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PLATES AND CHARTS

GEOLOGICAL AND MINERALOGICAL INVESTIGATIONS

I.

BASALTS FROM THE CARLSBERG RIDGE, INDIAN OCEAN

BY

JOHN D. H. WISEMAN, M.A., PH.D.

WITH AN APPENDIX ON THE RADIUM CONTENT OF SOME SUB-OCEANIC BASALTS FROM THE FLOOR OF THE INDIAN OCEAN

BY

J. H. J. POOLE, Sc.D.

WITH ONE PLATE AND FOUR TEXT-FIGURES.

I. INTRODUCTION.

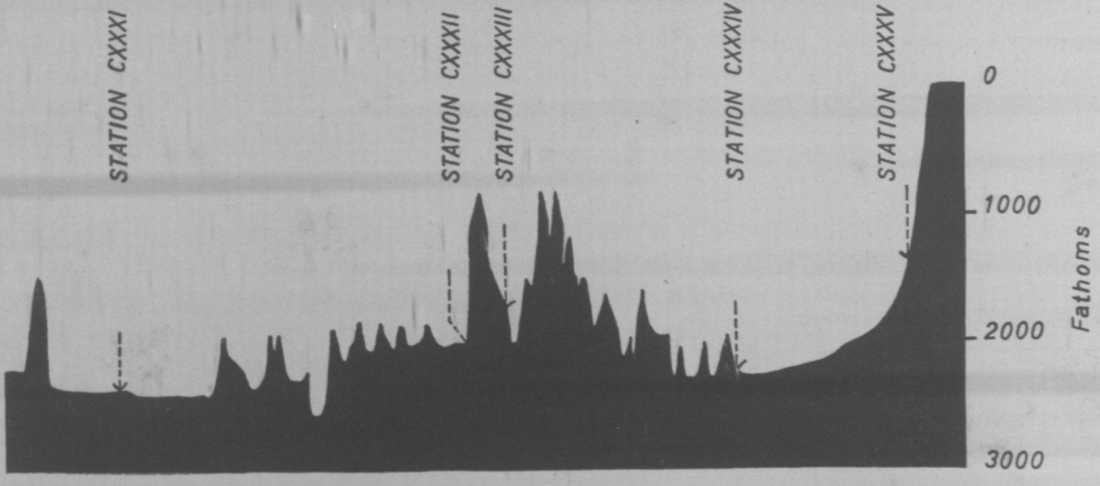
During the cruise of the "Mabahiss" from Zanzibar to Colombo at Station 133 (1° 25′ 54″ S. to 1° 19′ 42″ S. and 66° 34′ 12″ E. to 66° 35′ 18″ E.) several small rock fragments were brought up in the Monégasque net; and, since at this position there is no possibility of the material being transferred by floating ice, these specimens are of some interest as samples of oceanic rock foundations. The interest arises from our very limited knowledge of this subject, and such facts as are available are generally based on the petrography of oceanic islands or more indirectly on geophysical considerations. It was thought therefore that a description of both the chemical and petrographical features of these rocks, taken from the bottom of the ocean, would be a useful contribution, and thereby give some critical evidence concerning the theory held by many geologists that a large area of Gondwanaland now lies submerged to the west of India.

The Carlsberg Ridge, on which Station 133 is situated, was originally postulated by the Dana Expedition (Schmidt, 1932), but it was left for the John Murray Expedition to carry out a more detailed survey of this important tectonic feature. The ridge (Text-fig. 1A), according to Farquharson (1936), the Surveyor of the expedition, commences near Socotra, continues with a S.E. trend to the equator and then gradually swings round to the S.W., including in its course the Island of Rodriguez. Owing to the scarcity of soundings it is, perhaps, premature to consider it continuous, but the work of the Murray Expedition indicates that the ridge, perhaps crossed here and there by depressions, represents a major structural feature of the Indian Ocean. Inasmuch as it is a well established principle of geology that the greater crustal movements are invariably accompanied by vulcanicity, so the occurrence of igneous rocks at Station 133 is not unexpected, and it would seem that, if a further search were made along this ridge, volcanic ejectamenta would be found in some of the trawls.

The Carlsberg Ridge is a complex structure consisting of a series of ridges and furrows, which are suggestive of folding perhaps accompanied by faulting. At Station 133 the trawl was at a depth of approximately 3385 metres, and the topography of the sea floor in this neighbourhood is shown in Text-fig. 1B. It is interesting that at this station the oxygen content at first decreases, and after reaching a minimum increases towards the bottom owing to the presence of Antarctic water, whilst the temperature at 3000 metres was 1·9° C. The specimens are thus associated with sea-water at a very low temperature, containing at least 2·4 c.c. of oxygen per litre. No attempt was made to obtain a Bigelow tube sample, so the nature of the mud, if any, associated with the specimens is unknown.

About forty rock fragments, varying in size from 3½ in. to ½ in., came up in the trawl. Their shapes vary considerably, as shown in Pl. I, but apart from three or four more rounded specimens, there is a general tendency to angularity. All the rocks have a black appearance, but in the majority this skin is of negligible thickness. Exceptionally, however, it may attain to ⅓ in. (St. 133, 8), and then the specimens are rounded, as illustrated in Pl. I, fig. 1. If such a specimen is sectioned, the interior is revealed to be rock surrounded by a peripheral black coating (Pl. I, fig. 5). The junction between the coating and the kernel is sharp, and when the exterior zone is removed the angularity of the interior rock is well exhibited (Pl. I, fig. 4). It may be asked therefore whether all the specimens had originally a peripheral coating. This may well be so as this coating is easily removed, and in addition it is difficult to suggest a process capable of producing

TEXT-FIG. 1A.—Chart of Indian Ocean.

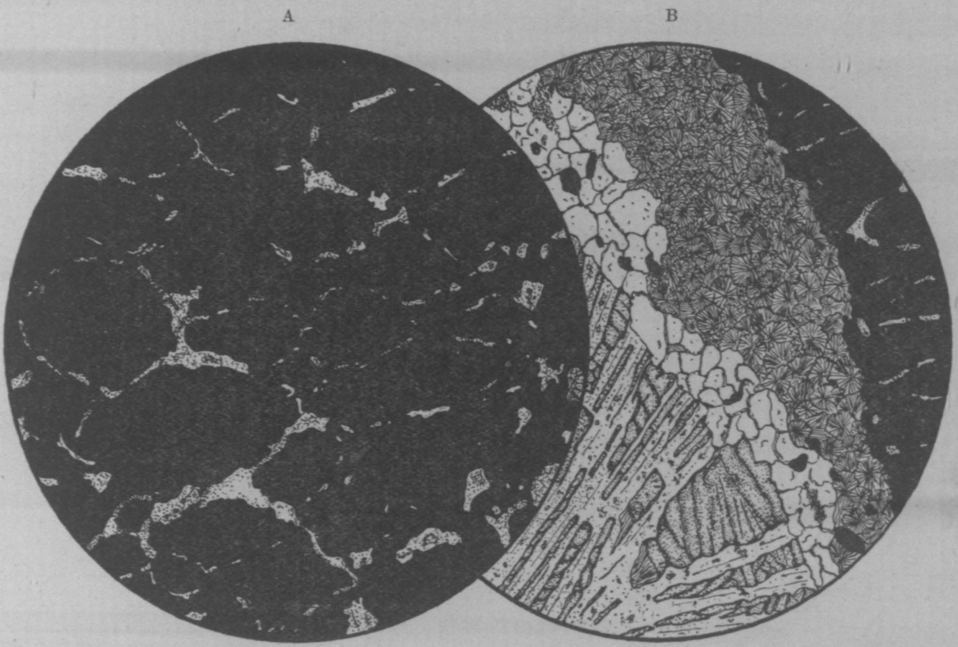


TEXT-FIG. 1B.—Section south-west of the Kardiva Channel.

such a feature on a few fragments and not on others. But against this hypothesis it could, with some justification, be urged that with the small amount of material in the net the trituration would be negligible, and so the question must be left unsettled.

II. NATURE OF PERIPHERAL COATING.

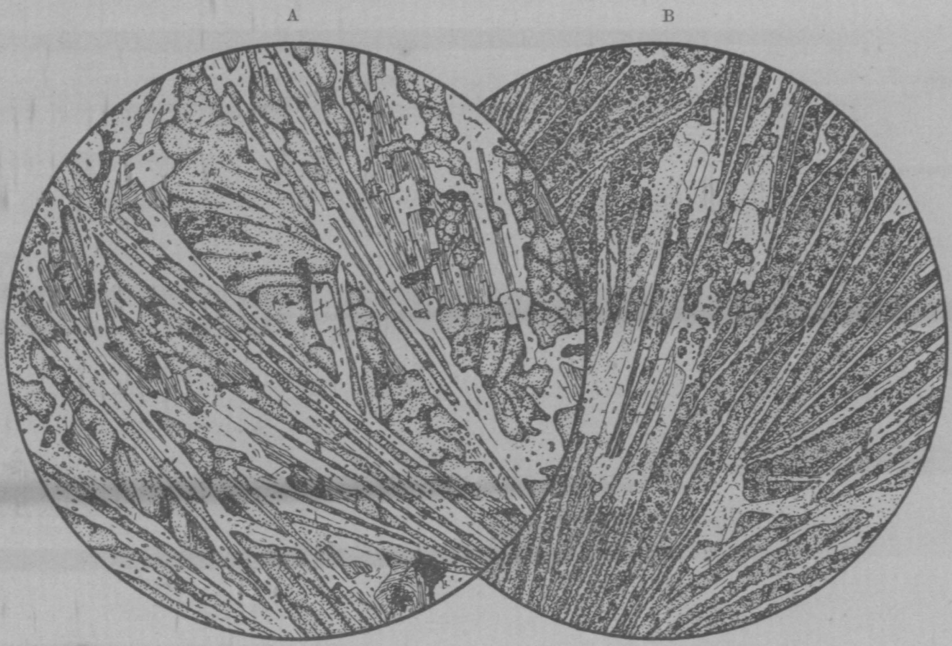
Concerning the nature of this coating it must be indicated that, in addition to the dark material, small light fragments occur, which have a rough radial arrangement. This feature can be made out in Pl. I, fig. 5, but is more clearly exhibited in Pl. I, fig. 3, which is magnified seven times. The junction between the rock and the coating is sharp, whilst the light-coloured material lies in a direction approximately perpendicular to the rock surface. A discussion concerning the nature of this coating will be given in a later report, and as it is similar to the manganese nodule material found at Station 166, only a brief description will be given.



