Chapter 4 Basic lavas: alterations and metamorphism.

The first subject which calls for notice under this head is the *partial decay* which has affected in varying degree the greater part of our basaltic lavas. Indeed very few of these rocks can be considered as absolutely in their pristine condition, consisting wholly of products from igneous fusion. There are good reasons for believing that only a part of the alteration observed is attributable to what may be strictly termed "weathering", *i.e.* the agency of surface waters percolating the rocks and carrying the atmospheric gases and other substances in solution. We have at least to consider the possibility, and indeed probability, that many of the effects may be *due to the action of water of volcanic origin* held, in vesicles and otherwise, in the lavas themselves; and possibly too of other "mineralising agents", although these have left little clear trace of their presence.<ref>No datolite or other boron mineral has been recorded from the Tertiary volcanic districts of Britain. Some apophyllites contain a small amount of fluorine, and this is the case in the only specimen from Skye yet analysed.</ref> Such action, conducted presumably at relatively high temperatures, and not long subsequent to the outpouring of the lavas, would properly be regarded rather as the final phase of vulcanicity than as a later and independent event.

The question here raised is one having a far wider bearing than is implied in its application to the Skye basalts, and a general discussion of it would not be in place here. It is worthy of note, however, that a comparison of these Tertiary lavas with similar ones of Palaeozoic age in various parts of Britain does not bring out any apparent relation between the antiquity of the several rocks and their state of preservation. It is instructive, too, to observe that the intrusive sills intercalated among the Skye lavas, and the dykes which intersect them, are always in a fresher condition than the lavas themselves, although the mineral composition is similar and no very great difference of age can in some cases be presumed. Still more striking is a comparison between the ordinary basaltic lavas of the plateau country and their metamorphosed representatives bordering the large plutonic intrusions. It is clear from the phenomena to be described below that the latter were at the time of these intrusions in the same altered condition as the former are now; while it is also evident that since the metamorphism, which transformed the decomposition-products into new substances, largely of species identical with the original igneous minerals of the basalts, these rocks have suffered no further noticeable change. We may fairly infer from this that the alteration, of the kind here considered, in the plateau basalts as now seen, has been effected almost wholly within a quite limited time immediately following their extrusion. Without pursuing the question farther, we shall, for convenience of description at least, endeavour to separate two kinds of alteration in the basaltic lavas: one belonging to the closing phase of volcanic activity and effected by the agency of heated water; the other, still in progress, due to atmospheric action and properly described by the term weathering.

Alteration of the former kind is everywhere observable, except where its effects have been obliterated by subsequent thermal metamorphism; but it is most notable in those rocks which are most conspicuously amygdaloidal. Doubtless these are the lavas which held most water when they solidified. The process has consisted mainly in the abstraction of material from the body of the rock, and especially from the felspars, to fill or partially fill the vesicles, fissures, or other vacant spaces. Such material is deposited in the vesicles and other cavities in new forms, viz. as minerals, usually, into the constitution of which the water itself enters. In this way the vesicles of the lava have become *amygdules* and the larger cavities *druses.* The smaller spaces are always filled, the larger ones partially filled or only lined: where empty vesicles are found it is only because subsequent weathering has removed the contents.

It is the amygdules and druses in the basalts that have made many places in Skye famous with mineralogists. We reproduce here, from various sources, chemical analyses of a number of the minerals.

I. Thomsonite, near Steinscholl: anal. Heddle, *Min. Mag.,* vol. *v.,* p. 119: 1883. Lost 0.848 per cent. moisture at 100° C.

II. Thomsonite, Storr: *ibid.,* p. 120.

III. Thomsonite (Faroelite), Storr: anal. Heddle, *Phil. Mag.* (4), vol. xiii., p. 53 1857.

IV. Thomsonite, Portree: *ibid.*

V. Thomsonite, Uig: *ibid.,* p. 54.

VI. Thomsonite, Uig, another specimen: *ibid.*

VII. Thomsonite, Old Man of Storr: anal. Thomson, cit. Heddle, *Min. of Scot.,* vol. ii., p. 111.

VIII. Scolezite, Portree: anal. Heddle, *ibid.,* p. 106.

IX. Scolezite, Storr: *ibid.* The total is there given as 95.55.

X. Mesolite, Talisker: anal. Heddle, *Phil. Mag.* (4), vol. xiii., p. 51: 1857.

XI. Mesolite, Storr: *ibid.,* p. 52.

XII. Mesolite, Kilmuir: *ibid.*

XIII. Mesolite, near Steinscholl: anal. Heddle, *Min. Mag.,* vol. *v.,* p.118: 1883. Lost 0.9 per cent. moisture at 100° C.

