PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES

Altered Basalts from Swallow Bank, an Abyssal Hill in the NE Atlantic, and from a Nearby Seamount

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III. WEATHERED AND METAMORPHOSED BASALTS

Altered basalts from Swallow Bank, an abyssal hill in the NE Atlantic, and from a nearby seamount

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[Plate 10]

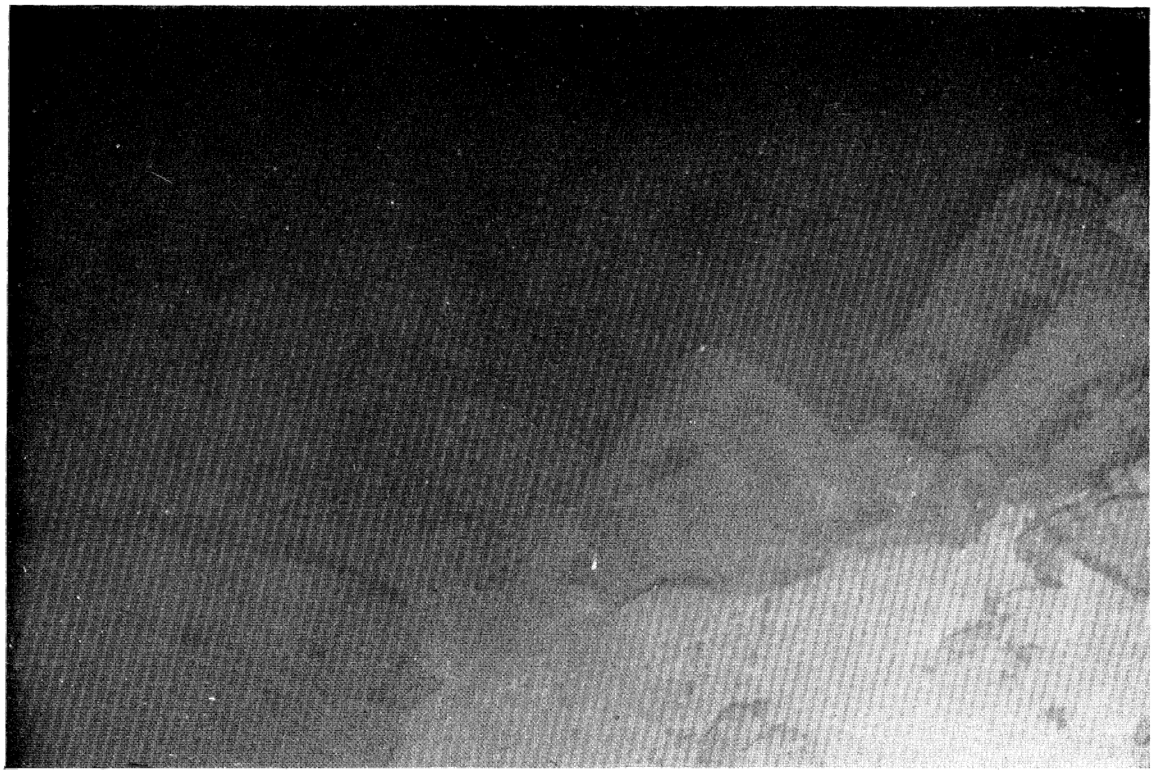
Three hundred and fifty-seven specimens dredged from Swallow Bank in 1958 are vesicular hypocrystalline porphyritic basalts. Chemical, thin section and X-ray studies were made. The least altered specimens gave an analysis close to the tholeiitic ocean floor basalt type. The glassy selvage of pillows altered sequentially to palagonite, fibro-palagonite and montmorillonite. Within the flows the mesostasis and pyroxene phenocrysts have been replaced by chlorophaeite, fibro-chlorophaeite and obscure chlorites, the calcic cores of plagioclase phenocrysts by a mesh of orthoclase plates and their sodic rims by (?) montmorillonite. Similar, but more extensive, mineralogical changes have affected the lavas from the seamount. Chemically, at Swallow Bank, the alteration of the flow interior involved increases in K_2O (from 1.0 to 3.5 g/100 g), in H_2O+ (from 1.2 to 5.2 %) and in oxidation ratio, Fe_2O_3:Fe_2O_3+FeO (from 71 to 98 %) with concomitant loss in CaO (from 11.1 to 2.3 %) and MgO (from 4.7 to 1.8 %). In these rocks radioactivity increased, seismic velocity decreased and intensity of magnetization remained substantially unchanged. Similar altered rocks could be widespread in layer 2 beneath the ocean.

Introduction

In May 1958 altered lavas were dredged by R.R.S. *Discovery II* from the floor of the deep Atlantic some 450 km west of the coast of Portugal (figure 1*a*). They were described in two unpublished dissertations in 1959 and 1961 which were briefly reviewed in two short publications (Matthews 1961*a*, 1962). They formed a link in the chain of argument that led to the conclusion that seismic layer 2 in the deep oceans consists of lavas and not limestones (Menard 1964). I regret that most of the data remained unpublished for more than 8 years; however, in the interests of brevity and contemporary relevance much of it must now remain so: the especially diligent reader will be welcome to borrow a copy of Matthews (1961*b*).

Swallow Bank is an elongated abyssal hill that projects through the sediment near the western margin of the Iberia abyssal plain (figure 1*b*). It rises some 300 m above the surface of the flat-lying turbidites and is about 30 km long by 1 km wide. *Discovery II* spent most of May, June and July thereabouts in 1958. Results from deep-current measurements, camera stations and echo sounding led to the conclusion, reached on board, that the bank has a steep scarp slope facing upcurrent to the WNW and littered with loose talus blocks, a top on which jointed rock outcrops were photographed (figure 2, plate 10) and a more gentle slope down to the ESE largely covered with globigerina ooze but having some rock steps. Some 300 kg of rock were obtained by dredging up the steep west face (Discovery station 3745), see figure 3, plate 10.

Two seismic refraction lines were shot parallel with Swallow Bank and a split profile across it. The results were puzzling but they suggested faulting in layer 3 and are consistent with Swallow Bank being an exposure of layer 2 and having a thickness of about 4 km of crust beneath it above the 'moho' situated at a depth of 9.5 km (M. N. Hill, personal communication). A magnetic survey indicated no consistent lineation. Swallow Bank lies about 1200 km from the crest



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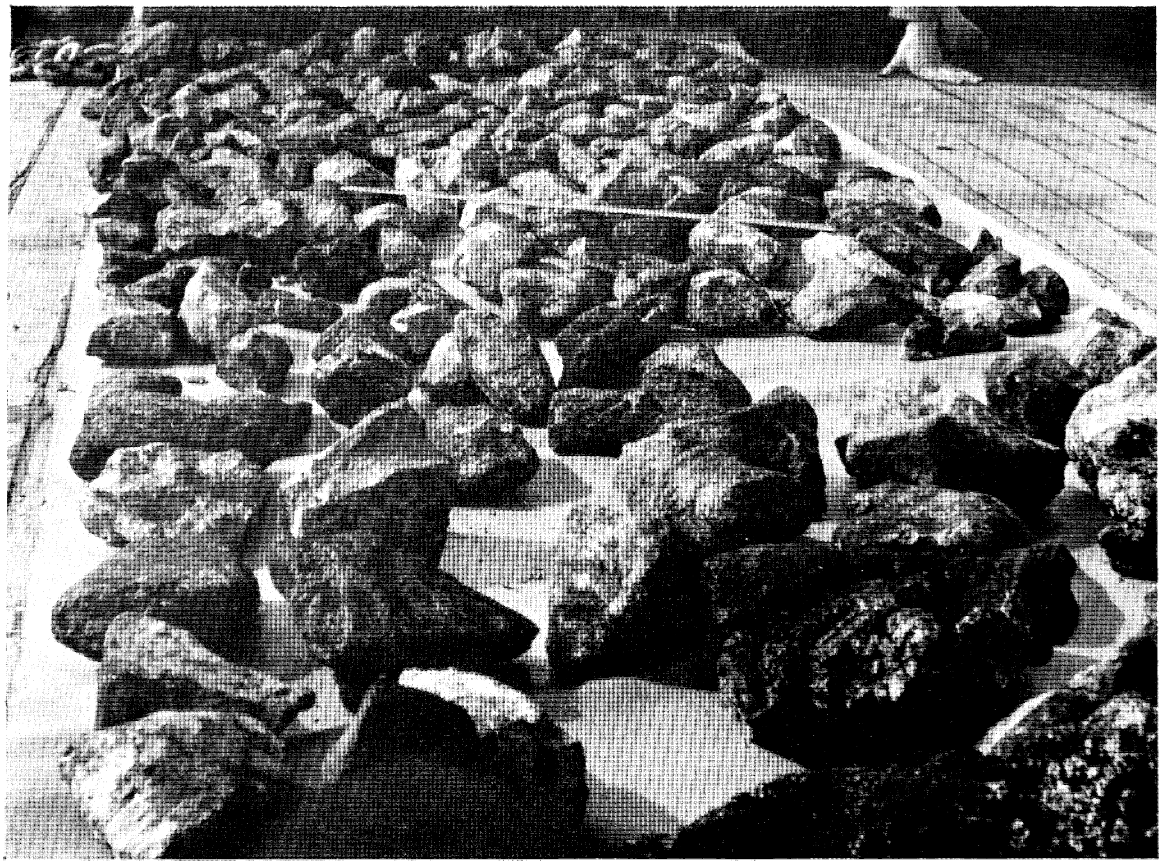

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PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES

FIGURE 2. Jointed outcrops or boulders of lava at the summit of Swallow Bank, 324 m above the abyssal plain. Underwater camera photograph by Dr A. S. Laughton. Width of picture about 3 m.

FIGURE 3. The collection from Swallow Bank laid out on deck with a metre ruler.

(*Facing p.* 551)

of the Mid-Atlantic Ridge; if the mean rate of spreading is 1.15 cm a^{-1} it may be that the lavas were erupted at the crest of the ridge some 105 Ma ago, i.e. in Cretaceous time.

