

Alteration products of olivine and pyroxene in basalt lavas from the Isle of Mull¹

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Summary. Flood basalts of the Isle of Mull were sampled in areas outside the metamorphic aureole of the central intrusions. Alteration products of olivine and pyroxene in these rocks are talc, chlorite, serpentine, iron oxides, brucite, calcite, and 'iddingsite'. Plagioclase feldspar in the same rocks is unaltered. 'Iddingsite' is less common than mixtures of chlorite and serpentine.

In two flows the only alteration product near the bottom is 'iddingsite' but at higher levels in the same flow green chloritic material replaces olivine. This variation is accompanied by an increase in the FeO/Fe₂O₃ ratio in the rock towards the flow top. Green alteration products may be converted to material optically identical with 'iddingsite' by heating in air at 600° C. Zoned patches of chloritic material have formed by crystallization of the late stage magmatic fluid, modified in composition by reactions with olivine and pyroxene.

ALTERATION products of ferromagnesian minerals in basic volcanic and hypabyssal rocks have formed the subject of several investigations in recent years (Sun, 1957; Wilshire, 1958, 1959; Brown and Stephen, 1959; Smith, 1959; Gay and LeMaitre, 1961; Sheppard, 1962). These studies have been mainly concerned with 'iddingsite' but Wilshire (1958) described several varieties of alteration products with features similar to those in the Mull lavas. This investigation was undertaken when a great variety of alteration products was observed during a study of the petrology of some of the flood basalts of Mull (Fawcett, 1961).

In their classic memoir on the Tertiary igneous rocks of Mull, Bailey *et al.* (1924) showed that basaltic lavas form a structural framework into which the various central intrusions were injected. The contact metamorphic and pneumatolytic effects of the intrusions on the lavas were described in some detail, particularly with respect to the mineralogy of vesicles and segregation veins. Specimens described in the present study,

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however, were all collected outside the zone of pneumatolysis as designated in the Mull memoir (fig. 1). Thus alteration products cannot be related to any source outside the lava flow. Chlorite that does not appear to have replaced any pre-existing mineral occurs in some flows. This material is included in the discussion as it is probably genetically

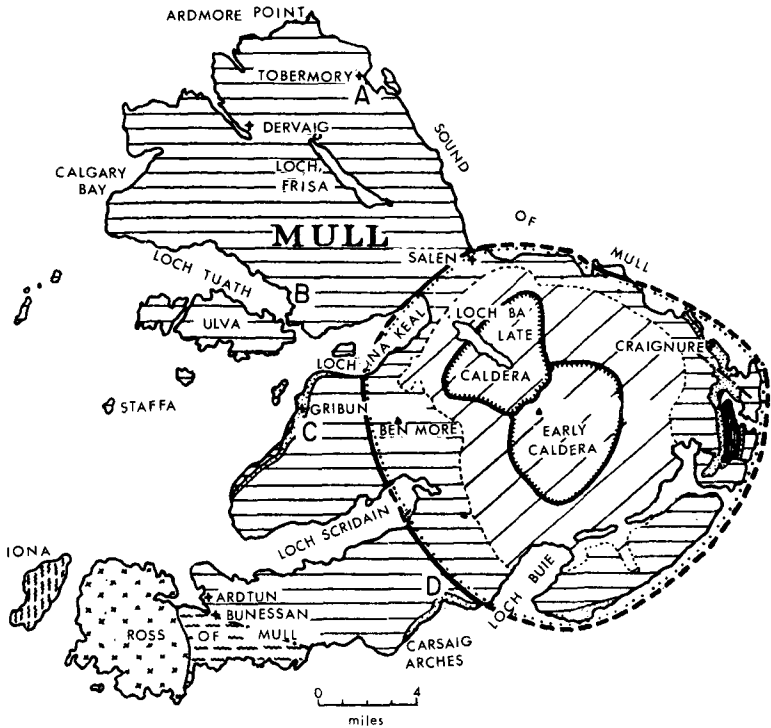


FIG. 1. Specimen localities: A, Tobermory; B, Lagganulva; C, Gribun; D, Carsaig Bay. At each locality the entire thickness of the lava pile was sampled. The limit of pneumatolysis is indicated by the heavy circle surrounding the calderas.

related to the processes involved in deuteric alteration. Only those features of the petrography that were relevant to a discussion of the alteration will be described in this paper; a full account of the petrography and petrogenesis will be published separately.