XIV. Uigite, near Uig: mean of duplicate analyses by Heddle, *Min. Mag.,* vol. *v.,* p. 27: 1882.

XV. Laumontite, Snizort: anal. Connell, cit. Hintze, Heddle, and others.

XVI. Laumontite, Storr: anal. Scott, *Edin. New Phil. Journ., vol liii.*, p. 284: 1852.

XVII. Laumontite, Skye: anal. Mallet, *Amer.* Jeurn. *Sci.* (2), vol. xxii., p. 179: 1856.

XVIII. Laumontite, Storr: anal. Heddle, *Min. of Scot.,* vol. ii., p. 91: 1901.

XIX. Laumontite, Storr: *ibid.*

XX. Laumontite, ?Skye: mean of duplicate analyses by Babo and Delffs, *Pogg. Ann.,* vol. lix., p. 341: 1843.

XXI. Stilbite (Sphaerostilbite), Storr: anal. Heddle, Greg and Lettsom's *Manual,* p. 164: 1858.

XXII. Stilbite (Hypostilbite), Skye: anal. Haughton, *Phil. Mag.* (4), vol. xiii., p. 509: 1857.

XXIII. Levyne, Quiraing: anal. Heddle, Min. *of Scot.,* vol. ii., p. 96: 1901.

XXIV. Chabasite, blue, Talisker: anal. Heddle, *ibid.,* p. 93.

XXV. Chabasite, white, Talisker: *ibid.*

XXVI. Acadialite (Chabasite), Talisker: *ibid.*

XXVII. Gmelinite, ?Skye: anal. Berzelius, cit. Heddle, *ibid.,* p. 96.

XXVIII. Analcime, Talisker: anal. Heddle, *ibid.,* p. 97.

XXIX. Gyrolite, Storr: anal. Anderson, *Phil. Mag.* (4), vol. i., p. 113: 1851.

XXX. Apophyllite, Storr: anal. Heddle, *Min. of Scot.,* vol. ii., p. 81: 1901. With 0.7 of fluorine.

XXXI. Pectolite, Storr: anal. Scott, *Edin. New Phil. Journ.,* vol. liii., p. 280: 1852.

XXXII. Pectolite, Talisker: anal. Heddle, *Phil. Mag.* (4), vol. ix., p. 253: 1855.

XXXIII. Okenite, An Leth Allt, Loch Brittle: anal. Stuart Thomson, *Trans. Geol. Soc. Glasg.,* vol. ix., p. 251: 1893.

XXXIV. Okenite, Dunan Earr an Sgùirr: anal. Heddle, ibid.

XXXV. Saponite, olive, Storr: anal. Heddle, *Trans. Roy. Soc. Edin.,* vol. xxix., p 100: 1879. Lost 13.652 per cent. moisture at 100° C.

XXXVI. Saponite, white, Quiraing: *ibid.* Lost 15.536 per cent. moisture at 100° C.

XXXVII. Saponite, yellow, Quiraing: ibid., p. 101. Lost 15.132 per cent. moisture at 100° C.

	I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII	XIII	XIV	XV	XVI	XVII	XVIII	XIX
SiO_2	39.696	39.016	41.32	41.20	43.172	43.21	40.33	45.61	45.92	46.714	46.724	46.26	45.615	46.150	52.04	53.048	53.95	51.98	51.09
Al_2O_3	29.949	28.125	28.44	30.00	29.30	29.03	29.00	25.91	25.32	26.617	26.698	26.48	24.465	21.638	21.14	22.943	20.13	20.34	21.29
Fe_2O_3		3.281											1.428					0.59	0.32
FeO	1.43																		
MnO	0.076												0.384						
MgO		0.646											0.461						
CaO	10.076	10.733	11.54	11.40	9.816	10.35	12.12	13.38	13.43	9.078	8.902	10.00	6.116	16.256	10.62	9.676	12.86	11.55	11.49
Na_2O	5.511	3.709	5.77	4.38	5.326	5.16	5.33	3.52	3.52	5.389	5.404	4.98	6.905	4.691					0.31
K_2O	0.378	1.01											0.567				0.87		
H_2O	13.073	13.985	13.26	13.20	12.40	12.46	13.22	12.56	12.36	12.831	12.925	13.04	12.246	11.731	14.92	14.639	12.42	15.78	15.37
	100.189	100.505	100.33	100.18	100.014	100.11	100.00	100.46	100.55	100.629	100.653	100.76	100.178	100.468	98.72	100.306	100.23	100.24	99.87
Specific gravity		2.147–2.131											2.103	2.284			2.252		

	XX	XXI	XXII	XXIII	XXIV	XXV	XXVI	XXVII	XXVIII	XXIX	XXX	XXXI	XXXII	XXXIII	XXXIV	XXXV	XXXVI	XXXVII
SiO_2	51.74	56.54	52.40	43.13	48.72	48.81	47.48	49.17	55.08	50.70	51.2	52.007	53.820	48.28	54.22	41.411	42.504	40.329
Al_2O_3	21.77	16.43	17.98	21.77	17.68	18.73	20.21	18.92	20.72	1.48		1.820		4.14	0.68	9.075	5.055	8.717
Fe_2O_3						0.08					1.09					2.054	0.852	1.972
FeO				1.38					1.09		0.09		{2.728}					
MnO											0.3					0.107	0.224	0.131
MgO			0.36							0.18	0.5	0.396				22.8	23.954	21.71
CaO	12.21	8.90	9.97	9.25	9.36	8.01	4.88		1.68	33.24	23.13	32.854	29.880	30.63	27.22	1.86	3.274	2.8
Na_2O		0.46	1.40	3.44	0.6	1.9	4.58	12.97	12.82		0.37	7.670	9.551	1.68	1.02		0.45	
K_2O			0.03	095	1.22	0.08	1.71	trace	0.57		5.49						0.171	
H_2O	14.68	17.05	17.83	20.20	21.88	23.07	20.80	19.73	8.54	14.18	17.02	5.058	3.760	15.69	16.64	23.433	23.679	24.338
	100.40	99.38	99.97	100.12	99.46	100.68	98.66	100.72	99.50	99.78	99.89	99.805	99.739	100.42	99.78	100.721	100.139	99.998
Specific gravity									2.248			2.784		2.198	2.246	2.296		

The minerals which contribute to fill the amygdaloid and geodic cavities of the basalts are very numerous. Most common of all are *zeolites* in great variety, several occurring together in the large amygdules of certain localities. In addition to radiating fibrous aggregates, which often occupy the smaller and more spherical cavities, chabasite, analcime, and stilbite are very frequently recognised. From mineralogical works a long list might be compiled,<ref>For our present purpose, such hydrous silicates as apophyllite, pectolite, and gyrolite may be loosely grouped with the zeolites.</ref> including thomsonite, mesolite, faroolite, laumontite, gyrolite, pectolite, apophyllite (with tesselite), prehnite scolezite, gmelinite, levyne, heulandite, epistilbite, sphaerostilbite, acadialite, and uigite. Some of the last-named are of rare and exceptional occurrence. Among localities known to collectors for the variety and beauty of their crystals are Talisker Bay, the Storr, the Quiraing, and a spot about a mile north of the last. Where two or more zeolites occur in the same cavity, they form successive coats more or less regularly disposed. The larger cavities are often not completely filled, the central space being either empty or occupied by water giving an alkaline reaction.