The Western Seamounts stand at the southwestern margin of the Iberia abyssal plain and are shown in the bottom left corner of the survey in figure 1*b*. They rise to twin peaks; the

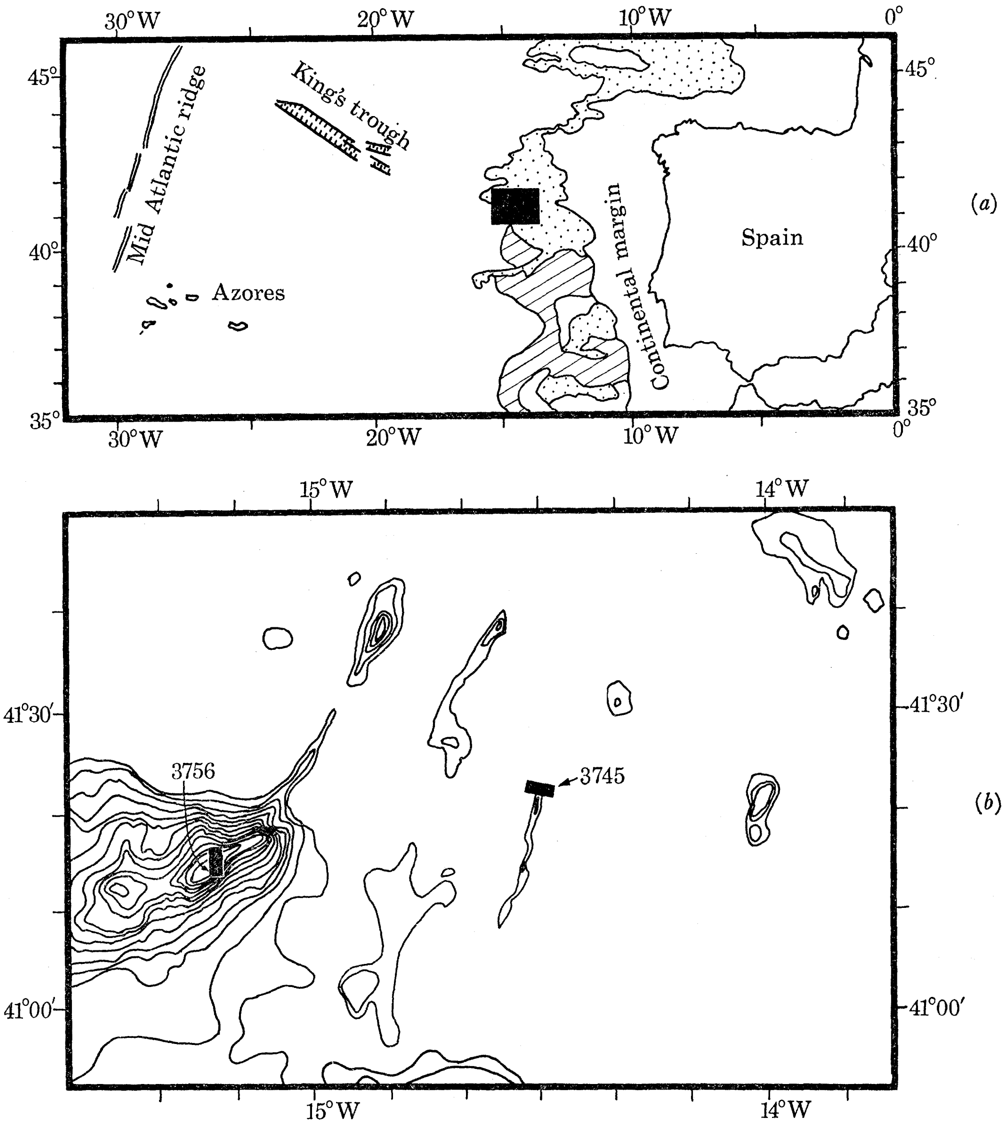

Figure 1. (*a*) Location of the Swallow Bank area (solid black, (*b*)) at the western margin of the Iberia abyssal plain. Dots show abyssal plains, shading shows areas with prominent seamounts. After Heezen & Tharp (1968) and Laughton in Matthews *et al.* (1969). (*b*) Bathymetry of part of the Iberia abyssal plain based on survey by R.R.S. *Discovery II* (A. S. Laughton, unpublished) showing position of dredge stations Discovery 3745 (Swallow Bank) and 3756 (Western Seamounts). 100 fathom contours show hills rising above the abyssal plain which slopes from 2812 fathoms in the NW to 2823 fathoms in the S.E. Uncorrected soundings at 800 fathoms ≡ 1 s. 1 fathom = 1.8288 m.

shallower, easternmost one reaching 2630 m (1400 fathoms uncorrected), 2700 m above the plain. About 50 kg of rock was obtained by dredging up the steep SE slope of this peak (Discovery Station 3756). Adjacent underwater camera stations showed rock outcrops and talus slopes (Laughton 1963).

The collection consisted of 362 pieces of rock from Swallow Bank and 65 from the Western Seamounts. All of them were encrusted with black 'manganese', ranging from incipient coatings less than 0.25 mm in thickness to thick cauliflower-like crusts up to 10 mm thick. The results of examination of the external features of the dredged stones (Matthews 1961 *b*) need not concern us here; they led to the suggestion of a process whereby nondescript angular blocks of rock may be detached from massive rock outcrops (Matthews 1961 *a*); such blocks formed 88 % of the collection from Swallow Bank and are frequently photographed on submarine talus slopes. This process is quite distinct from the alteration of the body of the lavas which concerns us here.

Thin sections of these highly altered rocks are 75 % semi-opaque mess. As it was impracticable to examine thin sections of all of them, the rocks were broken open and classified on the basis of textural distinctions visible under binocular microscope. Samples were selected for sectioning on the basis of this examination, 44 from Swallow Bank and 22 from the Western Seamount.

In 1961 two questions seemed to be posed by the altered rocks:

(1) What were the original lavas—were they tholeiitic or alkaline; do they reveal any mineralogical peculiarities indicative of an unusually deep seated origin for the magma?

(2) What alteration processes have affected them—have there been bulk chemical changes sufficient to affect the chemistry of the sea water, or mineralogical changes capable of supplying new detrital clay minerals to the seafloor? How has alteration affected their physical properties?

The first question is now of less significance than it was in 1961 because of the increasingly general recognition of a low-potash ocean floor basalt type (Engel, Engel & Havens, 1965) commonly found on minor features of the seafloor, and of alkali basalt series found on seamounts. These conclusions are based on examination of much fresher material than that from the Iberia plain area. In this paper we will merely summarize the answers that were given to the first question and concern ourselves principally with the second, the nature of the alteration process and its effects. Although it will appear that the Swallow Bank rocks represent extreme examples of alteration the chemical changes which accompanied it may be incipient in many fresher lavas on the deep-seafloor. The reader primarily interested in the chemistry of the alteration process is advised to skip hence to page 562.

Chlorophaeite and Palagonite

It will be useful to discuss these two mineraloids which occur abundantly in the altered lavas from the Western Seamounts and Swallow Bank now, although to do so involves some anticipation of results that could appear later in the paper. In the subaqueous alteration of lavas two rather similar alteration products may be formed which were originally distinguished by Peacock & Fuller (1928): chlorophaeite formed by hydrothermal alteration of the basic mesostasis of the lava, and palagonite formed by the action of hot exotic water on sideromelane glass. On land both these products may subsequently be altered to nontronite by cold groundwater (Allen & Scheid 1946).

Chlorophaeite was described from Iceland by Peacock (1926) and from the Columbia River plateau basalts by Peacock & Fuller (1928). Peacock describes the occurrence of chlorophaeite as 'in spherulites up to 8 mm in diameter, filling or lining cavities, as irregular patches in the groundmass, in veinlets, as pseudomorphs after olivine and pyroxene, and as a replacement of the vitreous base or mesostasis of basic extrusives'. Peacock & Fuller noted that chlorophaeite can be birefringent due to the presence of 'chloritic fibres'. Wiseman (1937) came to a similar conclusion on submarine material.

Campbell & Lunn (1927) described an occurrence of chlorophaeite in Scottish tholeiites where it is associated either with skeletal iron ores, glass and poorly crystalline potash felspar, or with chlorites and no glass. Green isotropic chlorophaeite with opal, equivalent to chlorite and replacing intersertal glass, was described from Scotland by Walker, Vincent & Mitchell (1952). Similar associations occur in the rocks from Swallow Bank.

Fuller (1931) studied some subaqueous flows among the Columbia River plateau basalts. He described the chilling of basalt flows erupted under water, the development of foreset beds of palagonite and sideromelane fragments, and the formation of ellipsoidal pillow lavas and massive palagonite tuffs. Later (1932) he described field evidence to show that the palagonitization of sideromelane is brought about by steam during the quenching of the glassy crust of the hot lava. The plausibility of the process has been demonstrated in the laboratory by Hoppe (1941) and similar conclusions have been reached for submarine material by Nayudu (1964) and Bonatti (1965).

Peacock (1926) described the conversion of sideromelane to palagonite among palagonite tuffs in Iceland:

sideromelane (+olivine and anorthite) refractive index 1.61
↓
sideromelane with iron globulites
↓
yellow isotropic gel palagonite, r.i. 1.50 [14 to 24% H_2O]
↓
faintly birefringent fibro-palagonite
↓
[earthy iron free grey palagonite (Peacock & Fuller 1928)].

The fibrous alteration product of palagonite was identified as a chlorite by Raw (1943) and earlier authors, but subsequently it has been shown to be the iron rich montmorillonoid, nontronite (Ross & Hendriks 1945; Allen & Scheid 1946). Chlorophaeite and palagonite were clearly distinguished by Peacock but subsequent authors before Stokes (1968) have not always maintained this distinction.

Chlorophaeite is a major constituent of some of the rocks from the Western Seamounts and a very common phase in the groundmass at Swallow Bank. Its occurrence and sparsely determined optical properties may be summarized thus:

Western Seamounts

Occurs (especially in the 'grey agglomerates') as a soft brown matrix engulfing relicts of lava. Slight birefringence masked by the brown colour of the mineraloid. Near the chalcedony lined vesicles the almost amorphous chlorophaeite (r.i. 1.54–1.56) becomes lighter in colour, minutely fibrous and more birefringent. Fibro-chlorophaeite: habit—aggregate textures, often radial with polarization crosses, and in veinlets; colour and pleochroism—darker brownish yellow to pale greenish yellow, $Z > X$; orientation—length slow; refractive index and birefringence—n_z 1.5 to 1.63, Δ 0.01 to 0.02.

