On sulphatic cancrinite and analcime (eudnophite) from Loch Borolan, Assynt.

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THE minerals to be described in this paper were collected, in conjunction with W. E. Fraser, who was carrying out a detailed study of the borolanite, from the road-metal quarry, opened in 1938, at Allt a' Mhuillin, Loch Borolan, Assynt, Scotland. They occur in pegmatitic patches and veins in borolanite.

I. SULPHATIC CANCRINITE.

This mineral is one of the chief constituents of the pegmatites. It forms large cleavable masses, associated with orthoclase, melanite, and a little dark mica. Calcite, sphene, zircon, and orthite are present as accessories. It often fills interstices between crystals of orthoclase. A preliminary examination has indicated that it is a common constituent of the spots in some types of borolanite, and further work will have to be done to determine its importance in this connexion. This is the first definite record of the occurrence of cancrinite in Britain.

The cancrinite is light blue to light greyish-blue in colour. It has a density of 2·42, and its hardness is 5. It effervesces in hydrochloric acid, and gelatinous silica is formed on heating. It is uniaxial negative, but occasionally it gives a biaxial interference-figure with a very small axial angle (2° or 3°). The highest refractive index is much lower and the birefringence much weaker than that of normal cancrinite. For sodium-light: ω 1·502, ϵ 1·497, $\omega - \epsilon$ 0·005.

The results of a chemical analysis of pure material are given in table I,

together with the molecular ratios. The atomic proportions calculated on the basis of Al+Si = 12 are included in table II.

TABLE I. Chemical analyses and molecular ratios of sulphatic cancrinite.

	I.	II.	III.	IV.	I.	II.	III.	IV.
SiO_2	34·76	33·70	34·78	35·29	0·579	0·561	0·579	0·588
Al_2O_3	30·81	29·40	28·77	28·79	0·302	0·289	0·282	0·282
CaO	3·87	4·18	1·27	1·49	0·069	0·075	0·023	0·027
SrO	0·32	0·08	—	—	0·003	0·001	—	—
Na_2O	18·90	18·52	15·59	15·65	0·305	0·299	0·252	0·252
K_2O	1·29	1·45	4·90	4·15	0·014	0·015	0·052	0·044
H_2O+	2·30	4·24⎱	7·01	7·62	0·139	0·275	0·389	0·423
H_2O-	0·20	0·72⎰						
CO_2	1·90	3·18	0·89	1·01	0·043	0·072	0·020	0·023
SO_3	5·93	4·65	6·25	5·76	0·074	0·058	0·078	0·072
Total	100·28	100·19	99·68	100·05				

I. Allt a' Mhuillin, Loch Borolan, Assynt, Scotland. Analyst, F. H. Stewart.
II. Beaver Creek, Colorado. Analyst, G. Steiger in Larsen and Steiger (1916). Includes TiO_2 0·07.
III and IV. Ilmen Mts., southern Ural. Analyst, Y. V. Morachevsky in A. N. Zavaritzky (1929). III includes Fe_2O_3 0·10, MgO 0·12; IV includes Fe_2O_3 0·19, MgO 0·10.

In 1893 Horne and Teall, in a paper on borolanite (pp. 174–175), state:

'A peculiar blue substance occurs wedged in between the large individuals of orthoclase in certain veins and is found also as a constituent of some of the white spots. It shows aggregate polarisation, and is decomposed by hydrochloric and sulphuric acids, with the separation of gelatinous silica and the evolution of bubbles.

After adding water to the hydrochloric acid solution and evaporating slowly, salt and gypsum crystals are developed—the former in great abundance. A partial analysis was made on about half a gramme of this substance, with the following result:—

SiO_2.	Al_2O_3.	CaO.	K_2O.	Na_2O.	SO_3.	Total.	Sp. gr.
36·1	28·4	3·2	1·8	16·2	5·9	91·6	2·41–2·43

Water and carbonic acid are present, but were not determined. The reaction of this substance with acid is suggestive of cancrinite, but the occurrence of sulphuric acid points to the conclusion that it is an alteration product after a mineral of the sodalite group.'

The blue mineral described by Horne and Teall is obviously the same as the sulphatic cancrinite from Allt a' Mhuillin. The analyses correspond fairly well, though the Allt a' Mhuillin one has about 3 % more $Na_2O + K_2O + CaO + SrO$. $SiO_2 + Al_2O_3$ is about the same. The material analysed by Horne and Teall was probably impure, as it is very unlikely that the 8 % needed to complete the analysis consisted solely of water and CO_2.