While zeolites and allied minerals are usually the chief, and often the sole, contents of the amygdules, they are frequently accompanied by other substances, and sometimes give place to them entirely. Among these may be mentioned chloritic minerals, which seem to belong to Heddle's division of the saponites as distinguished from the chlorites proper: indeed he has identified the species saponite from more than one locality. Calcite is not infrequent, and in some places occur chalcedony and onyx, less frequently crystalline quartz. Epidote is locally abundant, especially near the gabbro border, where it may possibly be connected with metamorphism due to that rock. In a few places iron-oxides (haematite and limonite) occur in quantity. Finally bitumen or asphalte is known, though not common, and Heddle states that calcite sometimes contains a considerable amount of this substance, while petroleum partly fills cavities at Talisker.<ref>See Heddle, *Mineralogy of Scotland,* 1901. From the same work we may add the sulphide tetrahedrite and, of very rare occurrence, native copper coated with malachite.</ref>

It can scarcely be doubted that the contents of the amygdules are, generally speaking, derived from the rocks themselves, and carried to the cavities, where they occur, dissolved in water, which need not have had any extensive circulation. The characteristic minerals are all such as might be expected from such a source. It is noticeable that the zeolites are mostly lime-zeolites or such soda-lime-zeolites as have lime for their principal base, the soda-zeolite analcime being almost the only exception.<ref>Even the analcime, in the only specimen analysed, contains a notable amount of lime. The absence of natrolite is especially to be remarked.</ref> It is reasonable to suppose that the original composition of the basalt, save as regards water, is represented by an analysis of the rock *inclusive* of the amygdules. The partial decomposition of some of the original minerals and the transference of derived materials to the vesicles were, it seems highly probable, carried on at somewhat high temperatures; the process being not an accident of "weathering" long posterior to and independent of the extrusion of the lavas, but rather a final result of the volcanic energy itself. The partial unmaking of these basaltic rocks and the"concurrent infilling of their vesicles and other cavities may have begun as soon as the lavas were solid, and continued throughout their cooling.<ref>Sir A. Geikie, *Ancient Volcanoes of Great Britain,* vol. ii., p. 189: 1897.</ref>.We know at least that the process was complete prior to the next events of which we have record in the district, the intrusions of the peridotites and gabbros; for the amygdules are metamorphosed in common with the rest of the rock in the vicinity of the peridotite, gabbro, and granite masses.

If the filling of the vesicles by zeolites and other minerals took place during the cooling of the lavas, and was a process requiring a prolonged time, it follows that the earlier-formed minerals must have crystallised at higher temperatures than those which followed.

The data are wanting which would enable us to apply this test. We might expect the content in water of the various compounds to afford some clue, and J. D. Dana,<ref>*Amer. Journ. Sci.,* vol. xlix., pp. 49–64: 1845.</ref> writing many years ago on this subject, with special reference to the Lake Superior region, remarked that the earlier minerals in general contain less water in their composition than the later. This rule, however, holds good only partially in Skye. Quartz and calcite are, as might be expected, always the earliest minerals in the amygdules in which they respectively occur, but the chloritic minerals come next, before even the least hydrous of the zeolites. Of the latter, too, chabasite, with as much as 20 per cent. of water, has usually crystallised first of all, though it is exceptionally found on both stilbite and analcime.

Apophyllite is found crystallised on gyrolite, this on mesolite and thomsonite, and mesolite on analcime, all in accordance with their percentages of water; but elsewhere analcime occurs on mesolite and even on apophyllite. It is clear that more than one factor goes to determine the particular mineral formed at any epoch, one being probably the relative proportions of lime and soda in solution.

The changes in progress in the rocks at the time when the amygdules were filled were evidently of a kind which resulted in the production chiefly of zeolites. In these minerals the molecular ratios $CaO + Na_2O : Al_2O_3 : SiO_2$ vary from 1 : 1 : 2 (thomsonite, mesolite, etc.) to 1 : 1 : 4 (analcime and laumontite), or exceptionally 1 : 1 : 6 (stilbite); thus corresponding generally, excepting the water, with the composition of the felspars from which they are derived. It appears, therefore, that the lime and soda, alumina, and silica have been abstracted from the felspars in the same proportions as they present in those minerals. This is very different from what occurs in ordinary weathering, and points to different conditions, of which high temperature is doubtless one.<ref>The well-known occurrence of zeolites formed from thermal waters in Roman masonry at Plombieres, etc., has an obvious bearing on this question, and the processes by which zeolitic minerals have been artificially produced are equally instructive. See Daubreé, *Etudes synthétiques de géologie expérimentale,* 1879.</ref>