The majority of observations were made with a standard petrological microscope but $2V$ measurements of olivines and pyroxenes were made on a universal stage; olivine compositions were determined from the

curve of Deer and Wager (1939). There is a considerable variation on the extent of alteration from one flow to another and in the more extreme cases it is difficult to characterize the basalt as belonging to either the tholeiitic or alkaline group. In all instances where a decision may be made (on the basis of an augite-bearing basalt being designated an alkali basalt and an augite + lime-poor pyroxene, a tholeiite) the basalts discussed in this paper are alkaline in character. The olivines, pyroxenes, and plagioclase feldspar will be described first, followed by descriptions of the alteration in a number of lava flows selected to illustrate the variable nature of the process.

Petrography

Olivine is present, frequently in two generations, in almost all lava flows examined in this study. Phenocrysts are colourless and subhedral, ranging up to 5 mm in length and 2 mm in width, the long axis being parallel to the *c* axis; average grains, however, are usually equidimensional and about 2–3 mm in size. Many crystals show a series of irregular fractures, roughly perpendicular to the *c* axis. There is often a gradation in the size of olivine crystals from the large phenocrysts down to the small groundmass granules 0.2 mm in diameter and it is not possible, in some lava flows, to distinguish groundmass and phenocryst olivine. Colour changes from large to small olivine crystals cannot be detected but a distinct change in composition from large to small olivines is reflected by the change in $2V$. The large crystals, phenocrysts in some flows, show $2V$ varying from $89^\circ (+)$ to $88^\circ (-)$, whereas the smallest groundmass olivines show values of $2V$ down to $73^\circ (-)$. There is no clear indication as to whether or not olivine crystals of intermediate size in any given lava flow are of intermediate chemical composition, between the phenocryst and the groundmass crystals. The compositional range of the olivines is Fe_{90} to Fe_{51} (Deer and Wager, 1939).

Pyroxenes in these lavas are exclusively augites, although some of the flood basalts on Mull do contain both augite and pigeonite. There is considerable variation in the size, colour, and habit of the augites; but optical determinations ($2V$ and β refractive index) show little variation, and these are typical pyroxenes of alkali basalts (Wilkinson, 1956). The colour of the clinopyroxenes varies from colourless and pale brown to the faint purple of titaniferous augites, and the habit varies from prismatic and granular crystals to anhedral poikilitic grains. Both olivine and plagioclase grains are found poikilitically enclosed by pyroxene plates. Zoning is a common feature of the pyroxenes with an increase in

intensity of the purple colour towards the crystal margins. In a very few instances the rims of the titaniferous augites show a faint green colour, presumably indicating a change in composition towards aegirine-augite. Colour zoning in titaniferous augites is not accompanied by a notable change in $2V$ as it is usually impossible to detect changes in $2V$ from core to the margin of the colour-zoned crystals.

Only in rare cases is plagioclase feldspar the principal phenocryst, but flow LF 124 does show this feature. More often feldspar crystals have dimensions similar to those of the olivines (up to 3 mm long) but the largest of the plagioclase laths rarely exceed 1 mm in width. Progressive zoning is frequently exhibited in both large and small plagioclase crystals. The most basic cores are $Ab_{29}An_{71}$, and the rims of the crystals vary in composition from Ab_{56} to Ab_{64} . Smaller groundmass feldspars in the porphyritic lavas have the same composition as the rims of large zoned crystals. Alteration of the feldspar is restricted to veining by pale green chlorite which sometimes forms a reticulate pattern through the feldspar crystals. Smaller labradorite and andesine crystals are usually clear and unaltered. The average composition of the feldspar, in rocks in which this mineral is not a phenocryst, is a sodic labradorite, $Ab_{46}An_{54}$.

