11. *The COMPOSITION of ROCKALLITE.* By HENRY STEPHENS WASHINGTON, Ph.D., For. Corr. Geol. Soc. (Read March 25th, 1914.)

Introduction.

AN igneous rock of quite exceptional chemical and mineral composition and of unusual petrographic interest is the granitic rockallite. This forms, in part, the small islet of Rockall, situated in lat. $57^{\circ} 36'$ N. and long. $13^{\circ} 42'$ W., about 170 miles west of the Hebrides, and about half-way between Ireland and Iceland. The haycock-shaped islet is almost inaccessible, and only three specimens of the rock are known to be in existence. To quote from a letter (dated December 9th, 1913) received from Prof. J. W. Judd, C.B., F.R.S.:

'Although a number of attempts have been made to examine Rockall, yet, so far as I know, only two landings upon it have been effected. Even in these two cases it was only possible for sailors to jump from a boat on to a projecting point of the rock, and to knock off pieces which they threw into the boat. A carefully-equipped expedition made two voyages to the rock in 1896, but on both occasions had to give up all attempts at landing upon it.'

The rock has been described petrographically in great detail by Prof. Judd,¹ who examined all three specimens, in a paper which forms one of the reports of the Irish expedition of 1896. To these reports the reader may be referred for descriptions of the islet and other information.

Prof. Judd's paper contains a chemical analysis of the 'Inskip' specimen, made by Mr. C. J. S. Makins. As this analysis is far from complete, ferrous oxide, titanium oxide, and water not having been determined, and only a 'trace' of potash reported, and as the rock is of so entirely exceptional a character, it was thought that a new and complete chemical analysis was desirable. Through the kind offices of Prof. Judd and the courtesy of the Governors of the Imperial College of Science & Technology, about half of the Inskip specimen (that analysed by Makins) was given to me for examination and analysis. It is not only a duty but a pleasure for me to acknowledge here my deep sense of gratitude to, and appreciation of the great courtesy and liberality of, these gentlemen for the opportunity to study this exceptionally valuable material. I can but feel gratified that the results of my examination not only confirm the observations of Prof. Judd and Mr. Makins, but have also added some new and rather important features of interest to the rock.

The specimen, as received from Prof. Judd, weighed about 17 grams. Two thin sections were cut, and a fragment of about 6 grams (with one thin section) has been deposited in the Petrographic Reference Collection of the United States Geological

¹ Trans. Roy. Irish Acad. vol. xxxi (1897) pp. 48-58. See also Geol. Mag. dec. 4, vol. vi (1899) pp. 163-67.

Survey. For the analysis about 8 grams were available, a few grams being reserved for optical study and contingencies. I would here express my thanks to Dr. F. E. Wright for kindly undertaking the special optical study of the pyroxene.

Petrographical Description.

The texture of the rock is granitic, somewhat porphyritic in the Inskip specimen according to Prof. Judd, although this was not very evident in my small piece, but non-porphyritic in the other two. It is fine-grained (millimetre-grained), and composed of small anhedral of colourless quartz, white felspar, and thick prisms of a greenish-black pyroxene, the three being present in about equal amount. These three minerals are all perfectly fresh, but there are small specks and patches of a powdery, pale yellow-brown, evidently ferruginous, decomposition-product, apparently limonitic. The water yielded by the analysis shows that the amount of this cannot be great. The specific gravity of this specimen is stated by Prof. Judd to vary between 2.92 and 2.94, that of the other two specimens being 2.77 and 2.71 respectively.

In thin section the rock is seen to be composed almost entirely of sodic pyroxene, alkaline felspar, and quartz, the pyroxene having crystallized first, then the felspar, and last the quartz, as noted by Judd. The pyroxene is in subhedral prisms, with no very definite terminations, and only seldom showing prism or pinacoid faces. Some small subhedral crystals are also included in the quartz and felspar. Cleavage is well-marked, and the crystals carry no inclusions.