Turning now to *true weathering,* the contrast becomes very apparent. The results here are, in the earlier stages, a partial chloritisation of the augite, serpentinisation of the olivine, carbonatisation of the felspars, etc., with some separation of silica. In the later stages we find complete disintegration of the rock, the original

minerals being totally destroyed. This has happened to some extent during the volcanic period itself, whenever any noteworthy pause occurred in the outpouring of the lavas, the surface of the last solidified flow being thus exposed to subaerial agents of destruction until it was covered by a new outburst. These old land-surfaces are marked by ferruginous, or siliceous and ferruginous, clays of composition very different from that of the basalts. The change consists, besides hydration, in the removal of a large part of the substance of the original rock, and the several ingredients have been removed in very different proportions. The alkalies and most of the lime are readily carried off; and part of the silica, and usually of the iron, goes also, the behaviour of these two constituents differing in different cases. This results in a relative enrichment in alumina, a substance which does not enter into easily soluble compounds, and the rock is reduced to a clay, siliceous or ferruginous according to the proportions of silica and iron-oxide which remain. The process, ideally complete, would give rise to a clay consisting practically of hydrated alumina; but this final stage does not seem to have been reached in the basaltic district of Skye. Here in the most altered deposits the alumina is probably still combined with silica.

Several writers have remarked the occurrence of *beds of clay,* usually more or less ferruginous, interbedded among the basalts in the northern and western parts of Skye. Macculloch<ref>*Description, of the Western Islands of Scotland,* vol. i., pp. 376, 377: 1819.</ref> noticed them especially in the great Talisker cliff (Beinn nan Cuithean), where the number of beds varies from eight or nine to twelve, fifteen, or even more in the precipitous face of 900 feet. Bone mentioned a reddish or purplish "bolar" substance in the same neighbourhood. In 1882 Heddle noticed a similar ferruginous clay, usually of a deep red colour, forming layers one or two feet thick at the Quiraing, and occurring also in a repeated series of beds at the Storr. He gave an analysis of the substance (column I. below), and pointed out its identity with the so-called plinthite of Antrim. The latter (A) had been regarded by Thomson as a distinct mineral, but is only a type of many clays in the Antrim district. The substance examined by Heddle is doubtless of similar nature to that at Talisker, for elsewhere he remarks at this place "bands of plinthite, of some inches in thickness, zoning the cliffs horizontally from bottom to top at distances of about 40 feet".<ref>*Min. Mag.,* vol. iv., p. xiii.: 1880.</ref>

In 1896 Sir A. Geikie drew attention again to the clays intercalated among the basalt-flows between Lochs Brittle and Dunvegan, and especially to the cliff at Rudha nan Clach, north of Talisker Bay, where "some conspicuous bands of lilac and red are interspersed among the basalts".<ref>*Quart. Journ. Geol. Soc.,* vol. lii., pp. 339, 340; 1896.</ref> He suggested that they might be worth examination from the economic point of view, as a possible source of aluminium; the clays of the basaltic district of Antrim being well known to include some of the bauxite type, which have been utilised for that industry. The analysis B, furnished by the Antrim Iron Ore Company, represents one of these Irish clays of such a grade as can be worked profitably as bauxite, and C a less siliceous sample which, in the dry state, must consist to the extent of 86 to 89 per cent. of the mineral bauxite, $H_6Al_2O_6$,. More than 20 per cent. of silica or 3 per cent. of iron is detrimental to the purpose in view, and consequently material such as that analysed by Heddle would be without value. The Company named have had partial analyses made of samples of clays from Skye, which appeared to be promising for the bauxite industry, but the results were of a disappointing kind. The General Manager, Mr Arch. Livingstone, has kindly communicated the particulars, as below. The specimens were from Rudha nan Clach, from Talisker, and from near the Talisker Distillery at Carbost on Loch Haiport. Each gave about 17 per cent. of moisture.

	I	A	B	C	D
SiO_2	29.547	30.88	14.50	3.26	50.75
TiO_2				4.53	
Al_2O_3	19.027	20.76	47.60	46.68	20.87
Fe_2O_3	28.013	26.16	2.30	2.74	15.90
FeO	3.251				
MnO	0.844				
CaO	2.234	2.60			0.72

H_2O (combined moisture)	10.704	19.60	18–00	25..13	10.50
H_2O (combined moisture)	6.687		17.00	17.00	
	100.307	100.00	99.40	99.34	98–74
Specific gravity		2.342			

I. Ferruginous clay ("plinthite"), Quiraing, Skye: anal. M. F. Heddle, Min. *Mag.,* vol. v., p. 26: 1882.

A. Ferruginous clay, brick-red ("plinthite"), Antrim: anal. Thos. Thomson, *Outlines of Mineralogy,* vol. i., p. 323 (in 7th ed., 1836).

B. Bauxite clay, Antrim.

C. Bauxite clay, less siliceous, Ballynure, Antrim.

D. Ferruginous and siliceous clay, bluish grey, southern part of Antrim: anal. Apjohn, see Delesse, *Ann. des mines,* (*5th ser.*), vol. xii., p. 419: 1857.

	SiO_2	Fe_2O_3
Rudha nan Clach (from "Iron Ore Bed")	32.37	19.09
Do. (under the "Iron Ore Bed")	33.45	17.68
Stream above Talisker Farm	34.86	15.60
Quarry above Talisker Distillery	51.88	12.95
Do., another sample	46.11	14.36
At or near the same place	45.85	14.35

The first three are evidently of the "plinthite" type, and are both too siliceous and too ferruginous for use; while the other three depart still further from the bauxite standard. These latter resemble in their content of silica another type of clay from Antrim, occurring at the base of the volcanic series (*see* column D).

