

The riebeckite-bearing dikes of Shetland

(With Plate III)

By JAMES PHEMISTER

With data on the chemical composition and constitution of riebeckite by
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Introduction.

THE peninsula in which the mainland of Shetland ends north of Ronas Voe and Colla Firth is occupied mainly by the Ronas Hill Granite. This body is intrusive into a metamorphic series consisting of orthogneiss on the north and paragneiss on the north-east, east, and south-east of the peninsula. It is a biotite-granophyre within which earlier bodies of basic rock varying from diorite to gabbro are found. It is unshered and unfoliated and is cut by a swarm of dikes with north-south trend which extends from the north coast to Ronas Voe. There is evidence also of the existence of dikes earlier than the granite. The later dikes comprise spessartine, microdiorite, porphyrite, quartz-felspar-porphry, and a great variety of felsites which are generally granophyric and spherulitic. Many of the felsites contain riebeckite and aegirine and have a corresponding blue or blue-green colour. From observation of chilling of dike against dike and intersection of dike by dike it has been found that the basic dikes, spessartine, microdiorite, and porphyrite, are the oldest of the suite, the quartz-felspar-porphyrines are older than the felsites, and the blue riebeckite-felsites are younger than white, pink, and dull red felsites which contain neither aegirine nor riebeckite.

The dikes of the swarm range in width from 2 to 30 feet, the only types which exceed the greater width being the quartz-felspar-porphyrines which may be 40-45 feet broad. In general the basic dikes are thinner than the acid. Composite dikes are frequent and may include porphyrite, riebeckite-felsite, and riebeckite-free felsite, the riebeckite-bearing member being the latest in all cases.

The sketch-map, fig. 1, shows a large proportion of the acid dikes of the swarm. The basic dikes, omitted for the sake of clarity, outcrop

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over the same area, and are equally numerous as the acid dikes. The riebeckite-bearing members are shown in solid black; the open outcrops include all other varieties of quartz-porphyry and felsite. The map shows that the riebeckite-bearing dikes have a more restricted distribution than the other types. They extend over a lenticular area rather more than 5 miles long and $1\frac{1}{2}$ miles wide at its greatest. They are most numerous, as are the other types, along the north-south median line of the granite and their number falls off rapidly beyond the north and south margins of the granite. They cut the diorite, the granite, and the gneiss, and two of them have been observed cutting the northern contact of the granite and gneiss. It is remarkable that no dikes of any type belonging to the swarm have been mapped east beyond the eastern wall of the granite.

The trend and distribution of density of the dikes show that during cooling the granite had a definite tendency to crack in a north-south direction and that potential cracks were most prolifically engendered along a median zone. The observed contacts of granite with gneiss are sharp and steep; both small and large structures in the gneiss are cut off cleanly and without distortion along the line of contact on the north and east. On the south margin the contact is rarely seen, but at a varying distance from its position a zone of brecciated gneiss cemented by granite is traceable from the Grud Burn eastwards to the mouth of Roer Water and thence northward for fully one mile parallel to the granite contact but separate from it. The intrusion of the granite appears to have been preceded by the development of an arcuate zone of fracture and brecciation, and the rising body of magma punched out a clean plug from the loosened country rock within this zone. There is no evidence that the gneiss was pressed aside during the intrusion and it may be assumed, therefore, that no centripetal pressure was exerted on the granite during its cooling. Contraction on cooling may then have produced actual or potential tensional cracks in a north-south direction parallel to the grain of the country rock, these eventually being opened and filled, in some cases repeatedly, during the final stage of activity, the intrusion of the dikes.

The riebeckite-bearing felsites.

These rocks occur in Shetland only in the small area outlined in fig. 1, but material from them has been found throughout the main island in the shape of stone axes and flensing knives. For such implements the toughness and durability of the rock and its capacity to take

