

Surinamite, a new Mg-Al silicate from the Bakhuis Mountains, western Surinam

I. Description, occurrence, and conditions of formation

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II. X-ray crystallography and proposed crystal structure

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Abstract

Surinamite, $(\text{Al}_{1.38}\text{Mg}_{1.12}\text{Fe}_{0.46}\text{Mn}_{0.04})^{\text{VI}}(\text{Si}_{1.51}\text{Al}_{0.49})\text{O}_{7.36}(\text{OH})_{0.64}$ is monoclinic, $P2_1/a$; $a = 9.64$, $b = 11.36$, $c = 4.95$ Å, $\beta = 109.0^\circ$, $V = 512.5$ Å³, $Z = 4$, $\rho_{\text{calc}} = 3.58$; strongest powder lines at 2.435, 1.99, 1.420, and 2.91 Å; $\alpha = 1.738$, $\beta = 1.743$, $\gamma = 1.746$, $2V_\alpha = 67-68^\circ$; $b = Y$; very strong dispersion such that in (010) the extinction angle between Z and the trace of a cleavage perpendicular to (010) is 31° for violet and 44° for yellow light; pleochroism, $Y = \text{violet}$, for vibrations in the optic plane (010), bright blue-green if parallel to the cleavage but very light-colored if perpendicular thereto; formed as minute (<0.2 mm) crystals, tabular on {010}, in a mylonitic spinel-, kyanite-, and sillimanite-bearing mesoperthite gneiss. The surinamite occurs in aggregates with biotite, kyanite, and sillimanite, which are probably pseudomorphs after cordierite, and formed under higher pressure granulite-facies conditions. Surinamite resembles sapphirine optically, in X-ray powder pattern, and in structure. A proposed crystal structure involving dense-packed oxide sheets as in sapphirine satisfactorily accounts for the spinel-like substructure reflections.

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Introduction

During microscopical investigation of the high-grade metamorphic rocks of the Bakhuis Mountains in western Surinam, a conspicuously pleochroic mineral was identified as sapphirine on account of its optical properties (de Roever, 1973a). However, subsequent electron microprobe analysis by Kieft showed the mineral to be a new Mg-Al silicate. About twenty-five grains, 40 microns and less in size, were hand-picked for a Debye-Scherrer photograph by Murray and later re-used for measurement of the optical constants by Klein, with assistance of Professor Dr. W.P. de Roever, and for determination of the

unit cell. The powder pattern resembled that of sapphirine, but confirmed that it was in fact a new mineral.

The simple composition of the mineral is in obvious contrast with its rarity. Furthermore, a phase of such a composition is not known from the extensively investigated MgO-Al₂O₃-SiO₂-H₂O system. However, the mineral may have been identified as sapphirine, in view of its close resemblance to this mineral, both as regards optical properties and powder pattern.

The name of the mineral derives from the country where it was found, Surinam, which became independent in 1975. Both the validity of the new mineral

and its name were approved by the Commission on New Minerals and Mineral Names of the I.M.A.

The sample locality is situated in the center of the Bakhuis Mountains, at 4°27'13" N and 56°57'39" W. The sample was collected more than ten years ago from a loose boulder amidst dense jungle, so that chances of recovery of more material are remote. The type-specimen, EW 1115, measuring now $4 \times 4 \times 1\frac{1}{2}$ cm, is stored with the Geological and Mining Service, Kleine Waterstraat 2-6, Paramaribo, Surinam.

Occurrence

The mineral was found in a mylonitic mesoperthite gneiss, with about equal amounts of medium-grained mesoperthite and quartz, and some oligoclase (for a more elaborate description see de Roever, 1973a). Minor constituents are green biotite, kyanite, sillimanite, surinamite, and green spinel. Accessories comprise opaque minerals, zircon, and small rutile needles (in quartz and mesoperthite). Sillimanite is present in three generations: (1) rather large individual crystals; (2) small crystals in aggregates together with biotite, kyanite, and surinamite; and (3) in very fine-grained fibrolite along shear zones. The spinel is a very fine-grained zincian pleonaste, $(\text{Fe}^{2+}_{0.40}\text{Mn}_{0.01}\text{Mg}_{0.215}\text{Zn}_{0.375})(\text{Al}_{1.94}\text{Fe}^{3+}_{0.06})\text{O}_4$, according to electron microprobe analysis.¹

Surinamite, in small crystals of up to 0.2 mm in size, is only found in aggregates together with biotite, kyanite and sillimanite. Locally, intergrowths have been found between kyanite and surinamite and between sillimanite and surinamite. Only about twenty grains of surinamite are present in a representative thin section, mainly because the number of aggregates in the sample is limited.