The pyroxene is of two kinds. A bright grass-green ægirite is abundant. The extinction-angle (Wright) varies from 3° to 5° , and the rather strong pleochroism is, as determined by Judd: a grass-green, b pale olive-green, c yellow-green, with the absorption $a > b > c$. The refractive indices, as determined by Wright, are a = about 1.765, $\gamma > 1.80 < 1.82$. This green ægirite forms usually the inner portions of the larger prismoids and most of the smaller, isolated, euhedral crystals. The other variety of pyroxene is a pale yellowish-brown acmite, with extinction-angles slightly greater than those of the ægirite. Its pleochroism is not so strong; a brown, b yellow-brown, c brownish yellow. Its refractive index is practically the same as that of the ægirite, but possibly a little higher, and, as Dr. Wright says, the difference optically between the two forms is not so pronounced as one might be led to expect from the difference in colour. This brown acmite generally surrounds the green ægirite, the border between the two being rather irregular but fairly sharp. Rarely the ægirite is exterior to the acmite, especially at the ends of prisms, and there are a few small crystals composed entirely of acmite. Cleavage does not seem to be as well developed in the acmite as in the ægirite.

The felspar occurs, for the greater part, as comparatively large,
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equant subhedral individuals, roughly square in outline. They generally show a fine polysynthetic twinning according to the albite law, Carlsbad twins being rare. The extinction-angles are low, and correspond to those of albite. No microperthite is to be seen. Generally these crystals contain toward the centre some dusty material, which high powers resolve into irregular specks of green *agirite*. Albite also forms some small thin laths, often in Carlsbad twins.

The quartz forms anhedral grains, and contains many minute liquid inclusions, which carry gas-bubbles, the volume of the gas-bubble being about 12 to 15 per cent. of the volume of the cavity (Wright). The form of these cavities is sometimes negative. There are a few small, apparently micrographic, intergrowths of feldspar and quartz. In these are to be seen very minute prismatic crystals of a colourless, highly-refracting, optically-positive, uniaxial mineral, which must be referred to *zircon*. The total amount of this in the sections cannot amount to more than about one-tenth of 1 per cent. Extremely rare and minute grains of *magnetite* are seen in places, and there are a few very small prisms of *apatite*. I could find none of the rare blue hornblende mentioned by Prof. Judd.

Chemical Composition.

The chemical analysis was made by me with the greatest care, by the methods advocated by Hillebrand and myself. *Zirconia* and the rare earths were especially looked for, because of the highly-sodic character of the rock, it being known that these elements are prone to association with sodic magmas.¹ The amounts of both which were found fully justify the search. The ' Ce_2O_3 ' of the analysis (II, p. 297) was chiefly composed of cerous oxide, as was shown by colour-reactions, but possibly yttrium, didymium, or other rare earths are present. Titanium and manganese were determined colorimetrically. Not a trace of chlorine was leached out of the rock by hot water. Nickel was not looked for, owing to the small amount of material.

It is evident that my analysis fully confirms the general features of Makins's analysis. They both show high silica, ferric oxide, and soda, and low alumina, ferrous oxide, magnesia, lime, and potash. The only noteworthy divergences in the determinations—those in silica, alumina, and soda, and possibly iron oxides, may reasonably be ascribed to the piece analysed by Makins containing a little more quartz and a little less albite and pyroxene than mine, a divergence which is perfectly possible when such small fragments only were available. His high manganese oxide is probably in large part alumina, as coprecipitation of this with the manganese, when the usual sodium-acetate method is used, is a frequent cause of high figures for manganese. The very small amounts of potash and

phosphorus pentoxide obtained by me would almost justify the application of the term 'trace' to them.