Swallow Bank

Chlorophaeite occurs in the matrix as an almost colourless or pale grey translucent material. In thin section: pale green or brown, forming an abundant mesostasis, low relief $n >$ balsam, aggregate extinction, birefringence $<$ first order grey. Transitions to fibro-chlorophaeite occur. Fibro-chlorophaeite: habit—micro-cryptocrystalline aggregates (mosaic), occasionally obscurely fibrous; length—slow, expecially in veins. Three varieties—

(1) replacing sodic rims of plagioclase phenocrysts; palest yellow, soft and soapy; r.i. about 1.54, aggregate birefringence about 0.003;

(2) in the groundmass; pale green, yellow or brown;

(3) in veinlets; moderate to deep yellow or green, occasionally pleochroic; r.i. 1.6 to 1.65 aggregate birefringence about 0.015 or more.

So far as the optical properties go, fibro-chlorophaeite could be chloritic, though most of the chlorites have lower birefringence and the leptochlorites with oxidized iron have higher refractive indices; alternatively they are consistent with montmorillonoids containing various amounts of iron.

Palagonite is found only in the collection from Swallow Bank. Its formation in a marine environment is now quite well understood (Nayadu 1964; Bonatti 1965). The products of alteration of the surface of the flow at Swallow Bank will be described here and not mentioned again. The two constituents of the chilled margin of the flow that are commonly found in the collection are a red glassy material and yellow palagonite.

Most of the broken boulders and cemented breccias (p. 558) preserve no unaltered glass and have lost their palagonitic tops. In them the outside surface is marked by a red layer 1 cm to 1 mm thick. This crust is brick-red in hand-specimen, rather hard and brittle, and has a dull to resinous lustre. In thin section it is seen to consist of flamboyant spherulites of limonite (orange in reflected light). The interstices are filled with colourless cryptocrystalline material (white in reflected light). Some of this is chalcedony but much is fibro-palagonite. Similar cryptocrystalline material replaces plagioclase phenocrysts in the crust. Loose grains of this oxidized devitrified glass occur frequently in the breccias and some of them show transitions to yellow palagonite which make it clear that the two are related. Only two rocks in the collection preserve any unaltered glass (sideromelane) and in one of these, shown in figure 3, the glass is clearly surrounded by this red glassy material.

Palagonite is abundant in the dredged collection. It occurs in the 'earthy' debris of cemented breccias, as pea-sized grains embedded in manganese crusts, as a component of the red crusts, in vesicles and occasionally in the groundmass of the lavas. It is soft, yellow and easily cut with a knife. In thin section it is pale green, brown or yellow. The largest grains are substantially isotropic with low relief but most grains are cryptocrystalline (fibro-palagonite) with similar relief and low aggregate birefringence (Δ about 0.004) sometimes showing polarization crosses, radius—slow. Transitions between cryptocrystalline and isotropic varieties leave no doubt that one is derived from the other.

Microcrystalline chalcedony, in radial aggregates showing polarization crosses, generally accompanies the birefringent derivatives of palagonite. In the cemented breccias grains of yellow palagonite are intimately associated with pale grey 'earthy' clay-minerals which appear to represent the final stages in the alteration of palagonite. These facts suggest the following mineraological sequence for the alteration of the chilled margins of the flows:

clear isotropic sideromelane
↓
red oxidized divitrified glass
↓
isotropic yellow palagonite
↓
pale grey clay

This sequence is almost identical with that described from Iceland by Peacock in 1926.

A specimen of palagonite, 3745.368, taken from a thrush egg sized lump in a cobble of cemented breccia was analysed with results shown in table 3. The analysis shows this specimen to be typical of the mineraloid, comparable with material from the South Pacific (Murray &

Renard 1891, p. 307). The analysed sample has refractive index 1.515 ± 0.005 and density $2.26\ \mathrm{g\ cm^{-3}}$.

X-ray studies were made in attempt to determine the nature of fibro-palagonite and fibro-chlorophaete. Diffraction photographs were obtained of pressure aggregates of the analysed specimen of palagonite, 3745.368, and of three specimens of clearly fibrous yellow and green fibro-chlorophaeite from the Western Seamounts, all extracted from the matrix of the grey agglomerate. Since the patterns were too weak to print the results are illustrated in table 1 which shows the calculated lattice spacings (for the first order) and the relative sharpness and intensity of the lines on the photographs. The patterns produced by the three specimens of fibro-chlorophaeite were all very closely similar and were unaffected by glycerol.

Table 1. X-ray data

Swallow Bank material

montmoril.	palagonite			
glyc.	glyc.	dry	chloroph.	sheridanite
17.7 v.s.	18.8 b.w.	13.8 b.m.	13.8 m.†	13.7 m.
8.85 w.			7.04 m.†	7.04 m.
			4.63 w.	4.68 s.
4.50 v.s.	4.50 s.	4.50 s.	*4.50 s.*	
		3.77 w.		
3.54 w.	3.51 w.		3.51 s.	3.51 v.s.
	3.32 w.		*3.16 w.*	
2.61 }			2.84 w.	2.83 m.
2.55 } v.s.	2.59 s.	2.59 s.	2.57 m.	2.58 m.
2.41 }			*2.37 w.*	
			2.02 v.w.	2.02 m.
				1.56 v.s.
			1.88 v.w.	1.53 v.s.
1.50 v.s.	1.51 m.	1.49 m.	1.51 s.	1.39 v.s.

Lines are very strong, v.s., strong, s., medium, m. or weak, w.,; broad, b.

† Another specimen gave 14.9 and 7.2 for these lines. Column 1 from Brindley (1951), Tables IV_7 and IV_2, column 5 from Brindley (1951), Table VI_3. Similar results are given in the second edition published in 1961.

The data obtained was compared with tables compiled by the Mineralogical Society (Brindley 1951) from which the results for a glycerol-montmorillonite complex and a clay mineral chlorite (sheridanite) are quoted. It was concluded that the results indicate the presence of a montmorillonoid (not nontronite) in the palagonite but not in the fibro-chlorophaeite specimens which appear to contain interlayer chlorites with basal spacings approaching those of montmorillonite. (A similar pattern to that given by the fibro-chlorophaeite might result from vermiculite but the relative strengths of the higher order basal reflexions are more consistent with chlorite.) Lines not explained by this hypothesis are shown in italics in the table. It thus appears that fibro-palagonite is properly equated with a montmorillonoid and the coloured fibro-chlorophaeite with a clay mineral chlorite. Seafloor alteration of palagonite may well be the source of much montmorillonite found in pelagic sediments (Matthews 1962; Nayudu 1964).

Western Seamounts

Station 3756: 41° 14′ N; 15° 12.5′ W. Depth 3430 to 3350 m. 65 specimens.

Classification based on examination of 47 hand-specimens: (1) microvesicular lavas (22 %); (2) amygdaloidal pumice (11 %); (3) 'grey agglomerate' (33 %); (4) 'pink agglomerate' (35%).

Descriptive petrography

There is no fresh material from this station to give a clue to the original composition of the lavas so no chemical analyses were made. However, the petrology of the rocks throws some light on the mineralogy of the alteration process and is therefore worth describing. It was tentatively concluded that the unaltered lavas belonged to an alkaline series.

(1) *Fine grained buff or grey microvesicular basalts* (22 %)

The ten specimens in this category are all basaltic lavas with highly altered groundmasses. Two are porphyritic: one has idiomorphic crystals of bytownite zoned An_{84} to An_{76}, the other has phenocrysts of labradorite and of pale greenish buff augite, the only example of fully crystalline pyroxene from the Western Seamounts. Plagioclase, An_{52}, occurs as small laths and microlites dusty with inclusions set in a largely opaque groundmass consisting of smears of limonite derived from late crystallizing rods of iron ores, granules and patches of yellow chlorophaeite and occasional patches of a felspathic mesostasis having refractive index about 1.56. One specimen has laths of andesine, An_{45}, and a quartzo-felspathic intergrowth with mean refractive index about 1.53. Vesicles are filled with spherulitic aggregates of fibro-chlorophaeite which also occurs as a replacement of calcic cores of bytownite phenocrysts.

(2) *Grey and purple amygdaloidal pumice* (*mugearite*) (11 %)

In these rocks corroded laths of oligoclase, about An_{14}, with trachytic texture, are set in a largely opaque matrix consisting of limonite and chlorophaeite. Large irregular cavities are lined with scarlet haematite, yellow limonite and bluish white chalcedony, and contain calcite and radiating prisms of the zeolite natrolite.

The vesicular lavas described so far show only the early stages of the alteration process. In the two remaining classes, the 'grey agglomerates' and the 'pink agglomerates', alteration is more advanced. Its products are those already mentioned: amorphous and fibrous chlorophaeite, calcite and zeolites. In the least altered rocks these are developed in cracks and vesicles but in the most altered they are prominent and replace all the original minerals so that it is not immediately obvious whether the original rocks were massive lavas or fragmental pyroclastics.

(3) '*Grey agglomerate*' (33 %)

The 'grey agglomerates' provide the clearest example of the alteration process; in them chlorophaeite is the dominant product. The least altered block is a large boulder consisting of perfectly interlocking cuboidal grains of basalt separated by thin films of calcite and purplish limonite. The core of this boulder is essentially homogeneous lava transected by irregular shatter cracks. The lava has euhedral phenocrysts of bytownite (*ca.* An_{50}) in a largely opaque groundmass. In the more altered examples the lava is extensively replaced by chlorophaeite so that the angular residual grains are embedded in a soft brown matrix and the rock appears to be fragmental. The most altered have relics of phenocrysts and of late crystallized iron ores set in brown slightly birefringent chlorophaeite. Narrow cracks traversing all the specimens contain fibro-chlorophaeite; wider cracks have euhedral calcite, limonite and minute rhombs of chabazite.

Provided that the rocks are correctly placed in a series there can be no doubt that they were formed by the *in situ* alteration of shattered basalts like those described in the first pargraph of this section. They are not altered fragmental rocks.

(4) '*Pink agglomerate*' (35 %)

Polished surfaces of the pink agglomerates reveal sharply bounded grains of reddened lava set in an earthy greenish matrix in which patches of calcite are prominent. Fluxion structures in the lava are orientated differently from grain to grain suggesting a fragmental origin for the rock but, in contrast, delicate felspar laths sometimes project across the grain boundaries suggesting that the matrix was derived by alteration of the lava grains *in situ*. Other specimens show a transition from heterogeneous pink agglomerate of lava grains and matrix to a more homogeneous core of altered vesicular lava inside. It is concluded, on balance, that the rock was formed *in situ* by the alteration of once continuous vesicular lava. In thin section the lava has small laths of oligoclase, flow orientated, set in a messy opaque matrix containing ovoids of fibro-chlorophaeite. Cavities contain anhedral calcite and chabazite and euhedral natrolite in clusters of radiating prisms which have not been fractured and must have formed after the grain boundaries.