Optical and physical properties

The crystal habit is platy parallel to (010), with one well-developed cleavage perpendicular to (010). The measurement of the optical constants—especially those for red and yellow light—is severely hampered by the very strong dispersion, strong absorption, and weak birefringence, as well as by the small size and limited number of the available grains. Moreover, the presence of foreign material along cleavage planes and crystal boundaries provided difficulties during measurement of the optic constants. For sodium light the indices of refraction are: $\gamma = 1.746$, $\beta = 1.743$ and

¹ 57.8% Al₂O₃, 19.3% FeO total, 0.4% MnO, 5.0% MgO, 17.9% ZnO, no Cr, Si, Ti; total 100.6 percent.

$\alpha = 1.738$. The birefringence is roughly equal for the different colors. The optical character is negative, with $2V_\alpha = 67 - 68^\circ$ for blue light (486 m μ), and similar values for 500 m μ and for 435 m μ (violet light), as well as by calculation from the refractive indices for sodium light.

The mineral is monoclinic, with the optical orientation $b = Y$, and γ /cleavage = 31° and 44° for violet and sodium light, respectively. The color is violet for $Y = b$. Within (010) the axes of the absorption surface do not correspond to those of the indicatrix. The mineral is bright green-blue for vibrations in (010) approximately parallel to the cleavage, and very light greenish-brown to colorless for vibrations in (010) approximately normal to the cleavage.

Optically the mineral resembles sapphirine, but has brighter, deeper, and somewhat different colors, and a slightly higher refringence. The specific gravity is at least greater than 3.3, and is evidently in the same range as that of sapphirine.

Chemical analysis

Chemical analysis was performed with the aid of a Geoscan microprobe of the Cambridge Instrument Company, using acceleration potentials of 15 and 20 kV. The standards used were wollastonite and diopside for Si (average of the two values obtained), corundum and kyanite for Al (idem), synthetic TiO for Ti, pure iron and olivine for Fe (idem), rhodonite for Mn, pure zinc for Zn, synthetic periclase and olivine for Mg (idem), and wollastonite for Ca. For the correction of mass-absorption and atomic number effects a modified version of the computer program of Springer (1967) was applied. In this modified program the mass-absorption coefficients of Heinrich (1966) are used.

The results of the analysis are given in Table 1. The values for Si, Al, Fe, and Mg represent the average of at least six measurements at 15 kV and two at 20 kV, each measurement lasting 50 seconds on two points. First the formula was calculated on a basis of O₁₅. In view of the rather low total and of structural considerations, however, (OH) groups might be present in the mineral (see addendum to this paper), so the analysis was recalculated on a basis of (O,OH)₈.

X-ray data

The powder pattern, made on a Debye-Scherrer camera of 11.5 cm diameter, is presented in Table 2. The strongest lines are similar to those of spinel (and in part to those of sapphirine). Their presence sug-

TABLE 1. Chemical composition of surinamite

	Average and range of values	Atomic ratios to O ₁₅	
SiO ₂	33.1 ± .2 ⁵	3.01	Formula on a basis of O ₁₅ :
Al ₂ O ₃	34.9 ± .3	3.75)	(Mg, Fe, Mn) _{3.00} (Al, Fe) _{3.99} Si _{3.01} O ₁₅
TiO ₂	.0 ⁵	-)3.99	or,
		(.24)	on a basis of O _{7.36} (OH) _{0.64} :
FeO*	12.2 ⁵ ± .1 ⁵	(.69)	(Al _{1.38} Mg _{1.12} Fe _{0.46} Mn _{0.04}) ₃ ^{VI} (Si _{1.51} Al _{0.49})
MnO	1.0 ⁵ ± .0 ⁵	.08)	O _{7.36} (OH) _{0.64}
ZnO	.0 ⁵	-)3.00	
MgO	16.4 ⁵ ± .2	2.23)	
CaO	.0 ⁵		Below limit of detection:
F	.0 ⁵		B ₂ O ₃ , Na ₂ O, K ₂ O, Cr ₂ O ₃
Total	97.8 ⁵		

*total iron as FeO

gests a dense structure, with oxygen atoms in a cubic close-packed arrangement (*cf* Moore, 1969).