	I.	II.	III.	IV.
SiO ₂	73·60	69·80	68·70	68·29
Al ₂ O ₃	4·70	5·10	6·85	8·71
Fe ₂ O ₃	13·10	13·23	9·93	11·60
FeO	n. d.	0·78	1·14	trace
MgO	0·11	0·11	0·26	0·40
CaO	0·37	0·72	1·34	0·51
Na ₂ O	6·96	8·04	7·01	10·63
K ₂ O	trace	0·22	1·58	0·67
H ₂ O+	n. d.	0·46	0·50	n. d.
H ₂ O-	...	0·31	...	...
CO ₂	...	none	...	...
TiO ₂	...	0·34	0·26	...
ZrO ₂	...	1·17	3·71	[incl. in SiO ₂ .]
P ₂ O ₅	...	0·07	...	...
SO ₃	...	none	...	...
Cl	...	none	...	...
S	...	none	...	...
Ce ₂ O ₃	...	0·37	...	...
MnO	0·93	0·12	trace	...
NiO	0·06	n. d.	...	...
BaO	...	none	...	...
Totals	<u>99·83</u>	<u>100·84</u>	<u>101·28</u>	<u>100·81</u>

- I. Rockallite, (II) III. (2) 3. 1. 5. Rockall. C. J. S. Makins, analyst. J. W. Judd, Trans. R. Irish Acad. vol. xxxi (1897) p. 54.
 II. Rockallite, "III. 3. 1. 5. Rockall. H. S. Washington, analyst.
 III. Ægirite-granite, II' 3". 1. 4. Ampasibitika, Madagascar. Pisani, analyst. A. Lacroix, 'Matériaux pour la Minéralogie de Madagascar' pt. 2, 1903, p. 235 (Nouv. Arch. Mus. Hist. Nat. Paris, ser. 4, vol. v).
 IV. Ægirite-granite, (II) III. 4. 1. "5. Capo alla Cuculla (Corsica). J. Deprat, analyst. Bull. Serv. Carte Géol. France, vol. xvii (1906) No. 114, p. 46.

Analysis II is of especial interest, because of some of the minor constituents. The absence of carbon dioxide, sulphur trioxide, and sulphur was to be expected, and they were only looked for in the regular analytical routine. The same applies to the absence of barium, as this element favours potassic rather than sodic rocks.¹ The amounts of titanium oxide and manganese monoxide are decidedly smaller than was expected, and the presence of what amounts to scarcely more than a 'trace' of phosphorus pentoxide is in accord with the rarity of apatite in the sections examined by me.

The two minor constituents that are of most interest are zirconia and ceria, both of which were found to be present in unexpectedly large amounts. In his letter referred to above, Prof. Judd suggests that the former may be due to zircons present in submicroscopic crystals, as no zircons were visible in his sections. In my two sections some very minute zircons were

¹ Cf. H. S. Washington, Carnegie Inst. Publ. No. 57 (1906) p. 188; and Trans. Am. Inst. Min. Eng. vol. xxxix (1909) p. 754.

found in the rare micrographic patches, as noted above. But the total amount of these must be very much less than one half of 1 per cent., probably not more than one tenth of 1 per cent. They certainly cannot be present in amount sufficient to account for the more than 1·5 per cent. of zircon which the amount of zirconia would furnish. We must, therefore, conclude that by far the greater part of the zirconia exists in the pyroxenes. This seems the more probable, as many of the sodic pyroxenes, such as lāvenite, hiortdahlite, etc., contain this element as an essential constituent. This point will be adverted to again.

The rare earths cannot be present as monazite or xenotime, as the small amount of phosphorus pentoxide is needed for the apatite known to be present,—a point also mentioned by Prof. Judd,—and there is no escape from the conclusion that the cerium, like nearly all the zirconium, must be present in the pyroxenes. It may be mentioned that the amount of ceria in rockallite is the highest known to me in any rock, among the many thousands of analyses that I have collected and studied, with the single exception of a nepheline-syenite from Ahuunge (Sweden), which is shortly to be described by Dr. P. Quensel. This rock contains 48·60 per cent. of silica, 8·74 of soda, and 0·59 of ceria, according to an analysis by Dittrich kindly communicated to me by Dr. Quensel.