It is concluded that the 'pink agglomerates' were formed by the hydrothermal alteration of partly glassy mugearites which may have been already intimately shattered during cooling. The change resulted in argilization of the rock with formation of abundant hydrated iron ores and fibro-chlorophaeite accompanied by the growth of calcite, natrolite and chabazite.

Swallow Bank

Station 3745: 41° 21′ N; 14° 28.5′ W. Depth 5320 to 4960 m. 382 specimens.

Classification based on examination of 344 hand-specimens is summarized in table 2, p. 562.

(*a*) *Classification based on external appearance*

(1) *Erratics* (1 %)

The collection included five erratics (1 % of the whole number): a porcellanous limestone, a coarse gneiss, a calcareous sandstone, a fine grained gneiss and a piece of altered pumice.

(2) *Cemented breccias* (5 %)

The most weathered of these slabs have angular blocks and chips of lava on which the reddened chilled margin can often be seen, more or less closely interlocking and overlain by a 'soil' consisting of palagonite and its grey (montmorillonoid) decomposition product, with sparse calcite and zeolites, all cemented together by a crust of black 'manganese' 1 cm or more in thickness. They represent the products of weathering of the shattered top of the lava flow and its exfoliated palagonite crust (Matthews 1961*a*).

(3) '*Broken boulder shapes*' (6 %)

The ideal shape of a specimen in this class is shown in figure 4. It has a spherical top, frequently red weathered and exfoliated and often manganese encrusted, and planar sides perpendicular to the top. The upper parts of the sides are manganese coated in continuity with the top but their lower parts are often bare. The specimens are petrologically characteristic, showing transition from the chilled margin at the top to holocrystalline rocks characteristic of Swallow Bank at the base. They are believed to be fragments of pillow lavas which broke up along radial joints during cooling.

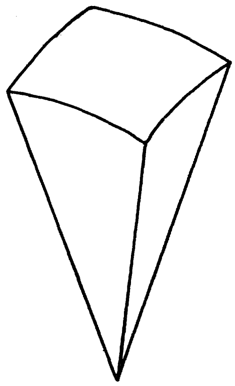

Figure 4. Idealized shape of 'broken boulders'.

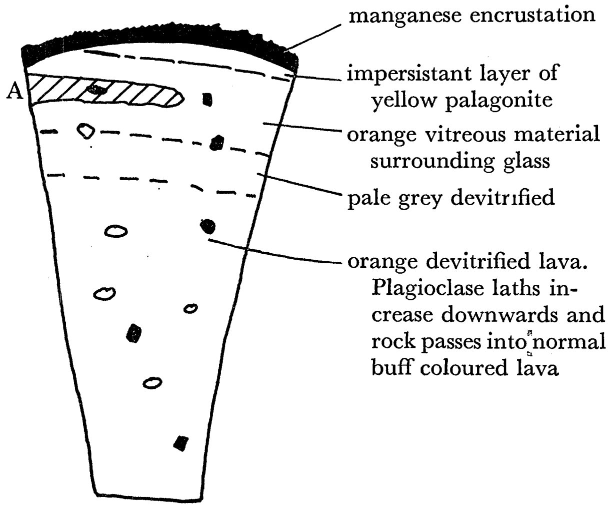

Figure 5. Sketch of progressive changes in lithology in a specimen of 'broken boulder shape' (3745.100). Drawn from a polished section 10 cm long. A, clear glass. Phenocrysts and vesicles shown conventionally.

(4) *Nondescript stones* (88 %)

A typical example from Swallow Bank is a subangular cobble, 9 cm across; the mean rounding index is 0.27 ± 0.07 and the median grade is 6 (Krumbein 1941).

The petrology of the broken boulders and nondescript stones is the subject of the rest of the paper.

(*b*) *Descriptive petrography*

(1) *The freshest rocks*

All the rocks from Swallow Bank are relatively soft altered vesicular leucocratic basalts except for three pebbles of mesocratic olivine basalt, a few small pieces of bedded vitric tuff and the five erratics. Initially the most informative specimens were the few in which the phenocrysts were still fresh. Most of them came from stones of 'broken boulder shape'. Only two specimens contained any unaltered glass. The best of them is illustrated in figure 5.

The letter A in figure 5 marks a patch of clear buff-coloured glass, isotropic, with refractive index 1.587 ± 0.003. The glass contains fresh euhedral phenocrysts of plagioclase and clino-pyroxene and a single phenocryst of olivine. Round the phenocrysts the glass is locally darkened and rendered semi-opaque with limonitic alteration products. Round the olivine phenocrysts, and round minute diamond-shaped relict crystals that are probably olivines, there are wider reaction rims. This is the only olivine recorded in the main part of the collection from Swallow Bank. The glass is transected by narrow veins of fibro-chlorophaeite.

For several centimetres beneath the glass the texture is dominated by flamboyant spherulitic structures in the groundmass. The phenocrysts are identical with those in the glass except that there is no olivine: plagioclase has rounded cores of bytownite (about An_{80}) rimmed with labradorite (about An_{70}) and occurs in handsomely twinned euhedral tablets up to 3 mm long, and pale green or colourless augite in stumpy euhedral prisms less than 1 mm across. The groundmass consists of almost opaque grey and brown materials spherulitically arranged and enclosing iron ores, plagioclase laths and ferromagnesian microlites, probably of clino-pyroxene. The opaque spherulites are of 'leucoxene' (grey in reflected light) near the glass but of limonite (orange in reflected light) elsewhere, arranged in handsome radiating brush-shaped areas whose ends often interdigitate with plagioclase microlites. The spherulites are up to 4 mm in diameter and each has a minute crystal at the centre; phenocrysts have been pushed to the margins. Between the spherulites is a sparse colourless cryptocrystalline mesostasis. This texture is typical of an oxidized devitrified glass.

Farther from the glass the spherulitic structures are less well developed and the groundmass consists of opaque limonitic smears and a more abundant yellowish cryptocrystalline mesostasis of fibro-chlorophaeite apparently developed at the expense of the pyroxene microlites and enclosing ores and minute plagioclase laths. Small open vesicles occur throughout the specimen; around them the groundmass contains a network of minute black needles.

An estimated mode at the hypocrystalline end is given in table 2 under class F.

Two chemical analyses were made of this specimen, one of a sample of the glass (of which only 5 g were available before splitting) the other of the hypocrystalline lava (table 3).

(2) *The more altered rocks*

Eighty per cent of the dredged stones from Swallow Bank reveal no trace of the chilled margin of the flow but are composed of altered hypocrystalline or holocrystalline lava from the interior. Their mineral constituents are fresh phenocrysts of plagioclase and clinopyroxene, plagioclase replaced by orthoclase and montmorillonite, fresh iron ores and 'manganese', and various groundmass materials.

Unaltered phenocrysts of clino-pyroxene and calcic plagioclase are present in the specimens assigned to class F (table 2) and in one or two others. Universal stage measurements suggest that the pyroxene is a diopsidic augite. When present the clino-pyroxene appears fresh; it is either present and fresh or absent, perhaps resolved into the groundmass. Alteration seems to proceed from the outside and the crystals seldom present wholly sharp margins to the ground-mass mesostasis. Phenocrystal plagioclase occurs in handsomely twinned tablets, frequently euhedral, and up to 3 mm in length. Compositions determined from combined Carlsbad/Albite twins lie in the range An_{76} (rims) to An_{85} (cores) for low-temperature forms.

In a very few of the freshest rocks the plagioclase phenocrysts remain intact, but in the majority, even of the fresh specimens in class F, first the calcic core and finally the whole crystal has suffered solution and subsequent replacement by other minerals. Solution and replacement have proceeded selectively along planes parallel to particular crystal faces. In a few examples only solution has occurred: the result is a tabular phenocryst in which the sodic rim remains but the calcic core is represented by a barred skeletal arrangement of plates of plagioclase, still distinguished from the groundmass of the lava by relatively high relief and birefringence. In the remaining examples in class F, only the rim of labradorite survives and the more calcic plagioclase of the core is entirely replaced by a lattice of orientated plates, optically continuous, of a colourless mineral which has very low relief and birefringence. Skeletal phenocrysts of this sort are conspicuous in hand-specimens of many rocks in classes A and B (figure 6), and in these rocks very little plagioclase remains: the calcic core is replaced by water-clear orientated plates, and the sodic rim by a clay–mineral aggregate that looks like soap.

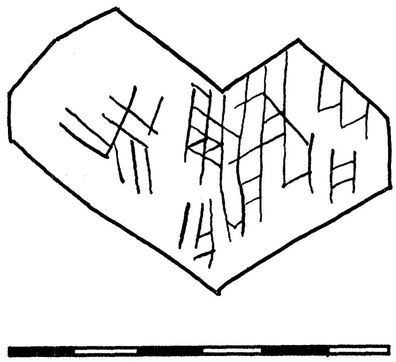

FIGURE 6. Sketch of a large, twinned, skeletal phenocryst in specimen 3745.190, illustrating how the skeletal plates generally lie parallel to crystal faces. The plane of the paper is the plane of flattening of the tabular pseudomorph and the plates are seen edge on. A third set of plates lie parallel to the paper and obscure the others over much of the area of the crystal. Scale of millimetres.

The plates are twinned and look like potash felspar. They are only about 0.03 mm thick. Optical properties determined on material extracted with great difficulty suggested the zeolite Harmotome ($n_\beta \leqslant 1.514 \pm$ *ca.* 0.003; biaxial positive?). X-ray powder photographs taken with Cu$K\alpha$ radiation in a 6 cm diameter camera for me by Dr P. Gay indicate a felspar and not a zeolite. It is concluded that the mineral is orthoclase. The soapy material replacing the rims of the crystals was identified optically as fibro-palagonite (montmorillonite) or as fibro-chlorophaeite (chlorite).

A precisely parallel case of replacement of plagioclase by orthoclase in the thin weathered rim of pebbles of dolerite embedded in a red clay core taken from 5450 m in the North Atlantic has been described by Mellis (1952, 1960).