Mr H. B. Woodward, who mapped the basalts in the vicinity of Portree for the Geological Survey, collected in 1894 a specimen bearing much apparent resemblance to the Irish bauxite from Leac Aghamnha, on the south side of Portree Harbour, and has supplied a note on the subject: "A sample was sent to Mr J. Hort Player, who very kindly examined it and made a partial analysis: this showed that the rock contained only about 30 per cent. of alumina, and it was evidently a somewhat altered volcanic ash — possibly a material from which bauxite might ultimately be produced by natural causes. The occurrence of bands of hardened red clay among the bedded basalts is well known. Bands of this nature, approaching to lithomarge, occur at Ben Tianavaig and other localities"

It will be seen that our present knowledge scarcely warrants any expectation that workable bauxite-clays of importance will be found in Skye. Further, although the samples of clays examined contain enough iron-oxide to render them unsuitable for this purpose, we have not discovered among the Skye basalts any important bedded iron-ores such as accompany the Irish clays, and have been worked concurrently with them. An important difference between the two districts is to be noted in this connection. While the basaltic group of Skye appears to be indivisible, that of Antrim falls into two well-marked sub-groups, separated in time by an interval which may have been very considerable. During this interval, while the Lower Basalts remained for a long time an exposed land-surface, the pisolitic iron-ores, the bauxites, lithomarges, and boles, and the associated plant-beds were formed, and they now divide the Upper from the Lower Basalts. In addition there are in Antrim minor beds of ferruginous clays intercalated among the basalts at various horizons, and it is with these, not with the main deposits, that the occurrences in Skye are to be paralleled.

Brick-red ferruginous clays, resulting from the decomposition of the basaltic lavas and doubtless of the same general character as the "plinthite" analysed by Heddle, are widely distributed, especially in the western part of the area surveyed, and may often be observed running as narrow bands along the face of the precipitous cliffs between Loch Brittle and Loch Harport. In a few cases, where they are associated with decomposed tuffs and impure carbonaceous seams, these clays may have been formed in shallow pools into which the material was washed, but in general they are to be regarded as due to the decomposition of the lava in place. This is often shown by the occurrence of intermediate stages of decay, giving a gradual transition from ordinary basalt to typical "plinthite"; and in some cases amygdules are evident in a rock which is otherwise completely converted to red clay. As a rule the seams do not exceed a very few inches in thickness, but there are exceptions to this rule. The thickest mass which we have observed reached between three and four feet. This is in Fiskavaig Burn, about 700 yards above the hamlet: its lateral extent cannot be traced. Basalts showing various stages of this kind of alteration, down to typical plinthite, may have a thickness of 10 or 15 feet, as in the burn above Drynoch Farm, near Loch Harport, and the Glen Caladale burn, west of the mouth of Loch Eynort.

The basaltic lavas in the vicinity of the large gabbro and granite intrusions invariably show the effects of *thermal metamorphism* in greater or less degree. In some places on the west side of the Cuillins the transformation they have suffered is such that to ordinary inspection the true nature of the rocks is almost completely disguised; but in general the altered lavas are still easily recognisable as such, though manifestly changed to some extent. They assume a dark grey colour, and are tougher and more compact than the unaltered rocks, breaking with a more splintery fracture. The amygdules, instead of perishing more rapidly, are now more durable than the body of the rock, and are prominent on a weathered face.

It is always found that the first indications of change appear in the chloritic and other alteration-products of the basalts and the contents of the amygdules.<ref>A few examples have been described in *Quart. Journ. Geol, Soc.,* vol. lii., pp. 386, 387; 1896.</ref> In other words, products formed at relatively low temperatures were affected more readily than minerals originally crystallised from igneous fusion. Indeed, many observations, in this district and elsewhere, point to the fact that hydrous compounds with part of their water only loosely held, and carbonates in the presence of available silica, enter into new combinations on a quite moderate elevation of temperature. With progressive metamorphism the essential minerals of the rock become in turn unstable, the augite being transformed before the felspar.

The most conspicuous secondary minerals in the general mass of the metamorphosed rocks are a greenish or yellowish-green rather fibrous hornblende and a brown biotite, separately or often together. Epidote is often found, and to considerable distances from the intrusions, in rocks showing but little other change; but it cannot be assumed that this mineral is always a product of thermal metamorphism. Of the hornblende and biotite, the former comes usually from direct transformation of the augite, a kernel of which is often left unchanged in the partially metamorphosed rocks. The biotite, on the other hand, seems from its disposition to be derived in great part from chloritic and other alteration-products of the original rock: for example, it occurs as minute flakes disseminated through the felspar (S2709) [NG 534 213]. Presumably the presence of alkalies and a deficiency of lime in spots where chloritic material was collected would tend to determine the formation of biotite rather than hornblende. It is clear, however, that the latter mineral too may sometimes be formed from the alteration-products, for we find it occupying little veins (S2699) [NG 587 240], or as actinolitic needles embedded in an aggregate of yellowish-green chloritic material (S2701) [NG 587 240]. Many of the slides show biotite forming in preference to hornblende in immediate proximity to grains of magnetite, which have probably furnished some iron for the purpose (S7128) [NG 541 234], etc..

The felspar of the basalt is often quite unchanged in the less metamorphosed rocks, although the augite may be far advanced towards total replacement by the minerals already mentioned. The earliest change seen in the felspar is a clearing of the crystals from the slight turbidity which they often show in the non-metamorphosed tocks: in the most altered rocks the felspars are completely re-crystallised, and little trace may remain of the original micro-structure of the rock. It is doubtful to what extent the original magnetite of the basalt is also recrystallised.