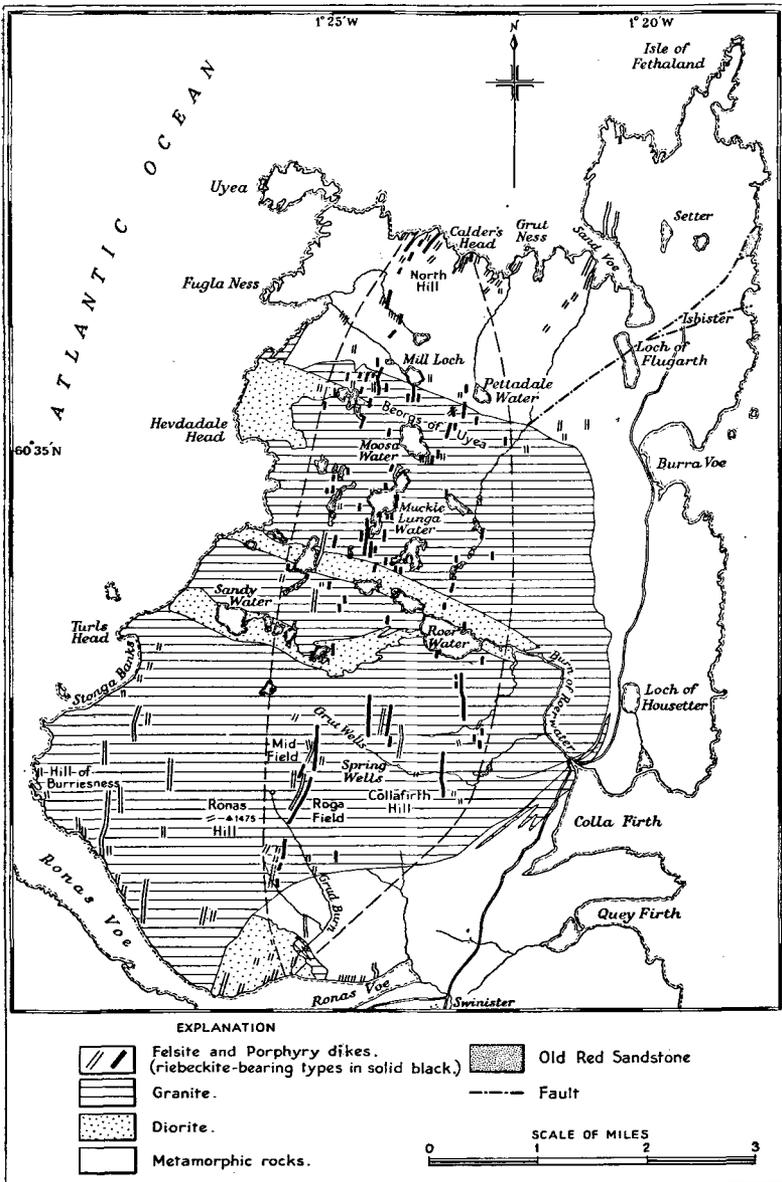


FIG. 1. The acid dikes, granite, and diorite of North Roe, Shetland. (Geological sketch-map, simplified from the manuscript 1-inch Geological Map.)

a clean, sharp edge render it pre-eminently suitable and former inhabitants of the island have evidently been well aware of its source.

The dikes are not quarried and they are so remote from transport that material from them would be expensive. Nevertheless, for special work they might repay working. Their texture and beauty render them admirably suited for curling stones and their colour might be especially effective in small monumental work and in ornamental design.

The riebeckite-bearing rocks are recognized at once by their colour, which is a blue varying in intensity from specimen to specimen according to the proportion and disposition of the riebeckite within the rock. The blue felsites were not observed by Hibbert or by Heddle, the earliest geological students of Shetland, and the first description of them is by Coles Phillips in 1926. His paper describes a dike of porphyritic riebeckite-granophyre, which is unusual in containing epidote, and provides chemical analyses of the dike and of the granite. He notes the similarity of dike and granite with regard both to chemical composition and to granophyric texture and refers both to the Old Red Sandstone period of igneous activity.

The riebeckite-bearing dikes include non-porphyritic homogeneous types ranging in tint from fairly deep blue to dove grey and stone grey, non-porphyritic, spherulitic types in which dark blue spots ranging from 1 mm. to 1 cm. in diameter are conspicuous in a pinkish or stone-grey matrix, and porphyritic, spherulitic types in which pink or red phenocrysts of feldspar, clear blebs of quartz, and deep blue spherules combine with a blue-sprinkled silver-grey ground to make an unusual and handsome stone. Variations in the proportion and size of phenocrysts and spherulites, relative to each other and to the groundmass, together with variation in the content of riebeckite, produce a wide range of colour and textural varieties. It is sufficient to describe here the two end-types.

(a) *The non-porphyritic, non-spherulitic riebeckite-felsites.*—These rocks are homogeneous and fine-grained, blue, purplish, or pale mauve in colour according as the ferriferous constituent is solely fresh riebeckite or includes less or more limonite. The typical specimen (35303),¹ of which the chemical composition is shown in col. 1 of table I, is composed microscopically of prismatic grains of micropegmatite and granular quartz among which diversely arranged slender prisms of riebeckite are uniformly distributed. Aegirine is usually present but generally in

¹ The numbers in brackets are serial numbers in the Geological Survey collection of Scottish sliced rocks.

subordinate proportion, and occurs mainly as stout subhedral prisms within the quartz pools infilling the mosaic of micropegmatite which is the main component of the rock. This intergrowth of quartz and felspar may be cryptopegmatite in which the two constituent minerals cannot be resolved but are indicated by an appearance of roughness arising from difference in refractive index of the contiguous particles, or it may be quite coarse and in general becomes coarser with distance from the centre of the grain. The micropegmatite has in general a plumose or bushy growth spreading from the centre of the grain, and in this character we find the link which joins this end-type to the spherulitic facies. The quartz of the intergrowth is usually in optical continuity with one of the grains which form the interstitial pools of quartz. The riebeckite prisms reach up to 0.5 mm. in length and are idiomorphic, yielding six-sided basal sections showing the amphibole cleavage and sometimes exhibiting zoning in different depths of colour (pl. III, fig. 2). Aegirine may be almost as abundant as riebeckite, as in specimen 37814, and the optical properties $\alpha = 1.768$, $\beta = 1.805$ indicate, according to Sabine's diagram (1950) of optical and chemical relationship, a composition of $(\text{Na}, \text{K})_{0.96}(\text{Mg}, \text{Fe}^{+2}, \text{Mn}, \text{Ca})_{0.08}(\text{Fe}^{+3}, \text{V}, \text{Ti}, [\text{Al}])_{0.96}$. The aegirine is therefore closely comparable with acmite from the Quincy granite-pegmatite and from Kangerdluarsuk (Washington and Merwin, 1927, pp. 239-241 and p. 249). The pyroxene may be almost entirely absent, and it was from a specimen (35303) containing very little aegirine that the riebeckite was separated for analysis. The composition and properties of the separated mineral form the subject of a subsequent section (p. 368).