It is not always possible to identify all the alteration products as mineral species for in many instances colour, habit, and birefringence are the only observable features and these are insufficient to characterize most fibrous minerals. Secondary minerals are commonly fibrous and very fine grained thus rendering virtually impossible the task of isolation and concentration for chemical or X-ray determinations. In the following general description of alteration products reference will be made to individual lava flows in instances of less common structures or products.

Olivine is the primary mineral most frequently involved in the alteration processes but in a number of flows the clinopyroxene is also affected. The most abundant alteration product is a fibrous mineral occurring in irregular patches both on the edges and inside olivine crystals. This material is usually colourless but may be pleochroic in various shades of pale green or, less frequently, yellow and yellow-brown. Birefringence of the secondary material ranges up to the top of the first order.

As well as the green alteration products, yellow, yellow-brown, brown, and red-brown materials frequently replace olivine. The name 'iddingsite' is usually given to this type of alteration product, but recent studies indicate that it is not a single mineral. Recent studies of

'iddingsite' have been made by Sun (1957), Wilshire (1958), Brown and Stephen (1959), Smith (1959), and Gay and LeMaitre (1961); and it appears from the various studies that the actual material studied was not of the same chemical composition and crystallographic constitution in each investigation. The results of these recent investigations will be more closely examined in later discussion. Absence of exsolved iron oxides around the altered olivines suggests that the iron of the original mineral is present in the alteration product. Anomalous interference colours indicate that some of the alteration product is a chlorite, but it is not possible to make a precise identification from the optic properties. A 50 % concentrate of the green alteration produce in flow LF 103 was obtained with the aid of a magnetic separator. The greater part of the impurity was labradorite, and the X-ray diffraction pattern of the material corresponds to a mixture of labradorite and a serpentine mineral similar to antigorite. The X-ray data and optical properties suggest that the dominant alteration product is intermediate in composition between antigorite and ferro-antigorite.

In many rocks both phenocryst and groundmass olivine have been altered and the dominant colour of the alteration product is green; however, there is considerable variation in colour not only from one flow to another but even within a single pseudomorph. Olivine phenocrysts in flow LF 103 are almost completely replaced by material that varies in colour from very pale brown to green and in patches is colourless. If, as in some instances, a relict core of olivine is preserved, the pale brown material surrounds the olivine and outer zones are green and in patches yellow-brown. Veins of the green material cut across the inner brown zones of the pseudomorph. The pale brown fibres are length slow, show straight extinction, and have a maximum birefringence of first-order orange. Non-fibrous pale brown material, which is probably a basal section of the fibrous pale brown mineral, shows birefringence up to second-order blue. Green material in the same pseudomorph is not as fibrous in character as the pale brown material, but its refractive index is lower than that of adjacent brown material as is the birefringence, which is never above first-order yellow. Non-fibrous green material gives an off-centred optic emergence interference figure with $2V$ 20–30° and a positive sign. The yellow-brown material is always present towards the edges of the pseudomorph and grades into the green mineral towards the centre of the crystal. A structural control of the crystallographic orientation of all varieties of alteration product by the host olivine is suggested by the simultaneous extinction of almost all material

within the pseudomorphs. In rare instances, however, the secondary minerals show completely random orientation. The colourless to pale brown material is probably talc, and the green mineral chlorite or serpentine.

Olivine pseudomorphs only rarely occur with opaque oxide minerals as is common in the association of serpentine and olivine. When present, the opaque material forms a thick rim around the pseudomorph inside which is a fibrous mineral, pleochroic in various shades of green. The pale green absorption colour corresponds to the fast direction and colourless to the slow direction. Fibres show straight extinction, are length slow and have a maximum birefringence of second-order green. In the majority of rocks iron oxides do not accompany the replacement of olivine by fibrous green material. The high birefringence of the alteration product in the above association indicates that it is not a true serpentine, and it is therefore assumed that iron from the original olivine has entered the replacement mineral.

