THE AMERICAN MINERALOGIST, VOL. 43, JANUARY–FEBRUARY 1958

ALTERATION OF OLIVINE AND ORTHOPYROXENE IN BASIC LAVAS AND SHALLOW INTRUSIONS

H. G. Wilshire, *University of Sydney, Sydney, Australia.*

Abstract

Alteration products of olivine and orthopyroxene, previously identified as iddingsite, bowlingite, and serpentine among other minerals, have been found to consist predominantly of mixed layer smectite-chlorite with a variety of accessory minerals. Alteration products from shallow basic intrusions may contain antigorite or chrysotile as well as smectite-chlorite, and are much richer in MgO than those from basic lavas. Optically isotropic varieties (chlorophaeite) are closely associated with smectite-chlorite minerals and sometimes have a poorly developed chlorite (?) structure.

It is probable that all of these secondary minerals can form by deuteric alteration, but evidence is presented which suggests that oxidized varieties (commonly containing goethite) may also form by weathering of green varieties. Implications of chemical and physical properties are discussed and it is concluded that equal volume replacement of Mg-rich olivine or orthopyroxene in basic lavas results in selective leaching of Mg which may be removed from the altered rock and recombined in the same secondary minerals in joints. Quantitative data for the effects of alteration on bulk composition of the enclosing rock are presented. In shallow intrusions, where there is little evidence of Fe-enrichment in residual solutions, complete solution of olivine is possible. Application of these results to some problems in soil clay mineralogy is briefly considered.

Introduction

Although many optical, chemical and *x*-ray data are now available for alteration products of olivine and orthopyroxene in igneous rocks, little attempt has been made to organize these data, with the consequence that relations among alteration products are not clearly understood and misidentifications based on inadequate data are common. The object of this study is to identify typical alteration products by *x*-ray techniques, to attempt an integration of ideas concerning their mode of origin and relationships, and to discuss possible implications of these relationships. A sampling problem is recognized in view of the widespread occurrence of these minerals and has been accounted for to some extent by selection of material from widely separated localities.

Previous Work

It is impossible to be exhaustive in the treatment of previous work, for the literature on these minerals is very large. Among the more important contributions are those of Ross and Shannon (1926) whose chemical formula of iddingsite is quoted in most textbooks, Peacock and Fuller (1928) who have presented the most comprehensive study of the occurrence and mode of origin of chlorophaeite, and Caillere (1935) and Caillere and Henin (1951) whose *x*-ray and thermal studies of bowlingite have led to redesignation of this mineral as saponite.

METHODS OF INVESTIGATION

X-ray powder photography using a Philips *X*-ray Diffraction unit was the principal method used in identification. Filtered copper radiation was found adequate except with optically isotropic material. Some basal spacing expansions were obtained from oriented aggregates using a Philips Geiger Counter Spectrometer with filtered copper radiation.

Refractive index measurements were made with standard immersion oils which were checked with a Leitz-Jelley refractometer. Olivine compositions were determined from n_y using Kennedy's curves (Troeger, 1951, p. 37). Refractive indices of the alteration products are quoted only to the nearest second decimal place because the index varies with the type of immersion oil used.

Plagioclase compositions were determined with the universal stage microscope using Turner's (1947) method and van der Kaaden's (1951) data. All measurements of 2V were also made with the universal stage microscope. All other mineral identifications and fabric descriptions were made with a standard petrographic microscope.

MODE OF OCCURRENCE AND IDENTIFICATION

In basic lavas olivine and orthopyroxene are commonly altered to a reddish-brown substance with high birefringence and refractive indices ranging from approximately 1.61 to 1.86. This is usually identified as iddingsite if it is pseudomorphic after olivine, and is assigned the chemical formula, $MgO \cdot Fe_2O_3 \cdot 3SiO_2 \cdot 4H_2O$ (Ross and Shannon, 1926). Average chemical analyses of iddingsite are given in Table 4A. Optically identical material in amygdules and joints is sometimes called chlorite. A recent *x*-ray investigation of iddingsite (Ming-Shan Sun, 1957) revealed the presence of goethite mixed with amorphous substances.

A green substance with moderate birefringence and refractive indices ranging from approximately 1.48–1.62 is also a common alteration product of olivine and orthopyroxene and is exceptionally abundant in shallow basic intrusions. Optically identical material occurs in amygdules and joints. This material has been assigned a wide variety of mineral names including bowlingite, serpentine, chlorite, nontronite, saponite, and vermiculite. Average chemical analyses, all of saponite from shallow intrusions, are given in Table 4A. *X*-ray and thermal studies by Caillere and Henin (1951) indicated a montmorillonite-type structure and this, combined with the chemical composition, led them to redefine bowlingite as saponite. Other *x*-ray powder studies of minerals fitting the optical