(b) *The porphyritic spherulitic felsites.*—The typical example of these dikes, which has been analysed, col. 2, table I, is a handsome rock (29704) showing in hand specimen pink prisms of felspar, dark clear blebs of quartz, and blue spherulites in a silvery grey groundmass plentifully besprinkled with tiny blue prisms of riebeckite. The phenocrysts and spherulites are of about the same order of size, namely 2 to 3 mm. in length of diameter. Under the microscope the porphyritic quartz and felspar are seen to be idiomorphic though mutually interfering when in cumulophyric aggregates. The quartz crystals are corroded, but not extensively, and the corrosion appears to be contemporaneous with crystallization of the groundmass since the corrosion embayments are not filled by the groundmass as a sack is filled with grain but show ill-defined walls penetrated by crystals of felspar and continuous with quartz granules of the groundmass. The felspar phenocrysts show

twinning according to the Carlsbad and Baveno laws, the optical axial angle is near to 90° and β is 1.523. In appearance the felspar is generally turbid, and may be homogeneous or consist of an intergrowth which resembles micropertthite. The two components of the intergrowth cannot, however, be distinguished by difference in refractive index but only by a difference in orientation. The optical properties show that the felspar is a soda-orthoclase, and when the intergrowth is on a fine scale and on a regular plan the crystal has the shot-silk appearance associated with this species of felspar. Rarely the phenocrysts include a water-clear soda-sanidine (37819) with small 2V (pl. III, fig. 4). Some show signs of xenocrystic origin, being replaced by microgranular aggregates of albite, orthoclase, and quartz (37813) and as illustrated by Phillips (1926, pl. viii).

The groundmass of the rock consists of micropegmatite spherulites which crowd upon one another and are cemented by clear granular quartz with which stout hypidiomorphic prisms of alkali-felspar are associated. Riebeckite forms fine needles, rarely intergrown with aegirine, which radiate from the centre of the spherulites and produce the blue spots so conspicuous in hand specimen (pl. III, fig. 3). The blue amphibole occurs equally abundantly as less slender prisms which are arranged diversely, some within the spherulites but most within the areas of granular quartz in association with aegirine. Where these pools of quartz are large the quartz, riebeckite, and aegirine increase in size, and intergrowth of riebeckite and aegirine is frequent, the *c*-axis of the two minerals coinciding and riebeckite being enclosed by aegirine. Alkali-felspar is present also and presents crystal outlines to all the other minerals and is often optically continuous with the felspar of the spherulitic micropegmatite. The mutual relations indicate that quartz was the latest mineral to crystallize and was preceded by aegirine, riebeckite, and felspar in that order.

Between these end-types lie many varieties. Some are non-porphyritic but finely speckled with tiny blue spherulites (37803), some only sub-spherulitic and with little radiating riebeckite (37818), while in others with good spherulitic structure the riebeckite is entirely in the matrix (cf. pl. III, fig. 5). Fluxional banding is shown by differences in size and abundance of microspherulites (37823) and by fluidal arrangement of riebeckite (37832).

It is noteworthy that the finer the grain of the riebeckite the more intense is the blue colour of the rock (28519, 37823), thus the bluest varieties are often from the chilled marginal portions of the dikes.

Felsites without riebeckite or aegirine.

White, pink, brown, and red felsites occur, as shown in fig. 1, over a much wider area than the riebeckite-bearing dykes. They occur as independent dikes, as dikes juxtaposed to the blue dikes, banded with the blue dikes, or they may themselves have minor blue portions. For example, the dike at the mouth of the Grud Burn at its south end consists of 16 feet of pink felsite in the centre with a blue tint appearing $1\frac{1}{2}$ feet from and deepening towards the margin; at its north end it is $1\frac{1}{2}$ feet wide and the bluish margins are only 4 inches broad.

The majority of the dikes without riebeckite are spherulitic or subspherulitic. The exceptions are the quartz-felspar-porphyrries (37846-7), which consist of a fine-grained felsitic groundmass containing no micropegmatite and carrying numerous and large phenocrysts of quartz and felspar, 1-2 cm. long, and sometimes smaller crystals of biotite (37848-9). Some of these porphyries contain much epidote and a little orthite (35143). These dikes are usually broad, reaching 45 feet in width.

There is the same diversity of texture in the pink, brown, and red felsites as in the riebeckite-bearing types. They are composed essentially of micropegmatite and cryptopegmatite which form tables or prisms with a stellate or sheaf-like arrangement or build spherulites. Felspar is common as small skeletal crystals at the centre of such subspherulitic growths and also as small subhedral prisms among the granular quartz which is interstitial to the micropegmatite prisms and is often optically continuous with the quartz of an adjacent micropegmatite individual. The dark mineral of the dikes is usually chlorite which exactly reproduces the various habits of riebeckite. Thus it may occur as ragged needles radiating in the spherulites (35300), or as diversely disposed needles among micropegmatite spherulites (37817, 37857). The chlorite is often studded with minute granules of ore; its acicular form is deceptive and due to a wavy but in general parallel juxtaposition of thin flakes. In some specimens its place is taken by green biotite (37845), and it may be that much of the chlorite is pseudomorphous after biotite. In the analysed rock (29703) the green mineral forms needles, up to 0.1×0.03 mm. in size, the outline of which suggests that the mineral is hard and has a high refractive index compared with ordinary chlorites. Birefringence is low, elongation fast, pleochroism Z yellow, X = Y apple green. The properties suggest a mineral of the chloritoid group, but further study is required for identification.