Olivine is sometimes replaced by pale brown material that has a very well-developed cleavage. There is no apparent structural control of the alteration by the host olivine but the two substances are in optical continuity. Fast and slow vibration directions coincide for both olivine and alteration product, and a decrease in maximum birefringence from third-order green to second-order green is visible in the latter. A narrow zone of opaque material often accompanies these brown alteration products of olivine. It was not possible to identify the material forming this zone, but it may be significant to note that the rim frequently forms an euhedral outline parallel to the margin of the former olivine crystal. It is not possible to say with certainty that the zone represents the original crystal margin for alteration products are present on both sides of the opaque material. This, however, may be a reflection of the volume difference between equal molecular amounts of olivine and the secondary material. A green fibrous mineral, probably chlorite, sometimes forms an incomplete zone outside the opaque rim, and the consistent orientation of fibres perpendicular to the rim is a striking feature. The chlorite fibres are strongly pleochroic, the slow ray corresponding to the length of the fibre and a green colour. The fast ray is colourless. When the rims of chlorite are most fully developed, optically identical material of much finer grain size fills the cracks and veins through the olivines.

An interesting series of variations in olivine alteration is shown in the lowest flow of the lava pile $\frac{1}{2}$ mile south of Balmeanach farm on the Gribun peninsula where the basalts rest on a red mudstone, about 10 feet

thick. Specimens were collected at the base of the flow and 4, 8, 16, and 20 feet above the base of the lava flow. In the basal specimen olivine phenocrysts are completely replaced by calcite, but green rims and the narrow veins within the crystal have been preserved. The alteration is almost certainly related to the presence of the underlying mudstone. Four feet above the base of the flow pseudomorphs after olivine range up to 2.0 mm long and 0.5 mm wide. The outlines of these subhedral and euhedral crystals are marked by a zone of material that varies in colour from yellow-brown and brown to red-brown; the maximum width of this zone is 0.05 mm. The rim is usually pleochroic in varying shades of light brown but interference colours are obscured by the intense absorption colour. A lamellar structure is sometimes developed and in such cases extinction is parallel to the lamellae. Olivine is often preserved in the cores of pseudomorphs, but sometimes it has been completely replaced by talc. Alteration of groundmass olivines is similar to that of the phenocrysts.

The dominant alteration product of olivine 8 feet above the base of the flow is a pale green fibrous material that is slightly pleochroic and rarely shows pale brown colours. Alteration is confined to narrow rims and veins. Brown and red-brown alteration products are very rare at this level in the flow. At 16 and 20 feet above the base of the lava flow the only alteration product of olivines is the pale green variety. This type of variation of olivine alteration products with height in the lava flow has also been observed in a flow that does not rest on a mudstone. Thus, although the pseudomorphing of olivine by calcite at the base of the flow described above may be ascribed to the presence of the underlying mudstone, the variations at higher levels cannot be attributed to this feature.

Chlorite is a common mineral in many of the Mull lava flows. Its mode of occurrence varies considerably from that of an alteration product after olivine or pyroxene to irregular globular masses (fig. 2). The poikilitic pattern of pyroxenes is retained by the chlorite, and enclosed plagioclase laths are completely unaltered. Isolated patches of chlorite occur between plagioclase laths with a pronounced zonal structure in each area. Individual chlorite fibres have a constant orientation perpendicular to the surrounding crystals, and there are often two distinct concentric zones of chlorite with the outer zone a darker green colour than that of the interior. Individual fibres of chlorite are extremely small, and pleochroism, in varying shades of green, is very slight. Where chlorite and pyroxene are adjacent the contact is quite sharp and does

not resemble the ragged junction between olivine and its alteration products. All refractive indices of the chlorite lie within the range 1.59–1.60, corresponding to those of the antigorite-ferroantigorite series (Winchell, 1951).