TEXT-FIG. 2.—Nature of peripheral coating, Carlsberg Ridge. A. × 33. Peripheral coating of variolitic basalt (St. 133, 8); the small light fragments have a tendency to outline globules of dark opaque manganese material. B. × 68. Junction of coating with variolitic basalt (St. 133, 8); the variolitic basalt is separated from the manganese material by quartz grains and a zone of fibrous chlorite arranged in stellate groups.

One of the most remarkable features is the large amount of water which the peripheral coating contains, for a determination by the usual Penfield method, without any special precautions being taken to avoid volatiles, gave 28·35% total water, of which 18·75% came off below 105° C. Further, when the material is treated with dilute hydrochloric acid, abundant chlorine is liberated, and small flakes of a colourless insoluble material are left behind. The majority of the flakes have a low refractive index (*ca.* 1·480), and they are for the most part isotropic, though a few may show slight birefringence. They are of two main types: those with a wavy or perhaps shard-like appearance when examined under the high power of the microscope, whilst others have a wavy structure in one portion and a featureless surface elsewhere. Their colour is faintly brown, but the intensity is very variable, even in a single flake. It will be sufficient for our purpose to remark that the flakes have characters similar to those occurring in the manganese nodules from Station 166. In addition to this isotropic substance, small quartz grains occur in the insoluble residue, but they are comparatively rare.

In a thin section of one of the rounded specimens (St. 133, 8), a small vein of manganese material, having its origin in the periphery, occurs in the interior rock. This vein can be seen in Pl. I, fig. 5, where it is shown by its slightly darker colour. In thin section the peripheral isotropic material has a colour of intenser brown than when isolated by means of dilute hydrochloric acid, though it is occasionally colourless. This feature may be connected with a film of manganese masking some of the flakes. Under the microscope the flakes have a tendency in places to outline globules of dark opaque material (Text-fig. 2A).



TEXT-FIG. 3.—Variolitic basalts, Carlsberg Ridge. A. × 68. Augite-basalt (St. 133, 8); the felspar occurs as thin untwinned laths, and in places the augite is altered to chlorite (linear shading). B. × 152. Oxidized basalt (St. 133, 5); the variolitic character of this basalt can still be made out in spite of its alteration; most of the original glass is oxidized and the brownish alteration product is shown by lighter shading.

Occasionally the black opaque material occurs in direct contact with the interior basalt without any trace of a transition, but generally a thin zone of quartz grains, giving undulose extinction, is found between it and the interior, whilst in other places the quartz grains are separated from the manganese material by a green fibrous mineral, arranged in small stellate groups (Text-fig. 2B). This mineral, giving first-order interference colours, has positive elongation, and is probably a chlorite. In a tangential section of the periphery, in addition to the isotropic substance and occasional quartz grains, small felspar crystals, showing lamellar twinning, and more rarely diopside can be recognized.

III. PETROGRAPHY OF ROCKS.

About fifteen thin sections were cut from the Carlsberg Ridge specimens, so a representative idea can be formed about the composition of the rocks from this station. Considered as a whole, they are of a decided basaltic character, but no olivine has been found. Many of the rocks have undergone considerable chloritic alteration, but others are moderately fresh. Four representative moderately fresh rocks have been analysed, and the petrography and chemistry of these types will be described below.

(*a*) AUGITE-BASALT.

The interior of specimen Station 133, 8, of which the peripheral coating has been previously described, is a very fine-grained holocrystalline basalt (Text-fig. 3A). The felspar, occurring as thin untwinned laths, generally shows a sub-ophitic relation to the augite, but in addition tiny granules of augite sometimes occur inside it. In composition it is an oligoclase with about 25% anorthite ($\gamma = 1{\cdot}548 \pm 0{\cdot}003$). The augite, having a faint purple colour suggestive of titanium, occurs for the most part as small crystals between the felspar laths and exhibits no crystal shape. It is optically positive, and the refractive indices are: $\gamma = 1{\cdot}732 \pm 0{\cdot}004$, $\alpha = 1{\cdot}703 \pm 0{\cdot}004$. In clinopinacoidal sections the maximum extinction angle is 50° ($Z : c$). A green fibrous chlorite, showing low interference colours and with positive elongation, is associated in small amounts with the augite, and is clearly, for the most part, secondary after the augite. No olivine occurs in the thin section, agreeing with its absence in the norm, and quartz has not been detected.

The chemical composition of this basalt is given in column 1, Table I. In preparing the rock for analysis care was taken to avoid both the manganese vein and the peripheral portions. The main chemical feature of the basalt is the high soda and low potash, and in connection with the manganese periphery it should be noted that the basalt contains a normal amount of MnO. The normative composition of the felspar is $Ab_{61}An_{39}$, whilst the observed composition is $Ab_{75}An_{25}$. An altered augite-andesite described by Thomson (1909) from Mt. Anketel, Western Australia, has a similar composition (column 2), except that the titania and soda are lower, whilst the manganese is unusually high. A basalt from Folsam, New Mexico (Washington, 1917*a*) (column 3), is chemically similar, apart from the slightly lower soda and the appreciably higher potash. The basalt erupted by Stromboli (Perret, 1916) in November, 1915, has a similar composition (column 4), but the soda is lower and the potash very much higher. A close comparison may be made with a post-Eocene basaltic dolerite described by Chautard (1907) from Cape Verde, Senegal (column 5), but the potash content is more than three times as much as in the Carlsberg Ridge specimen.

These comparisons illustrate the unusual composition of the Indian Ocean basalt, for rocks of similar composition usually contain more potash, and apart from the abnormal, very much altered augite-andesite from Mt. Anketel the author is not aware of any rock showing similar chemical characteristics. The main fact to be explained is the high soda and the low potash, and it will be subsequently shown that this feature characterizes all the basalts from the Carlsberg Ridge. The possibility of this being related to the action of sea-water is discussed on a later page.

TABLE I.

	(1)	(2)	(3)	(4)	(5)
SiO_2	52·24	53·11	53·27	51·05	52·15
TiO_2	1·83	0·40	1·30	0·83	2·31
Al_2O_3	15·02	15·55	15·43	15·09	15·40
Fe_2O_3	2·93	1·26	2·43	2·07	2·60
FeO	6·31	7·17	6·50	6·88	7·45
MnO	0·14	0·59	0·12	0·13	—
MgO	6·01	6·50	6·16	6·52	7·05
CaO	8·73	8·93	8·18	11·34	8·31
Na_2O	4·02	3·03	3·51	2·53	3·85
K_2O	0·21	0·28	1·71	2·02	0·70
H_2O+	2·25	3·12	0·62	0·15	0·88
H_2O-	0·50	0·04	—	—	—
P_2O_5	0·20	—	0·50	1·44	0·09
CO_2	*Nil*	0·32	*Nil*	—	—
Inclusive	—	0·07	—	—	—
	100·39	100·37	99·73	100·12	99·70
Norms.					
Quartz	2·34	3·66	1·14	—	—
Orthoclase	1·11	1·67	10·01	12·23	4·45
Albite	34·06	25·15	29·34	22·53	32·49
Anothite	22·24	28·08	21·41	27·24	22·24
Diopside	16·13	13·20	12·61	13·82	15·27
Hypersthene	13·56	22·37	17·34	12·38	14·82
Olivine	—	—	—	4·22	2·50
Magnetite	4·18	1·86	3·48	2·09	3·71
Apatite	0·34	—	2·43	1·52	—
Ilmenite	3·50	0·76	1·34	3·70	4·10

(1) Basalt with augite and oligoclase (St. 133, 8), Indian Ocean. Analyst: J. D. H. Wiseman.

(2) Augite-andesite, Mt. Anketel, Western Australia. 'W. Austr. Geol. Sur. Bull.,' XXXIII, 1909, p. 148.

(3) Basalt, Folsom, Colfax County, New Mexico. 'U.S. Geol. Sur.,' Prof. P. XCIX, 1917, p. 608.

(4) Basalt. 'Amer. Journ. Sci.,' XLII, 1916, p. 451.

(5) Basaltic dolerite, Pointe de Fanu, Cape Verde, Senegal. 'Bull. Soc. Geol. Fr.,' VII, 1907, p. 437.

(*b*) OXIDIZED VARIOLITIC BASALT AND DISCUSSION ON SUBAQUEOUS OXIDATION OF GLASSY BASALTS.

The second specimen analysed (St. 133, 5) is a fine-grained rock with ovoid areas of about 1 mm. diameter, filled with a soft brownish substance. In thin section it is variolitic (Text-fig. 3B), the minute felspar laths being arranged in a radiating fashion. A felspar phenocryst occurs in one portion of the slide, and its composition is oligoclase. Tiny granules, frequently very much altered, occur between the felspar laths, and occasionally they are well enough preserved to be identified as augite, but more generally these granules are too much altered for optical determinations. In addition to the above minerals a brownish substance, which may either be isotropic or anisotropic, occurs both in the ground-mass as well as in the ovoid areas. The refractive index of this material ranges from about 1·570 to 1·585. Peacock and Fuller (1928) have described a basaltic glass from Columbia River, Washington, with a refractive index of 1·583, and so it seems probable that some of the isotropic material may represent unaltered volcanic glass. The brownish substance is in places fibrous and slightly birefringent, and it is suggested that the fibrous material is an alteration product of the glass. The common alteration of basic volcanic glass is to palagonite—a term applied by von Waltershausen (1845) to material forming the brown ground-mass of a tuff from Palagonia, Sicily. Later von Waltershausen (1853) realized the structural relation of palagonite to basic volcanic glass, whilst the transition of glass to palagonite has been emphasized more recently by Fermor (1925) and Peacock (1928). In a recent paper the latter author (Peacock, 1926) indicates that the Icelandic palagonite-tuffs have originated by the hydration of a basic volcanic glass, and he emphasizes that hydration is accompanied by extensive oxidation of the iron content—an opinion which to-day finds very general acceptance. All investigators of the palagonite problem appear to agree on its low but variable refractive index, and frequent statements occur in the literature that palagonite is sometimes birefringent, due to incipient molecular organization in the gel structure. Murray and Reynard (1891*a*) in their descriptions of similar material dredged by the "Challenger" mention the transition of basic glass into palagonite; and these authors record the anisotropy sometimes exhibited, but no accurate refractive index measurements are given. In view of the observations of these investigators it might be urged that the brownish anisotropic material in the specimen under consideration was produced by hydration and is to be identified as palagonite. With this identification, however, I cannot concur, since the refractive index is much too high. It is at present impossible to arrive at a positive conclusion about its exact nature, but it is interesting to mention that this material has also been found at Station 166, where it is associated with palagonitic material of low refractive index. It is possible to suggest as an hypothesis that the fibrous substance represents a chlorite with a large amount of water between the thin fibres, but such a suggestion must be taken with reserve. It is, however, safe to assume from the analytical evidence that the anisotropic substance is produced during hydration, since there is 2·46% of uncombined water in the analysis, but no hypothesis, other than suggesting that the fibrous material is a chlorite, can be advanced to explain its moderately high refractive index.