The plates are subject to alteration of two kinds: they may be crowded with sericitic flakes or they may be altered to a clay–mineral aggregate like that which replaces the sodic rims. The smaller plagioclase phenocrysts merge without any distinct break in size into the laths and microlites of felspar in the groundmass and suffer similar alteration so that in the most altered rocks all the plagioclase is wholly replaced and swallowed up in a sea of the cryptocrystalline aggregate of the groundmass (fibro-chlorophaeite).

After the phenocrysts, iron ores are the least messy constituents of the rocks. Magnetite occurs as equant grains about 0.01 mm across, and a network of slender black needles embedded in the groundmass mesostasis frequently surrounds vesicles. Patches and veins of 'manganese' penetrate the rocks and are the seat of abundant radioactivity.

Four mineraloids, with plagioclase and ores, make up the groundmass. These are chlorophaeite and fibro-chlorophaeite forming an abundant mesostasis sometimes rendered opaque by a network of needles of ores, limonite, leucoxene and perhaps some palagonite. The identification of leucoxene, based on its white colour in reflected light, is suspect since the rocks show no increase in TiO_2.

Table 2 enumerates the classification and lists estimated modal analyses of typical specimens.

Table 2. Modal analyses

class	percentage of whole collection	phenocrysts	%	groundmass	%
A	13	chlorophaeite replacing orthoclase in pseudomorphs of plagioclase	20	chlorophaeite ± ores	10
				limonite	60
				ores	6
		shattered clino-pyroxene	< 1	manganese	4
B	28	pseudomorphs after plagioclase		unaltered plagioclase	15
				altered plagioclase	5
		in chlorophaeite	5	chlorophaeite ± ores	25
		in orthoclase	10	limonite and leucoxene	30
				ores	10
C	16	none		unaltered plagioclase	10
				chlorophaeite ± ores and sericite	60
				limonite and leucoxene	20
				ores (mostly network)	10
D	14	none		unaltered plagioclase	5
				chlorophaeite ± ores	50
				limonite and leucoxene	35
				ores (mostly network)	10
E	10	none		residual plagioclase	trace
				orthoclase replacing plagioclase	15
				chlorophaeite ± ores and sericite	50
				limonite	15
				fibro-chlorophaeite veins	10
				ores	10
				manganese	trace
F	7	pyroxene	1	plagioclase	13
		plagioclase	14	ores incl. manganese	10
		vesicles	5	limonite	37
				chlorophaeite	20
Z	11	see next section			

(3) *Other minor types*

Class Z of the classification includes the extreme or aberrant examples that do not fit into the other classes: yellow rocks, often with fresh phenocrysts, in which the groundmass is dominantly palagonitic (4 %); mesocratic olivine basalts (2 %); vitric tuff (1 %); erratics ($1\frac{1}{2}$ %) and five specimens that are extreme examples of the normal classes, including a specimen analysed (table 3) because it appeared to be the most altered rock in the whole collection.

(4) *Summary of the mineralogy of the alteration process*

The oxidized devitrified glass on the chilled margin of the flow has been converted to yellow palagonite, and the palagonite has subsequently altered to birefringent fibro-palagonite (montmorillonite) and finally to pale-coloured clay minerals (Peacock & Fuller 1928; Bonatti 1965).

The calcic cores of plagioclase phenocrysts have been replaced by skeletal plates of potash felspar (Mellis 1952) and the plates have subsequently become crowded with flakes of sericite. Their sodic rims have been replaced by cryptocrystalline montmorillonoids.

Augite phenocrysts, plagioclase laths and the glassy residuum of the lava have all been replaced by chorophaeite and fibro-chlorophaeite, a crypto-crystalline chlorite, with or without chalcedony, and the groundmass has been rendered opaque with limonite, leucoxene (?), rods of iron ore and smears of 'manganese' (Peacock 1926; Wiseman 1937; Walker *et al.* 1952). Similar changes have resulted in almost complete argilization of the rocks on the Western Seamounts.

The internal evidence does not indicate the temperatures at which these alterations took place. I speculate that the conversion of glass to palagonite and of residuum to chlorophaeite took place at high temperature immediately after eruption, the replacement of plagioclase by orthoclase and formation of zeolites on the Western Seamounts at moderate temperatures (< 200 °C) during initial cooling or subsequent hydrothermal episode; argilization was probably deuteric (cold) but might have been hydrothermal. The alteration of fibro-palagonite to grey (iron-free) montmorillonoids took place within the breccias, and therefore at 0 °C.

We see within the rock reactions that transform the original high temperature mineral assemblage into one in equilibrium with the cold, wet environment of the seafloor, a clay–mineral rock of cryptocrystalline montmorillonoids and chlorites. The most altered specimen selected for analysis was just that—almost white in colour and soft enough to scratch with a finger nail.

(*c*) *Chemistry*

Five specimens from Swallow Bank have been analysed: palagonite, the glass and hypocrystalline lava of 3745.100 (densities 2.74 and 2.72 g cm^{-3} respectively), a characteristic lava of class C (3745.2, density 2.45) and an extreme example of alteration from class Z (3745.81, density 2.38). All of them have been described above. The analyses were by W. H. Herdsman and Co. of Glasgow. Results are given in table 3.

(1) *The original lavas*

The question of the affinities of the Swallow Bank magma—tholeiitic, alkali or high alumina—loomed much larger in 1960 than it does in 1970. It will be seen from table 3 that there are significant differences between the composition of the fresh glass and the hypocrystalline lava adjacent to it; these differences were explained as being due to incipient alteration of the hypocrystalline rock and to the inclusion of an unrepresentative proportion of phenocrysts in the small sample of glass available for analysis (rather than to the iron enrichment of the exterior of the flow described by Correns in 1930). The two analyses were combined and recalculated to 100 and are shown in table 4.

The results shown in this table, and the consideration of plots of total alkalis against silica, iron enrichment against silica and alumina against alkalis, led to the conclusion that the unaltered Swallow Bank magma was marginally tholeiitic. This conclusion accords with the observation of a reaction relation between olivine and the melt. The postulated Swallow Bank magma agrees quite closely with the mean composition of oceanic tholeiites given by Engel *et al.* (1965).

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TABLE 3. CHEMICAL ANALYSES

Mass of oxide in 100 g of sample

	glass	hypocrystalline	typical	most altered	palagonite
SiO_2	48.14	49.31	47.44	47.11	41.96
TiO_2	1.28	1.25	1.88	1.55	1.63
Al_2O_3	13.37	17.21	15.58	18.37	16.06
Fe_2O_3	9.18	6.27	10.52	8.74	9.39
FeO	2.84	2.52	0.68	0.16	nil
MnO	0.08	0.16	0.15	0.14	0.08
MgO	6.22	4.71	2.89	1.84	3.69
CaO	11.46	11.16	6.87	2.34	1.49
Na_2O	2.19	2.73	2.94	2.41	1.82
K_2O	0.96	1.45	2.96	3.48	3.48
H_2O^- 105° C	1.94	2.02	4.90	8.52	13.99
H_2O^+ 105° C	2.20	1.15	2.35	5.20	6.34
CO_2	0.04	0.02	0.73	nil	nil
P_2O_5	0.15	0.16	0.28	0.22	0.01
Cl	0.04	0.05	0.11	0.18	0.22
total	100.09	100.17	100.28	100.26	100.16
total iron	8.66	6.35	7.89	6.24	6.56
o.r. %	74.4	69.1	93.3	98.0	100
less O for Cl	0.01	0.01	0.02	0.04	0.05
	100.08	100.16	100.26	100.22	100.11
specimen 3745.	100	100	2	81	—

TABLE 4. RECOMPUTED ANALYSES

	Engel, Engel & Havens	Swallow Bank postulated magma	norm	
SiO_2	49.3	51.7	Qz	3.1
Al_2O_3	17.0	18.0	Or	6.1
Fe_2O_3	2.0	2.1	Ab	18.9
FeO	6.8	6.6	An	35.6
MnO	0.2	0.2	Ne	—
MgO	7.2	5.0	Di Wo	8.9
CaO	11.7	11.7	Di En	5.0
Na_2O	2.7	2.3	Di Fs	3.6
K_2O	0.2	1.0	Hy En	7.3
TiO_2	1.5	1.3		
H_2O	1.3	—	Hy Fs	5.0
P_2O_5	—	0.2	Ol	—
			Il	2.4
			Mt	3.0
			Ap	0.3
totals	99.9	100.1		99.2

(2) *The alteration process*

Columns 1 to 4 of table 3 show the progressive bulk chemical changes that accompanied alteration. In comparing these analyses we can assume either that mass remains constant, or that volume remains constant, or that some particular major oxide, for example alumina, remains constant. Of these assumptions, the second is the most plausible and the proportional composition of 100 cm^3 of material is shown in table 5. Similar tables were prepared assuming constant alumina. We have also to consider whether all of the water in the altered rock is really combined at all and for this purpose the ratio Cl/H_2O is tabulated.

On all counts we see: no change in MnO, marked oxidation of Fe and increase in H_2O, possible loss of SiO_2 but marked loss of MgO and CaO, marked gain in K_2O.