Geological setting and its implications for the conditions of formation of surinamite

The Bakhuis Mountains, a horst zone in the center of the Precambrian Guiana Shield, consists for the greater part of rocks of the charnockite suite, sillimanite gneisses, amphibolite-facies amphibolites and related rocks, and pyroxene-bearing granites. The rocks of the charnockite suite are found in the core, which may represent the deepest exposed part of the Precambrian Shield in Surinam, whereas the other rocks predominate near the edges of the Bakhuis Mountains (Dahlberg, 1973; de Roever, 1973b).

The rocks of the charnockite suite are migmatites, consisting of granulite-facies melanosomes and charnockite-suite hypersthene-bearing leucosomes. Sillimanite gneisses and related rocks such as that bearing surinamite, garnet-mesoperthite gneisses, charnockitic quartzites, spessartine quartzites and carbonate-bearing rocks form local intercalations. The rocks of the charnockite suite have a simple mineralogy, consisting of hypersthene ± clinopyroxene ± hornblende ± biotite + plagioclase/antiperthite ± quartz ± perthite, formed during migmatization. These granulite-facies assemblages have been locally and incompletely recrystallized into assemblages of garnet + clinopyroxene + quartz +

albite to oligoclase. This witnesses a higher-pressure phase of granulite-facies metamorphism, during which hypersthene + plagioclase became incompatible (de Roever, 1975).

The sillimanite gneisses near the edges of the Bakhuis Mountains may be younger than the rocks of the charnockite suite and the surinamite-bearing mesoperthite gneiss (de Roever, 1973b). Yet they show a similar pattern of metamorphism, with an older low-pressure phase and a younger high-pressure phase, both in the granulite facies. The gneisses are migmatites, with granitic to tonalitic leucosomes, in part with mesoperthite as the main feldspar. Cordierite, biotite, and sillimanite are the main mafic minerals formed during migmatization, accompanied by minor hypersthene, garnet, corundum and opaque minerals. Other assemblages, with sapphirine, are rare. One gneiss contains cordierite (with quartz inclusions), sapphirine (in lamellar intergrowths with cordierite), corundum, green spinel and quartz. A

TABLE 2. X-Ray powder data of surinamite

11.3 w	2.675 w	1.816 vw	1.226 w
7.05 m	2.64 w	1.762 vw	1.188 w
4.68 w	2.505 vw	1.722 vw	1.173 w
4.52 w	2.435 vs	1.596 w	1.135 w
4.36 w	2.37 w	1.534 vw	1.001 w
4.035 w	impurity	2.315 w	0.994 w
3.79 w		2.27 vw	0.825 a ₁ w
3.57 w		2.185 vw	0.822 a ₂ w
3.36 w	impurity	2.04 w	0.816 a ₁ m
3.20 w	impurity	1.99 vs	0.815 a ₂ w
3.10 w		1.96 vw	0.801 a ₁ m
2.91 m		1.92 vw	0.800 a ₂ w
2.74 w		1.85 vw	1.288 w

mesoperthite-gneiss contains sillimanite, hypersthene, and sapphirine as isolated crystals—implying the coexistence of sapphirine and quartz (*cf* Chatterjee and Schreyer, 1972; Seifert, 1974). Emery-like rocks contain sapphirine-cordierite(?)—green spinel-opaque material (Dahlberg, personal communication) and sillimanite-garnet-sapphirine-corundum-green spinel-opaque material.

The later phase of higher-pressure metamorphism is witnessed in the sillimanite gneisses by the ubiquitous break-down of cordierite only, the remainder of the rocks being more or less unaffected. In all samples studied cordierite has been replaced partly or totally and the break-down has been observed over thousands of square kilometers, not only in the Bakhuis Mountains but also in the comparable Coeroeni area to the SE. In the latter area medium-grade break-down assemblages prevail, containing for example muscovite, biotite, andalusite, sillimanite, kyanite, gedrite, chlorite, staurolite, garnet, and dumortierite, (Kroonenberg, 1973; Kroonenberg and de Roever, 1975). In the Bakhuis Mountains the break-down assemblages consist mostly of (brown) biotite, sillimanite, kyanite, quartz, and opaque material, often hypersthene, and locally garnet. Most of these minerals show symplectitic intergrowths with quartz. Kyanite and hypersthene of similar grain-size commonly occur together in one pseudomorph, and the hypersthene grains may protrude into kyanite. Locally the break-down assemblages consist only of lamellar intergrowths of hypersthene and sillimanite (\pm quartz). Very rarely, sapphirine-brown biotite-kyanite pseudomorphs have been formed after cordierite, in quartz-rich mesoperthite gneisses. The formation of biotite + hypersthene + Al_2SiO_5 + quartz by the break-down of cordierite implies not only a considerable rise in pressure (Schreyer and Seifert, 1969), but also in temperature, the temperatures again reaching those of the granulite facies. It may be questioned whether the kyanite and hypersthene were really formed together, as the hypersthene- Al_2SiO_5 assemblage without biotite in the Bakhuis Mountains is hypersthene-sillimanite, without kyanite, and as the kyanite-hypersthene assemblage would require extremely high pressures. Indeed, in nature, this assemblage has only been observed twice (Morse and Talley, 1971; Bondarenko, 1974; *cf* Chinner and Sweatman, 1968).