Rounded patches of chlorite occur extensively in some lava flows in the Tobermory area. This chlorite does not appear to be replacing any



FIG. 2. Zoned patch of chlorite unrelated to any pre-existing mineral; outer zone dark green, inner zone light green.

pre-existing mineral. Zoning and structure of these patches is similar to that described above and the increased intensity of the green colour is accompanied by a small increase in refractive index. Following the data of Winchell (1951) and Hey (1954), this corresponds either to an increase in the proportions of iron and alumina or to an increase in the ferric:ferrous ratio in the chlorite. The centres of rounded chlorite patches are sometimes filled with an unidentified pale brown mineral that is mainly isotropic but rarely shows a faint birefringence. The three-dimensional form of the chlorite patches is not easy to visualize. In no instance, however, do the thin sections cut longitudinally across such vesicles, and this fact, together with the absence of any indication of

vesicles in the hand specimens, suggests that the chlorite occupies isolated and irregular patches throughout the rocks.

Calcite is a common constituent of some of the more altered rocks. It is present in the interstices of some lavas and sometimes forms the core of irregular chlorite-rimmed patches. As calcite is never present in unaltered rocks it is assumed that it was formed when lime was released by alteration of pyroxene to chlorite. The ferromagnesian constituents of the pyroxene can be incorporated into the alteration product, but lime is never a significant component in chlorites.

Discussion

The red-brown variety of olivine alteration product has been the subject of several recent investigations. Lawson (1893) gave the name 'iddingsite' to such material, and Ross and Shannon (1925), using both optical and chemical data, deduced its formula as $MgO \cdot Fe_2O_3 \cdot 3SiO_2 \cdot 4H_2O$. They concluded that 'iddingsite' is most probably a deuterite mineral formed in the presence of heat, water, and gases in an oxidizing environment. Edwards (1938) supported the Ross and Shannon theory and suggested that the alteration product formed before the lava flow came to rest. An essential facet to Edwards's hypothesis is that a crust should form on the lava surface that effectively seals all volatile material inside the flow.

X-ray studies of 'iddingsite' published during the last few years (Brown and Stephen, 1959; Gay and LeMaitre, 1961) prove conclusively that 'iddingsite' is not a single mineral. Material examined during their investigations may not have been of the same physical and chemical constitution in each case, and detailed results, therefore, may not be identical in each investigation. The undoubted conclusions that may be drawn from both single-crystal and powder X-ray studies are that 'iddingsite' consists of a mixture of iron oxides, in various stages of oxidation and hydration, intimately associated with a layered silicate that is probably a variety of chlorite.

The various green alteration products of olivine have not received the same detailed attention as the red-brown alteration products. Such material is usually dismissed briefly in petrographic descriptions as a variety of serpentine, but as Wilshire (1958) has pointed out, the names bowlingite, chlorite, nontronite, saponite, and vermiculite have all been applied to similar material. Both chlorite and serpentine were recognized by the authors of the Mull Memoir but their descriptions were

mainly directed towards the lavas within the zone of pneumatolysis (Bailey *et al.*, 1924, p. 141).

The physical conditions and chemical relationships involved in the transformation of forsterite were set out by Bowen and Tuttle (1949) in their consideration of the system $\text{MgO-SiO}_2\text{-H}_2\text{O}$. Although the experimental data referred only to the iron-free minerals, the authors considered iron-bearing olivines to be stable in the presence of excess water vapour to temperatures below 430°C at 15 000 lb in². A true antigorite does not occur in the lavas examined in this study, and the olivine alteration products are only rarely accompanied by large quantities of iron oxides, which commonly accompany serpentinization. The fibrous green alteration product may therefore be either a chlorite or a member of the antigorite-ferroantigorite solid solution series; powder X-ray diffraction data support the latter alternative.