The constancy of MnO is relevant to the much debated question of the provenance of the manganese which forms the pelagite ('manganese') encrustations on submarine rocks. It clearly does not support an origin in weathering basalts, although the Swallow Bank rocks are seamed with cracks on the faces of which 'manganese' occurs in arborescent films, and

TABLE 5. CHEMICAL ANALYSES

Mass of oxide in 100 cm^3 of sample

	glass	hypocrystalline	typical	most altered	palagonite
SiO_2	131.90	134.12	116.23	112.12	94.83
TiO_2	3.51	3.40	4.61	3.69	3.68
Al_2O_3	36.63	46.81	38.17	43.72	36.30
Fe_2O_3	25.15	17.05	25.88	20.80	21.22
FeO	7.78	6.85	1.67	0.38	nil
MnO	0.22	0.44	0.37	0.33	0.18
MgO	17.04	12.81	7.08	4.38	8.34
CaO	31.40	30.36	16.83	5.57	3.37
Na_2O	6.00	7.43	7.20	5.74	4.11
K_2O	2.63	3.94	7.25	8.28	7.86
H_2O^- 105 °C	5.32	5.49	12.01	20.28	31.62
H_2O^+ 105 °C	6.03	3.13	5.76	12.38	14.33
CO_2	0.11	0.05	1.79	nil	nil
P_2O_5	0.41	0.44	0.69	0.52	0.02
Cl	0.11	0.14	0.27	0.61	0.50
total	(274.24)	(272.46)	(245.81)	(238.80)	(226.36)
total Fe	23.73	17.27	19.33	14.85	14.83
Cl/H_2O^-	0.021	0.025	0.022	0.030	0.016
Cl/H_2O^+	0.018	0.045	0.047	0.049	0.035

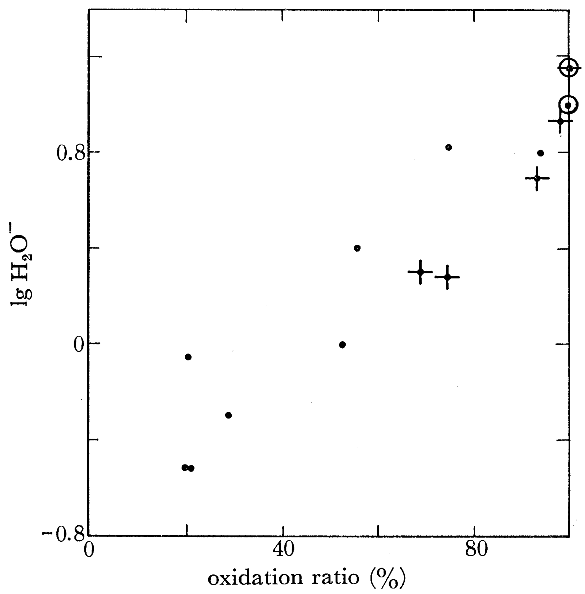

FIGURE 7. Plot of content of uncombined water (lg H_2O^-) against oxidation ratio, $Fe^{3+}/(Fe^{3+}+Fe^{2+})$. Analyses from Correns (1930), Wiseman (1937), Diller quoted by Allen & Scheid (1946) (palagonite, ringed) and Swallow Bank (crosses).

most thin sections encounter patches of 'manganese' in the groundmass; clearly, there has been some redistribution within the rocks.

In a paper on basalts dredged from a depth of 4000 m on the Carlsberg Ridge Wiseman (1937) drew attention to the oxidation of iron in analysed submarine lavas. He concluded that oxidation is confined to lavas containing some glass and that 'a high percentage of ferric iron is invariably accompanied by a large amount of uncombined water'. In figure 5 data assembled by Wiseman are combined with new data from Swallow Bank. The figure suggests a relation between oxidation ratio and the content of uncombined water.

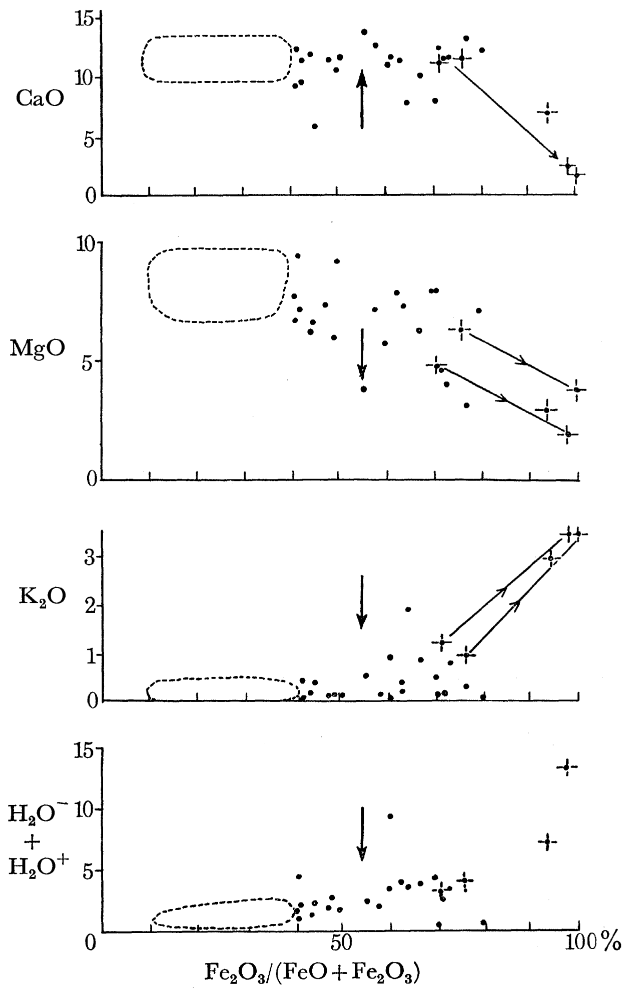

FIGURE 8. Plots of H_2O, K_2O, MgO and CaO against oxidation ratio, $Fe_2O_3/(FeO+Fe_2O_3)$. The dashed area encloses the field of non-weathered or slightly weathered basalts, dots are weathered basalts and crosses are Swallow Bank basalts. Based on about 100 published analyses available in October 1969. (J. R. Cann, personal communication.)

The entries in tables 3 and 5 suggest that conversion of sideromelane to palagonite, and probably alteration of the flow interiors, was accompanied by some loss of silica. The availability of silica in solution is shown by the films of chalcedony that line the vesicles and by the spherulitic aggregates of chalcedony associated with fibro-palagonite. The alteration of the flows was unquestionably accompanied by a large net loss of lime and magnesia. Precipitated

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calcite is rare in the collection from Swallow Bank, although it does occur in cracks and in the 'soil' of the cemented breccias. In this context it is interesting to note that authigenic dolomite has been encountered above altered basalts during recent drilling (Murata & Erd 1964; Peterson *et al.* 1970).

The analyses show a clear gain in potash in the altered rocks, indeed, this is the most striking chemical effect. The only reported secondary mineral able to accomodate this potash is orthoclase.

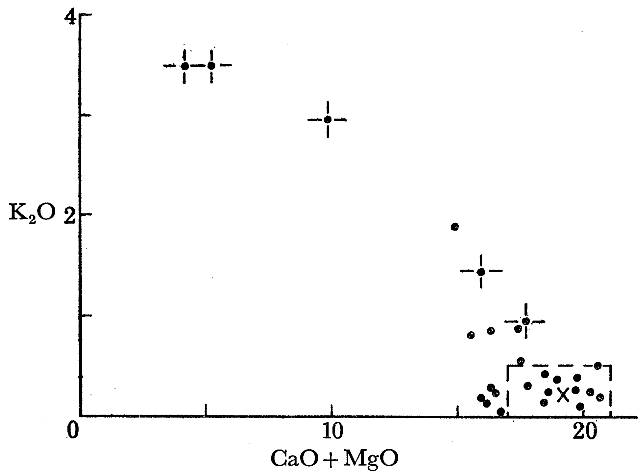

FIGURE 9. Plot of K_2O against CaO + MgO for the same data as figure 8.

The discussion so far has taken the least altered rocks from Swallow Bank as the starting-point. I am indebted to Dr J. R. Cann for figures 8 and 9 in which he has compared the analyses from Swallow Bank with data from published analyses of fresh and slightly altered submarine lavas. These two figures confirm that there is a relation between water content and oxidation ratio and suggest, somewhat less strongly, that alteration generally involves loss of MgO and frequently involves loss of CaO and gain in K_2O. They show clearly that the Swallow Bank rocks represent an extreme of alteration when compared with other analysed samples, perhaps because petrologists will not work on such unpromising material. J. R. Cann (personal communication) has suggested that 'It is clear from these results that analyses of ocean-floor basalts with oxidation ratios greater than 0.55 ($Fe_2O_3/(FeO + Fe_2O_3)$) cannot, as some authors have done, be treated as fresh basalts to which water has been added and which have been oxidized, and thus they must not be used in formulating schemes for the petrogenesis of basalts of the ocean floor.' The value 0.55 is indicated by arrows in figure 8.

PHYSICAL PROPERTIES OF BASALTS FROM SWALLOW BANK

(*a*) *Radioactivity*

It is a remote possibility that submarine basalts are much more radioactive than their subaerial equivalents and that this might provide a partial explanation of the approximate equality of terrestrial heat flow in the two environments. The experiments described in this section were undertaken with this in mind.

Bulk assays were made of specially prepared samples of typical specimens through the kindness of Mr R. H. V. Bowie at the Atomic Energy Section of the Geological Survey in London. Heat production has been calculated using constants quoted by Birch (1954). For comparison a typical value for granite is about 7 cal g^{-1} (29 J g^{-1}) in 10^6 years and for basalt about 1 cal g^{-1} (4 J g^{-1}).

These results indicate that the manganese is quite strongly radioactive and that the rocks themselves are about as radioactive as normal granites. They also suggest that the most altered rocks are the most radioactive. If altered lavas of this type form an appreciable part of layer 2 under the oceans their radioactivity is not negligible even if it is not an original property of the lavas.

The radioactivity of manganese nodules has been ascribed to preferential deposition of ionium (Th_{230}) and/or thorium (Th_{232}) from sea water. To find out whether radioactivity in the Swallow Bank rocks was uniformly distributed or concentrated near the margins, and to confirm that the unaltered glass was less radioactive than the altered holocrystalline rocks, experiments

Table 6. Radiometric assays

class	specimen	assay equivalent U_3O_8 parts per million	rate of heat production cal g^{-1} Ma^{-1}	(J g^{-1} Ma^{-1})
F	3745.216	12 ± 2	8.5	(36)
C	3745.2	12 ± 2	8.5	(36)
Z	3745.81	16 ± 2	11	(46)
—	manganese	48 ± 2	34	(142)

were made using nuclear photographic emulsions sensitive to α-particles. The results indicated that the unaltered glass is not radioactive; the small patch available for study did not give a count above background, but the hypocrystalline and holocrystalline rocks did. 'Manganese' in patches and veins, and veins of fibro-chlorophaeite both gave a high count. There was no concentration of activity near the margin of the rocks.

It was concluded that the original magma was not abnormally radioactive but that the rocks had aquired radioactivity associated with the secondary minerals formed during hydrothermal or deuteric alteration.

(*b*) *Magnetic properties*

Measurements of magnetic properties were made on 44 cylinders of lava cut from 26 dredged specimens chosen to cover the whole range of alteration. Intensity of magnetization (I) and susceptibility (k) were measured using an astatic magnetometer and confirmatory determinations of susceptibility were made on an a.c. inductance bridge.