In some dikes chloritized biotite is micro-porphyrritic as in the quartz-felspar-porphyrries but their association with the others is shown by the

abundance of spherulitic micropegmatite and acicular chlorite (37829). Epidote is often present in the biotitic types (35138).

Among the brown felsites is a 2-foot dike, cutting the granite towards the west end of the Beorgs of Uyea, which exhibits spherulitic structure particularly well (pl. III, fig. 1). A similar dike, in which the spherulites are not so large but have sharp peripheries so that on weathering they fall out as small balls, occurs in the burn south of North Hill.

Composition, classification, and age of the felsites.

Chemical analyses of three of the felsites are given in columns 1, 2, and 3 of table I, in which is quoted also Coles Phillips's analysis of a riebeckite-granophyre from Grut Wells (see fig. 1), another member of the series described in this paper. Analyses of similar or allied Scottish rocks are quoted in cols. B and C. Those of the well-known riebeckite-orthophyre of Holy Island, Arran, and riebeckite-microgranite of Ailsa

TABLE I. Chemical composition of riebeckite-bearing and other felsites.

| | 1. | 2. | A. | 3. | B. | C. | D. | E. |
|--------------------------------|--------|--------|--------|--------|--------|--------|--------|--------|
| SiO ₂ | 76.20 | 76.13 | 74.79 | 75.88 | 75.20 | 74.75 | 73.35 | 78.02 |
| Al ₂ O ₃ | 11.03 | 11.21 | 10.93 | 11.19 | 12.65 | 12.59 | 14.38 | 11.98 |
| Fe ₂ O ₃ | 1.58 | 1.66 | 2.26 | 2.44 | 1.53 | 1.47 | 1.96 | 1.45 |
| FeO | 1.45 | 1.45 | 1.64 | 1.10 | 0.28 | 0.53 | 0.34 | — |
| MgO | 0.12 | 0.11 | 0.04 | 0.15 | 0.26 | 0.00 | 0.09 | — |
| CaO | 0.20 | 0.25 | 0.53 | 0.44 | 0.60 | 0.37 | 0.26 | 0.21 |
| Na ₂ O | 4.90 | 4.30 | 4.25 | 4.04 | 5.67 | 4.68 | 4.33 | 4.16 |
| K ₂ O | 4.39 | 4.39 | 4.79 | 4.39 | 4.14 | 4.95 | 5.66 | 3.96 |
| H ₂ O + | 0.14 | 0.13 | 0.19 | 0.12 | } 0.12 | 0.46 | — | } 0.33 |
| H ₂ O — | 0.05 | 0.04 | 0.27 | 0.07 | | 0.11 | — | |
| TiO ₂ | 0.24 | 0.28 | 0.36 | 0.31 | 0.12 | 0.08 | — | — |
| P ₂ O ₅ | 0.15 | 0.17 | — | 0.00? | — | 0.03 | — | — |
| MnO | 0.05 | 0.06 | n.d. | 0.06 | 0.10 | 0.01 | — | — |
| | 100.50 | 100.18 | 100.05 | 100.19 | 100.67 | 100.03 | 100.37 | 100.11 |

1. Granophyric riebeckite-felsite, non-porphyrific, non-spherulitic type (29707). Beorgs of Uyea, 1,300 ft. 10° S. of W. of the outflow from Mill Loch, North Roe, Shetland. Analysed by B. E. Dixon, *Summ. Progr. Geol. Surv. Gt. Brit.*, 1934, for 1933, Part 1, p. 90.

2. Granophyric riebeckite-felsite, porphyritic spherulitic type (29704). Beorgs of Uyea, 1,000 ft. SW. of outflow from Mill Loch, North Roe, Shetland. Analysed by B. E. Dixon, *Summ. Progr. Geol. Surv. Gt. Brit.*, 1934, for 1933, Part 1, p. 90.

A. Riebeckite-granophyre, Grut Wells, North Roe, Shetland. Analysed by F. Coles Phillips, *Geol. Mag.*, 1926, vol. 63, p. 75.

3. Spherulitic brown felsite, 'eyed' type (29703). Beorgs of Uyea, 1,060 ft. 31° S. of W. of outflow from Mill Loch, North Roe, Shetland. Analysed by B. E. Dixon, *Summ. Progr. Geol. Surv. Gt. Brit.*, 1934, for 1933, Part 1, p. 90.

B. Aegirine-felsite, Cnoc an Droighinn, Assynt, Sutherland. Analysed by W. Pollard; B. N. Peach et al., 'The Geological Structure of the North-west Highlands', *Mem. Geol. Surv. Gt. Brit.*, 1907, p. 449.

C. Quartz-riebeckite-felsite. Durrington Little Law, Berwickshire. Analysed by J. Jacob; J. Irving, *Geol. Mag.*, 1930, vol. 67, p. 540.

D. Paisanite. Mosquez Cañon, Apache Mts., Texas. Analysed by A. Osann, Tschermak's Min. Petr. Mitt, 1896, vol. 15, p. 439.