TABLE 1. *X*-RAY DATA: SAMPLES UNTREATED

Group 1											
1			2			3			4		
d	I*	Id†	*d*	I	Id	*d*	I	Id	*d*	I	Id
14.0 Å	m	S	14.0 Å	m	S	15.49 Å	ms	S	7.3 Å		
4.80	vw	S	4.92	vw	G; S	4.52	s	S	7.0	mw	K
4.46	m	S	4.49	ms	S	4.30	vw	F?	4.47	s	K
4.18	s	G	4.15	vs	G	3.37	vw	Q?	4.19	vs	G; Q
3.70	vw	F	3.71	vw	F	3.26	vw	F?	3.35	vs	G; Q; K
3.35	vw	Q	3.33	w	Q	2.59—			3.22	vw	K
3.21	m	F	3.20	m	F	2.52	m	S	2.72	vw	K
2.94	vw	F	2.70	m	G; S	1.71	w	S	2.66	vw	G
2.69	m	G; S	2.59	m	S	1.513	mw	S	2.55	m	K
2.59	w	S	2.50	vw	S				2.43	ms	G; Q
2.52	vw	S	2.44	s	G				2.28	vw	G; K
2.44	ms	G	2.25	vw	S				2.24	vw	G; Q; K
2.22	vw	S	2.15	vw	S				2.19	vw	G; K
1.71	m	G; S	1.96	vw	S				2.12	vw	Q; K
1.56	vw	S	1.79	vw	S				1.82	vw	Q; K
1.509	w	S	1.72	s	G; S				1.71	w	G; K
1.455	vw	S	1.60	vw	S				1.67	w	Q; K
			1.563	vw	S				1.544	mw	Q; K
			1.510	mw	S				1.495	mw	G; K
			1.460	vw	S				1.459	vw	G; K
									1.377	w	Q

* I = intensity, visually estimated.

† Id = identification. S = smectite-chlorite; F = feldspar; G = goethite; Mg = magnetite; Ca = calcite; Q = quartz; Mi = mica; T = talc; Se = sepiolite; Sp = serpentine; K = kaolinite.

1. Carmel Bay, California. Pseudomorphs after olivine.
2. Carmel Bay, California. Pseudomorphs after olivine.
3. Santa Rosa, California. Pseudomorphs after olivine.
4. Orange, New South Wales. Joint-filling.

Group 2									Group 3		
5			6			7			8		
d	I	Id	*d*	I	Id	*d*	I	Id	*d*	I	Id
14.0 Å	vs	S	16.0 Å			15.4 Å			15.0 Å		
7.13	vvw	S	14.5	vs	S	14.0	vs	S	14.0	s	S
4.60	m	S	7.8—			4.55	m	S	7.4—		
4.25	vw	Q	7.0	vvw	S	4.25	mw	Q	7.0	s	S; Sp
4.02	vw	F	5.0	vw	S	3.70	vw	F	4.83	m	S
3.33	w	Q	4.52	s	S	3.34	s	Q	4.57	m	S
3.17	s	F	4.26	vw		3.19	w	F	3.84	w	Ca
3.03	w	Ca	3.21	m	F	2.96	m	Mg; F	3.61	m	S; Sp
2.95	w	F	2.59	s	S	2.70	w	S	3.03	vs	Ca
2.88	m	F	2.47	mw	S	2.59	vw	S	2.89	vw	S
2.83	w	S	2.28	vw	S	2.52	vs	Mg; S	2.65—		
2.71	w	S	2.20	vw	S	2.44	vw	S	2.41	w	S
2.54	w	S	1.90	vvw	S	2.29	vw	S	2.50	mw	Ca; S; Sp
2.50	w	S	1.72	w	S	2.12	vw	S	2.28	m	Ca; S
2.47	w	S	1.533—			2.09	m	Mg; S	2.09	m	Ca
2.12	vw	S	1.512	s	S	1.82	vw	Q; S	1.91	ms	Ca
2.09	vw	S	1.314	w	S	1.71	w	Mg; S	1.87	ms	Ca
2.05	vw	S				1.66	vw	S	1.74	vw	S
1.99	vw	S				1.61	m	Mg; S	1.63	vw	Ca
1.96	vw	S				1.535	w	Q; S	1.60	w	Ca
1.74	vw	S				1.515	vw	S	1.540	s	S
1.546	vvw	S				1.480	ms	Mg; S	1.506	mw	S
1.531	m	S				1.453	vw	S	1.443	w	Ca
1.487	w	S				1.379	w	Q; S	1.418	w	Ca
1.472	w	S							1.326	vw	S
1.387	vw	S							1.299	vw	S
									1.230	vw	S

5. Ebbetts Pass, California. Pseudomorphs after hypersthene.
6. Orange, New South Wales. Joint-filling.
7. Carmel Bay, California. Pseudomorphs after olivine.
8. Prospect Hill, Sydney, New South Wales. Joint-filling.

TABLE 1. (*continued*)

Group 3											
9			10			11			12		
d	I	Id	*d*	I	Id	*d*	I	Id	*d*	I	Id
14.5 A	vs	S	14.0 Å	w	S	15.0 Å	s	S	15.0— Å		
12.10	vw	Se?	9.35	w	T	10.0	vvw	Mi	14.0	vs	S
9.50	w	T	7.5—			7.4—			7.30	s	S; Sp
7.5—			7.0	vs	S; Sp	7.0	s	S; Sp	4.87	vw	S
7.0	s	S; Sp	4.57	s	S	5.0	vvw	Mi	4.58	mw	S
5.88	vw	Se?	3.89	w		4.55	s	S	4.32	vw	Q
4.90	m	S	3.62	s	S; Sp	3.60	m	S; Sp	3.61	m	S; Sp
4.57	s	S; Se?	3.13	w	T	3.35	mw	Mi	3.33	m	Q
3.66	s	S; Sp	3.03	w	Ca	3.19	w	F	3.03	w	Ca
3.25	m	T	2.85	vw	S	2.99	m	F	2.66	vw	S
2.90	ms	S	2.66—			2.90	w	S	2.48	vw	S; Sp
2.65	w	S	2.41	w	S	2.62	w	S	1.545	s	S
2.58	2	S; Sp	2.50	vs	S; Sp	2.51	s	S; Sp	1.514	vw	S
2.43	s	S	2.33	vw	S	2.45	w	S			
2.27	m	S	2.28	vw	S; Ca	2.20	vw	S			
2.08—			2.15	m	S	2.13	vw	S			
2.00	w	S	2.09	vw	Ca; S	2.05	vw	S			
1.88	vw	S	1.96	w	S	1.83	vw	S			
1.74	w	S	1.91	vw	Ca; S	1.76	vw	S			
1.71	vw	S	1.87	vw	Ca; S	1.62	vw	S			
1.576	vw	S	1.79	mw	S	1.540—					
1.540	s	S	1.74	w	S	1.520	s	S			
1.508	mw	S	1.64	vw	S	1.425	vw	S			
1.401	vw	S	1.56	vw	S	1.315	vw	S			
1.324	w	S	1.573	s	S						
1.299	vw	S	1.503	s	S						
			1.412	w	S						
			1.329	w	S						
			1.307	m	S						
			1.278	w	S						
			1.252	vw	S						
			1.167	w	S						