The most interesting metamorphic effects are found in connection with the amygdules. We have seen that these, in a very large proportion of the Skye basalts, consist of zeolites, two or more being often associated within the same cavity. In the metamorphosed rocks the amygdules present a dead-white aspect not unlike that seen in many of the unchanged lavas, but they are notably harder, and on examination are found to be of felspar. This *conversion of lime- and lime-soda-zeolites into lime-soda-felspars* by thermal metamorphism is one that might be expected on chemical grounds, although it does not appear to have been recorded from other districts. In many cases it must involve little more total chemical change than the expulsion of the water, and it is indeed merely a restoration of the original minerals of which the zeolites are the degraded representatives.

The felspars in these metamorphosed amygdules ((Plate 17), Figs. 4 and 5) form an aggregate of interlocking crystals or allotrio-morphic crystal-grains with a somewhat dusty appearance in thin slices. Often they are apparently untwinned, but fine twin-lamellation is also very frequently seen. Measurements of extinction angles in different cases indicate oligoclase, andesine, and andesine-labradorite, besides more basic varieties, and more than one of these may occur in intimate association. Probably the kind of felspar formed in any particular part of an amygdule depended upon the composition of the zeolitic substance at that spot, for we have reason to believe that in ordinary thermal metamorphism interchange of material is restricted within very narrow limits.<ref>See Harker and Marr, *Quart. Journ. Geol. Soc.,* vol. xlix., pp. 368, 369: 1893.</ref> That the transformation of the zeolites into felspars took place very readily, *i.e.* did not demand a very elevated temperature, appears from the fact that it has occurred in specimens which exhibit no other sign of metamorphism (S7460) [NG 537 196]. Further, we have found little indication of the replacement being a gradual process, for only rarely do a few patches of unchanged zeolite remain in the heart of the new-formed felspar (S7127) [NG 544 230].

Felspars are often the only contents of the metamorphosed amygdules, but in other cases we find various minerals in addition, doubtless when the zeolites have occupied the original cavity in company with chloritic material, calcite, etc. Epidote is a not infrequent associate of the felspar, in grains or imperfect crystals — always at or near the boundary of the amygdule, and sometimes forming a continuous border, which lies mainly within the boundary but may also encroach slightly upon the general mass of the rock. It is of earlier crystallisation than the new felspar, which is often seen to be moulded upon it (Plate 17), Fig. 5). The epidote is nearly colourless in thin slices. Its bi-refringence is very variable, and some of the crystals appear to be rather zoisite than epidote. Probably the mineral formed at any spot depended upon the relative quantities of lime and iron available for its composition. Occasionally a few rose-coloured grains indicate some content of manganese, and may be termed withamite (S7461) [NG 532 211]. In other slices an augite mineral, perhaps malacolite, and a fibrous faint-green hornblende occur as constituents of the metamorphosed amygdules. They may be intimately associated with felspar to build a crystalline aggregate of fine texture. They have crystallised before the latter mineral, and needles and fibres of the hornblende are seen penetrating both the felspar and certain small patches of clear quartz which occur only sparingly.

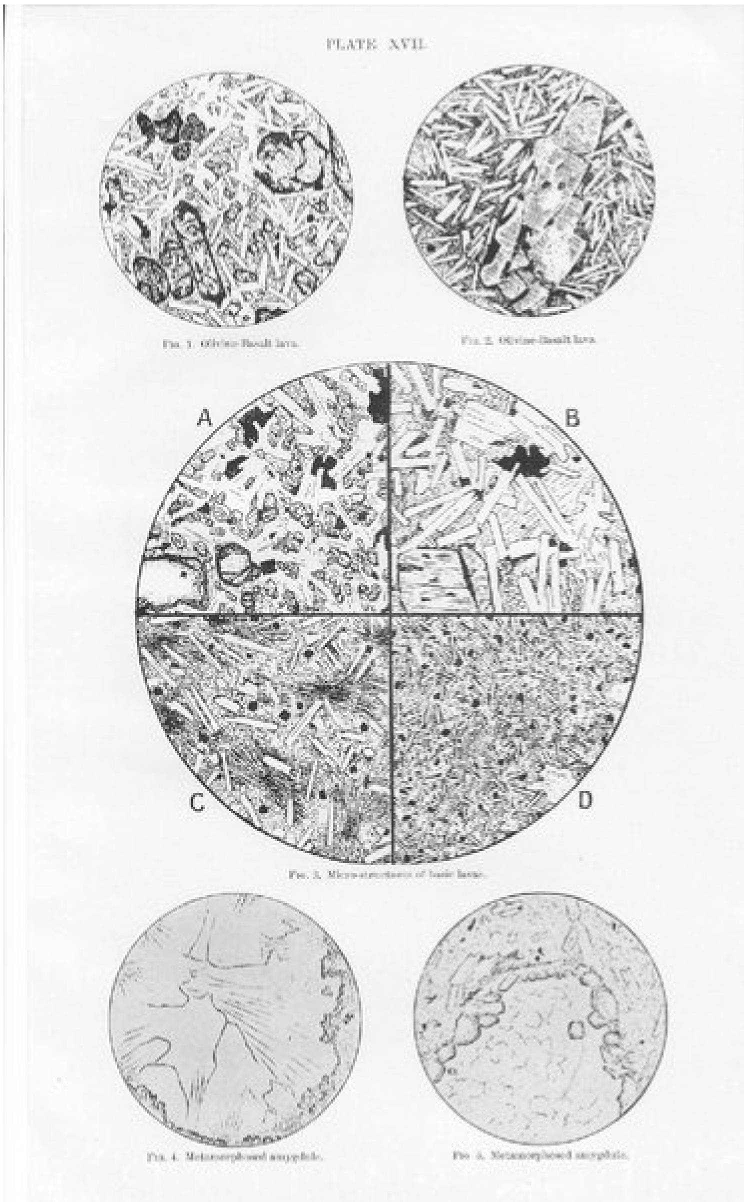
Summarily, these metamorphosed basic lavas have the same general characteristics as have been described for similar rocks elsewhere — e.g., for those of Lower Palaeozoic age near the granites of Shap and Eskdale in the English Lake District; but the Skye basalts present a special feature of interest in the abundant formation of felspars at the expense of zeolites in the amygdaloidal cavities.