In the Geological Survey Memoir on the 'Geological structure of the north-west Highlands of Scotland' (1907, pp. 445–446), a white or pale blue alteration product 'presumably after nepheline', is mentioned,

occurring in a pegmatite immediately east of Allt a' Mhuillin. An analysis of the white substance is given, and this shows 1·67 % SO_3 and 0·57 % CO_2. It is remarked that 'The presence of sulphuric acid is remarkable, and suggests the presence in the original rock of a mineral of the Hauyn group. Chlorine was looked for but not found.'

Apart from three other records of sulphatic cancrinite, cancrinite analyses usually show that no SO_3 is present. A few have very small amounts of SO_3. A cancrinite from Siksjöberg, Sweden,[1] contained 0·54 %, one from Miask, Ural,[1] 0·32 %, from Dôdo, Korea (Kôzu, 1931), 0·08 %, and from Iron Hill, Colorado (Larsen and Foshag, 1926) 0·03 %. In 1916 Larsen and Steiger described a sulphatic cancrinite, with 4·65 % SO_3, from Beaver Creek, Colorado; it was nearly colourless and occurred in an altered uncompahgrite associated with apatite, perovskite, and melilite. An analysis was made by Steiger, and this is quoted in table I above. In 1929 Zavaritzky described a bluish sulphatic cancrinite from the Ilmen Mountains, southern Ural, which occurred as small nests and veinlets in large crystals of nepheline in pegmatite veins in nepheline-syenite. He gives two analyses by Morachevsky which are quoted in table I, and which show 6·25 and 5·76 % SO_3. In 1931 Belyankin described a blue sulphatic cancrinite, very similar to that of the Ilmen Mountains, from Vishnevy Mountains, southern Ural. It occurred in a felspar quarry, and was associated with nepheline, aegerine, dark mica, ilmenite, magnetite, sphene, and zircon. He gives an analysis,[2] but estimates that the analysed material contained 10 % of scolecite and gibbsite as impurities. He suggests the name vishnevite (wischnewite) for the sulphatic end-member of the series. In 1911 Lacroix described a mineral from the nepheline-aegerine-syenite of the Los Islands, West Africa, which he named losite, and which he said was a member of the cancrinite group with low birefringence. It is fibrous and elongated parallel to the vertical axis, and occurs replacing nepheline. It is uniaxial negative, $\omega - \epsilon$ 0·011–0·012. The lowest refractive index is about 1·49–1·50. 'En raison de la biréfringence donnée plus haut, l'indice maximum peut être estimé à environ 1·51.' It gelatinizes readily with acid. The properties of this mineral indicate that it is a sulphatic cancrinite, but unfortunately it has not been analysed. In 1912 Lacroix described another occurrence of losite in a nepheline-gneiss from Madagascar.

Table II shows the atomic proportions, calculated on the basis $Si + Al$

[1] Analyses are given in C. Hintze, Handbuch der Mineralogie, 1897, vol. 2, p. 881.

[2] This analysis is not quoted, because of the presence of impurities, and because the summation of the analysis, as printed, is not correct.

= 12, from the analyses of a synthetic lime-free cancrinite, two normal cancrinites (figures taken from Berman, 1937), and the sulphatic cancrinites.

TABLE II. Atomic proportions of cancrinite and sulphatic cancrinite, taking $Si + Al = 12$.

		Synthetic (Friedel).	Litchfield, Maine.	Iron Hill, Colorado.	Beaver Ck., Colorado.	Allt a' Mhuillin.	Ilmen Mts.	Ilmen Mts.
					II.	I.	III.	IV.
Si ...	...	5·98	6·10	5·86	5·92	5·87	6·08	6·12
Al ...	...	6·02	5·90	6·14	6·08	6·13	5·92	5·88
Ca ...	...	—	0·93	1·61	0·79	0·70	0·24	0·28
Sr ...	...	—	—	—	0·01	0·03	—	—
Na ...	...	7·17	6·38	5·19	6·30	6·19	5·28	5·26
K ...	...	0·50	0·02	0·11	0·32	0·28	1·09	0·92
O ...	...	23·79	23·69	23·59	23·69	23·71	23·43	23·43
H$_2$O	...	2·30	2·16	2·68	2·90	1·41	4·08	4·40
CO$_2$	...	1·05	1·51	1·61	0·76	0·44	0·21	0·24
SO$_4$	...	—	—	—	0·61	0·75	0·82	0·75

The general formula, $W_{7-8}Z_{12}O_{24} \cdot N \cdot sH_2O$, is given by Berman (1937) for the cancrinite group, where $W = Na, Ca, K$, with Na and Ca predominating, $Z = Si : Al = 1 : 1$, and $N = CO_3, SO_4$. The four analyses of sulphatic cancrinite would correspond to the general formula:

$$(Na,K,Ca,Sr)_{6-8}(Si,Al)_{12}O_{24}(SO_4,CO_3)_{1-2} \cdot 1-5H_2O.$$
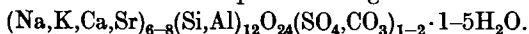
The water-content varies greatly, and in the Allt a' Mhuillin mineral it is very low. The Ilmen Mountains sulphatic cancrinite is very rich in water and low in oxygen.