The results of the chemical investigation on this rock are given in column 1, Table III, and chemically it is similar to the augite-basalt (Table I, column 1) previously described. As before, the rock is characterized by negligible potash and over 3% soda. The silica is slightly lower than before, but the alumina is almost identical. Concerning the state of oxidation of the iron it is interesting to note that the iron is mostly in the ferric condition, and this oxidation is correlated with the hydration of the rock. In this connection the author (Wiseman, 1936*a*) has recently described a rock, dredged from a depth of 744 fathoms near to Providence Reef, showing a similar oxidation. In this paper it is concluded that the oxidation is directly connected with the sea-water, and is not due to subaerial weathering, as proposed by Pirrson (1914*a*) for the basalts of Bermuda

Island. It is difficult to imagine in the case of the Carlsberg Ridge variolitic basalt, found at a depth of nearly 4000 metres, how subaerial oxidation can have occurred, unless of course we regard it as representing a sunken remnant of Gondwanaland—a hypothesis which will subsequently be shown to be highly improbable. In the literature confirmatory evidence for the oxidizing power of sea-water is found in a recent paper by Correns (1930*a*), who examined a basalt collected by the Meteor Expedition from the Mid-Atlantic Ridge. Correns gives analyses of both the kernel and peripheral portions; in the interior he reports 2·30% Fe_2O_3 and 7·55% FeO, whereas in the periphery the amounts are 16·56% Fe_2O_3 and 0·93% FeO. These figures give a very positive demonstration of the oxidation and the concentration of the total iron in the periphery. Similarly, in analyses by Sipöcz (Murray, J., and Reynard, 1891*b*) of the peripheral and interior portions of a basalt dredged from near the Sandwich Islands, oxidation occurs, and we may judge from these and other examples that the protective action of sea-water, as suggested by Pirrson and others, is unsupported by oceanographical investigations. Such a feature is, of course, not really surprising, for according to modern investigation, sea-water, even at great depths, frequently contains appreciable oxygen. Thus, at Station 133 the oxygen content at a depth of 3000 metres is 2·41 c.c. per litre, whilst at the surface it contains 3·68 c.c. per litre. It is this latent oxygen which is responsible for the subaqueous oxidation in many oceanic basalts, but the Murray specimens indicate that the presence of oxygen is not sufficient unless the rock is of a suitable character.

In the ankaratrite-limburgite from Providence Reef the augite and olivine is set in a dark opaque substance, which represents original glass, whilst the basalt described by Correns from the Mid-Atlantic Ridge also contains glass in its interior. Similarly, in the specimen dredged by the "Challenger" Expedition from near the Sandwich Islands the interior is glassy whilst the exterior is largely palagonite. From these examples we may suggest that the presence of glass favours subaqueous oxidation, and in this connection it is significant that glass-free basalts from the Carlsberg Ridge have suffered no such change. The available analytical information, bearing on the problem of oxidation and the nature of the rock, is summarized, for convenience, in Table II.

TABLE II.

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)
Fe_2O_3 . .	16·56	7·62	6·74	5·89	2·93	2·30	2·21	1·91	1·73	14·57
FeO . .	0·93	2·28	4·42	4·70	6·31	7·55	7·39	6·68	10·92	—
H_2O- . .	6·26	6·61	2·46	1·03	0·50	0·27	0·86	0·25	n.d.	n.d.

(1) Olivine-basalt, peripheral portion, Mid-Atlantic Ridge. 'Chemie der Erde,' V, 1930, p. 83.

(2) Ankaratrite-limburgite. Originally glassy. Providence Reef. 'Trans. Linn. Soc. Zool.,' ser. 2, XIX, p. 440.

(3) Variolitic basalt (St. 133, 5), Carlsberg Ridge. Contains some glass.

(4) Variolitic basalt (St. 166, 6° 55′ N., 67° 11′ E.). Originally had a glassy base.

(5) Basalt (St. 133, 8), Carlsberg Ridge.

(6) Interior of glassy basalt, Mid-Atlantic Ridge, *op. cit. supra.*

(7) Basalt (St. 133, 12), Carlsberg Ridge.

(8) Dolerite (St. 133, 15), Carlsberg Ridge.

(9) Unaltered glass nucleus, near Sandwich Isles. 'H.M.S. "Challenger", Deep Sea Deposits', 1891, p. 463.

(10) Decomposed coating of basic volcanic glass, near Sandwich Isles, *op. cit. supra.*

An examination of this table reveals that a high percentage of ferric iron is invariably accompanied by a large amount of uncombined water, a feature which is very well illustrated by comparing the 2·46% of H_2O- (column 3) in the oxidized variolitic basalt with the low uncombined water content in the unoxidized rocks (columns 5, 7, 8) from the same station. An oxidized variolitic basalt, originally glassy, from Station 166 shows the same high water content (column 4), whilst a similar feature is shown by the Providence specimen (column 2). In the basalt from the Mid-Atlantic Ridge nearly 6% more water occurs in the oxidized periphery than in the glassy interior (columns 1 and 6). The "Challenger" specimens (columns 9 and 10) show a great increase of ferric oxide in the peripheral zone as compared with the unaltered interior, but unfortunately the analyses by Sipöcz are decidedly incomplete, for H_2O- is not determined, nor is there any estimation of ferrous oxide in the decomposed coating.

After what has been stated above there can be little doubt that the presence of glass was essential, in the specimens under consideration, for subaqueous oxidation of basalts. It has been previously mentioned that this contention is supported by the four Carlsberg Ridge analyses, for three rocks containing no glass are unaffected by sea-water (columns 5, 7 and 8). It is impossible, in this case, to account for this by a difference in conditions, for all the specimens are from the same locality ; so the conclusion that the subaqueous oxidation is, in general, governed by the glassy character of the rock, seems justified. It is not suggested by this that all glassy rocks must *a fortiori* have undergone oxidation, for they may be of too recent age, or on the other hand, the surrounding conditions may not be suitable for such a process to take place.

A fairly close comparison, apart from the state of oxidation of the iron, can be made with a basalt analysed by Washington (1917*b*) from Mt. Etna (Table III, column 2), and with a basalt from Victoria, Australia (Table III, column 3). In both these basalts the ferrous iron content approximates probably to that occurring in the variolitic basalt before oxidation, whilst in addition the amount of uncombined water is low. A significant feature is the appreciable potash as compared with the insignificant amount in the Carlsberg Ridge specimen. In a basalt from Lake Balaton, Hungary (Emszt, 1906) (Table III, column 4) the percentage of ferric oxide is greater than ferrous, and the soda is approximately the same as in the Carlsberg Ridge specimen, whilst the potash is moderately low. Unfortunately Emszt gives no petrological description of this rock, nor has the uncombined water been estimated, so it is impossible, from the original paper, to determine its true nature. In column 5 of the same table the composition of a basalt showing similar chemical features is recorded from Bradshaw Mountains, Arizona (Jagger and Palache, 1905), and it is described as representing a border facies approximating to the surrounding basalts in composition, but probably representing a locally differentiated facies of basalt. Washington classes the analysis in his tables under the heading of "altered rocks", a classification which seems justifiable on account of the 1·24% of uncombined water.

From this brief comparison it may be concluded that, although fresh basalts of similar composition—apart from the state of oxidation of the iron—occur in other areas, they invariably contain higher potash. The lowness of potash is, as will be emphasized later, a feature characteristic of the Carlsberg Ridge station.

TABLE III.

	(1)	(2)	(3)	(4)	(5)
SiO_2	47·58	48·46	47·46	46·78	46·74
TiO_2	2·10	2·03	3·10	1·78	1·04
Al_2O_3	15·05	15·92	16·12	14·66	16·96
Fe_2O_3	6·74	3·42	2·96	7·25	6·44
FeO	4·42	8·00	9·39	5·22	4·13
MnO	0·14	0·18	0·25	—	0·23
MgO	5·71	5·05	5·70	6·81	6·18
CaO	10·97	10·02	7·27	9·61	11·90
Na_2O	3·19	4·13	3·51	3·08	3·13
K_2O	0·04	1·61	1·74	0·45	0·50
H_2O+	0·99	0·01	0·57	1·78	0·89
H_2O-	2·46	0·03	0·72		1·24
P_2O_5	0·23	0·65	0·78	0·45	0·56
CO_2	*Nil*	*Nil*	*Nil*	—	0·58
Inclusive	—	0·23	0·07	—	—
	99·62	99·74	99·64	99·37	100·52
Norms.					
Quartz	2·64	—	—	—	—
Orthoclase	0·56	9·45	10·56	2·78	2·78
Albite	27·25	15·68	29·34	28·82	26·20
Anorthite	26·41	20·29	23·07	24·74	31·14
Nepheline	—	4·83	—	—	—
Diopside	21·17	20·24	6·12	15·61	19·65
Hypersthene	4·50	—	5·44	8·61	1·56
Olivine	—	8·50	11·71	1·12	4·11
Magnetite	8·82	4·87	4·41	10·67	9·28
Hæmatite	0·64	—	—	—	—
Apatite	0·34	1·68	2·02	1·01	0·93
Ilmenite	3·95	3·80	5·93	3·34	1·82

(1) Variolitic basalt (St. 133, 5), Carlsberg Ridge, Indian Ocean. Analyst: J. D. H. Wiseman.

(2) Basalt, lava of 1910, Mt. Etna, Sicily. 'U.S. Geol. Sur.,' Prof. P. XCIX, 1917, p. 618.