9. Prospect Hill, Sydney, New South Wales. Joint-filling.
10. Prospect Hill, Sydney, New South Wales. Joint-filling.
11. Prospect Hill, Sydney, New South Wales. Pseudomorphs after olivine.
12. Dumbuck Quarry, Milton, Scotland. Joint-filling.

Group 3						Group 4					
13			14			15			16		
d	I	Id	*d*	I	Id	*d*	I	Id	*d*	I	Id
14.5 Å	vs	S	14.5— Å			15.0— Å			15.0— Å		
7.2	s	Sp; S	14.0	s	S	14.0	s		14.0	s	
4.84	vw	S	7.1	s	S; Sp	4.45	s		4.5	vvw	
4.59	w	S	5.37	w		2.60	s		4.48	vw	
4.26	vw	Q	4.57	vw	S	1.535	vw		2.59	vw	
3.62	m	Sp; S	4.26	m					1.55	vvw	
3.33	m	Q	3.58	vs	S; Sp						
1.73—			3.14	w							
1.71	vw	S	3.05	w	Ca						
1.541	s	S	2.74	vw	S						
			2.65	vw	S						
			2.51	vw	S; Sp						
			2.25	vw	S; Ca						
			1.83	m	S						
			1.63	vw	S						
			1.58	vw	S						
			1.539	vw	S						
			1.430	vw	S						

13. Bowling Quarry, Dumbartonshire, Scotland. Joint-filling.
14. Bowling Quarry, Dumbartonshire, Scotland. Joint-filling.
15. Locality unknown. Vesicle-filling.
16. Walla Walla, Washington, Vesicle-filling.

description or mode of occurrence of this material are those of Bradley (1945), (vermiculite), Prider and Cole (1942), (nontronite), and Earley and Milne (1956), (regularly interstratified montmorillonite-chlorite).

When the alteration product, whether it occurs as pseudomorphs after mafic minerals, joint-filling or in amygdules, is optically isotropic it is usually called chlorophaeite (Peacock and Fuller, 1928). It is characterized by a refractive index ranging from 1.50 to 1.62, optical isotropy, and a bright orange to deep green color. Average chemical analyses are given in Table 4A.

INTERPRETATION OF THE *X*-RAY POWDER PHOTOGRAPHS

The data presented in Tables 1, 2, and 3 are representative of 170 powder photographs of 60 specimens. Sample numbers are arranged so that the same number refers to material from the same bulk sample. These are divided into four groups, nos. 1–4, which represent red, oxidized alteration products usually called iddingsite; nos. 5–7, which represent green alteration products in lavas; nos. 8–14, which represent green alteration products in shallow intrusions; and nos. 15–16, which represent optically isotropic alteration products.

Group 1

Photographs of untreated material (Table 1) are characterized by a broad but strong reflection near 14 Å. Rarely very weak second and third order reflections from the basal spacing occur. A few specimens have a reflection near 7 Å with no 14 Å reflection. A weak 060 reflection typically occurs between 1.49–1.51 Å, although two lines are frequently present in the region (1.49–1.54 Å) in which the 060 reflection for dioctahedral

TABLE 2. *X*-RAY DATA: BASAL SPACINGS OF GLYCOLATED SAMPLES

Sample Number	*d*	I
1	15.38 Å	m
2	15.8	mw
3	16.35	s
6	16.05	vs
7	16.5	s
8	15.22	vs
9	15.1	vs
10	14.5	w
11	15.5	vs
12	15.5	s
13	15.5	s
14	15.77	ms

and trioctahedral structures occurs. With ethylene glycol treatment (Table 2) the basal spacing expanded to 15–16 Å. Upon heating to 500° C., a new line appeared between 9.5–10 Å in specimens having a 14 Å spacing (untreated). Heating to 700° C. (Table 3) produced no additional results. Higher order reflections from the basal spacing and the 7 Å structure disappear with heating to these temperatures.