The properties of the sulphatic cancrinites and of some normal cancrinites are given in table III, with the weight percentage of SO_3, and SO_3 as molecular per cent. of $(SO_3 + CO_2)$.

TABLE III. Optical data of cancrinite and sulphatic cancrinite.

Locality.	ω.	ϵ.	$\omega - \epsilon$.	Sp. gr.	Wt. % SO$_3$.	SO$_3$ mol. % of (SO$_3$+CO$_2$).
Litchfield, Maine	1·522	1·499	0·028	2·448	—	—
Miask, Ural ...	1·5244	1·4955	0·0289	2·453	—	—
Korea ...	1·5238	1·5015	0·0223	2·44	0·08	0·74
Iron Hill, Colo. ...	1·524	1·501	0·023	2·51	0·03	0·26
Beaver Ck., Colo....	1·509	1·500	0·009	2·443	4·65	44·56
Allt a' Mhuillin ...	1·502	1·497	0·005	2·423	5·93	63·18
Ilmen Mts. ...	1·493—1·492	0·0007	2·35	6·25—5·76	79·43—75·84

Figures for Litchfield and Miask were taken from C. Hintze, Handbuch der Mineralogie, 1897, vol. 2, p. 877.

From the data in table III it can be seen that the birefringence de-

creases from 0.028^1 in cancrinite to nearly zero in the sulphatic cancrinite from the Ilmen Mountains. Larsen and Steiger (1916, p. 334), discussing the sulphatic cancrinite from Beaver Creek, state that 'Sulphatic cancrinite has a much lower birefringence than cancrinite and it is not unlikely that a member of the group somewhat richer in sulphate has zero birefringence and that the pure sulphate member is optically negative'. (By 'negative' the authors must mean positive, as all *normal* cancrinites are negative.) The more recent evidence supports these views.

Of the two refractive indices the higher (ω) is the one most affected. It falls fairly rapidly from 1.524^1 (0 % SO_3) to 1.493 (79.43 % SO_3, as mol. % of $SO_3 + CO_2$). The changes of the lower refractive index (ϵ) are rather unreliable, as all the values shown come within the range of Dana's values for cancrinite. However, in the sulphatic members ϵ decreases with increase of SO_3.

The optical properties may be influenced to some extent by the water-content, which is very variable. The remarkably low density of the sulphatic cancrinite from the Ilmen Mountains is probably due to its high water-content (4.08–4.40 atomic proportions).

II. ANALCIME.

Analcime was found in a patch about a foot in width near the centre of the quarry, associated with orthoclase, melanite, sphene, and orthite. It formed a large white cleaved mass, with a vitreous lustre. There are three well-developed cleavages at right angles to each other.

It has a hardness of just over 5, and a density of 2.268. It gelatinizes with acid, and fuses readily to a colourless glass. A chemical analysis is given in table IV with the molecular values and the atomic proportions calculated on the basis $O = 14$.

TABLE IV. Chemical analysis of analcime from Allt a' Mhuillin, Loch Borolan, Assynt, Scotland. Analyst, F. H. Stewart.

				Molecular ratios.	No. of metal atoms to 14 oxygens.	
SiO_2	...	...	52.89	0.8804	Si ...	3.909
Al_2O_3	...	...	24.63	0.2417	Al ...	2.146
CaO	...	...	0.19	0.0034	Ca ...	0.015 ⎫
Na_2O	...	...	13.31	0.2147	Na ...	1.906 ⎬ 1.99
K_2O	...	...	0.73	0.0078	K ...	0.069 ⎭
H_2O+	...	...	7.66	0.4412	H ...	3.918
H_2O-	...	...	0.29		O ...	14.000
			99.70			

[1] The properties of normal cancrinites vary. This is the value given by Larsen and Berman (1934, p. 78). Dana's values are ω 1.515–1.524, ϵ 1.491–1.502, sp. gr. 2.42–2.5 (Textbook of mineralogy, 4th edition, 1932).

This analysis corresponds to the formula $(Na,K,Ca)_2Al_2Si_4O_{12}.2H_2O$. There is a little replacement of silicon by aluminium.