Mode.

As the thin sections were small and the granularity relatively coarse, measurement of the mode by Rosiwal's method was not undertaken. But, since the mineral composition of the rock is very simple, the mode may be readily ascertained by readjustment of the norms, which are given on a later page. In these calculations orthoclase is reckoned in with albite, the minute amounts of magnetite and apatite are neglected, the ilmenite is assumed to enter ægirite (for reasons which are given later), and the zirconia to enter the pyroxenes. Data, such as would enable us to ascertain the exact relative amounts of the green ægirite and brown aegirite, are lacking; but the former is undoubtedly present in greater quantity. The mode of I is taken from Prof. Judd's paper:—

	I.	II.
Quartz	38	30·4
Albite	23	26·4
Ægirite-aegirite.....	39	43·2

It will be seen that these figures confirm the conclusion drawn from the first inspection of the analyses, that my portion of the Inskip specimen contained somewhat less quartz and more albite and pyroxene than that analysed by Makins. It will also be evident, on comparing the modes and norms, that the mode is essentially normative.

Classification.

In the current classifications rockallite is generally considered as a highly sodic variety of the alkali-granites, although nothing is known of the structural geology of the islet, except that the rockallite overlies an apparently bedded or foliated rock of unknown character. In the 4th edition of his 'Mikroskopische Physiographie' Rosenbusch described it under the granites (vol. ii, pt. 1, 1907, p. 79), but is inclined (*ibid.* p. 611) to consider it as a grorudite (ægirine-quartz-tinguaite), belonging to the dyke-rocks, with which also Prof. Judd compares it. This is an apt example of the fallacy of basing the classification of a rock on the particular portion of the lithosphere where it happened to consolidate, rather than only on characters inherent in the rock itself.

According to the Quantitative Classification, the norms of the two analyses figure out as follows:—

	I.	II.
Q	37·80	30·18
Or		1·12
Ab	24·10	25·15
Z		1·83
Ac	30·95	37·88
Di	1·70	2·64
Hy	5·08	
Mt		0·23
Il		0·61
Ap		0·17

They both, therefore, fall in the subrang rockallose, with the general symbol III. 3. 1. 5. Makins's specimen however, is transitional towards the dosalane class, and the domalkalic order, with the exact symbol (II) III. (2) 3. 1. 5, and mine more nearly central, having the symbol "III. 3. 1. 5. It is worthy of note, as indicating the highly exceptional character of this rock, that these two analyses of rockallite are the only representatives of the subrang rockallose (III. 3. 1. 5) among about eight thousand analyses now collected by me.

Affinities of Rockallite.

Both Judd and Rosenbusch remark on a similarity with the grorudites of Brögger. They resemble each other in so far as the qualitative mineral composition is concerned, but the grorudites contain less pyroxene and more felspar, especially considerable orthoclase (as shown by their analyses), and Judd finally considered them as quite distinct from his rock. Similar distinctions also hold good for the pantellerites, with which Judd tentatively compares rockallite on the basis of Foerstner's analyses, but which we now know to be incorrect in many particulars.¹ In recent years there has been an extension of our knowledge of highly sodic

¹ Cf. H. S. Washington, Journ. Geol., Chicago, vol. xxi (1913) pp. 702, 707, and vol. xxii (1914) p. 19.

petrographic provinces, and two of these furnish analyses of ægirite-granites which resemble rockallite quite closely. That which resembles it most is the ægirite-rich portion of the alkali-granitic mass of Ampasibitika in Madagascar, the analysis of which is given under III in the Table on p. 297. This has been described by Prof. Lacroix, who calls attention to its close analogy with rockallite. Another is an ægirite-granite from Corsica (Analysis IV), in which island Dr. Deprat has discovered a small province of highly sodic rocks. The symbols of these two granites are respectively II'. 3". 1. 4 and (II) III. 4. 1. "5, which express very clearly their relations to the two fragments of rockallite.

The Pyroxene.