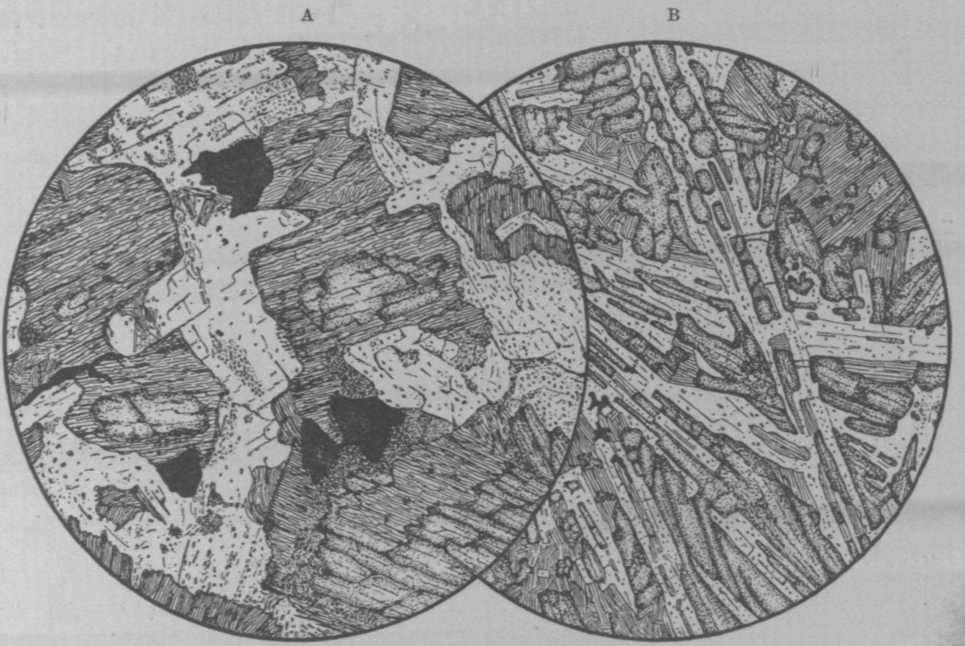
(3) Basalt, Newlyn, Victoria. 'A. R. Sec. Min. Vict.,' 1912, p. 62.

(4) Basalt, Lake Balaton, Tóti hegy, Komitat Zala. 'Jahresbericht d. Kgl. Ungarischen. Geolog. Anstalt.,' 1906, p. 338.

(5) Basalt, Little Ash Creek, Bradshaw Mts., Arizona. 'Geologic Atlas of United States,' folio 126, 1905, p. 7.

(c) Hornblende-Augite-Dolerite and Significance of Hornblende.

The third specimen analysed (St. 133, 15) is a small angular black fragment, which on a fractured surface has a slightly greenish appearance. The thin section is remarkable for its content of green fibrous hornblende, as well as augite and plagioclase. The felspar, occurring as moderately broad short laths (Text-fig. 4A), has for the most part crystallized before the augite. It rarely exhibits twinning and has a variable composition, for some of the larger laths may be as basic as $Ab_{29}An_{71}$ ($\gamma = 1{\cdot}572 \pm 0{\cdot}002$), whilst others are as acid as oligoclase-andesine ($\alpha = 1{\cdot}546 \pm 0{\cdot}002$). Hornblende, sometimes occurring as a peripheral border to augite, has clearly been derived from that mineral, and has a refractive index $\beta = 1{\cdot}640 \pm 0{\cdot}002$, whilst $Z : c = 24°$. It is pleochroic from Z = faint blue-green to X = light yellowish-green. The colourless augite occurring as individual crystals and as kernels to the fibrous hornblende has $\gamma = 1{\cdot}709 \pm 0{\cdot}004$ and $\alpha = 1{\cdot}687 \pm 0{\cdot}004$, and the maximum extinction angle $Z : c = 37°$. A little iron-ore is present, and here and there a small patch of chlorite showing anomalous interference colours. Glass is absent in this rock.



TEXT-FIG. 4.—Hornblende-dolerite and variolotic basalt from the Carlsberg Ridge. A. × 68. Hornblende-augite-dolerite (St. 133, 15); compared with the other Carlsberg Ridge basalts this has a relatively coarse texture; the hornblende (wavy shading), derived from the augite, occurs as a peripheral border to that mineral as well as in individual crystals. B. × 68. Variolitic augite-basalt (St. 133, 12); the oligoclase occurs as thin laths in a roughly radiating fashion, and the chlorite (linear shading) is intimately associated with the augite.

The presence of green hornblende in this specimen is interesting, as it is the only specimen from the Carlsberg Ridge which contains that mineral. The absence of glass and the relative coarseness of the rock indicate that it cooled slower than those previously described, but yet it has not the coarse texture that is characteristic of gabbros. It would seem logical, both on textural considerations and from the presence of hornblende, to classify this rock with the dolerites in spite of the fact that it has a close chemical relationship to the associated basalts. A metamorphic origin might be urged by some for this rock, as the production of hornblende from augite is an established metamorphic process. But as hornblende, chlorite, albite and epidote are the normal products of low-grade regional metamorphism of basic igneous rocks (Wiseman, 1934), so it would be reasonable to expect, if the hornblende had a metamorphic origin, the felspar to be more albitic and to be associated with abundant epidote. Since this is not the case, a metamorphic origin of the hornblende is suspect. On the other hand, it would be difficult to subscribe to the view that the hornblende is of intratelluric crystallization, for its occurrence as fibres projecting into the plagioclase makes such a contention untenable. To the author it would appear more reasonable to regard the hornblende as produced by end-stage reactions. Read (1935), in a recent paper on the gabbros from Haddo House district, Aberdeenshire, has described the production of a green fibrous amphibole by a post-magmatic modification of the original pyroxene, and it would seem that a similar reaction has taken place in the case of the Carlsberg Ridge specimen.

It would be a rational inquiry to ask why hornblende occurs in only one specimen from the Carlsberg Ridge and not in the other basaltic specimens of similar composition. Further, it might be suggested that the hornblende rock belongs to a different period of vulcanicity than the other basalts. Although such a contention cannot be definitely disproved, the close chemical resemblance between the basalts and dolerite from this station would favour a contemporaneous origin, or at least an origin belonging to the same igneous cycle. The moderately coarse texture of the hornblende-dolerite, when compared with those of the more normal basalts from this area, indicates, as has been mentioned previously, that the cooling history of this rock was different from those of the more normal basalts. Consequently the difference in texture implies a different habitat for solidification, and hence the possibility of end-stage reactions whilst the other specimens were unaffected.

The chemical composition of the hornblende-augite-dolerite is given in Table IV, column 1. The analysis is similar to the variolitic basalt (Table I, column 1) described on an earlier page, and the low potash is again a distinctive feature. It is noteworthy that in this rock there is no apparent oxidation of FeO to Fe_2O_3, and with this the small amount of uncombined water and the absence of glass in the original specimen is correlated. Lewis (1908) has described from the Palisades of New Jersey a basalt (column 2) with a comparable composition, apart from larger potash and total iron. The same difference is shown by a basalt from El Salto de San Anton, Mexico (column 3), which according to Guild (1906) contains olivine and an orthorhombic pyroxene. A chemically similar diorite described by Alvisi (1912) from Elba (column 4) has an almost identical amount of soda, but the potash is three times as great as in the hornblende-dolerite. It is interesting to note the similarity between the norms of the Elban diorite and the Carlsberg Ridge dolerite.

It is evident, then, from Table IV that, although rocks of similar composition occur in other regions of the world, yet no comparable analyses, which have extremely low potash content, are known. This again illustrates the abnormality of these rocks with regard to potash.

(*d*) VARIOLITIC BASALT.

The fourth rock analysed from the Carlsberg Ridge is a fine-grained variolitic basalt. In thin section it resembles the variolitic basalt (St. 133, 8) previously described, the thin felspar laths occurring in a roughly radiating fashion (Text-fig. 4B). The felspar is an oligoclase with about 26% anorthite ($\gamma = 1{\cdot}548 \pm 0{\cdot}002$), and rarely exhibits lamellar twinning. Augite, occurring as small crystals between the felspar laths, has a very faint purple colour, and its refractive indices are $\alpha = 1{\cdot}679 \pm 0{\cdot}004$, $\gamma = 1{\cdot}728 \pm 0{\cdot}004$, whilst the extinction angle $Z : c = 50°$. A greenish chlorite, with positive elongation, is

TABLE IV.

	(1)	(2)	(3)	(4)
SiO_2	51·71	51·77	51·56	52·21
TiO_2	1·39	1·13	1·81	2·13
Al_2O_3	14·36	14·59	15·24	13·93
Fe_2O_3	1·91	3·62	2·73	3·62
FeO	6·68	6·90	5·99	6·01
MnO	0·14	0·05	0·15	—
MgO	8·28	7·18	8·30	7·56
CaO	9·90	7·79	7·67	10·24
Na_2O	3·33	3·92	3·74	3·30
K_2O	0·09	0·64	1·85	0·25
H_2O+	1·67	1·85	0·16	0·35
H_2O-	0·25	0·46	0·15	—
P_2O_5	0·13	0·18	0·47	—
CO_2	*Nil*	—	—	—
Inclusive	—	—	0·12	—
	99·84	100·08	99·94	99·60
Norms.				
Quartz	0·36	—	—	2·94
Orthoclase	0·56	3·89	11·12	1·67
Albite	27·77	33·01	31·44	27·77
Anorthite	24·19	20·29	19·18	22·24
Diopside	19·43	14·77	12·17	22·73
Hypersthene	19·81	16·88	6·81	12·48
Olivine	—	1·39	10·15	—
Magnetite	2·78	5·34	3·94	5·34
Apatite	0·34	2·13	1·24	—
Ilmenite	2·74	0·34	3·34	4·10

(1) Hornblende-augite-dolerite (St. 133, 15), Carlsberg Ridge, Indian Ocean. Analyst: J. D. H. Wiseman.

(2) Basalt, Springfield, New Jersey. 'N. J. Geol. Sur. Ann. Rep.,' 1908, p. 159.

(3) Basalt, El Salto de San Anton, Mexico. 'Amer. Journ. Sci.,' XXII, 1906, p. 170. In this reference the amount of potash is given as 1·25%, but Washington considers this an error, and he gives 1·85 as the corrected value.

(4) Diorite, Elba. 'Mem. Soc. Toscana di Sci. Nat.,' XXVIII, 1912, p. 205.

associated with the augite, its colour being quite distinct from the yellowish-green chlorite occurring in the other variolitic basalt (St. 133, 8). Most of the chlorite is secondary after augite. No original olivine occurs in the thin sections, nor does any of the chlorite have the appearance of arising from that mineral, though there is 13% of normative olivine in the rock. It may be that olivine was never represented, and in this connection it is not unusual to find olivine in the norm, whilst it is absent in the mode. With the addition of small patches of iron-ore and an occasional grain of yellowish epidote the rock is completed.

The composition of this variolitic basalt is given in Table V, column 1, and the high percentage of soda and the low potash is again characteristic. No oxidation of the ferrous oxide appears to have taken place, and in this connection it is interesting to emphasize the absence of glass and the small amount of uncombined water. In column 2 the analysis of an essexitic-gabbro described by Lacroix (1909) is recorded, and apart from the higher potash content has a similar composition. A further comparison can be made with a basalt described by Washington (1909) from Graham Island, near Sicily (column 3), but the potash is much higher. In the basalt from Graham Island and the gabbro from Cantal the amount of combined water is considerably smaller than that occurring in the variolitic basalt—a feature which is no doubt connected with the occurrence of chlorite in the variolitic basalt.