The usual expansion of the 14 Å spacing with glycol solvation and collapse with heating indicate the presence of vermiculite or smectite.* A possible means of distinguishing these by Mg-saturation and glycerol expansion was suggested by G. F. Walker (Pers. comm.). No change in expansion was observed after a 24 hour treatment with saturated $MgCl_2$ solution indicating that the structure is a smectite. Since the expansion is rarely to the full limit (17 Å) expected of glycol solvation, it is possible that the smectite is randomly interlayered with chlorite. Absence of higher order reflections, which render this interpretation difficult to evaluate, may be due to auto-oxidation. As will be shown later, alteration takes place before consolidation of the magma is complete so that high temperatures and, in lava flows, oxidizing conditions may be expected. It is concluded, therefore, that oxidized alteration products are composed predominantly of smectite-chlorite. Goethite is almost always present, quartz and calcite are common constituents and talc and mica rare constituents.

Group 2

These powder photographs (Tables 1–3) are nearly identical with those of group 1 and are interpreted in the same way. The more common occurrence of higher order reflections from the basal spacing is attributed to incomplete oxidation of iron (which also accounts for optical differences). Evidence presented in a later section suggests that weathering of green alteration products can result in extraction and oxidation of iron, producing aggregates which are optically identical with oxidized varieties, this process possibly accounting for differences in position of the 060 reflection between the two. Calcite is common in these aggregates, while magnetite, quartz and feldspar sometimes occur. Talc is a rare constituent.

Group 3

Powder patterns of untreated material (Table 1) from shallow intrusions are characterized by a strong reflection between 14 Å and 15 Å with nonintegral higher order reflections from this spacing of comparable in-

---

* The term smectite (Brown, 1955) denotes members of the montmorillonite group.

tensity. The 060 reflection is usually strong and near 1.54 Å, although it is usually accompanied by a weaker line near 1.50 Å. With ethylene glycol treatment (Table 2), the 14 Å spacing expanded to 15–16 Å and gave rise to a nonintegral series of higher order lines. Upon heating to 500° C. a new line appeared between 9.4–10 Å in most specimens, at 11.78 Å in one specimen. Heating also resulted in a considerable reduction in intensity of higher order reflections from the basal spacing so that these patterns are, with the exception of differences in intensity and position of the 060 reflection, identical with most heated specimens of Group 1. Since heating was done in air, oxidation of iron produces from the green alteration products an aggregate which is optically identical with natural oxidized types. Heating to 700° C. (Table 3) produced no additional results.

TABLE 3. *X*-RAY DATA: BASAL SPACINGS OF HEATED SAMPLES

23 hr. 700° C.		23 hr. 700° C.		21 hr. 525° C.		23 hr. 700° C.		25 hr. 700° C.		2 hr. 710° C.	
1		2		3		6		7		8	
d	I	*d*	I	*d*	I	*d*	I	*d*	I	*d*	I
9.82	m	9.77	mw	9.5	vs	9.60	vs	9.93	s	9.5	vvw
23 hr. 700° C.		23 hr. 525° C.		23 hr. 700° C.		2 hr. 710° C.		1 hr. 480° C.			
9		10		12		13		14			
d	I	*d*	I	*d*	I	*d*	I	*d*	I		
11.78	vs	9.45	m	9.6	s	9.40	vvw	10.4	w		

This behavior again indicates that an expanding 14 Å structure is present. That this is probably interlayered with a non-expanding 14 Å structure is indicated by the nonintegral series of higher order reflections. It is also possible that variable amounts of smectite-chlorite are mechanically mixed with a kaolin-type structure (antigorite or chrysotile), the latter giving rise to strong reflections near 7.2 Å and 3.6 Å. In specimens showing large expansion with glycol solvation, the second order reflection split, one line being roughly half the spacing of the expanded spacing, the other occurring at about 7.2 Å, which strongly suggests a mechanical mixture of a serpentine mineral with the smectite-chlorite. An attempt was made to separate the two, but without success. Although

Hargreaves and Taylor (1946) found that conversion of chrysotile and antigorite to olivine takes place at about 600° C., no reflections belonging to olivine were found in photographs of material heated to and above this temperature.

Material from shallow intrusions is therefore composed at least in part of smectite-chlorite with possibly one or both of the serpentine minerals. Considerable variation in proportions of these components occurs among different samples. Minor amounts of talc, mica, quartz and possibly sepiolite are sometimes present.

Group 4

Optically isotropic alteration products are closely associated with anisotropic material which is optically identical with members of Group 1. In addition, optically isotropic material is itself sometimes submicroscopically crystalline, giving diffuse reflections corresponding to the strongest lines in powder photographs of Group 1. No change in position of the basal reflection was observed with heat and glycol treatment, so that it is probable that the incipient structure is chlorite. Absence of higher order reflections may again be due to auto-oxidation of iron. Goethite and calcite (optically detectable) are sometimes present.

Differential Thermal Analysis

With the exception of specimen no. 14, thermograms (Fig. 1) of specimens from shallow intrusions all have endothermic peaks between 100–200° C. which are attributed to loss of adsorbed water from the smectite component. Absence of this peak in no. 14, which also has a smectite component, is not explained. The second endothermic peak, representing loss of structural water, is typically broad and occurs anywhere between 535°–700° C. It is likely that this behavior reflects variation in the proportions of chlorite and smectite. In most specimens this peak is followed by another, relatively sharp endothermic peak, representing decomposition of the aggregate, between 780–840° C. In specimens 13 and 14, this peak is followed by another endothermic peak at 865° C. and 820° C., respectively. Doubling of the last endothermic peak probably indicates decomposition of different components of the aggregate at different temperatures. Most samples show a final exothermic peak between 820°–860° C. indicating the formation of new mineral phases.

