $HFeAl_5Si_2O_{13}$. S. L. Penfield and J. H. Pratt, On the chemical composition of staurolite... Amer. Journ. Sci., 1894, ser. 3, vol. 47, p. 81.

[4] $H_2Fe_4Al_{18}Si_8O_{48}$. F. Hörner, 1915, loc. cit.

kite is 1·5 %.   Since errors from three different experimental deter-
minations, viz. chemical analysis, density, and X-ray work, are
involved the closeness of approach of the oxygen figure to an integral
number 48 is reasonable.   The numbers of atoms other than oxygen
in the unit cell have been calculated on a basis of 48 oxygen atoms
per unit cell and are included in table 2.

TABLE 2.   *Atomic contents of unit cell of lusakite and staurolite.*

		1.	2.	3.	4.	5.	6.	7.
Sp. gr.	...	3·767	3·773	3·728	3·748	3·775	3·759	3·753
O ...	...	47·3	48·6	48·3	48·4	48·4	48·0	47·9
Si ...	...	7·75	7·71	7·70	7·68	7·76	7·75	7·80
Ti ...	...	0·11	—	—	—	—	0·16	0·15
Al ...	...	17·01	17·45	17·70	17·39	17·79	17·61	17·00
Fe^{III}	...	1·06	1·01	0·59	0·59	0·58	0·49	0·38
Fe^{II}	...	0·81	2·26	2·44	2·60	2·91	2·97	3·11
Ni ...	...	0·20	—	—	—	—	—	—
Co ...	...	1·93	—	—	—	—	—	—
Mn	...	0·02	0·08	0·14	0·12	—	—	—
Mg	...	1·09	1·10	0·76	0·75	0·80	0·74	0·86
H ...	...	2·26	3·75	4·12	4·04	3·16	2·73	3·78

1. Lusakite, Lusaka, Northern Rhodesia. A. W. Groves, 1934.
2. Staurolite, Burnsville, North Carolina. ⎫
3.   ,,   Windham, Maine, U.S.A.   ⎬ S. L. Penfield and
4.   ,,   St. Gotthard, Switzerland. ⎭ J. H. Pratt, 1894.
5.   ,,   Lisbon, New Hampshire. ⎭
6.   ,,   Aschaffenburg, Bavaria.   ⎫ F. Hörner, 1915.
7.   ,,   Pizzo Forno, St. Gotthard. ⎬

Comparing these figures for staurolite with those for the unit-cell
content proposed by Náray-Szabó it is clear that chemical analyses
reveal a much higher content of aluminium atoms and only half the
number of hydroxyl groups.   Previous workers have generally con-
sidered that the accuracy of chemical analyses of staurolite is invali-
dated by the presence of inclusions of quartz and kyanite with which
latter mineral staurolite readily forms parallel intergrowths. Lusakite
shows under high magnification myrmekitic inclusions of quartz; and
intergrown kyanite may also be present.   The silicon content for both
minerals is, however, almost constant and ranges from 7·68 to 7·80
atoms per unit cell.   This is evidence for the comparative unimpor-
tance of the inclusions in the chemical analyses, since there is already
a slight deficiency in the amount of silicon (8 atoms) required by
X-ray theory.
    The total number of atoms in the unit cell of lusakite excluding

oxygen is 32·2. Since the space-group permits only fourfold positions in the crystal-structure, this figure should be 32. The contents of the unit cell are therefore 8[RO.Al$_2$SiO$_5$], if it is assumed that the deficiency in silicon is made up by aluminium, R including Fe, Co, Ni, Mg, Al, and H. The aluminium atoms have a sixfold co-ordination and it is probable that each atom comprised in the layers 4RO is associated with four shared oxygen atoms and two hydroxyl groups. The contents of the unit cell may then be written [4(Fe,Mg,Co,Ni)O. H$_2$Al$_2$O$_4$]+[8Al$_2$SiO$_5$]. The contents of the unit cell of staurolite lead to a similar expression, viz. [4(Fe,Mg,Mn)O.H$_2$Al$_2$O$_4$]+[8Al$_2$SiO$_5$], which departs, however, slightly from the figures shown in table 2. The sum of all the atoms excluding oxygen ranges from 32·7 to 33·4. The space-group excludes the possibility of 33 atoms; so again the number has been rounded off to 32 with the result of decreasing the water content. This may be justified, since Penfield does not separate his analytical figure into H$_2$O + and H$_2$O −. We are of opinion that for lusakite this interpretation of the data in table 2 is an approach to the truth. The layers of the sandwich structure proposed by Náray-Szabó for staurolite are therefore far less simple than he postulated. They do not lie midway in composition between 4Fe(OH)$_2$ and 4FeO, but must also contain two aluminium atoms. The space-group is possibly only a close approximation to V_h^{17}. The intensities of diffraction would be little influenced in a cell of this size by two weakly diffracting aluminium atoms.

Genesis.—A specially interesting feature about lusakite is the fact that it has been formed by the replacement of kyanite. Under the microscope are seen all stages of replacement from the narrow fringe of lusakite at one end of a kyanite crystal with tongues working up the cleavage (fig. 4), to crystals of lusakite containing only small residual cores of kyanite (fig. 5). Parallel growth is not sufficient to explain these observations. The partially replaced kyanite being triclinic does not always extinguish parallel to the associated lusakite. The presence of myrmekitic quartz suggests either that the replacing cobalt solution was siliceous or that it represents silica displaced from the kyanite. In support of the latter suggestion is the fact that the chemical analysis shows that the kyanite has lost nearly 3 % of its silica if the alumina content is assumed to have remained constant. Magnetite has largely cut across and replaced the kyanite and lusakite, but whether it is introduced or simply redistributed magnetite is impossible to say.