TABLE V.

	(1)	(2)	(3)
SiO_2	49·43	49·10	48·97
TiO_2	1·94	2·92	3·95
Al_2O_3	15·04	15·75	16·37
Fe_2O_3	2·21	1·00	1·33
FeO	7·39	8·80	8·56
MnO	0·23	—	0·06
MgO	8·40	6·35	6·22
CaO	6·69	8·56	7·49
Na_2O	4·45	4·47	4·09
K_2O	0·11	1·91	1·72
H_2O+	3·16	0·75	0·38
H_2O-	0·86	—	0·08
P_2O_5	0·19	0·22	1·04
CO_2	*Nil*	—	—
Inclusive	—	—	0·08
	100·10	99·83	100·34
Norms.			
Orthoclase	0·56	11·12	10·01
Albite	37·73	24·10	34·58
Anorthite	20·57	16·96	21·13
Nepheline	—	7·67	—
Diopside	9·61	19·26	7·91
Hypersthene	6·38	—	—
Olivine	13·00	12·34	14·44
Magnetite	3·25	1·39	1·86
Apatite	0·34	0·67	2·35
Ilmenite	3·65	5·62	7·45

(1) Variolitic-augite-basalt (St. 133, 12), Carlsberg Ridge. Analyst: J. D. H. Wiseman.

(2) Essexitic-Gabbro, Font-des-Vaches, Cantal, France. 'C. R.,' CXLIX, 1909, p. 546.

(3) Basalt, Graham Island, near Sicily. 'Amer. Journ. Sci.,' XXVII, 1909, p. 138.

IV. GENERAL CHEMICAL FEATURES OF THE CARLSBERG RIDGE ROCKS.

The analyses of three basalts and one dolerite are reproduced together in Table VI for easier comparison, the Carlsberg Ridge analyses being arranged in order of increasing silica percentage. Inspection of these four analyses reveals that, whilst there is a slight variation in the silica percentage, the alumina remains practically constant. All four analyses are characterized by a moderately high soda percentage, which varies between 3·19 and 4·45, whilst the potash is very low, ranging from 0·21% to 0·04%. The total iron content is, perhaps, smaller than that usually occurring in basalts, but in one analysis there has been an oxidation of ferrous iron to the ferric condition, and with this the 2·46% of uncombined water is correlated. With regard to the lime and magnesia there is no systematic variation, for the lime may be greater or smaller than the magnesia. Titania, phosphorus and manganese occur in amounts normal for basalts, whilst the considerable H_2O+ is related to the presence of chlorite. Briefly, then, the chemical investigation bears out the relationship of these rocks one to each other, and emphasizes their dominant characteristic, namely, high soda and very low potash.

TABLE VI.

	(1)	(2)	(3)	(4)	(5)
SiO_2	47·58	49·43	51·71	52·24	48·58
TiO_2	2·10	1·94	1·39	1·83	1·77
Al_2O_3	15·05	15·04	14·36	15·02	14·58
Fe_2O_3	6·74	2·21	1·91	2·93	1·89
FeO	4·42	7·39	6·68	6·31	7·65
MnO	0·14	0·23	0·14	0·14	0·46
MgO	5·71	8·40	8·28	6·01	6·36
CaO	10·97	6·69	9·90	8·73	9·80
Na_2O	3·19	4·45	3·33	4·02	4·02
K_2O	0·04	0·11	0·09	0·21	0·43
H_2O+	0·99	3·16	1·67	2·25	2·93
H_2O-	2·46	0·86	0·25	0·50	0·68
P_2O_5	0·23	0·19	0·13	0·20	0·19
CO_2	*Nil*	*Nil*	*Nil*	*Nil*	1·00
Inclusive	—	—	—	—	0·29
	99·62	100·10	99·84	100·39	100·63

(1) Variolitic basalt (St. 133, 5), Carlsberg Ridge. Analyst: J. D. H. Wiseman.

(2) Variolitic-augite-basalt (St. 133, 12), Carlsberg Ridge. Analyst: J. D. H. Wiseman.

(3) Hornblende-augite-dolerite (St. 133, 15), Carlsberg Ridge. Analyst: J. D. H. Wiseman.

(4) Augite-basalt (St. 133, 8), Carlsberg Ridge. Analyst: J. D. H. Wiseman.

(5) Spilite, Mullion Island, Cornwall. "Geology of Lizard and Meneage," 'Mem. Geol. Sur. E. & W.,' 1912, p. 185.

In the above discussion we have emphasized the rarity of comparable analyses. On account of this it might be urged that the low potash content is not an original feature, but is due to a possible leaching effect of the sea-water. Fortunately, in addition to the difficulty of accounting for the preferential removal of the alkalis there is some definite evidence on this point, for at Station 166 one or two specimens of angular basalt were found in the trawl consisting mainly of manganese nodules. An analysis has been made of a variolitic basalt from this station. The potash content is 0·57%, whilst the soda is 2·34, and since this basalt contains appreciable potash it is inconceivable to imagine preferential leaching at one station and not at the other when both rocks came from similar depths. It is therefore concluded that the low potash content at Station 133 represents an original feature. Whether this is a characteristic of the Carlsberg Ridge as a whole is a matter for future work, but the occurrence of a variolitic basalt with appreciable potash from Station 166 would indicate that such a feature is not common to the whole Indian Ocean.

It might be considered from the association of soda-rich, potash-poor basalts with deep-sea deposits that they owe their peculiar chemical composition to hydrothermal replacements under the influence of heated sea-water, but as will be shown subsequently, there are objections which make such an hypothesis improbable. It would therefore seem that some petrogenetic theory other than alteration by heated sea-water or by leaching is required.

V. RELATION TO THE SPILITIC SUITE.

In composition the Carlsberg Ridge rocks have some resemblance to spilites, and in Table VI, column 5, the composition of the Mullion spilite (Flett and Hill, 1912*b*) is recorded. According to Dewey and Flett (1911) the spilitic rocks are, as a rule, very much decomposed and the felspars are always rich in soda. The principal constituent is felspar; next in importance is augite of pale brown colour whilst, in addition, some of them have contained a fair amount of glassy base, which is devitrified and decomposed. A large number of spilites are variolitic and the augite occurs as irregular masses exhibiting a sub-ophitic texture. The Carlsberg Ridge basalts agree in general with this description, and in addition they have a chemical resemblance to rocks of the spilitic suite, as they are all rich in soda, but they are, on the whole, much poorer in potash than normal spilites. Mineralogically the felspar is never more acid than basic oligoclase, whilst in spilites it is typically albite-oligoclase. From these considerations it is reasonable to consider these rocks as basalts with spilitic affinities.

The occurrence of such rocks at the bottom of the Indian Ocean is significant, as spilites are frequently regarded as submarine. A brief survey of the literature reveals that spilites and keratophyres are frequently associated with marine sediments in such a manner as to suggest a submarine eruption. Such rocks occur in Cornwall (Flett and Hill, 1912*a*), Devon (Flett and Dewey, 1912), Wales (Jones and Cox, 1913), Scotland (Peach and Horn, 1899), Australia (Benson, 1913), Germany (Brauns, 1909), Czechoslovakia (Kettner, 1917), Norway (Carstens, 1924; Goldschmidt, 1916), Sweden (Beskow, 1927*a*), East Indies (Verbeek, 1905), and America (Knopf, 1918); but the keratophyres of Nevada are, according to Knopf (Knopf, 1921), subaerial, and so are the skomerites of Wales (Thomas, 1911). From this brief presentation it may be judged that although the spilitic rocks are mainly the products of submarine eruptions, they are very rarely subaerial. A similar conclusion has been recently emphasized by Gilluly (Gilluly, 1935) when discussing the spilites of eastern Oregon. The frequency of spilites with marine sediments would favour a submarine origin for the Carlsberg Ridge rocks, but a fuller discussion of this problem will be left for a subsequent page.

It might be urged by some that the occurrence of basalts with spilitic affinities on the Carlsberg Ridge supports Beskow's (Beskow, 1927*b*) contention that the spilites are produced by hydrothermal replacements under the influence of heated sea-water. Beskow considers that the major chemical change is the leaching of potassium, and an increase of soda largely of marine origin. Daly (1914) supports a rather similar idea, for he regards the intense albitization as being produced by the eruption of lavas through wet sediments, and he invokes the action of resurgent water for the transference of soda. Although it is not within the province of this paper to discuss the spilitic problem, it is suggested that the submarine rocks investigated from the Indian Ocean give little support for the hydrothermal action of heated sea-water. Thus, in a rock collected at a depth of 744 fathoms near to Providence Reef only 1·72% of soda is present, whilst the potash (0·95%) is quite appreciable. As stated in the original paper (Wiseman, 1936*b*), this rock has a submarine origin, and hence according to Beskow there should be a possibility of hydrothermal action. But such a process cannot have taken place, for the alkali content is normal. Similarly, in a previously mentioned variolitic basalt from Station 166 the alkali content is normal; the composition of this rock is recorded in Table VII, column 2, but the petrographical description will be reserved for a later publication. It would therefore seem, both from the above evidence and from other oceanic rocks described in the literature, that submarine basaltic eruptions do not of necessity involve the production of spilites. From this it would seem unnecessary to invoke the action of heated sea-water to account for the spilitic tendency of the Carlsberg Ridge basalts, but rather that the soda-rich potash-poor feature is an inherent tendency of the magma itself. It is not suggested that the oligoclase crystallized out of the molten magma as such, for as demonstrated by Eskola (1925), the subophitic nature of the pyroxene opposes such a contention, but that the albitization of a more basic plagioclase was a property of the magma itself and did not require the aid of external agencies. As to the period of albitization, it must have taken place before the eruption of the small fragments, and hence presumably in the volcanic neck.

VI. COMPARISON WITH OTHER ROCKS.

(*a*) The Indian Ocean.

In Table VII one new analysis of a rock from the floor of the Indian Ocean is given; column 1 represents the average of the three unoxidized Carlsberg Ridge rocks, column 2 a new analysis of a variolitic basalt from Station 166, whilst column 3 is a limburgite from Providence Reef. In the two latter analyses the ferrous iron has been largely oxidized to the ferric condition. Although the chemical evidence is very limited, the analyses of the first three columns support the hypothesis of a basic substratum to the Indian Ocean, and from the available evidence it would seem that the soda-rich potash-poor basalts are not characteristic of the area as a whole, but are a local variety of a basaltic type.

TABLE VII.