E. White material forming small lithophysae in solid black obsidian. Obsidian Cliff, Yellowstone Park, Wyoming. Analysed by S. L. Penfield; J. P. Iddings, 7th Ann. Rep., Director, U.S. Geol. Surv., 1888, p. 282.

Norms of the Shetland micrographic felsites.

| | | 1. | 2. | 3. |
|--------|--------|----------|----------|----------|
| Q | ... .. | 33.18 | 34.02 | 35.10 |
| or | ... .. | 26.13 | 26.13 | 26.13 |
| ab | ... .. | 31.96 | 33.01 | 33.01 |
| ac | ... .. | 4.62 | 2.77 | 0.92 |
| ns | ... .. | 0.98 | — | — |
| di | ... .. | 0.26 | 0.48 | 0.86 |
| wo | ... .. | — | — | 0.46 |
| hy | ... .. | 2.40 | 1.73 | — |
| mt | ... .. | — | 0.93 | 2.78 |
| hm | ... .. | — | — | 0.16 |
| il | ... .. | 0.46 | 0.61 | 0.61 |
| ap | ... .. | 0.34 | 0.34 | — |
| symbol | ... .. | I. 4.1.4 | I. 4.1.3 | I. 4.1.3 |

Craig (Tyrrell, 1928, p. 237) are similar but lower in silica and richer in alkalis. For comparison the analysis of paisanite (col. D) and of the white material forming lithophysae in the spherulitic obsidian of Obsidian Cliff are also shown.

Among themselves the Shetland rocks are almost identical, though the three analysed differ widely in texture and the brown one differs markedly in the mineralogy of the dark minerals. It will be noticed that there is little acmite in its norm and that as compared with the riebeckite-felsites the brown contains more iron and also more alumina though considerably less alkalis. This chemical distinction corresponds with diagnosis of the green mineral in the brown felsite as an iron aluminium silicate resembling chloritoid.

In his description of the dike from Grut Wells, Coles Phillips gave it the name riebeckite-granophyre and this classification is appropriate if the term granophyre is used as defined by Rosenbusch. All the rocks, however, are not porphyritic and it might be better to describe them generally as micrographic riebeckite-felsites.

Age.—The dikes are later than the granite but so closely related areally, structurally, and petrographically to it that they must belong to the same igneous episode. The granite is later than a large fault which courses north-east and is parallel to a fault which lets down Old Red Sandstone conglomerate and sandstones into the schists on the coast east of Setter. The granite may therefore be later than the local Old

Red Sandstone sediments. Finlay (1930, p. 693) accepts the granite as of lower Old Red Sandstone age. He suggests, however, that the riebeckite-felsites are of Tertiary age. Since there are in Scotland riebeckite-bearing lavas or intrusions of Ordovician, Caledonian, and Carboniferous as well as of Tertiary age, no conclusion on the question of age can be reached on the basis of mineralogical similarity.

Composition and constants of riebeckite.

Riebeckite was separated from a specimen (35303) of the non-porphyrific non-spherulitic type in which the amphibole formed prisms averaging 0.1 mm. long and 0.01 mm. broad and in which only a very little aegirine was present. It was necessary to crush the rock to pass the 300 B.S. sieve in order that the amphibole could be obtained without adherent quartz and felspar. Separation was effected by sinking in bromoform. Grain counts on several mounts showed that the impurities were: aegirine 0.02, quartz 0.007, felspar 0.008 %.

Before examination the mineral powder was cleaned successively with chloroform and alcohol and was dried at a temperature of 105° C. After determination of specific gravity, the mineral was again dried at 105° C. and was finally allowed to dry in air. The chemical determinations carried out on the semi-micro scale gave the figures shown in col. I of table II. In the other columns analyses are quoted for riebeckites which are of similar composition and of which some of the optical properties have been determined.

TABLE II. Chemical analyses, optical constants, &c., of riebeckite.

| | I. | A. | B. | C. | D. | E. |
|------------------------------------|-------|--------|--------|--------|--------|---------|
| SiO ₂ ... | 51.3 | 51.79 | 51.94 | 49.92 | 46.98 | 51.01 |
| Al ₂ O ₃ ... | 2.7 | 0.68 | 0.20 | 1.99 | 1.29 | 0.80 |
| Fe ₂ O ₃ ... | 14.2 | 14.51 | 18.64 | 13.35 | 11.93 | 16.41 |
| FeO ... | 18.5 | 21.43 | 19.39 | 18.46 | 23.38 | 17.62 |
| MgO ... | n.d. | 0.10 | 1.37 | 2.07 | 0.13 | 0.22 |
| CaO ... | 1.1 | 1.28 | 0.19 | 1.25 | 1.91 | 0.19 |
| Na ₂ O ... | 6.0 | 6.16 | 6.07 | 6.55 | 8.90 | 7.98 |
| K ₂ O ... | 1.4 | 1.10 | 0.04 | 0.95 | 2.74 | 1.80 |
| H ₂ O + | 1.9 | 1.30 | 2.58 | 2.03 | 1.10 | } 0.91 |
| H ₂ O - | 0.1 | 0.10 | 0.31 | 0.24 | none | |
| TiO ₂ ... | 1.9 | 1.28 | — | 0.65 | 1.49 | 0.96 |
| MnO ... | 0.9 | 1.15 | — | 2.24 | 0.24 | 0.48 |
| F ... | 0.3 | 0.20 | — | 0.45 | — | 1.70 |
| | 100.3 | 101.08 | — | 100.15 | — | 100.64* |
| Less O for F... | 0.1 | 0.09 | — | 0.19 | — | 0.71 |
| Sum ... | 100.2 | 100.99 | 100.73 | 99.96 | 100.09 | 99.93 |