The thermogram of no. 6 (from a lava) is very similar to that of nontronite. No. 4 is the weathered equivalent of no. 6. The endothermic peak at 305° C. in the latter is due to decomposition of goethite, while the peak at 545° C. may be due to kaolinite.

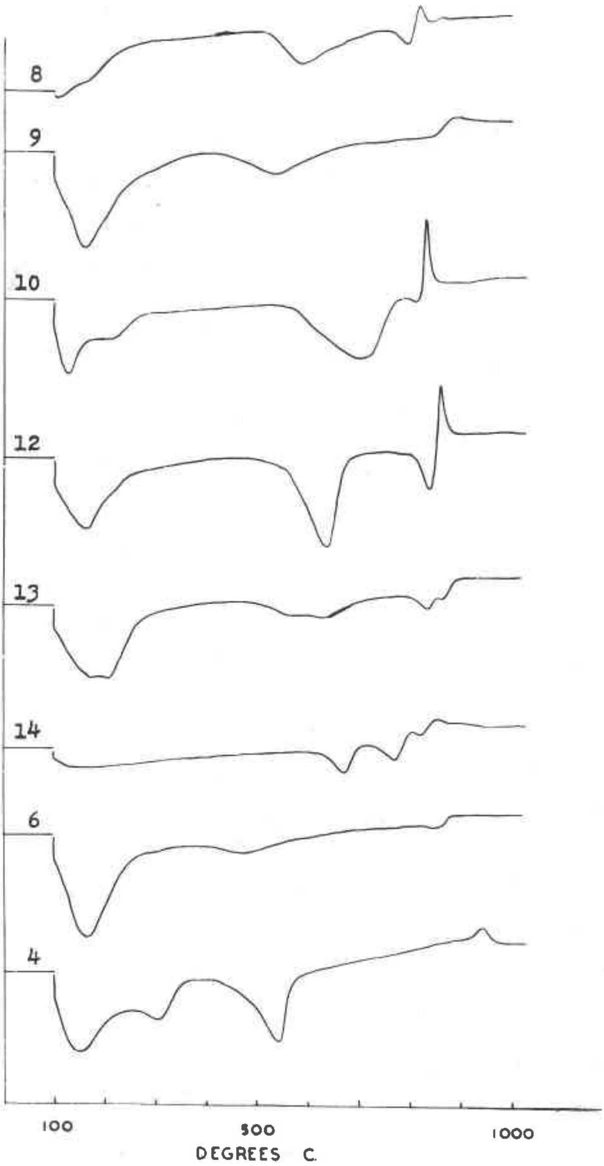

FIG. 1. Differential thermal analyses.

PETROLOGY

Specimens of basalt flows containing both red and green varieties of alteration products were obtained from Carmel Bay, California (type locality for iddingsite; Lawson, 1893), from near Santa Rosa, California, Hawaii, Orange, New South Wales, and from Tertiary lavas near Ebbetts Pass, California.

Carmel Bay, California

At Sunium Point a series of basalt flows outcrop with an exposed thickness exceeding 75 feet. Weathering to a depth of approximately 20 feet has resulted in bleaching of the groundmass and alteration of pyroxene and plagioclase phenocrysts. The only obvious mafic mineral is red pseudomorphs after olivine. In very deeply weathered material pseudomorphs after olivine may be detected only with a hand lens. Below the weathered zone the groundmass is black, fresh pyroxene phenocrysts may be seen with a hand lens, and, at the base of the exposure, the alteration product of olivine is green.

Weathered rocks are characterized microscopically by an abundance of smectite-chlorite and goethite pseudomorphs after olivine, plagioclase and pyroxene phenocrysts completely replaced by a colorless to pale green fibrous material with moderate birefringence, set in an intergranular groundmass of altered plagioclase microlites, granular and euhedral pyroxenes, iron oxides and unaltered apatite. Small amounts of pale green to brown interstitial material is often present, while biotite occurs rarely.

Almost all of the specimens show a distinct flow banding in the plagioclase microlites. There is commonly a concentration of very finely crystalline green to brown material and iron oxides in bands parallel to the flow banding, appearing as a distinct macroscopic lineation on cut surfaces. Pseudomorphs after olivine within these bands are distorted (Figs. 2 and 3).

In unweathered specimens the same textural relations hold, but olivine is usually the only altered mineral. Augite (2V 45°–48°) and plagioclase (An_{53-62}) aggregates are common. In some specimens the groundmass pyroxenes consist in part of colorless euhedra of orthopyroxene which are partly altered to green smectite-chlorite (?). Iron oxides occasionally predominate over clay minerals in pseudomorphs after olivine, while in several specimens green and red alteration products occur side by side in the same pseudomorphic aggregate (Fig. 4). Pseudomorphs are usually connected by delicate stringers, which appear to be thin films coating plagioclase and pyroxene microlites, of material optically identical with that in the pseudomorphs, and sometimes have halos of the same secondary minerals.