	(1)	(2)	(3)	(4)	(5)	(6)	(7)
SiO_2	51·12	46·55	40·10	48·62	46·49	48·22	50·61
TiO_2	1·72	1·17	3·72	2·00	2·86	2·72	1·91
Al_2O_3	14·81	18·13	14·54	17·69	14·28	14·74	13·58
Fe_2O_3	2·35	5·89	11·27	3·76	2·90	2·24	3·19
FeO	6·79	4·70	3·37	5·76	9·43	9·38	9·92
MnO	0·17	0·09	0·13	—	0·16	—	0·16
MgO	7·56	3·82	11·48	5·25	8·87	7·01	5·46
CaO	8·44	13·69	10·89	8·76	11·23	12·26	9·45
Na_2O	3·93	2·34	1·72	4·45	2·74	2·23	2·60
K_2O	0·13	0·57	0·95	2·27	0·48	0·89	0·72
H_2O+	2·36	1·33	—	0·75	0·20	0·06	1·70
H_2O-	0·54	1·03	—	0·29	0·52		0·43
P_2O_5	0·14	0·92	1·39	0·59	0·27	0·35	0·39
CO_2	*Nil*	*Nil*	—	—	—	—	—
Inclusive	—	0·10	0·44	—	—	—	—
	100·06	100·33	100·00	100·19	100·43	100·13	100·12

(1) Average of three unoxidized rocks from the Carlsberg Ridge.

(2) Variolitic basalt, Station 166. Analyst: J. D. H. Wiseman.

(3) Limburgite, Providence Reef. Recalculated without water and calcite. 'Trans. Linn. Soc. Zool.,' ser. 2, XIX, p. 440.

(4) **Basalt, Tonnere Cliff, Rodriguez.** 'Minèralogie de Madagascar,' III, 1923, p. 239.

(5) Average of two basalts from Mauritius. 'Quart. Journ. Geol. Soc.,' LXXXIX, 1935, p. 5, and 'Minèralogie de Madagascar,' III, 1923, p. 239.

(6) Average of eight basalts from Réunion.

(7) Average of eleven Deccan Trap analyses. 'Bull. Geol. Soc. Amer.,' XXXIII, 1922, p. 774.

According to Farquharson, as I have mentioned before, Rodriguez lies on a continuation of the Carlsberg Ridge, and if this is so it would be reasonable to expect a relation between the rocks of this island and those from Station 133. Although the "Venus" Expedition (Balfour, 1879) called at Rodriguez, no detailed description of the lavas is given in their reports, but Lacroix (1923*c*) describes the island as consisting of olivine-basalts which occasionally contain nepheline, and he gives an analysis of a basalt (Table VII, column 4). If this analysis is representative of the island, then the lavas of Rodriguez are much richer in potash than those from the Carlsberg Ridge station. Consequently the available evidence would indicate that the basalts are of a different type to those of the Carlsberg Ridge. This observation, if true, is of some significance in any discussion on the regional extent of the Carlsberg Ridge, for frequently igneous rocks erupted within a period of magmatic activity and on a given tectonic line show a certain community of chemical and petrographical features. It might be reasonably expected, then, that if Rodriguez lies on a direct continuation of the Carlsberg Ridge, the basalts would be characterized by low potash; but this is not the case, and consequently the petrological evidence does not favour such a prolongation of the ridge. A critical examination of the hydrographical evidence in favour of placing Rodriguez on a continuation of the

Carlsberg Ridge reveals only two soundings between latitude 5° S. and the island, and hence too much reliance cannot be placed on a contention based on such meagre hydrographical evidence. If, on the other hand, Rodriguez is not on the Carlsberg Ridge, then the different character of its basalts finds a natural explanation.

The available soundings suggest a deep depression between Rodriguez and Mauritius, and the Antarctic bottom drift which, according to the results of the Murray Expedition, comes up between these islands, gives support to such a contention. It is possible therefore that Rodriguez and Mauritius lie on different structural lines, but Mauritius and Réunion are probably on the same bank. Whether these two islands lie on a continuation of the Seychelles bank is a matter for future confirmation, but the work of the Percy Sladen Trust Expedition (Gardiner, 1907) to the Indian Ocean indicates the possibility of a channel intersecting this bank.

Mauritius, situated 100 miles E.N.E. of Réunion, is essentially volcanic. Several investigators—Bory de Saint Vincent (1804), Darwin (1845), Clark (1867), Drasche (1878), Haig (1895)—have described this island, but it was left for Shand (1935) and Lacroix (1923*c*) to study the petrology of the lavas. The lavas are mostly olivine-basalts of normal character, but in addition trachyte occurs at La Selle. Washington (1930*b*) has remarked on this association for the Intra-Pacific volcanoes, for he states that " there are now known to be very few islands or island groups in the Pacific that are wholly basaltic and without trachyte or basanite ". A similar association has been recorded on Réunion (Lacroix, 1923*b*), Madagascar (Lacroix, 1923*a*) and Christmas Island (Smith, 1926). In Table VII, column 5, the average of two basalts from Mauritius is given, and this column is remarkably similar to the average basalts from Réunion (column 6). Further, the compositions of the trachytes are alike. From these facts it would seem that the rocks of Mauritius and Réunion are comparable—a conclusion agreeing with the hypothesis that these islands are on the same structural bank. In the absence of trachytic types the rocks from Station 133 obviously differ from those of Mauritius and Réunion, and, furthermore, are poorer in potash. To the author it would seem premature to compare, as Lacroix has done, Rodriguez with Mauritius, but it is perhaps significant that no trachyte was brought back in the collections of the " Venus ", whilst the analysed basalt is richer in alumina than the average basalts from Mauritius and Réunion.

Some oceanographers (Schott, 1935) consider that the islands of New Amsterdam, St. Paul, Kerguelen and Heard lie on a continuation of the Indian Ocean ridge, but such an hypothesis must, owing to the scarcity of soundings, be relegated to the realm of speculation. It is interesting, however, to compare the petrology of these islands with the rocks from Station 133. New Amsterdam is situated south-east of Réunion and north-east of Kerguelen, whilst St. Paul is on the same meridian, but 50 miles further south. All the islands are volcanic, and were studied in 1866 by Hochstetter (1866), and more recently by Phillipi (1905). New Amsterdam is completely basaltic, and Lacroix (1923*d*) reports in two recent analyses 0·79 and 0·51% K_2O ; so it is evident that the basalts of this island contain appreciable potash. In the reports of the German expedition a volcanic " bomb " is described from a depth of 2414 metres at a station 114 miles north-east of that island. It is significant that in the analyses of this " bomb ", incomplete as they are, 1% of potash occurs, giving support to our contention that the low potash content of the Carlsberg Ridge rocks is not related to the action of sea-water. St. Paul is geologically more complicated, but in the eight available analyses the potash is never below 0·67%.

Kerguelen comprises a great number of small islands and is situated 70° E. and 50° S. The islands are made up, apart from a bed of lignite, of basalts, trachytes and phonolites, and the smallest potash content in the fourteen available analyses is 0·85%. Heard Island, situated about 300 miles S.E. of Kerguelen, was investigated by the "Challenger" Expedition, the rocks being basalts, trachytes and limburgites, all of which contain appreciable potash (0·95 to 3·22%). It may be judged even with this cursory presentation that the rocks of New Amsterdam, St. Paul, Kerguelen and Heard have little resemblance to those from the Carlsberg Ridge.

(*b*) THE DECCAN TRAPS.

The great continent of Gondwana has appeared on many maps since Suess first named it, and it has furnished convenient paths for the wandering floras and faunas. The hypothesis that the oceanic basins may have once been extensive continents was conceived before the theory of isostasy. According to this theory if the continents, consisting of relatively light rock, sank several thousand feet, they would produce a negative gravity anomaly, which is contrary to the facts so far as they are known, for the ocean basins are practically in equilibrium, or with a slight tendency to a positive anomaly. Nor can it, as Willis (1932) pointed out, be suggested that Gondwanaland consisted of relatively heavy basalt, which has now sunk to its equilibrium level, for such a mass would, when it rose above the waters, constitute a very heavy load on the earth's crust. The difficulty might possibly be overcome by postulating the association of basaltic and granitic types on Gondwanaland, and in connection with its possible constitution it is interesting to compare the rocks from Station 133 with the Indian basalts.

The Deccan traps, extruded towards the end of the Cretaceous or possibly in Lower Eocene times, cover an area of more than 200,000 square miles in central and western India. At Bombay Oldham (1893) gives a minimum thickness of 7000 ft., and it is unlikely that such a thickness of lavas would cease abruptly on the coast without some continuation under the sea. Washington (1922*a*), in a valuable contribution, has made a detailed chemical study of the Deccan traps involving eleven new rock analyses, and according to that investigator the most striking feature of the series is their uniformity in composition. In eight analyses the silica varies from 48·6 to 50·1, whilst three have higher silica. The larger group is characterized by high iron oxides, varying from 12·6 to 14·5%. Corresponding to this high FeO the amount of MgO is low, whilst the potash is appreciable in all the analyses. In Table VII, column 7, Washington's average Deccan trap is recorded, and compared with the average Carlsberg Ridge basalt it is much richer in total iron and potash, but poorer in magnesia and soda. There is therefore no close chemical similarity between the Deccan traps and the rocks from Station 133, and consequently the author cannot concur with Coates's (1934) tentative correlation of the rocks from Station 133 with the Deccan traps. It is significant to mention in this connection that the radium content of the Deccan traps is very much greater than in the rocks from Station 133.

From the above considerations the author is led to believe that if the rocks from Station 133 and 166 represent remnants of Gondwanaland, then the composition of this hypothetical continent was different from the Deccan traps. The thesis that the rocks at Stations 133 and 166 are of submarine origin has already been advanced, and it has been suggested that the association of igneous rocks with a major tectonic structure, as well as their semi-spilitic nature (which is so characteristic of basalts from geosynclinal areas), give valuable confirmatory evidence to such an hypothesis. In addition, the subaqueous oxidation of the variolitic basalt appears, to the author, to support this contention, for it is argued that if the basaltic fragments were remnants of Gondwanaland the oxidation would in all probability be subaerial. Subaerial oxidation has, according to Pirrson, taken place in the igneous platform of Bermuda Island, where an oxidized zone of considerable thickness rests on unoxidized basalts. It is significant that in the petrographical descriptions by Pirrson and Thomas (*1914b*) no record is made of glass in the unoxidized melilite-basalts, lamprophyres, monchiquites and keratophyres. Pirrson considers that the oxidized products were formed from similar petrological types, so in this locality profound subaerial oxidation took place in spite of the fact that the rocks originally contained little or no glass. Similarly, Merrill (1897), when discussing the weathering of diabases, mentions that oxidation of the iron is a characteristic feature, but he makes on limitation of this process being dependent on the presence of glass, whilst a similar conclusion may be deduced from the analyses given by Harrison (1933) in his recent study on the tropical weathering of igneous rocks. It is a fair conclusion from these examples to regard subaerial oxidation as taking place quite independently of the presence of glass, and it is suggested that if such a process had affected the Carlsberg Ridge specimens, then oxidation would be common to them all. But this is not the case, for of the four analysed specimens, three show no trace of oxidation, and only one specimen, containing original glass, has been affected. We conclude from this evidence that the oxidation was submarine, and consequently the specimens, in all probablity, do not represent remnants of Gondwanaland. In connection with subaqueous oxidation, it is interesting to emphasize that in the rocks so far examined glass is essential for oxidation —a feature connected with the limited oxidizing power of sea-water and the instability of the metastable glassy phase.