The surinamite- and sillimanite-bearing mesoperthite gneiss—found as mentioned before in the charnockitic center of the Bakhuis Mountains—seems to correspond largely to the sillimanite gneisses

of the rims of this horst zone, both in its granitic leucosome with mesoperthite, and in its mafic minerals. The aggregates of biotite, sillimanite, kyanite, and surinamite are either roughly equidimensional or flattened by mylonitization. They all contain the same minerals in roughly the same proportions. This, together with the restriction of surinamite to the aggregates, and the small grain-size of the constituents as compared to the size of the aggregates, strongly suggests that the aggregates represent pseudomorphs, probably after an Al-rich, Mg-Al silicate in view of the constituents. The aggregates evidently represent pseudomorphs after cordierite, since cordierite pseudomorphs are ubiquitous in the other gneisses and biotite-kyanite-sillimanite aggregates in the other gneisses were never found to represent anything other than cordierite pseudomorphs.

The break-down reaction might then be more or less given by:



The green biotite is not considered in this reaction since in other rocks (SW Bakhuis Mts., Coeroeni area) green biotite in pseudomorphs is a lower-grade product. In the surinamite-bearing sample it may have been formed—together with more aluminosilicate—by the break-down of surinamite, as was indeed locally observed, or by the break-down of cordierite relics.

As described above, the break-down assemblages of cordierite through most of the Bakhuis Mountains indicate higher-pressure granulite-facies conditions. Therefore the break-down of cordierite to surinamite + aluminosilicate evidently also took place under higher-pressure granulite-facies conditions. This seems to be confirmed by the dense structure of surinamite and, correspondingly, the considerable volume reduction ($\sim 20\%$) accompanying the above reaction, which is larger even than that associated with break-down of cordierite into hypersthene + sillimanite + quartz.

According to experiments by Seifert (1975), boron-free kornepine, close to $\text{Mg}_4\text{Al}_6\text{Si}_4\text{O}_{20}(\text{OH})_2$, which has a composition close to that of surinamite, would be a high-pressure phase in the granulite facies. Simplified reactions between surinamite and boron-free kornepine show a decrease in volume for production of surinamite, suggesting it to be formed at still higher pressures than boron-free kornepine. Similar relations may be found for surinamite with respect to sapphirine.

Consequently, the observed association of surinam-

ite, notably in intergrowths with kyanite, would require extremely high pressures, and might witness typical high-pressure granulite-facies conditions.

Note added

A second occurrence of surinamite has probably been found in central Australia by P. J. Woodford and A. F. Wilson (*Neues Jarhb. Min. Monatsh.*, in press). Microprobe analysis gives identical results, with a similar low total of 97 percent. The occurrence, in a cordierite- and kyanite-bearing granulite, confirms the here postulated granulite-facies conditions of formation.

Acknowledgments

Professor W. Uytendogaardt is thanked for the use of the Geoscan electron microprobe in the Institute of Earth Sciences of the Free University, Amsterdam. Mr. R. P. E. Poorter of the Geochemistry Branch of the Vening Meinesz Laboratory, Utrecht, aided in checking a possible content of boron. Dr. G. J. Borradaile was so kind as to correct the English text. Professor Dr. W. P. de Roever provided support and many suggestions during this study. Finally the first author is indebted to the Director of the Geologische Mijnbouwkundige Dienst of Surinam for permission to prepare the manuscript.