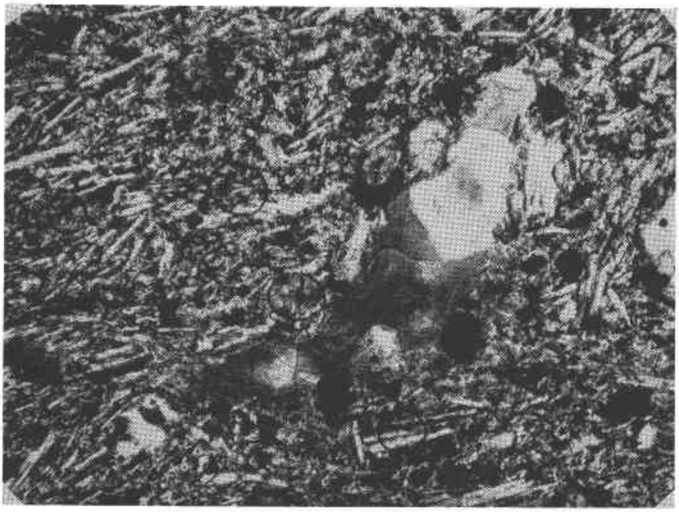

FIG. 2. Pseudomorph after olivine distorted by flow of the enclosing lava. Plane polarized light. ×45.

Rocks from another locality about a mile east of Sunium Point show nearly identical textural and mineralogical relations, except that augite (2V 46°–54°)-plagioclase (An_{54-68}) aggregates are usually larger than those in the Sunium Point flows, and, although often very deeply weathered, colorless clay pseudomorphs after these aggregates are obvious in

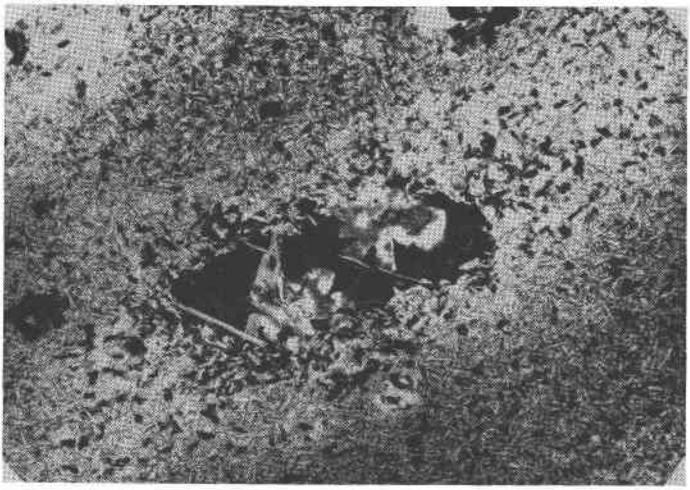

FIG. 3. Smectite-chlorite, iron oxide, biotite pseudomorph after olivine distorted by flow. Color banding is opposite from usual. Plane polarized light. ×30.

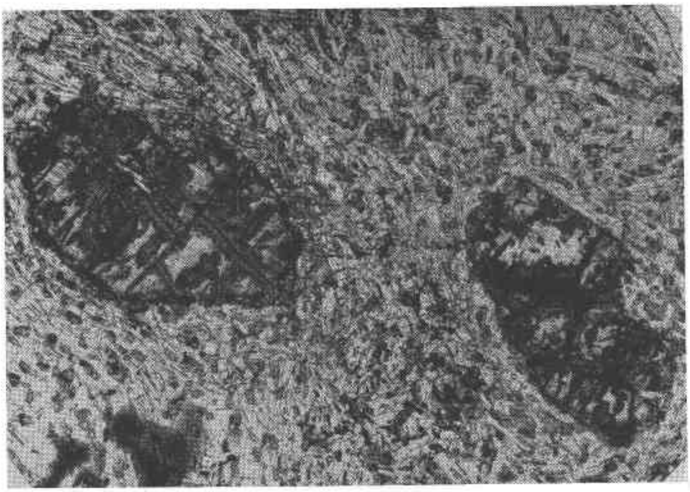

FIG. 4. Oxidized and green smectite-chlorite pseudomorphs after olivine. Plane polarized light. ×70.

hand specimen. Pseudomorphs after olivine are dull brown to nearly colorless and, when nearly colorless, are distinguished from weathered pyroxene and plagioclase only by their form.

In thin section, the material replacing pyroxene-plagioclase aggregates is colorless to pale green, has a moderate birefringence and occurs as randomly oriented fibers in the pseudomorphs.

Santa Rosa, California

All of these specimens are weathered and in some all the major minerals are altered and pseudomorphs after olivine are bleached. Most specimens are characterized by olivine phenocrysts (Fo_{85-95}) partly altered to iron oxides and smectite-chlorite, plagioclase (An_{60-69}) and some augite (2V 53°–57°) phenocrysts set in an intergranular groundmass composed of plagioclase, iron oxide and clinopyroxene microlites with accessory apatite. A small amount of optically isotropic pale green or brown mesostasis is usually present. Flow banding in plagioclase microlites is conspicuous and parallel to this are bands in which the clay minerals and iron oxides are concentrated. The bands are often connected by stringers of the same minerals resulting in a crudely rectangular or polygonal pattern. Pseudomorphs after olivine within these bands are distorted and alteration of olivine is complete. Within the polygonal areas olivine is incompletely altered to green smectite-chlorite. Identical secondary minerals, including optically isotropic varieties, also occur in microscopic amygdules in the bands (Fig. 5). Weathering has produced the same