The most interesting mineral in rockallite is the pyroxene, some optical data of which, as determined by Wright, have been given on a preceding page. The chemical composition of the two pyroxenes as a whole is very readily calculated from the analytical data, and the results obtained by Judd and myself are given below, together with some recent analyses of other ægirites, and one acmite. The earlier analyses may be consulted in the mineralogical text-books of Dana and Hintze.

	V.	VI.	VII.	VIII.	IX.	X.
SiO ₂	51·97	50·63	50·45	51·73	51·08	51·35
TiO ₂	...	0·77	0·90 ¹	0·64	0·66	...
ZrO ₂	...	2·67	0·08 ¹	...	...	...
Al ₂ O ₃	none	none	1·78 ²	1·91	0·80	1·59
Ce ₂ O ₃	...	0·84	...	...	...	...
Fe ₂ O ₃	33·48	29·92	23·42	31·86	29·30	32·11
FeO	...	1·64	5·26	0·87	2·29	2·59
MnO	2·41	0·28	0·10	0·60	1·11	0·37
NiO	0·20	...	...	...	...	...
MgO	0·37	0·25	1·48	0·14	trace	none
CaO	0·52	1·41	5·92	0·87	2·54	trace
Na ₂ O	10·97	11·59	9·84	11·43	11·50	11·39
K ₂ O	none	none	0·24	0·40	...	trace
H ₂ O	none	none	0·55	0·20	1·04	...
Totals	<u>99·92</u>	<u>100·00</u>	<u>100·02</u>	<u>100·65</u>	<u>100·32</u>	<u>99·40</u>

¹ Determined by H. S. W.

² Corrected for TiO₂ and ZrO₂

V. Ægirite-acmite, Rockall. Calculated by Judd.

VI. Ægirite-acmite, Rockall. Calculated by Washington.

VII. Ægirite, Magnet Cove (Arkansas). G. Steiger, analyst. Am. Journ. Sci. ser. 4, vol. xiii (1902) p. 36.

VIII. Ægirite, Quincy (Massachusetts). C. H. Warren, analyst. Am. Journ. Sci. ser. 4, vol. xxxi (1911) p. 553.

IX. Ægirite, Brevik (Norway). S. Hillebrand, analyst. Tscherm. Min. Petr. Mitth. vol. xxxii (1913) p. 249.

X. Acmite, Brevik (Norway). C. Doelter, analyst. Tscherm. Min. Petr. Mitth. vol. i (1878) p. 381.

It will be seen that the two calculated compositions of the Rockall ægirite agree fairly well, apart from the presence of minor constituents and the probably too high manganese oxide of No. V.

The Rockall pyroxene resembles other ægirite-acmites in general features, but is notably lower in ferrous oxide, especially in comparison with the older analyses. It is also markedly lower in lime, except in the case of the Quincy ægirite (VIII). The amount of titanium oxide is comparable with those in the Quincy and Brevik minerals. As the presence of this constituent was strongly suspected also in the Magnet Cove ægirite, Dr. Steiger not having determined it in his analysis, I obtained, through his kindness, a portion of the material analysed by him, in which I determined titanium oxide and zirconia. The results are given in No. VII, the original figure for alumina (2.76) being corrected for their presence.

There are apparently only five analyses in the literature of brown acmite,¹ and while these are of early date, incomplete, and not wholly satisfactory, they all differ consistently from the analyses of ægirite in their much lower proportion of lime. Ægirite and acmite unquestionably are closely related chemically, crystallographically, and optically in many respects; but the marked differences in colour, character, and strength of pleochroism, and apparently also, but to a less extent, in extinction-angle, indicate a constant chemical difference between the two. This matter has been discussed both by Prof. Doelter and by Prof. Brögger, but without either investigator arriving at any definite conclusion. This may be attributed in part to the difficulty of obtaining pure acmite substance for analysis, as it is commonly intergrown with ægirite; and in part to the faulty character of the analyses which have been made of this mineral.