Rather surprisingly, the results obtained showed no convincing correlation with degree of alteration. Values of remnant intensity of magnetization lay in the range 1 to 10×10^{-3} e.m.u. with a median value 5×10^{-3}. Determinations of volume susceptibility varied between the two instruments though they lay in the same range and were consistent with the known errors of measurement. Values lay between 1 and 10×10^{-4} e.m.u. and had a median value between 3.5 and 5.5×10^{-4}. Konigsberger's ratio (I/kH) lay between 8 and 34 with a median value of 21. Effective susceptibility, $(I+kH)/H$, has a median value 10×10^{-3} e.m.u./oersted cm^3 (figure 10). Detailed results are in Matthews (1961*b*). Check measurements of the intensity of magnetization of five specimens were made on a spinner magnetometer by Dr J. Ade-Hall and gave essentially identical results (personal communication).

Comparison of these results with values obtained on other seafloor and terrestrial basalts indicates that alteration at Swallow Bank has not made any substantial change in the intensity of magnetization; there is, of course, no evidence about possible changes in direction of magnetization.

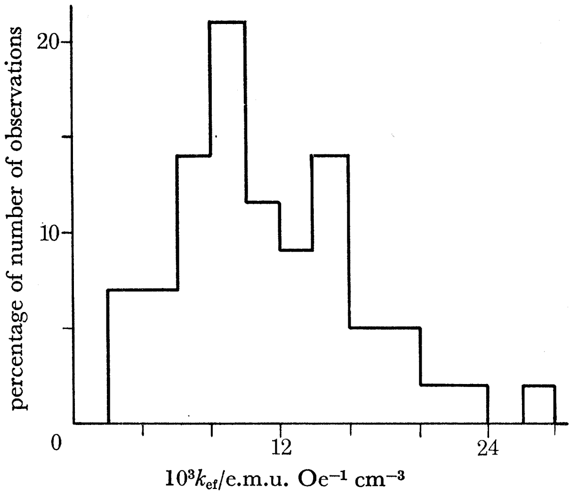

FIGURE 10. Histogram showing distribution of effective susceptibility $(I+kH)/H$, in 43 cylinders cut from 23 dredged stones. $H = 0.437$ Oe (*ca.* 35 A m^{-1}).

(*c*) *Seismic velocity*

Seismic velocity was measured in 45 water-saturated cylinders cut from 27 specimens; the surviving cylinders were subsequently used for the magnetic measurements. Two sets of experiments were made: in the first the velocity was measured parallel with an axial stress of a few atmospheres in a screw press at atmospheric pressure. Prior experiments established that, at the frequencies used (about 1 MHz), the cylinders were effectively 'short and fat' so that the velocity measured, V_p, was that of a compressional wave travelling in an unbounded medium. An ultrasonic pulse technique was used, developed from that of Laughton (1957). In a second set of experiments the effect of external pressure on five jacketed specimens was studied using a pressure pot similar to the one developed by Wyllie, Gregory & Gardiner (1958).

The results of the first experiment are shown in figure 11*a*. Although there is no absolute connexion between lithology and velocity there is a clear tendency for above average velocities (> 3.5 km s^{-1}) to occur in the fresher rocks of class F and for below average velocities to occur in the most altered rocks of classes C and D. The bulk of the lavas at Swallow Bank belong to classes B and C (table 2) and these rocks have velocities in the range 2.8 ± 0.3 km s^{-1}.

In the second experiment differential (compacting) pressures up to 1600 kgf cm^{-2} (160 MN m^{-2}) were employed, i.e. the difference between the pressure of oil surrounding the jacket and the pressure of the pore fluid, here maintained as atmospheric, was up to 1600 kgf cm^{-2}. The two fresh specimens gave typical results indicating that a pressure of about 1000 kgf cm^{-2} (100 MN m^{-2}) was sufficient to close the intercommunicating pores (figure 11*b*). The three less fresh specimens all crushed at about this pressure and the velocity in them continued to increase smoothly. Clearly they had never been subjected to such pressures in nature (1000 kgf cm^{-2} would be reached at a depth of about 7 km below the seafloor). All the specimens showed an increase of velocity above the velocity measured in the screw press of about 20 to 30 %, about 0.5 km s^{-1}, at a pressure of 1000 kgf cm^{-2}. This is clearly the limit of the correction which should be applied to the results obtained in the screw press (figure 11*a*) to give the seismic velocity of the rocks at Swallow Bank.

The conclusion drawn is that the seismic velocity of the bulk of the flows at Swallow Bank is

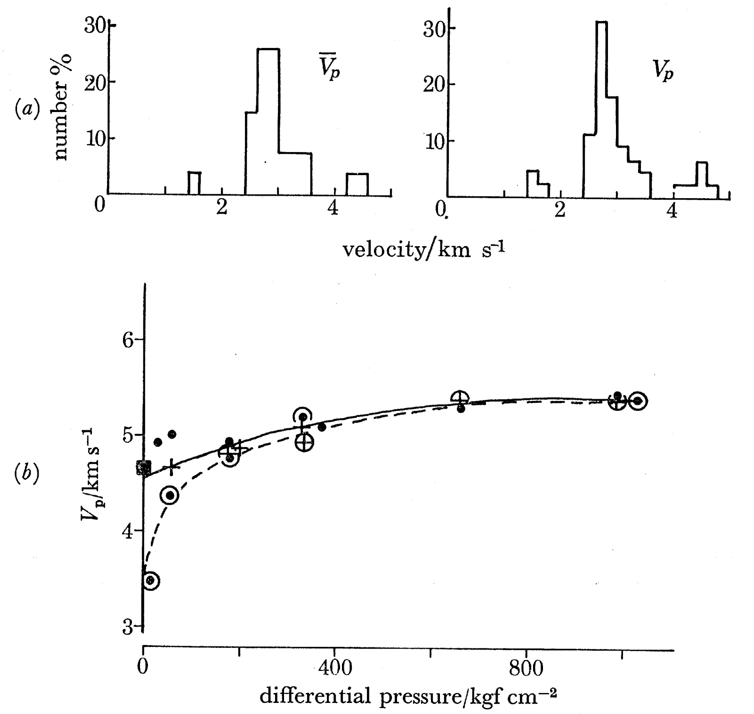

FIGURE 11. (*a*) Two histograms showing distribution of compressional wave velocities measured in screw press in 45 water-saturated cylinders of Swallow Bank lavas. V_p, 45 single observations; $\overline{V}_p$, 27 means. (*b*) The effect of pressure on velocity in a cylinder of relatively fresh lava (3745.234A1). Dots are measurements taken with increasing pressure, crosses with decreasing pressure on water saturated specimen. (Ringed dots and crosses are measurements on dry specimen.) Square indicates velocity measured in the screw press.

a little less than 3.5 km s^{-1}. For comparison, velocities measured with a similar technique in 14 terrestrial basalt specimens (unpublished) fall in the range 4.3 to 6.4 km s^{-1} and have a mean of 5.3 ± 0.6 km s^{-1}. The velocity at Swallow Bank has apparently been reduced by the alteration, which is hardly surprising. The probable velocity there is a little below the velocities usually found in layer 2 beneath the oceans which lie in the range 4.2 to 5.8 km/sec and have a mean of 5.07 and a standard deviation of 0.63 km s^{-1} (Raitt 1963). However, it is clear that altered basalts like those at Swallow Bank could well form an appreciable part of layer 2 where their slightly lower velocity could be easily masked by a few less altered flows. This conclusion endows their study, particularly the chemical changes associated with their alteration, with a possible significance extending far beyond the Iberia abyssal plain from which they were dredged.

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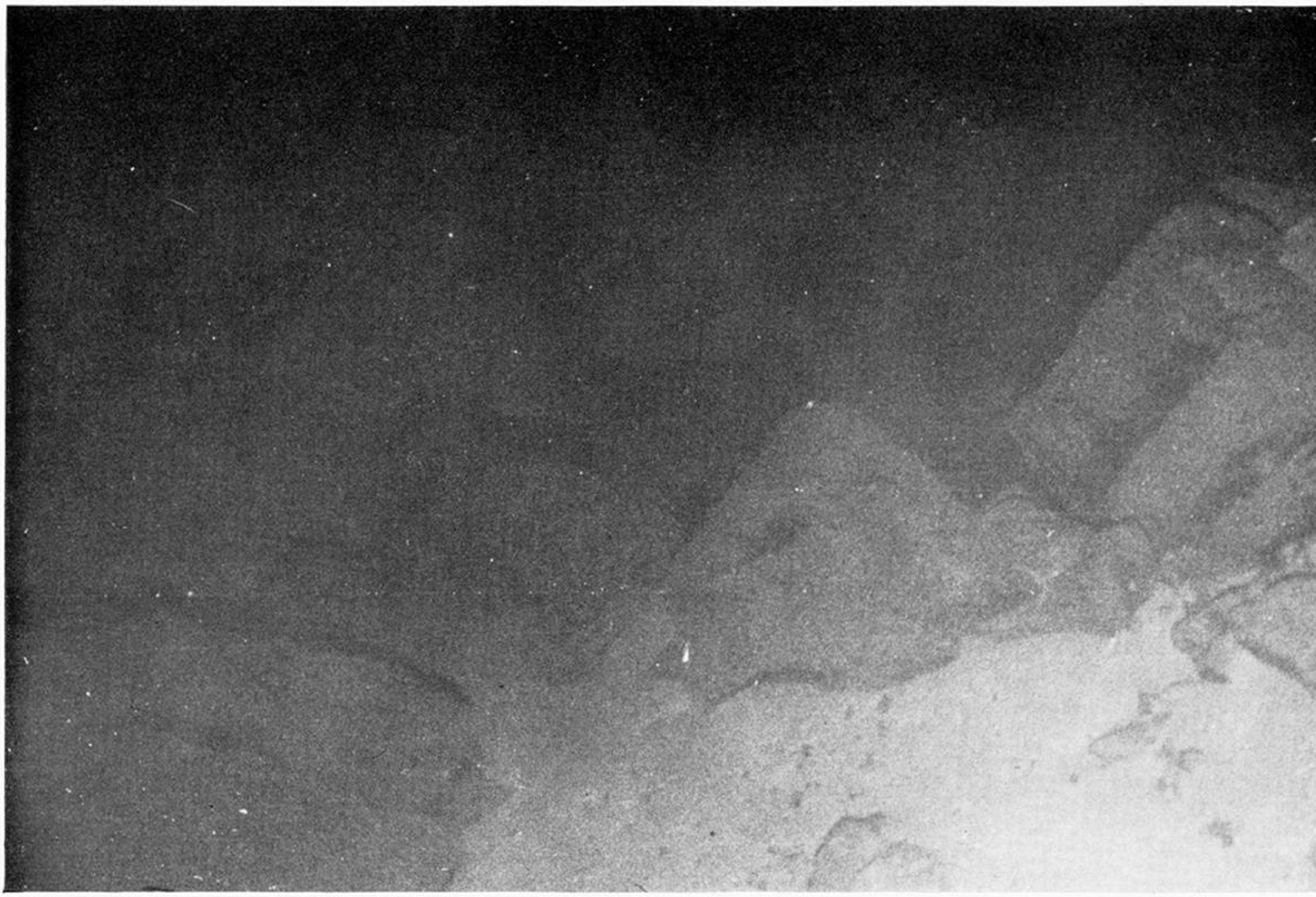
References (Matthews)