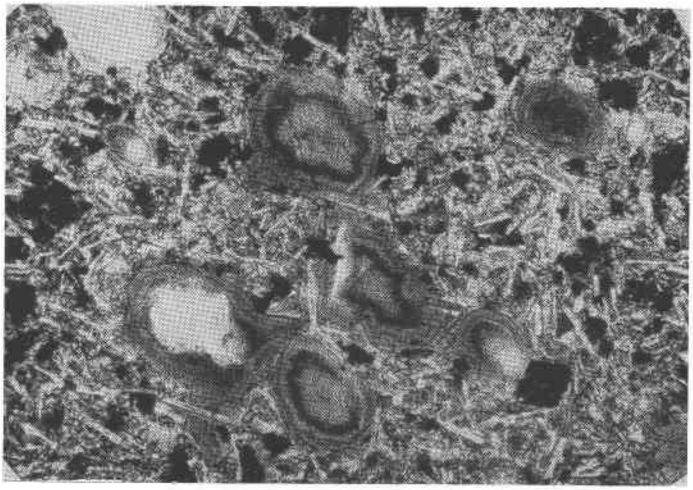

FIG. 5. Smectite-chlorite vesicle-filling. Plane polarized light. ×45.

effect as in the Carmel Bay specimens. Cores of altered olivines are occupied by a colorless, fibrous material which is randomly oriented.

Hawaiian basalts

Specimens, from the museum collection, University of California, consist of olivine phenocrysts (Fo_{75-80}) partly or completely altered to oxidized smectite-chlorite, iron oxide aggregates, augite (2V 52°) or titanaugite and plagioclase (An_{20-49}) phenocrysts in an intergranular groundmass composed of plagioclase, granular clinopyroxene and iron oxide microlites with accessory apatite. Olivine microlites are present in some specimens.

Orange, New South Wales

These specimens were obtained from a small quarry in a single basalt flow, the surface of which has been severely weathered. Part of the flow has well developed columnar jointing and adjacent to each joint plane the basalt has a dark rim approximately 0.5″ wide in which olivine has been altered to smectite-chlorite and iron oxides. The same minerals also occur as thin films coating the joint surfaces. For a distance of about 10 feet below the surface both the joint-filling and the altered rims are bright orange red.

The unaltered rock consists in part of augite (2V 48°–50°) phenocrysts and aggregates which ophitically or subophitically enclose plagioclase laths (An_{50-55}) and often enclose rounded grains of olivine. In areas between the evenly distributed pyroxene-plagioclase intergrowths, the rock consists of plagioclase laths and olivine phenocrysts (Fo_{85-95}), some of which are highly resorbed, set in a glassy groundmass. Some iron oxides, rounded olivine grains, rod-shaped clinopyroxenes and skeletal plagioclase crystals are distributed through the glass. In the altered rims below the weathered zone, olivine has been partly or wholly converted to green smectite-chlorite; in a few cases (Fig. 6) red cores are surrounded by green rims, but the opposite relations may be seen in the same thin section. Green smectite-chlorite also occurs as thin films along cleavages and fractures in plagioclase and clinopyroxene grains and along grain boundaries (Fig. 7). Such veinlets disappear at crystal-glass boundaries and the glass is locally altered, the veinlet reappearing in crystals on the opposite side of the altered glass. In a few places these veinlets occupy micro-shear zones (Fig. 8). Within the weathered zone joint-filling and alteration products of olivine and glass are red aggregates of kaolinite and goethite. With a few mineralogical and textural differences, this occurrence is nearly identical with that recorded by Smedes and Lang (1955).

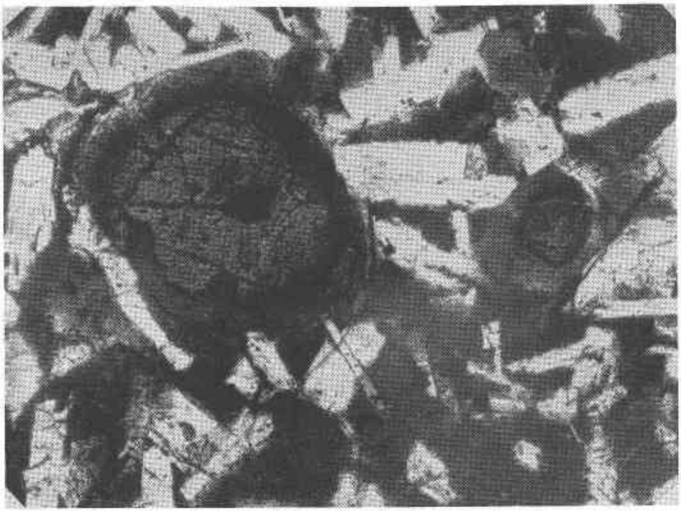

FIG. 6. Pseudomorphs after olivine consisting of oxidized smectite-chlorite cores and green smectite-chlorite rims. Plane polarized light. ×115.

Ebbetts Pass, California

Green smectite-chlorite is very widespread in the Tertiary lavas of the Mehrten Formation as an alteration product of olivine in basalts and of hypersthene in andesites. It is also present in amygdules and as coatings on joint surfaces. In many places it occurs in isolated patches several inches to several feet across within flows, and in these occurrences its dis-

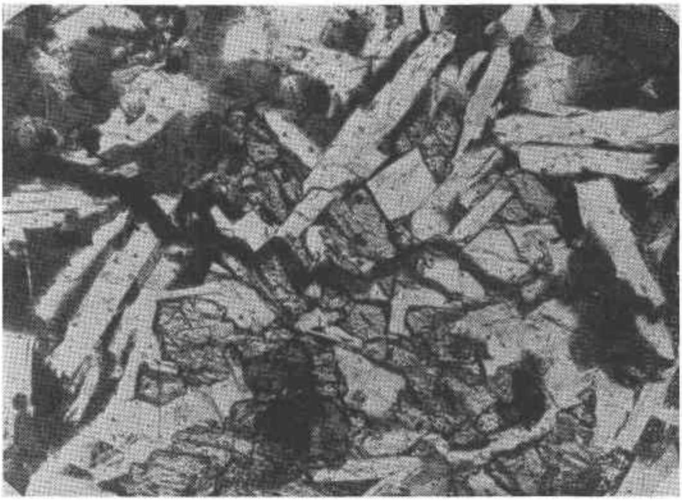

FIG. 7. Smectite-chlorite veinlet. Note control of grain boundaries and fractures on position of the veinlet. Plane polarized light. ×105.