Manuscript received, May 12, 1975; accepted for publication, October 14, 1975

II. X-ray crystallography and proposed crystal structure

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Experimental

A small blue sub-equant fragment of surinamite measuring 40 microns in average dimension was mounted normal to the {010} plane and prepared for single crystal study using $\text{CuK}\alpha$ radiation. Owing to the extremely small size of the crystal, long exposure 15° oscillation (eight hours) and Weissenberg (four days) single crystal photographs were required. A b -axis rotation photograph, Weissenberg photographs of the ($h0l$), ($h1l$) and ($h2l$) planes and one precession photograph (b^* horizontal on film) were prepared. Although the diffraction spots were very small, they were sharp and well-resolved. All reflections could be unambiguously referred to one unit cell. For the observed $h0l$ reflections, $h = 2n$; for $0k0$, $k = 2n$. No other systematic absences were observed.

The structure cell parameters are listed in Table 1. Owing to the small size of the crystal and the difficulty in indexing powder data in the absence of a full three-dimensional data set, the errors are essentially determined by the quality of the measurement of the reciprocal lattice points on film. They are estimated to be about $\pm 0.02\text{\AA}$ in a and b and $\pm 0.01\text{\AA}$ in c . The β angle probably is accurate within $30'$.

Surinamite as a dense-packed oxide structure

The available chemical analysis and the cell data are sufficient information to assess the cell contents if it is assumed that surinamite is a dense-packed oxide structure. This is a good assumption since strong

spinel-like substructure reflections were noted and since the compound is chemically similar to sapphirine. If surinamite is, indeed, cubic close-packed, then it must be possible to relate its cell geometrically to that of sapphirine.

Moore (1969) showed that sapphirine has the same dense-packed oxide framework as spinel but differs in the nature of the octahedral (M) and tetrahedral (T) occupancies. The dense-packed oxide sheets in sapphirine are parallel to {100}. Sapphirine is monoclinic, a 11.27 \AA , b 14.40 \AA , c 9.93 \AA , β 125.5 $^\circ$, space group $P2_1/a$, with $(\text{Mg}_{3.5}\text{Al}_{4.5})^{\text{VI}}(\text{Al}_{4.5}\text{Si}_{1.5})^{\text{IV}}\text{O}_{20}$, $Z = 4$. In sapphirine the distance between four dense-packed layers equals $a \sin \beta$ since the origin of the cell is at the midpoint of an octahedral edge, so the repeat interval is $A \cdot BCAB \cdot C$, the origin at $A \cdot B$ and at $B \cdot C$

TABLE 1. Surinamite. Structure cell criteria

$a(\text{\AA})$	9.64 \pm 0.02
$b(\text{\AA})$	11.36 \pm 0.02
$c(\text{\AA})$	4.95 \pm 0.01
$\beta(^\circ)$	109.0 \pm 0.5
$V(\text{\AA}^3)$	512.5
space group	$P2_1/a$
Z	4
density g cm^{-3}	3.58
formula unit	$[\text{Al}_{1.38}\text{Mg}_{1.12}\text{Fe}_{0.46}\text{Mn}_{0.04}]^{\text{VI}}$ $[\text{Si}_{1.51}\text{Al}_{0.49}]^{\text{IV}}\text{O}_{7.36}(\text{OH})_{0.64}$
M.W.	276.63

TABLE 3. Surinamite: proposed atomic coordinates for the anion frame (ideal model)

Atom	x	y	z
O(1)	0.125	0.000	0.750
O(2)	.125	.250	.750
O(3)	.125	.500	.750
O(4)	.125	.750	.750
O(5)	.125	.125	.250
O(6)	.125	.375	.250
O(7)	.125	.625	.250
O(8)	.125	.875	.250

Proof of cubic close-packing

The encouraging results thus far obtained narrow down the possible structure type for surinamite. Since the three crystallographic axes are defined with respect to the orientation of the dense-packed sheets, the origin is fixed on the basis of the symmetry group $P2_1/a$ and the displacement $\tan(\beta-90^\circ)$. The correct origin must not violate cubic close-packing. The origin fulfilling all these requirements is fixed at the center of an octahedron. Figure 1 shows an oxygen packing diagram based on the proposed anion coordinates in Table 3, and it is seen that all restrictions are fulfilled.

The distributions of the cations must await formal crystal structure analysis; suffice it to say that the octahedral cations are distributed at levels $x = 0, 1/4, 1/2$, and $3/4$.

Manuscript received, May 12, 1975; accepted for publication, October 14, 1975.

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