(*c*) EAST AFRICA.

Tertiary lavas are well developed in East Africa, and as Gregory (1921) suggests that the eruption of the Kapiti Phonolite (late Cretaceous) probably coincided with the foundering of the Indian Ocean, it is interesting to inquire whether there is any geological resemblance between this region and the Carlsberg Ridge. Furthermore, as the Carlsberg Ridge has a superficial resemblance to the reflected image of the African Rift, it might be urged, by some, that the two structures are tectonically related, and consequently the lavas might exhibit similar petrological characteristics. Among the investigators of the African lavas are Gregory (1900), Prior (1903), Neilson (1921), Smith (1931), Holmes (1932) and Jérémine (1935), and the work of these authors indicates that the rocks are of a distinctly alkaline nature. As potash-poor types are unknown it is concluded that the rocks of this region do not resemble the Carlsberg Ridge, and in order to emphasize this dissimilarity an average analysis of twenty-four East African basalts has been compiled (Table VIII, column 2). Compared with the Carlsberg Ridge specimens the African basalt is typically poorer in silica and soda, but richer in potash and total iron.

TABLE VIII.

	(1)	(2)	(3)	(4)	(5)
SiO_2	51·12	43·12	49·54	50·63	50·06
TiO_2	1·72	3·04	0·78	1·63	1·96
Al_2O_3	14·81	13·77	16·47	15·82	15·51
Fe_2O_3	2·35	4·75	2·30	4·44	3·88
FeO	6·79	7·98	7·55	5·79	6·23
MnO	0·17	—	0·19	0·04	0·15
MgO	7·56	8·07	11·43	5·79	6·62
CaO	8·44	11·13	7·91	7·36	7·99
Na_2O	3·93	3·07	2·62	4·27	4·00
K_2O	0·13	2·58	0·30	2·31	2·10
H_2O+	2·36	1·98	0·95	1·47	1·16
H_2O-	0·54		0·27		
P_2O_5	0·14	0·52	0·08	0·43	0·25
CO_2	*Nil*	—	—	—	—
Inclusive	—	—	0·21	0·07	0·08
	100·06	100·01	100·60	100·05	100·00

(1) Average of three unoxidized basalts from the Carlsberg Ridge.

(2) Average of twenty-four alkali-basalts from East Africa. Localities: Mikeno, Visoke, Nirogongo, Kitelema, Bolingo, Katwe, Mukira, Adolphe Frédéric, Goma, Nyamunaka, Fort Ternan, Rogate River, Nyeri Road, Settima Scarp, Nyuki Scarp, Ngurumman Scarp, Lodwar, Kakalai, Lokitaung, Naivasha.

(3) Augite-olivine-basalt, Atlantic Ocean, 1° 56′ S., 12° 40·7′ W. 'Chemie der Erde.' V, 1930, p. 83.

(4) Average composition of Atlantic floor. 'Ann. Rep. Smithson. Inst.,' 1920, p. 307.

(5) Average composition of Pacific floor. 'Ann. Rep. Smithson. Inst.,' 1920, p. 307.

(*d*) OTHER OCEANIC REGIONS.

The lavas of volcanic oceanic islands, which are generally assumed to represent the material below, furnish for the most part the only direct evidence about the rocks that form the Atlantic and Pacific Ocean floors. Seismological evidence indicates that oceanic foundations are largely basaltic, for according to Angenheister (Gutenberg, 1932), the velocity of the longitudinal wave near the surface of the sub-Pacific crust is 6·5 to 7·0 kilometres per second, which is appropriate to crystallized basalt, whilst Hiller's study of the transmission of one type of surface wave under the Pacific leads to a like result, for he finds the velocity 3·69 kilometres per second (Hiller, 1927). Further, the work of Meinesz (1932) in the Pacific has made it exceedingly probable that the whole basin is in isostatic equilibrium, and suggesting thereby the existence of heavier rocks below, with considerable variations in density or chemical composition, or both. The basic substratum concept is supported by such authorities as Joly (1925*b*) and Jeffries (1929), whilst more recently Daly (1933) has suggested that in the open Pacific there is 80 kilometres of gabbro, and below that a substratum of vitreous basalt. Washington (1929) has emphasized that the intra-Pacific volcanoes are basaltic, but with certain peculiarities.

Many of the Pacific lavas are so rich in olivine that they have been given a special name—" oceanite "—and the same author has remarked on their association with alkaline lavas. In general basalts predominate to such an extent that the alkaline lavas constitute not more than 1 or 2% of the Pacific Rocks, but their presence throughout the whole basin is one of the striking characteristics. Washington considers that the Atlantic basin is petrographically more complex, and he distinguishes three regions: firstly, the Mid-Atlantic Ridge, secondly the islands (Madeira, Canary and Cape Verde Islands) which lie on the western continental shelf of Africa, and thirdly the Arctic Islands, Iceland, Jan Mayen, the Faröes, etc.

The Mid-Atlantic Ridge, which represents a long narrow submarine mountain range, extends from near Iceland in the north to about 57° S. latitude, and includes in its course the Azores, Ascension, Tristan da Cunha, and the very significant St. Paul's Rocks. The lavas of these ridge islands, apart from St. Paul's, which is a metamorphosed dunite (Washington, 1930*a*), resemble those of the intra-Pacific islands, as they are predominantly basaltic, with the characteristic association of trachytes. In the Atlantic, however, basalts rich in olivine are much less abundant, whilst the alkaline lavas are of more frequent occurrence. St. Helena, situated 900 kilometres east of the summit of the Mid-Atlantic Ridge, consists of a volcanic cone rising from the sea floor at a depth of 4200 metres. Daly (1927), in a recent investigation, states that St. Helena is largely basaltic, whilst the remainder is phonolitic. In four basalt analyses given by that author the potash content varies between 0·84 and 1·37%, whilst the total iron is comparable to that occurring in normal plateau basalts. Ascension (Smith, 1930; Daly, 1922) is largely composed of olivine basalts, but trachytes, obsidians and rhyolites occur. Of considerable importance are the granitic and syenitic xenoliths, which suggest that the Ascension cone rests on some older foundation. Esenwein (1929) gave an account of the petrology of the Azores. These islands are characterized by the usual association of basalts and trachytes, and in several new analyses the potash content is normal, whilst the iron is rather high.

It is a natural inquiry to ask whether the basalts of such islands, derived from eruptions of the central type, are really representative of the basic substratum. Although there is at present insufficient evidence to answer this question, the evidence obtained by the " Meteor " Expedition (Correns, 1930*b*) about the Mid-Atlantic Ridge is significant, for a basaltic rock containing augite, olivine and bytownite was dredged up from a depth of 2000 metres at 1° 56′ S., 12° 40′ W. The analysis of this submarine basalt is reproduced in Table VIII, column 3, and compared with the average basalts from St. Helena, Ascension and the Azores it is considerably poorer in total iron, but richer in magnesia. Further, on the basis of this one analysis it would seem that, although the Carlsberg Ridge specimens have comparable total iron, they are poorer in alumina and magnesia than the submarine Mid-Atlantic Ridge.

The average composition of the Atlantic floor derived by Washington (1920) from seventy-two analyses is given in Table VIII, column 4, and apart from the characteristic higher potash, this average resembles the Carlsberg Ridge rocks, whilst a similar remark applies to the composition of the Pacific floor (Table VIII, column 5) derived from fifty-six analyses. It is unfortunate that Washington does not record the relative number of basalts used in computing his averages, but the high potash and the low iron is no doubt partially related to the inclusion of trachytes and related rock types. We may judge from these oceanic comparisons that although the basalts of the Carlsberg Ridge are different from many of the basalts of the Atlantic and Pacific Islands, they have, apart from the lower potash, a comparable composition to Washington's average rocks from these regions.

(e) PLATEAU BASALTS.

Although there is little agreement among geophysicists concerning the earth's interior, the concept that the continental crust is floating on a universal substratum of sima, basaltic, or gabbroic in composition, meets with fairly general acceptance. It is generally assumed that the average composition of the basaltic substratum is similar to that of the plateau basalts (Joly, 1925*a*), and that the deeper ocean floors, being for the most part devoid of the lighter outermost crust, represent the basaltic substratum (Wegener, 1924). It is therefore of some interest to inquire whether the Carlsberg Ridge specimens have similar chemical characteristics to the plateau basalts. In 1922 Washington (1922*b*) gave a summary of the Deccan, Oregonian, Thulean, Patagonian and Palisadian plateau basalts, and we have in the foregoing pages compared the Deccan Traps with the Carlsberg Ridge, and noted that the former are much richer in total iron and potash, but poorer in soda. It is significant that this feature is common to all Washington's average plateau lavas, as will be readily seen from an inspection of Table IX, which is abbreviated so as to show only the essential constituents.

TABLE IX.

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
Fe_2O_3 . .	2·35	6·74	5·89	3·19	2·37	3·58	3·41	4·05	3·59
FeO . .	6·79	4·42	4·70	9·92	11·60	9·38	8·58	9·19	9·78
Na_2O . .	3·93	3·19	2·34	2·60	2·92	2·90	2·92	2·22	2·59
K_2O . .	0·13	0·04	0·57	0·72	1·29	1·01	0·72	0·59	0·69

(1) Average of three unoxidized specimens from the Carlsberg Ridge.
(2) Oxidized variolitic basalt from Carlsberg Ridge.
(3) Oxidized variolitic basalt from Station 166.
(4) Average Deccan basalt. 'Bull. Geol. Soc. Amer.,' XXXIII, 1922, p. 797.
(5) Average Oregonian basalt. *Op. cit. supra.*
(6) Average Thulean basalt. *Op. cit. supra.*
(7) Average Palisadian basalt. *Op. cit. supra.*
(8) Average of seven analyses of Plateau Magma type from Mull.
(9) Average of world plateau Magma. 'Igneous Rocks and Depths of the Earth,' New York, 1933, p. 201.