Allen, V. T. & Scheid, V. E. 1946 Nontronite in the Columbia River Region. *Am. Miner.* **31**, 294–312.
Birch, F. 1954 Heat from radioactivity. In *Nuclear geology* (ed. H. Faul), pp. 148–174. London.
Bonatti, E. 1965 Palagonite, hyaloclastites and alteration of volcanic glass in the ocean. *Bull. volcan.* **28**, 257–270.
Brindley, G. W. (ed.) 1951 *X-ray identification and crystal structures of clay minerals*. London: Mineralogical Society.
Campbell, R. & Lunn, J. W. 1927 The tholeiites and dolerites of the Dalmahoy syncline. *Trans. R. Soc. Edinb.* **55**, 495–504.
Correns, C. W. 1930 Über einem Basalt vom Boden des Atlantischen Ozeans und Seine Zersetzungsrinde. *Chemie Erde* **5**, 76–86.
Engel, A. E. J., Engel, C. G. & Havens, R. H. 1965 Chemical characteristics of oceanic basalts and the Upper Mantle. *Bull. geol. Soc. Am.* **76**, 719–734.
Fuller, R. E. 1931 The aqueous chilling of basaltic lava on the Columbia River Plateau. *Am. J. Sci.* 5th Ser. **21** (124), 281–300.
Fuller, R. E. 1932 Concerning basaltic glass. *Am. Miner.* **17**, 104–107.
Heezen, B. C. & Tharp, M. 1968 *Physiographic diagram of the North Atlantic Ocean*, 2nd ed. Geol. Soc. Am. Inc.
Hoppe, H. J. 1941 Untesuchungen an Palagonittuffen und uber ihre Bildungsbedingungen. *Chemie Erde* **13**, 484–514.
Krumbein, W. C. 1941 Measurement and geological significance of shape and roundness of sedimentary particles. *J. sedim. Petrol.* **11**, 64–72.
Laughton, A. S. 1957 Sound propagation in compacted ocean sediments. *Geophysics* **22** (2), 233–260.
Laughton, A. S. 1963 Microtopography. In *The sea*, vol. 3 (ed. M. N. Hill), pp. 437–472, Figs. 2, 9, 25, 26, 28. London: Interscience.
Matthews, D. H. 1961*a* Lavas from an abyssal hill on the floor of the N. Atlantic Ocean *Nature Lond.* **190**, 158–159.
Matthews, D. H. 1961*b* Rocks from the Eastern North Atlantic. Unpublished Ph.D. dissertation, Cambridge University.
Matthews, D. H. 1962 Altered lavas from the floor of the Eastern North Atlantic. *Nature, Lond.* **194**, 368–369.
Matthews, D. H., Laughton, A. S., Pugh, D. T., Jones, E. J. W., Sunderland, J., Takin, M. & Bacon, M. 1969 Crustal structure and origin of Peake and Freen Deeps. *Geophys. J.R. astr. Soc.* **18**, 517–542.
Mellis, O. 1952 Replacement of plagioclase by orthoclase in deep-sea deposits. *Nature, Lond.* **169**, 624.
Mellis, O. 1960 Gesteinsfragmente im roten Ton des Atlantischen Ozeans. *Meddn från oceanogr. Inst. Göteborg*, Ser. B, **8**, 1–17.
Menard, H. W. 1964 *Marine geology of the Pacific*. New York: McGraw-Hill.
Murata, K. J. & Erd, R. C. 1964 Composition of sediments from the experimental Mohole project (Guadalupe site). *J. Sedim. Petrol.* **34**, 633–655.
Murray, J. & Renard, A. F. 1891 Deep-sea deposits. *Rep. Challenger Exped.* London: H.M.S.O.
Nayudu, Y. R. 1964 Palagonite tuffs (hyaloclastites) and the products of post-eruptive processes. *Bull. volcan.* **27**, 391–410.
Peacock, M. A. 1926 The petrology of Iceland. Pt. I. The Basic Tuffs. *Trans. R. Soc. Edinb.* **55**, 51–76.
Peacock, M. A. & Fuller, R. E. 1928 Chlorophaeite, sideromelane and palagonite from the Columbia River Plateau. *Am. Miner.* **13**, 360–383.
Peterson, M. N. A. *et al.* 1970 *Initial reports of the deep sea drilling project*, Vol. II, pp. 148, 419. Washington: U.S. Government Printing Office.
Raitt, R. W. 1963 The crustal rocks. In *The Sea*, vol. 3 (ed. M. N. Hill), pp. 85–102. London: Interscience.
Raw, F. 1943 Some altered palagonite tuffs from Jamaica and the origin and history of their chlorites. *J. Geol.* **51**, 215–243.
Ross, C. S. & Hendriks, S. B. 1945 Minerals of the montmorillonite group. *U.S. Geol. Surv. Prof. Pap.* 205 B.
Stokes, K. R. 1968 Further investigations into the nature of the mineral chlorophaeite and its relation to palagonite. *Proc. geol. Soc. Lond.* (1649), 116–118.
Walker, F., Vincent, H. G. C. & Mitchell, R. L. 1952 The chemistry and mineralogy of the Kinkell tholeiite, Stirlingshire. *Miner. Mag.* **29**, 895–908.
Wiseman, J. D. H. 1937 Basalts from the Carlsberg Ridge, Indian Ocean. *Sci. Rep. John Murray Exped.* III. Brit. Mus. (Nat. Hist.).
Wyllie, M. R. J., Gregory, A. R. & Gardner, G. H. F. 1958 An experimental investigation of factors affecting elastic wave velocities in porous media. *Geophysics* **23** (3), 459–493.



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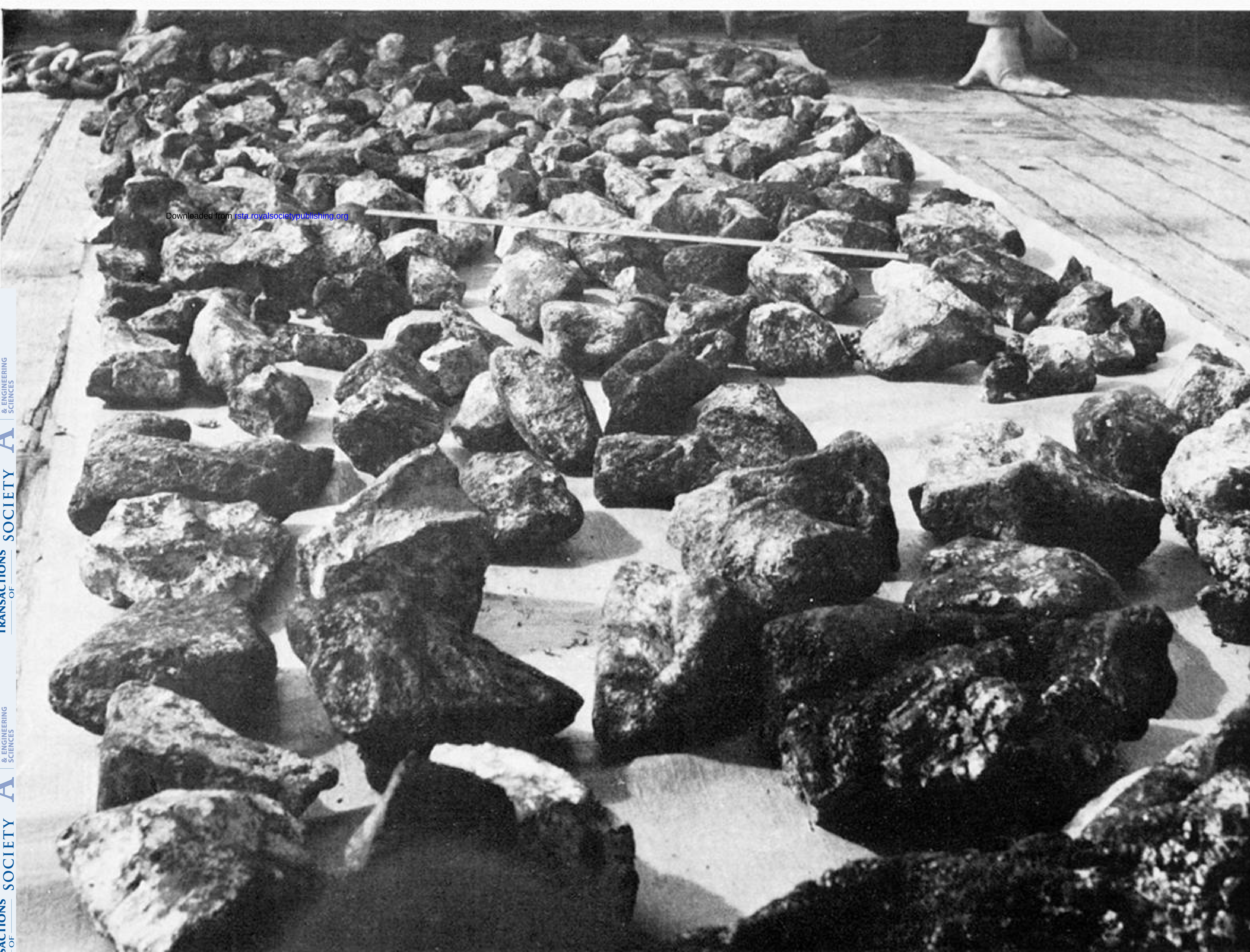

3

PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES

FIGURE 2. Jointed outcrops or boulders of lava at the summit of Swallow Bank, 324 m above the abyssal plain. Underwater camera photograph by Dr A. S. Laughton. Width of picture about 3 m.

FIGURE 3. The collection from Swallow Bank laid out on deck with a metre ruler.