Tilley and Flett[1] have described an anthophyllite-cordierite-rock from Kenidjack, Cornwall, in the aureole of the Land's End granite, as being derived from the metamorphism of dolerites which had previously lost much of their soda by weathering.   The description is closely applicable to the rock associated with the lusakite-rock.

The metamorphism of an aluminous iron laterite formed by more intense weathering might well give rise to a quartz-kyanite-magnetite-rock.   The possible source of the cobalt is even more speculative and a hydrothermal origin during the later stages of metamorphism must be invoked.   Again, as an alternative, the oxidation of a cobalt-iron sulphide disseminated in an argillite with subsequent burial beneath sediments followed by metamorphism would conceivably produce a quartz-magnetite-lusakite-rock.   No other cobalt occurrences are known in the district, however, although a nickeliferous outcrop was found in a mass of serpentinized basic rock about ten miles to the south.

If lusakite can be regarded as equivalent to staurolite, the change from the definitely high-grade stress-mineral kyanite to the lower-grade lusakite suggests retrograde metamorphism due to relief of pressure.

Possible uses.—The very small size of the deposit precludes the exploitation of the lusakite as a source of cobalt, especially as that metal is being produced very cheaply in large quantities as a by-product of the Rhodesian copper belt.   The beautiful colour is unfortunately only seen in thin section so that the mineral is of no use as a gemstone.   The possibilities of using it for producing a cobalt blue in pottery and as a pigment are being investigated.

Summary.—Lusakite is a cobalt-bearing variety of staurolite from Northern Rhodesia and has been named after the new capital of that colony.   The orthorhombic crystals have unit-cell dimensions a 7·86, b 16·62, c 5·65 Å. ($a:b:c = 0{\cdot}473:1:0{\cdot}340$), space-group V_h^{17}, and

[1] C. E. Tilley and J. S. Flett, Summ. Prog. Geol. Surv. Great Britain for 1929, 1930, part 2, pp. 24–41. [M.A. 4–402.]

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the unit cell contains $8[RO.Al_2SiO_5]$, where $R = Fe,Co,Ni,Mg,Al,H$. The empirical formula is $H_2O.4(Fe,Co,Ni,Mg)O.9(Al,Fe)_2O_3.8SiO_2$. Hardness $7\frac{1}{2}$, specific gravity 3·767, n about 1·74. The following striking features justify the new name :

1. It is the only silicate mineral containing a significant amount of cobalt (CoO 8·48 %).

2. An intense cobalt-blue colour best seen in thin sections under the microscope.

3. Strong pleochroism from light cobalt-blue to deep violet-blue.

4. It has been formed by the metasomatic replacement of kyanite.

EXPLANATION OF PLATE XXIV.

Micro-sections of the lusakite-bearing rock showing quartz (clear white), magnetite (black), kyanite (clear), and lusakite (grey).

FIG. 1. Quartz-magnetite-lusakite-kyanite-rock showing foliation. ×5.

FIG. 2. Typical habit of the lusakite crystals. ×11.

FIG. 3. Myrmekitic quartz in lusakite. ×80.

FIG. 4. Partial replacement of kyanite by lusakite. Myrmekitic quartz in lusakite (upper left). ×11.

FIG. 5. Residual core of kyanite in a crystal of lusakite. ×17.
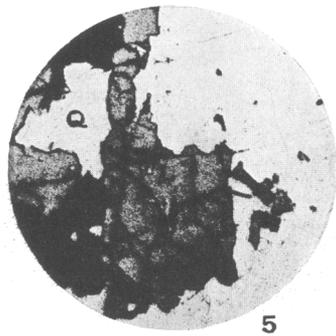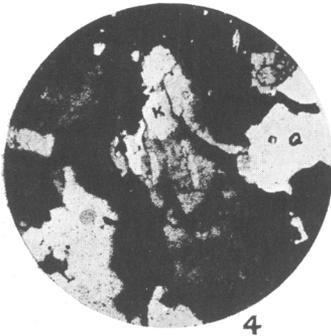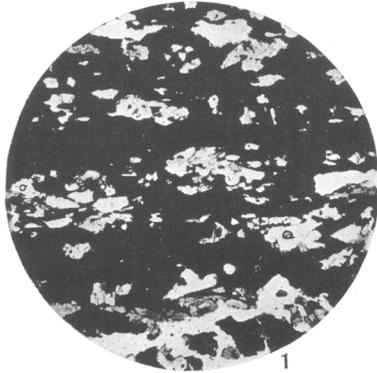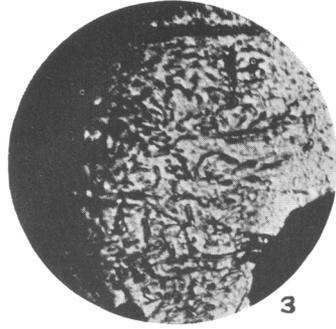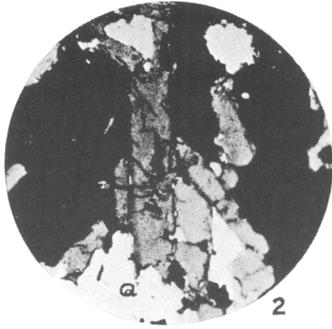
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