The available evidence would suggest therefore that the floor of the Indian Ocean is characteristically different from the plateau magmas of the world. It is possibly confirmatory of this hypothesis that the basalt dredged from 2000 metres by the "Meteor" Expedition contains low total iron (Table VIII, column 3), and that Washington's averages for the Atlantic and Pacific floors (Table VIII, columns 4 and 5) show a similar feature as well as high soda. It is significant that in 1926 Washington (1926), when commenting on recent analyses from the Hawaiian Islands, states, "There are greater differences between them (*i. e.* the lavas of Hawaii and the Leeward Islands) and the Deccan traps or plateau basalts, shown chiefly in higher silica and iron oxides and lower magnesia of the latter ".

Objections can be raised against this suggested difference between the average plateau magma and the floor of the Indian Ocean on the score of the few analyses, but taken in conjunction with the analyses from other oceans, it may be considered a fair indication of its nature. In any case these analyses are the only ones as yet available, and the indications offered by them are of interest, provided their tentative character is kept in mind.

VII. SUMMARY AND CONCLUSIONS.

In the foregoing pages petrographical descriptions and chemical analyses have been given of four Carlsberg Ridge rocks dredged from a depth of 3385 metres (St. 133, 1° 25′ 54″ S., 66° 34′ 12″ E.), as well as an analysis of a variolitic basalt from Station 166 (6° 55′ 18″ N., 67° 11′ 18″ E.). The specimens from Station 133 are, for the most part, angular, but some are more rounded and have a coating of manganese nodule material. Three of the described rocks are basalts, whilst one is a hornblende-augite-dolerite. Chemically they have some spilitic affinities, and are characterized by low total iron, moderately high soda and very low potash. The possibility of the alkali content being related to the action of sea-water is discussed, and it is suggested that the high soda low potash feature represents an inherent tendency in the parental magma.

The Carlsberg Ridge rocks differ both petrographically and chemically from the basalts of Rodriguez, and it is indicated that these rocks give little support to Farquharson's suggestion that this island lies on a continuation of the Carlsberg Ridge.

It is concluded that the basalts from the floor of the Indian Ocean are not sunken representatives of the Deccan traps, for they are too poor in total iron and potash. Similarly the hypothesis that they are remnants of Gondwanaland is rejected, for the rocks have no close resemblance to the basalts from neighbouring regions ; secondly, the oxidation is subaqueous and not subaerial, as might reasonably be expected if they were remnants of a former continent ; and thirdly, their association with a major structural feature gives confirmatory evidence to a submarine origin.

Apart from the low potash, the Carlsberg Ridge specimens are comparable to average rocks from the Atlantic and Pacific Oceans, and the available evidence would suggest that the basaltic substratum of the Indian Ocean differs from the Plateau magmas of the world by a lower total iron content. The geophysical significance of this does not seem to have been previously appreciated.

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IX. APPENDIX: THE RADIUM CONTENT OF SOME SUB-OCEANIC BASALTS FROM THE FLOOR OF THE INDIAN OCEAN.

By J. H. J. Poole, Sc.D.

Through the kindness of Dr. J. D. H. Wiseman I have been enabled to measure the radium content of some basalt specimens dredged up from the floor of the Indian Ocean. The results are of some interest, since, as far as I know, this is the first occasion on which basalt specimens from such depths have been available for radium content measurements. It is hoped also to determine their thorium content at some future date, but all radio-active measurements show that a rock deficient in radium is also deficient in thorium, so that the low values of radium content obtained for these basalts may be taken to indicate a low thorium content also, pending exact measurements.

The procedure employed for measuring the radium content of the basalts was Prof. Joly's original electric furnace method, in which the rock powder is fused with a mixture of alkali carbonates and a small quantity of boric acid in an electric furnace at about 1100° C. During this process the rock is decomposed with the evolution of a large quantity of CO_2 and any radon contained in the rock is liberated. The CO_2 is absorbed by soda-lime and the radon transferred to a previously standardized gold leaf electroscope. By observing the increase in the rate of leak of the electroscope, the amount of radium present in the rock can be estimated. Usually about 8 g. of rock is used for each determination. This method has been previously fully described (1).

All the precautions mentioned in the former papers, such as freeing the carbonates and boric acid from radon by solution in water and evaporation to dryness immediately before use in the furnace, were adopted. The type of electroscope employed, however, was slightly modified, the container of the gold leaf system being made of aluminium instead of glass, as previously. Theoretically this should be better, as in a glass envelope there is a possibility of error due to an irregular distribution of electric charge on the dry inner surface of the glass, but actually no difference in the behaviour of the electroscope could be detected. This is probably due to the fact that, for the excessively small ionization currents measured, the glass acts as a fairly good conductor either through conduction or displacement currents. The electroscope was standardized as formerly by adding a known amount of uraninite dissolved in borax glass to the rock powder. Its constant was $0{\cdot}85 \times 10^{-12}$ g. of radium per scale division per hr. This value is very similar to that of the previous electroscopes employed. As a further check on the standardization, a repeat experiment was made on a basalt from Colorado, whose radium content had previously been twice measured, and a practically identical value was obtained.

The locality of origin and the radium contents of the available specimens are given in the following table :

Specimen.	Latitude.	Longitude.	Depth in metres.	Radium content 10^{-12} g. per g.
Basalt near Tillanchong (R.I.M.S. "Investigator")	8° 32′ N.	94° 10′ E.	2270	0·43
Augite-basalt, St. 133, 8	1° 26′ S.	66° 34′ E.	3385	0·46
Variolitic augite-basalt, St. 133, 12	,,	,,	,,	0·49
Hornblende augite-basalt, St. 133, 15	,,	,,	,,	0·49
Basalt, St. 166, 6	6° 55′ N.	67° 11′ E.	4793–4850	0·46
Mean value	—	—	—	0·466

The chief interest in the values obtained centres in their great uniformity and their low value. The freshness of the Tillanchong basalt, combined with the fact that it is probably of recent origin, indicates that this low radio-activity did not originate through a possible abstraction by the sea-water. Jeffreys (2) commented on a similar uniformity in the results for the Hawaiian basalts. It is noteworthy also that the basalt from near Tillanchong in the Nicobar Islands is at a considerable distance from the specimens from the neighbourhood of the Carlsberg Ridge, yet its radio-activity is practically the same. This fact, taken in conjunction with their low radium content, mean value about $0{\cdot}47 \times 10^{-12}$, compared with $0{\cdot}77 \times 10^{-12}$ for the Deccan basalts and 0·75 for all plateau basalts, suggests that possibly we may be dealing with the parent basaltic strata from which the granites and surface basalts are derived. It is interesting to point out that these radioactive determinations support the idea put forward by Dr. Wiseman that the Carlsberg Ridge basalts are chemically quite distinct from the Deccan traps, and therefore cannot be their sunken representatives.

I have consulted Dr. Jeffreys as to the probable composition of the floor of the Western Indian Ocean, and he informs me that little is known either from seismological or gravitational data. It is usually considered, however, that whereas the floor of the Atlantic may be composed of more acid materials than basalt, the Pacific is probably floored with basalt, and in the absence of definite contrary evidence, we might assume that the Western Indian Ocean is similarly floored.

In any case the results fully confirm the view that the deeper the probable origin (*i. e.* the place where the rock solidified) of a rock, the less its radio-activity. It might be noted that the values for these basalts lie between the previous values obtained for surface basalts and eclogites, the latter being presumably of deeper origin.

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DESCRIPTION OF PLATE.

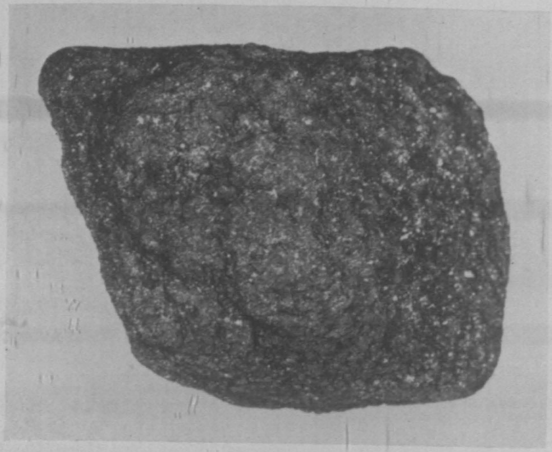
FIG. 1.—This specimen has a distinctly rounded appearance due to the peripheral coating of manganese nodule material. × 1 (St. 133, 8).

FIG. 2.—The exterior features of the hornblende-augite-dolerite are distinctly angular, and the peripheral black coating is of negligible thickness. × 2 (St. 133, 15).

FIG. 3.—This photograph of a sectioned specimen shows the junction between the interior basalt and the exterior black coating. The junction is sharp and the insoluble material occurs in a roughly radial direction. × 7 (St. 133, 8).

FIG. 4.—When the exterior manganese zone of a rounded specimen is removed an angular basaltic fragment is left behind. × 1 (St. 133, 8).

FIG. 5.—This section of a rounded specimen shows the exterior manganese material surrounding an angular fragment of basalt. The lighter material represents fragments of the insoluble material arranged in a radial direction. × 1 (St. 133, 8).



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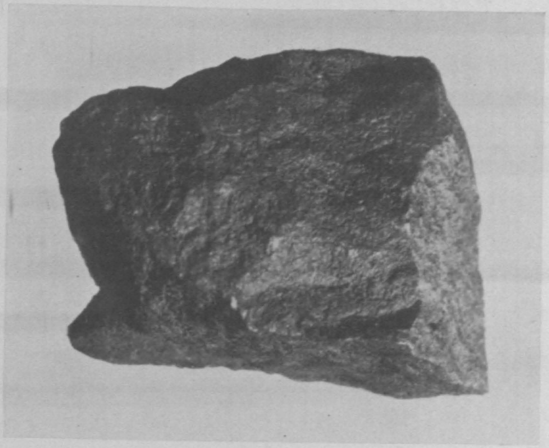

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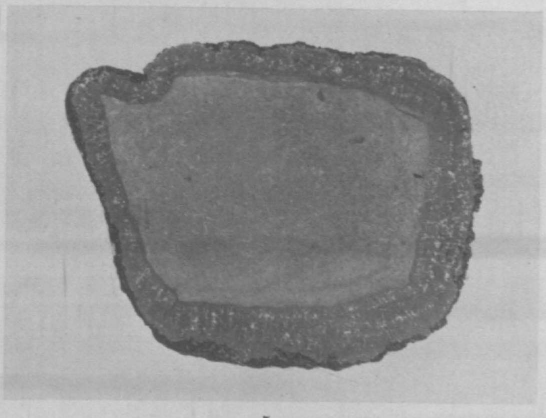

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