The effects described are the most usual results of thermal metamorphism in the basalts, and may be observed in various stages of development to distances of half a mile or more from the boundaries of the large plutonic masses. In some places, however, changes of a more radical kind mark a higher grade of metamorphism, in which the basalts may almost lose all semblance to the appearance of their unaltered representatives. This most extreme stage of metamorphism, involving complete reconstitution of the rocks, is found in some of the basaltic lavas in contact with the gabbros and peridotites on the western and south-western fringe of the Cuillins. A good locality for studying the effects is near a little tarn to the N.E. of An Sgùman, not far from the boundary of the gabbro. Here are dark-grey finely crystalline rocks with amygdules often indicated by small lighter ovoid patches or light rings with a dark interior. A thin slice (S8731) [NG 437 191] shows that the component minerals, olivine, magnetite, augite, and felspar, with the possible exception of the first, are all new-built. The micro-structure is precisely that of the rocks termed pyroxene-granulites<ref>Not the "granulitic" structure of Judd.</ref> by the German petrographers. The augite forms rounded granules, and the magnetite, though sometimes with an indication of the octahedral form, is also rounded (*see* (Plate 18), Fig 1). Olivine is abundant, though not evenly distributed. The felspar (labradorite), with albite and carlsbad twinning, is moulded upon all the other minerals, and shows little crystal-outline of its own. The minerals composing the metamorphosed amygdules are simply augite and felspar, the olivine and magnetite not entering, though grains of these may trench on the margin. There is a border of augite grains enclosing an aggregate of felspar, and sometimes (as in the figure) an inner ring of augite concentric with the other. This augite, and less clearly that in the body of the rock, has a faint reddish tint in the slice, with slight pleochroism. In this as in many other points the rock recalls the pyroxene-granulites<ref>Some rocks in the neighbourhood of Druim an Eidhne, which are probably metamorphosed lavas of this kind, have not been separated on the map from the gabbros. They are mentioned under the head of "granulitic gabbros" in Chapter 8., and their structure is illustrated in Fig. 22.</ref> of Saxony, and there is a resemblance, possibly suggestive, between the highly altered amygdules and some of the curious eye-like structures found in the latter rocks. The amygdules doubtless consisted before metamorphism of a lime-soda-zeolite with an outer layer of some chloritic mineral and sometimes a second layer of the same. The zeolite has given rise to a felspar, as in the other occurrences noted above, while the chloritic mineral has, in these most highly metamorphosed lavas, been transformed, not into hornblende, but into augite. Further, there is in this extreme grade of metamorphism no uralitisation of the augite in the body of the rock, but only recrystallisation.

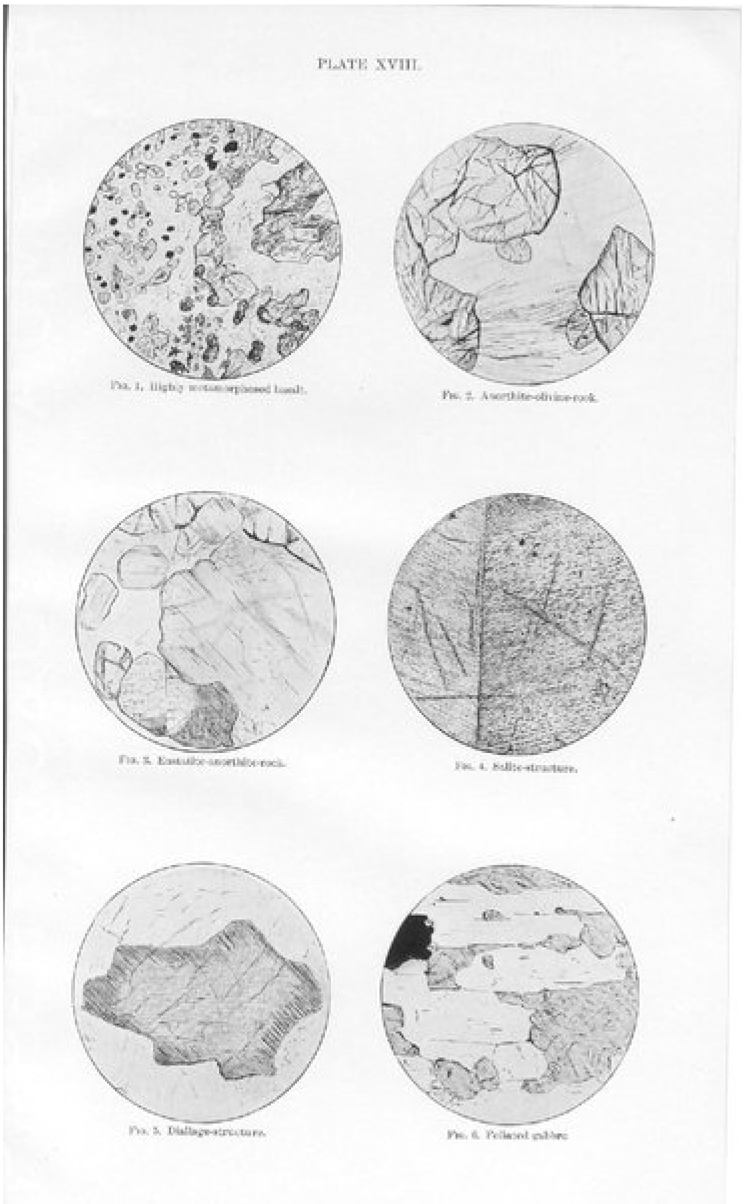
In specimens of such a rock as this there is nothing to suggest its true nature and origin except the amygdules, which are themselves much disguised, and have lost something of the sharpness of their outline. In extremely metamorphosed basalts from other localities, where the amygdaloidal structure was wanting, only close examination of the field-relations enables us to assign the rocks to their proper place. This is especially the case where, as we shall observe later, portions of the basaltic lavas have been, quite locally, fused in contact with the gabbro magma and partially incorporated in it. The most highly metamorphosed examples are sometimes quite as coarse in texture as many of the larger dykes and sills of dolerite in the district.