The refractive index for sodium-light is $1.486 - 1.488$ and the mineral shows a very definite birefringence, up to 0.002. It usually gives a biaxial interference-figure, optically negative, and occasionally a uniaxial figure. The birefringence varies, and some small patches are isotropic. The mineral nearly always shows lamellar twinning, which is best developed parallel to one of the cleavages; this cleavage will be called the 'vertical' cleavage, so as to define a direction. The optic axial angle varies from $0°$ to $40°$. The optic axial plane is generally only slightly inclined to the 'vertical' cleavage, but some cleavage flakes show a remarkably wide variation in its position. For example, in one cleavage flake roughly normal to α the position of the optic axial plane varies quite irregularly up to nearly $90°$ from the 'vertical' cleavage about the axis of the microscope, and up to $20°$ about the horizontal axes. Within a lateral motion of 0.3 mm. in one part of the slide, the axial angle decreases from $35°$ to $0°$ and then opens out at right angles and increases to $30°$.

The best developed twin-lamellae are parallel to the 'vertical' cleavage, and usually almost parallel to the axial plane. They are seen as fine lines, often discontinuous, in cleavage flakes roughly normal to α and γ. Only very occasionally are the lamellae large enough for determination of the extinction-angles, and in these cases the extinction is usually symmetrical, up to $10°$ on either side of the 'vertical' cleavage. Twin-lamellae are usually seen parallel to the other two cleavages, but these are not nearly so well defined, and they are often irregular and spindle-shaped.

Some sections show dodecahedral twinning, as a very fine set of lamellae at $45°$ to the cleavages, but these are rare. Another type of dodecahedral twinning has been seen in some sections normal to γ. Here large untwinned lamellae up to 5 mm. across with straight extinction alternate with lamellae which show twinning on a minute scale parallel to the two cleavages. The twinned lamellae have in general a slightly oblique extinction of $1°$ to $3°$. The boundaries between these two types of lamellae are sometimes sharp and straight, but often very irregular.

Birefringent twinned analcimes have been described from many localities, and probably the most noteworthy of these is the analcime from Låven, in south Norway, which was first described by Weibye in 1850, and which he called eudnophite. He gave measurements of interfacial angles of crystals which he said were orthorhombic and which showed the prism, brachypinakoid, and macrodome, but these were proved later

to be measurements of felspar crystals (Brögger, 1890, pp. 565-566). The rest of his material was shown by Brögger to be a birefringent variety of analcime showing lamellar twinning. Brögger gave a detailed description of the Låven analcime, and described and figured orientated sections. The mineral occurred as white, semi-transparent icositetrahedra, enclosed in felspar. It showed good cubic cleavage. The most important twin-lamellae were parallel to the three cubic cleavages, but subordinate dodecahedral lamellae were also present. The birefringence varied, some parts being isotropic. The mineral was usually biaxial, but occasionally uniaxial. These anomalies described by Brögger are exactly similar to those of the Allt a' Mhuillin analcime. Brögger also describes small icositetrahedral crystals, in which the periphery shows a zonal arrangement parallel to the icositetrahedral edges, and the nucleus shows lamellar twinning. This zonal arrangement has not been seen in the analcime from Allt a' Mhuillin, which does not show crystal faces. Sector twinning, which has often been recorded in analcimes,[1] is also absent.

The optical anomalies shown by analcime have never been satisfactorily explained. Klein (1897) described the effects of heating and loss of water on the optical properties, and he found that when analcime was heated in a dry atmosphere the birefringence increased with loss of water. When the mineral was heated to 250° in the presence of water vapour it usually became isotropic, but on cooling it became birefringent again. Analyses of the Låven eudnophite, as Brögger pointed out, show no deficiency in water-content.

The fact that the optical properties of the Allt a' Mhuillin mineral vary so much, and so irregularly, indicates that the anomalies might be due to some sort of strain during crystallization. However, this problem must remain unsolved at present.

The writer is indebted to Professor C. E. Tilley for valuable help and criticism. The material was collected while the writer was a Kilgour Scholar at Aberdeen University, and the determinative work was carried out at Cambridge during the tenure of a Carnegie Research Scholarship.

SUMMARY.

A sulphatic cancrinite, with 5·93 % SO_3, is described from Loch Borolan, Assynt, Scotland, and compared with three other sulphatic cancrinites previously described, and with normal cancrinites. They form an

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[1] Cyclopean Islands and Kerguelen (Arzruni and Koch, 1881), Japan (Jimbō, 1915), Texas (Lonsdale, 1928), &c.

isomorphous series, in which SO_3 replaces CO_2, and the sulphatic end-member has not yet been recorded. The influence of the SO_3 content on the optical properties is discussed. It is shown that the higher refractive index (ω) and the birefringence decrease fairly rapidly with increasing SO_3. The mineral probably changes from negative to isotropic and then to positive, with increasing SO_3 content.

A birefringent variety of analcime occurs in a pegmatitic patch in the borolanite, Loch Borolan. It is optically negative and usually biaxial. It shows twin-lamellae parallel to the cubic cleavages, and occasional subordinate dodecahedral lamellae. The optical anomalies are very similar to those of eudnophite, and it is suggested that they may be due to strain during crystallization.

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