Crystallographic and phase-equilibrium studies have shown that both chlorite and serpentine may be converted to olivine-rich mineral assemblages at elevated temperatures and pressures. Brindley and Ali (1950) and Brindley and Zussman (1957) examined the crystallographic aspects, and Bowen and Tuttle (1949), Yoder (1952), Roy and Roy (1955), and Gillery (1959) the phase relations of the reactions involved. Starting materials for most of these studies were either synthetic glasses and oxide mixtures or the sheet minerals themselves. There is no doubt, however, that the reactions are reversible and olivine may react to produce serpentine- or chlorite-rich assemblages.

Petrographic evidence indicates that clinopyroxene may also be altered to chlorite; there are, however, no experimental data on this reaction. A comparison of chlorite and clinopyroxene analyses shows that CaO must be released during such a reaction, as it is not incorporated into the chlorite minerals. This is supported, in the lavas examined, by the restriction of calcite to those rocks in which pyroxene as well as olivine shows the effects of alteration.

It was stated above that much of the chlorite in some rocks cannot be considered as a replacement product. The shape of these chlorite masses and the orientation of crystals within the masses themselves suggest that the chlorite has been precipitated directly from a liquid phase. Battey (1956), Nicholls (1959), and Bailey and McCallien (1960) have all described primary chlorite in spilitic lavas but the problem of primary¹ chlorite in basaltic lavas has not yet been thoroughly

¹ Primary is used here in the sense that the chlorite is not related directly to the alteration *in situ* of any pre-existing mineral.

investigated. In the present case the chlorite is most likely a quenching product formed during rapid cooling of the lava flow. Orientation of individual crystals and the complete absence of glass from the ground-mass suggest that the chlorite was precipitated directly from a late-stage fluid, but it is also possible that the chlorite crystallized from a glass during cooling that followed the initial extrusion quench. It is not possible to state with certainty whether or not this material passed through a glass phase during cooling. The formation of chlorite by the rapid cooling of a liquid is reported by Schreyer and Yoder (1964) in their studies of the system Mg-cordierite-water.

TABLE I. Recalculated olivine analysis ($\text{Fo}_{80.6}$) after reduction of MgO from 43.15 % to 12.24 %. (Olivine analysis taken from Yoder and Sahama, 1957, p. 481.)

	SiO ₂	TiO ₂	Al ₂ O ₃	Fe ₂ O ₃	FeO	MnO	MgO
Olivine	38.53	0.04	0.74	0.67	16.60	0.27	43.15
Recalculated analysis	58.95	0.06	1.13	1.03	25.40	0.41	12.24

Wilshire (1958) suggested that volatile-rich fluids causing alteration of ferromagnesian minerals leach MgO from those minerals, and the material then in solution is deposited in veins and vesicles. However, it is Wilshire's opinion that these solutions contain a fairly high concentration of iron. This is not likely in the present case involving alkali basalts. Chemical analyses collected by Wilshire (*ibid.*, p. 141) show that the products of alteration are undoubtedly more iron-rich than the original minerals, but it is probably incorrect to make generalizations regarding movement of iron and magnesium on the basis of average analyses of alteration products. The chemical composition of the alteration product should be compared only with the composition of mafic minerals in that same rock. Olivine crystals themselves may well be the source of iron in alteration products. The analysis of an olivine ($\text{Fo}_{80.6}$) is given in table I. If the MgO content of this mineral is reduced, say by leaching, from 43.15 % to 12.24 % then the FeO content of the residual material rises from 16.6 % to 25.4 %. It is thus not necessary to postulate iron enrichment of the late-stage fluids to account for the chemical composition of alteration products. Any leaching process will affect the proportion of the principal oxides in the original mineral. Chemical analyses collected by Wilshire (*ibid.*, p. 141) indicate that green material occupying veins and vesicles is less iron-rich than that from the pseudomorph, and therefore the introduction of iron, either from the late-stage fluids or some other source, is unnecessary for the production

of the various green alteration products from olivine. Chlorite in the centre of the globular masses has a higher refractive index than that of the margins. This is interpreted as a reflection of a higher $\text{Fe}^{2+}/\text{Fe}^{3+}$ ratio at the margins owing to falling oxygen pressure with continued crystallization.