Metamorphism imparts to the basalts a quality of hardness and durability which they lack in other conditions, and it is only in this state that they form strong features. The summit of Glamaig is an example. Here, as has been described in another place,<ref>Harker, *Proc. Camb. Phil. Soc.,* vol. x., pp. 270–272, Pl. XI.: 1890.</ref> the rocks are highly magnetised in a manner which we shall have to note as characteristic much more generally of the gabbro of the mountains and the dolerite sills of the plateaux.

In conclusion, it may be mentioned that the basaltic lavas in numerous isolated places have become *brecciated* as a result of crushing. Usually these crushed basalts present the appearance of a conglomerate rather than a breccia, the several fragments being rounded as if they had been rolled over and ground together. Good examples are seen along Allt nam Meirleach, a branch of the Tungadal River. Other places where the basalt has locally the appearance of a conglomerate are — Inver Meadale; Coire nan Sagart, on the slope of Broc-bheinn; and Allt a' Choire Gaisteach, a tributary of the Vikisgill Burn. Some of the sections suggest that the breaking up of the rock in this way may have been facilitated by a certain spheroidal parting with incipient exfoliation. The intrusive sills associated with the lavas are not crushed. This must be attributed to the superior rigidity of these rocks, for it cannot be supposed that the brecciation of the lavas was earlier than the intrusion of the sills.



(Plate 17) Fig. 1. × 20. Olivine-basalt lava, above schoolhouse, Braes, S. of Portree: showing olivine replaced by a mineral comparable with iddingsite. See p. 34. Fig 2. (S6772) [NG 520 363] × 20. Olivine-basalt lava, Rudha Buidhe, near Braes, S. of Portree: showing another type of pseudomorph after olivine. See p. 34. Fig 3. × 40. Microstructures of the basic lavas. A. (S8185) [NG 42 28] "Granulitic" structure in olivine-basalt, near bridge over Allt Fionnfhuachd, Drynoch; the rock analysed. See pp. 31, 36. B. (S9246) [NG 47 29] Ophitic structure in hypersthene-basalt, lower part of Allt Dearg Mòr, near Sligachan. A bastite pseudomorph after hypersthene appears in the lower left-hand corner. See pp. 36, 38. C. Ocellar structure in basalt at base of group, S. of Sgùrr nan Each: a type rich in augite and without olivine. See p. 37. D. (S9366) [NG 614 273] Microlitic structure in augite-andesite, S. coast of Scalpay: the augite is mostly chloritised. See p. 37. Fig. 4. (S7460) [NG 537 196] × 10. Metamorphosed amygdule in basalt, close to granite on E. side of Blath-bheinn; showing a crystalline aggregate of new plagioclase felspar, partly with radiate grouping, replacing zeolites. See p. 51. Fig. 5. (S2700) [NG 587 240] × 10. Metamorphosed amygdule in basalt, near granite, Creagan Dubha, N. of Beinn Dearg Mhòr (of Strath): showing a granular crystalline aggregate of new felspar, derived from zeolites, with a border of epidote grains. See pp. 51, 52.



(Plate 18) Fig 1. (S8731) [NG 437 191] × 20. Highly metamorphosed amygdaloidal basalt, near gabbro, N.E. of An Sgùman. The rock is completely reconstituted, and presents the appearance of some so-called pyroxene-granulites. The figure shows part of an amygdule, now consisting of alternate zones of augite and felspar. See pp. 52, 53. Fig. 2. (S9238) [NG 470 200] × 20. A northite-olivine rock (troctolite) in the peridotite group, lower part of An Garbh-choire: consisting simply of olivine and anorthite, the latter often traversed by numerous fine fissures, which radiate from the olivine grains. See p. 73. Fig. 3. (S8705) [NG 456 219] × 20. Enstatite-anorthite-rock (norite) in the peridotite group, N. of Sgùrr a' Coir' an Lochain, near Coruisk. The chief constituents are enstatite and anorthite, the latter interstitial to the former. At the bottom of the figure is a crystal, half of enstatite, half of diallage, and immediately to the left of this a crystal-grain of olivine. See p. 74. Fig. 4. (S7462) [NG 520 214] × 100. Augite of gabbro on the W. slope of Blath-bheinn: showing the basal striation, accentuated by a fine "schiller" structure, and combined with the orthopinacoidal twin to give the "herring-bone" arrangement. See p. 109. Fig. 5. × 10. Augite of gabbro at head of Loch Scavaig: showing the prismatic cleavage and diallage - structure. The latter, parallel to the orthopinacoid, is developed only in the marginal portion of the crystal. See p. 109. Fig. 6. (S7849) [NG 49 22] × 10. Foliated gabbro in the banded part of the group, Druim an Eidhne: showing a parallel orientation of the component crystals. See p. 119.