*Includes 0.56 % Li₂O.

| | | | | | | | | |
|---------------------|-----|-----|---------------|---------------|-------|---------------|--------|----------|
| α | ... | ... | 1.701 | | 1.698 | | 1.691 | 1.687(?) |
| β | ... | ... | 1.710 | 1.695 | 1.699 | 1.6934 | 1.694 | 1.697 |
| γ | ... | ... | 1.717 | yellow | 1.706 | | 1.699 | 1.703 |
| γ - α | ... | ... | 0.016 | — | 0.008 | 0.003-4 | 0.008 | — |
| Sign | ... | ... | — | — | + | — | + | — |
| 2V | ... | ... | ? ca. 80° | large | — | large | large | — |
| $c: a$ | ... | ... | 3°-4° | 4°-5° | 0° | 0° (red) | 3°-5° | 9° |
| | | | | | | 3°-5° (blue) | | |
| O.A.P. | ... | ... | \perp (010) | \perp (010) | Z = b | \perp (010) | Z = b? | — |
| Sp.gr. | ... | ... | 3.32† | 3.391 | — | 3.371 | ... | — |

† Determined by pycnometer. The value 3.32(5) was obtained also by P. A. Sabine using the method of immersion in heavy liquids. Sabine notes that the powdered mineral displayed some variation on each side of this figure.

I. Riebeckite separated from granophyric riebeckite-felsite (35303). East end of the Beorgs of Uyea, North Roe, Shetland. New analysis by C. O. Harvey.

A. Riebeckite, crystal from pegmatite. Quincy, Mass. Quoted from C. Palache and C. H. Warren, Amer. Journ. Sci., 1911, ser. 4, vol. 31, p. 549.

B. Fine fibrous, blue crocidolite. Kliphuis, S. Africa. Analysed by H. E. Vassar; M. A. Peacock, Amer. Min., 1928, vol. 13, p. 256. The optical properties refer to an acicular facies.

C. 'Osannite', from pegmatitic patches in umptekite. Quoted from A. Vendl, Zeits. Krist., 1924, vol. 60, p. 139.

D. Riebeckite, from granite. Mill Mt., New Hampshire. Analysed by F. A. Gonyer; R. W. Chapman and C. R. Williams, Amer. Min., 1935, vol. 20, p. 512.

E. Riebeckite, from granite. South Kigom Hills, Nigeria. Analysed by F. A. Gonyer; R. A. Mackay, R. Greenwood, and J. E. Rockingham, Bull. Geol. Surv. Nigeria, no. 19, 1949, p. 49.

Note on the determination of $H_2O > 105^\circ C$.

Accurate determination of combined water in some minerals is difficult for several reasons (Harvey, 1939). These are mainly concerned with the difficulty of ensuring that the expulsion of combined hydrogen from the mineral and its recovery in the form of water are complete.

Methods in which the temperature is inadequate or which restrict the supply of atmospheric oxygen, for example, the Penfield method, may yield figures for hydroxyl which are smaller than the true value. Internal oxidation of ferrous iron by hydroxyl (the 'basaltic hornblende' reaction, discussed by Hallimond, 1943) may cause some liberation of gaseous hydrogen, which, in the absence of an adequate supply of atmospheric oxygen, may be lost instead of being oxidized to and being weighed as water.

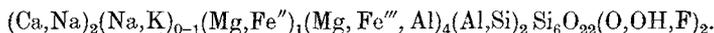
The smallness of the sample of riebeckite did not allow much scope for experimentation, but a figure for $H_2O > 105^\circ C$. which is believed to be in error by less than ± 0.1 was obtained by a special method. This was a modified semi-micro adaptation of the method described by Harvey (*loc. cit.*, 1939), a platinum-rhodium tube being used and complete con-

version of hydroxyl to free water being facilitated by heating the mineral powder with a flux containing sodium tungstate and potassium permanganate. Other methods also were applied and the figures obtained were as follows:

| | | | |
|--|-----|-----|-----------------------------------|
| Semi-micro Penfield method | ... | ... | 1.78 % H ₂ O > 105° C. |
| Special method | ... | ... | 1.92 % " |
| Calculated from loss on ignition at 1000° C. | | | 2.16 % " |

As figures obtained by the Penfield method tend to be low, and as the figure calculated from 'loss on ignition' includes any loss of fluorine and alkalis, the intermediate figure obtained by the special method should be nearest to the correct figure. This figure was accepted and rounded off to 1.9 %.