The presence of ceria and other rare earths and the large amount of zirconia found in the rockallite, which can be present only or for the greater part in the pyroxenes, suggests that herein is to be found the essential difference between ægirite and acmite: that is, that these constituents are characteristic of acmite, but not of ægirite. All the silicates which contain much cerium, as melanocerite, allanite, cerite, mosandrite, and rinkite, are yellow or yellow-brown, with weak pleochroism. Similarly, it is well known that the zirconia-bearing pyroxenes,—rosenbuschite, lâvenite, wöhlerite, hiortdahlite—are all yellowish and have generally weak pleochroism. It may, therefore, be considered possible or probable that ceria and zirconia form an essential part, and are characteristic, of the molecule of the brown acmite, while they are wanting, or are present only to a slight extent, in the green ægirite.

This is, as yet, merely a suggested hypothesis, and, in order to decide the question, complete analyses are needed both of brown acmite and green ægirite, especially that associated with the former. The smallness of the amount of zirconia found by me in the Magnet Cove ægirite (which was the only appropriate material available), would seem to favour the view here advanced; but, of course, a single determination is quite inadequate to settle the matter. The chemical study of these minerals is to be undertaken in the near future.

¹ C. Hintze, 'Handbuch der Mineralogie,' vol. ii (1897) p. 1134, nos. i-v.

DISCUSSION.

Prof. W. W. WATTS commented on the exhaustive character of Prof. Judd's account of rockallite from the very scanty amount of material at his disposal. The speaker referred to the strange fact that the rocks of so many of the islands off Britain showed characters unrelated to those of any known rocks on the mainland. He cited especially, in this connexion, Ailsa Craig, Lundy, the Wolf Rock, Bear Island, and Rockall.

Dr. J. W. EVANS referred to the fact, to which Dr. Harker had drawn attention in his Presidential Address to the Geological Section of the British Association at Portsmouth in 1911, that alkaline rocks were apt to occur on the margin of igneous areas. Those of Kathiawar, for instance, were found in an outlying portion of the basalts of the Deccan Trap: they might be compared with the Rockall intrusive, which was associated with basaltic rocks, found by dredging in the neighbourhood, that might (as Prof. Grenville Cole had suggested) be of the same age as those of the North-East of Ireland and the Inner Hebrides. The earlier accounts of Rockall which attributed to it a larger area, and in one case mentioned another island in the immediate neighbourhood, might be explained on the supposition that a portion of the basaltic platform had once emerged above the surface of the sea, and had since been removed by marine erosion.

Mr. F. P. MENNELL said that he was interested in the Author's suggestion concerning the presence of cerium in the acmite. His own experience in Tropical Africa showed that cerium commonly occurred in the granites as the silicate orthite, or allanite; but there was another occurrence, interesting in the present connexion. Near Bulawayo a rock consisting essentially of microcline and augite occurred. The latter mineral was not aegirite or acmite, but was evidently an alkaline variety—as it was pleochroic, and had an extinction-angle smaller than that of most pyroxenes. In some altered varieties of the rock it was changed to epidote, and certain offshoots were practically transformed into feldspar-epidote rocks. The epidote contained brown patches of orthite, which must have been formed from substances originally present in the ferromagnesian mineral.

He noticed that the Author did not regard geological occurrence as an important factor in rock-classification. But, after all, this was the real difference between, for instance, granite and rhyolite. Those who worked at igneous rocks in the field would, he thought, be sorry to give up such intelligible principles as occurrence in favour of purely artificial systems like the Quantitative Classification of which Dr. Washington was joint author.

Mr. R. S. HERRIES thought that the fact that large islands had been placed, in accordance with reports of early navigators, on the Rockall and other banks was probably due to clouds settling upon the banks and causing at a distance the appearance of land. He reminded the Fellows of a landing on the island, effected some few years ago, when a liner from North America ran on to it and was wrecked with loss of life. Had there been any geologists among the survivors, more specimens of the rock might then have been obtained.