Vertical variation in the nature of alteration products in certain lavas has already been described. To recapitulate, however, olivine at the base of the flow is pseudomorphed by calcite and 4 feet above the base the alteration products are all of the red-brown variety 'iddingsite'. At higher levels in the flow the red-brown alteration product is replaced

TABLE II. Results of FeO and Fe_2O_3 determinations at three levels in flow LF 210

Specimen number	Height above base of flow	Total iron (Fe_2O_3)	FeO	Fe_2O_3	$\text{FeO}/\text{Fe}_2\text{O}_3$
LF 210 D	16 ft	14.06	10.71	2.18	4.91
LF 210 C	8 ft	14.95	10.78	2.99	3.60
LF 210 B	4 ft	14.73	9.99	3.84	2.60

by the green variety. The almost complete replacement of olivine by calcite is unusual and probably results from boiling of vapour from the underlying mudstone. The close association of 'iddingsite' and the green alteration products in the same lava flow provides a good opportunity to study the relationships between the two types of material.

FeO and Fe_2O_3 determinations were made on the rocks LF 210 B, LF 210 C, and LF 210 D, which are respectively 4, 8, and 16 feet above the base of the flow. Results of these determinations are shown in table II. The variation in $\text{FeO}/\text{Fe}_2\text{O}_3$ is most striking, with the highest Fe_2O_3 content corresponding to the 'iddingsite'-bearing level of the flow. It is also interesting to note that there is no significant variation in the total iron content of the flow at the three levels examined. As the change in the alteration product is the only variable noted during petrographic examination of these three specimens, the analyses suggest that the relationship between red and green alteration products and vesicle fillings is essentially one of oxidation state of iron. If this hypothesis is correct it should be possible to produce the red material from the green alteration product by heating the latter material in air.

Four rocks—LF 103, LF 210 B, LF 210 C, and LF 210 D—were selected for heating experiments. Thin slabs of rock, suitable for sectioning, were heated in air at 600°C for 28 hours, and comparison of sections cut before and after heating yielded the following results:

LF 103. Pale yellow-brown material of the original pseudomorph was much brighter after heating and in patches became red-brown. Birefringence was masked by the colour, and the core of the pseudomorph contained patches of a dull grey mineral, probably brucite. The irregular patches of chlorite were rimmed by opaque material, presumably exsolved iron oxide, and centres of the patches remained unaltered pale green chlorite.

LF 210 B. The yellow-brown rims around olivines became intensely bright red-brown after heating and the cores, initially pale brown in colour, showed pleochroism from dark green to pale yellow-brown similar to the original crystal margins. Relict olivine and iron oxides appeared unaltered by heating, but veins and cracks were occupied by red material in contrast to the initial green. The outer margins of chlorite patches changed from green to opaque, and inner chlorite zones became dark brown in contrast to the original pale green.

LF 210 C. The green material associated with olivine prior to heating changed to various shades of yellow and red-brown. Patches of chlorite associated with pyroxenes and also in the interstices were yellow-brown after heating. Iron oxides, presumably exsolved from the chlorite, appeared after heating, in an intimate mixture with the alteration product.

LF 210 D. Initial green alteration products were completely absent after heating. Olivine and pyroxene were unaltered, but secondary minerals were all dark red-brown in colour and there was an abundance of iron oxides.

The results of these heating experiments strongly suggest that the essential relationship between the various alteration products of ferromagnesian minerals in basaltic rock is the extent of the oxidation state of iron. Although it was not possible to analyse materials used in the experiments described above, petrographic observations indicate that green alteration products were converted to material optically identical to the red-brown 'iddingsite'. Products of alteration observed in this study and also by more detailed X-ray studies of other workers are a sheet mineral of the chlorite-serpentine group that is intimately mixed with iron oxides in various states of oxidation and hydration. The precise nature of the sheet mineral and the iron oxide is controlled by the composition of the original mineral, the composition of the late-stage fluid and, probably most important, the temperature and rate of cooling during the alteration process.

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