Unit-cell formula.—The X-ray studies of Warren *et alia* (1930) and work by Berman and Larsen (1931) have provided a general formula for the monoclinic amphiboles which shows the limits of isomorphous replacements. This unit-cell formula may be written:



On the basis of 24 (O, OH, F) the unit cell of riebeckite from Shetland contains the following numbers of ions:

| | | | | |
|-------|-----|-----|-------|--------|
| Si | ... | ... | 7.82 | } 8.00 |
| Al | ... | ... | 0.18 | |
| Al | ... | ... | 0.32 | |
| Ti | ... | ... | 0.22 | } 6.88 |
| Fe''' | ... | ... | 1.63 | |
| Fe'' | ... | ... | 2.36 | |
| Mn | ... | ... | 0.12 | |
| Na | ... | ... | 1.78 | |
| Ca | ... | ... | 0.18 | |
| K | ... | ... | 0.27 | } 2.07 |
| OH | ... | ... | 1.92 | |
| F | ... | ... | 0.15 | |
| O | ... | ... | 21.93 | |

The unit cell contains only seven metal atoms and the atoms of the group (Na, K)₀₋₁ of the general formula, which are usually assigned to the 'vacant space' of the amphibole structure, are not present in the riebeckite. Little aluminium is associated with silicon in fourfold co-ordination.

The deficiency of 0.12 atoms (7.00—6.88) is unexplained. It is improbable that experimental error can account for more than a minor part of this deficiency. The excess (OH + F) 0.07 may easily be due to experimental errors.

In order to make the similarity to the general formula clearer, some of the Na may be assigned to the Fe'' group of ions and some to the

(Ca,Na) group, K, the largest of the cations present, being unsuitable for inclusion in the Fe group. The distribution of the ions is then as follows:

| | | | | | | | | | |
|--------|-----|------|---|------|--------|-----|------|---|-------|
| Si ... | ... | 7.82 | } | 8.00 | Na ... | ... | 1.55 | } | 2.00 |
| Al ... | ... | 0.18 | | | Ca ... | ... | 0.18 | | |
| Al ... | ... | 0.32 | } | 4.88 | K ... | ... | 0.27 | } | 2.07 |
| Ti ... | ... | 0.22 | | | OH... | ... | 1.92 | | |
| Fe''' | ... | 1.63 | } | 4.88 | F ... | ... | 0.15 | } | 21.93 |
| Fe'' | ... | 2.36 | | | O ... | ... | | | |
| Mn... | ... | 0.12 | | | | | | | |
| Na ... | ... | 0.23 | | | | | | | |

Optical constants.—Because of the high absorption and considerable dispersion of riebeckite, satisfactory determination of the optical constants of this mineral has always proved difficult. Many chemical analyses have been made, but the corresponding optical data are available in only a few cases. Optical study of the Shetland riebeckite was carried out on mounted thin sections, on the powder separated for analysis, and on a thin section made in the usual way and washed clean of canada balsam. Only on fragments picked from this washed section was it possible to obtain optical values related with certainty to the crystal axes because: (1) the powder consists almost wholly of cleavage plates, and (2) the usual method of recognizing by interference figures grains orientated normal to a principal vibration direction is impracticable owing to the high absorption of grains of a size large enough for tests with the conoscope. By fragmentation of a thin section, however, basal sections of the amphibole needles could be isolated and the two corresponding principal refractive indices determined by immersion in oils. In a thin section, normally about 0.03 mm. thick, the mineral is almost opaque in one direction and certainty of the relative refractive indices of oil and mineral was still found difficult of achievement, but it is believed that the following figures are not greatly in error:

| | | | |
|------------------|-----------------|------------------|------------|
| α = 1.701 | β = 1.710 | γ = 1.717 | (Na light) |
| indigo blue | brownish yellow | indigo blue | |

The direction of greatest refractive index, γ , bisects the acute angle between the cleavages, and that of least refractive index, α , is inclined at about 3 or 4 degrees to the prism axis. Therefore the optic axial plane is normal to (010). Measurement by Berek compensator on a basal section gave $\gamma - \beta$ equal to 0.007–0.008. It proved impracticable to measure $2V$ by the universal stage owing to the difficulty of determining extinction positions. In a prolonged search for an interpretable conoscopic picture only one showing an emergent optic axis was found; the

isogyre was diffuse but distinctly curved, the curvature suggesting a $2V$ of about 80° and a negative sign.

On comparing the results of this study with previous determinations (table II) it will be seen that the refractive indices and birefringence of the Shetland riebeckite are relatively high. They compare closely, however, with values recorded by Suzuki (1938-39) for crocidolite from a quartz-albite-schist from Hokkaidô, namely

$$n_1 = 1.700-1.706, \quad n_2 = 1.712-1.719.$$

It is interesting to find general agreement that the optic axial plane is normal to (010) and that the direction of vibration of the yellow ray lies in (010). The varying determinations of refractive index, birefringence, sign, and the lack of information on the optic axial angle show that in the study of riebeckite there still lies a field of research.

X-ray data.—Powder photographs of the analysed riebeckite (35303) were made by P. A. Sabine, who has provided the data summarized in table III. The intensities of lines on the photograph were measured by means of a microphotometer and are given relative to unit intensity for the strongest line.

TABLE III. Interplanar spacings and intensities of lines observed on an X-ray powder photograph (X 88) taken with Co- $K\alpha$ radiation, wavelength 1.7902 Å., in a 9 cm. camera. Riebeckite, North Roc, Shetland.

| <i>d</i> | Intensity | <i>d</i> | Intensity | <i>d</i> | Intensity |
|----------|-----------|----------|-----------|----------|-----------|
| 8.42 Å | 1.00 | 2.60 Å | 0.06 | 1.684 Å | 0.02 |
| 4.51 | 0.23 | 2.54 | 0.06 | 1.661 | 0.07 |
| 3.34 | 0.09 | 2.38 | 0.03 | 1.639 | 0.03 |
| 3.27 | 0.14 | 2.33 | 0.05 | 1.619 | 0.06 |
| 3.13 | 0.59 | 2.18 | 0.09 | 1.594 | 0.02 |
| 2.81 | 0.11 | 2.03 | 0.04 | 1.504 | 0.06 |
| 2.72 | 0.23 | 1.809 | 0.07 | 1.458 | 0.02 |

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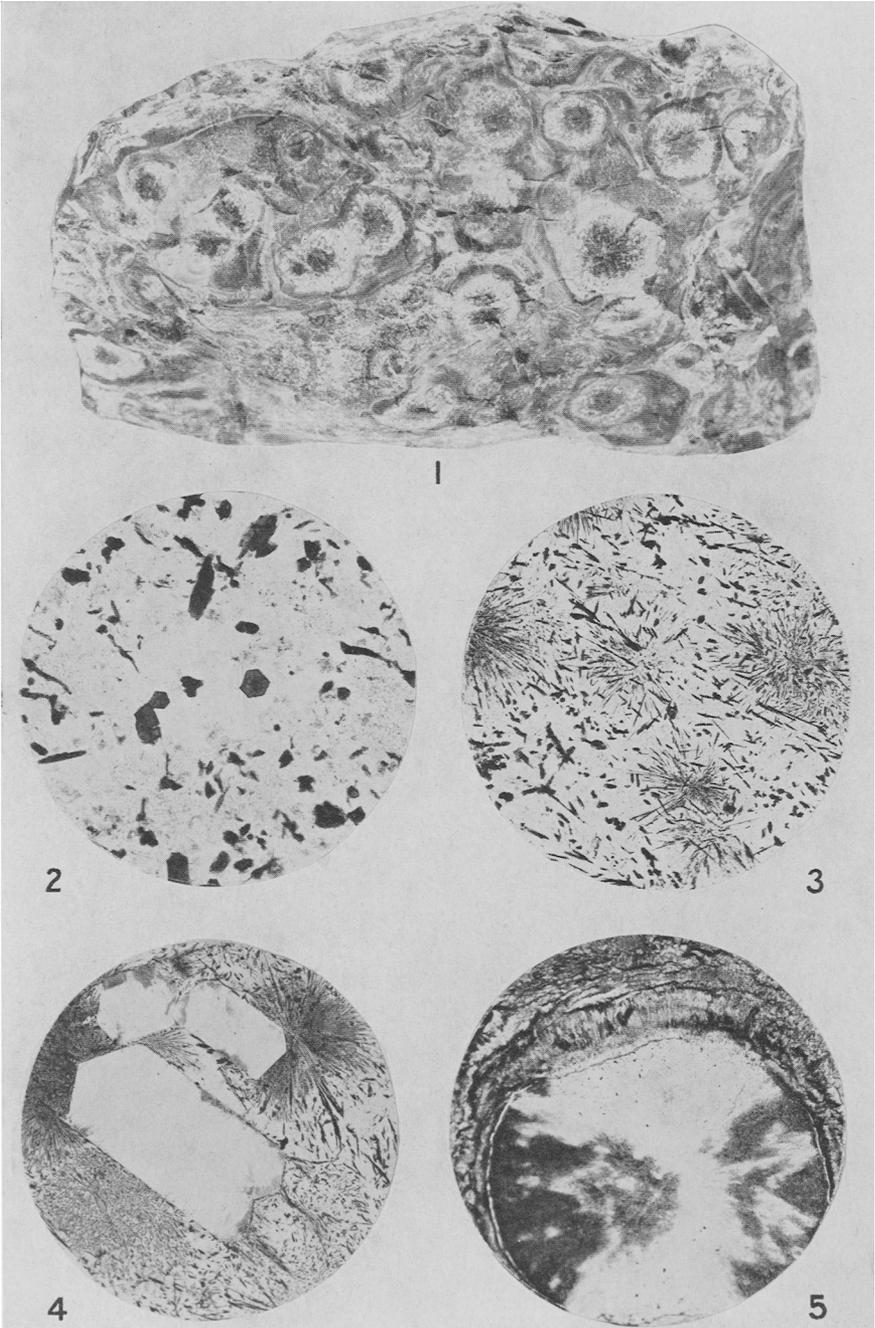
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EXPLANATION OF PLATE III.

- FIG. 1. Spherulitic felsite, brown, 'eyed' type. ($\times \frac{7}{8}$ natural size.) Cf. table I, col. 3.
- FIG. 2. Riebeckite-felsite, non-porphyritic, non-spherulitic type. 37810. $\times 24$. Idiomorphic prisms of riebeckite are set in a base of micropegmatite and quartz.
- FIG. 3. Riebeckite-felsite, non-porphyritic, spherulitic type. 28515. $\times 9$. Riebeckite radiates as needles along radially spherulitic growths of micropegmatite, and forms stouter prisms in the granular quartz, micropegmatite, and felspar between the spherulites.
- FIG. 4. Riebeckite-felsite, porphyritic, spherulitic type. 37819 A. $\times 10$. Spherulitic growths of micropegmatite and riebeckite spread from phenocrysts which project skeletal processes into the spherulites.
- FIG. 5. Spherulitic felsite. 28520. $\times 10$. A core of radially arranged cryptopegmatite is surrounded by secondary growths in which riebeckite is concentrated along concentric narrow zones.
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