tribution shows no relation to weathered surfaces. Coats (1940) mentioned some of these occurrences and referred to the alteration product as bastite. In view of the common retention of hypersthene cores, there is no doubt that this mineral alters to a product optically identical with that which replaces olivine. The andesitic lavas also commonly have ortho-

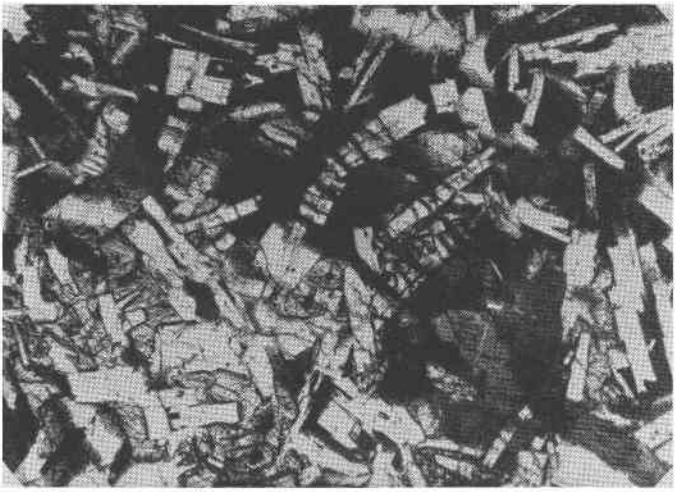

FIG. 8. Smectite-chlorite veinlets occupying micro-shear zone. Glass is locally altered to smectite-chlorite. Plane polarized light. ×55.

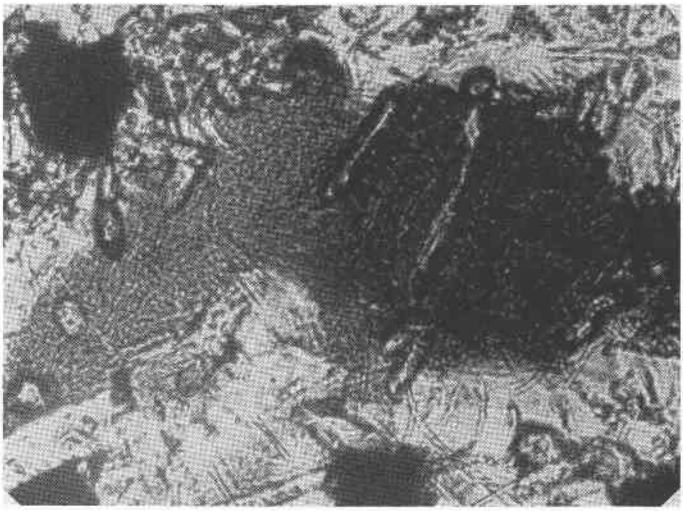

FIG. 9. Pseudomorph after olivine and material extracted during alteration. Plane polarized light. ×345.

pyroxene microlites partly or completely altered to the same mineral, while the clinopyroxene microlites have remained unaltered. Aggregates pseudomorphic after hypersthene commonly contain calcite and sometimes contain cristobalite.

Specimens of altered shallow basalt intrusions were obtained from Bowling Quarry, Dumbartonshire, Scotland (type locality of "bowlingite"; Hannay, 1877); from Dumback Quarry, Milton near Bowling; and from Prospect Hill near Sydney, New South Wales.

Bowling Quarry, Scotland

Material from this locality was all taken from joints where it occurs as veins $\frac{1}{2}''$–$1\frac{1}{2}''$ thick. According to Hannay (1877) it also occurs as vesicle-filling and as pseudomorphs after olivine in the dolerite. Other constituents of the rock are unaltered.

Dumbuck Quarry, Scotland

This material has the same mode of occurrence as that from Bowling Quarry. In thin section green smectite-chlorite pseudomorphs olivine microphenocrysts and occurs as interstitial filling and as thin films coating other minerals (Fig. 9). It is commonly intergrown with a colorless, micaceous material. A few plagioclase phenocrysts (An_{60-57}) which enclose clinopyroxene grains occur along with the altered olivine in an intergranular groundmass composed of plagioclase, clinopyroxene and iron oxide microlites with accessory apatite.

Prospect Hill, New South Wales

Green smectite-chlorite is abundant in this dolerite intrusion, occurring as joint-filling, fibrous aggregates pseudomorphic after olivine and as interstitial filling. In the dolerite phases it is commonly associated with green and brown mica while in pegmatitic phases it occurs as interstitial filling and rarely as pseudomorphs after olivine. In the chilled margin olivine phenocrysts (Fo_{70-85}) are fresh or partly altered, altered phenocrysts being connected by veinlets of optically identical material. Weathered parts of the chilled margin show partial oxidation of alteration products, grading away from exposed surfaces into green alteration products. Such relations may be seen in a single thin section. Specimens used in this study were selected from joints and pseudomorphs after olivine.

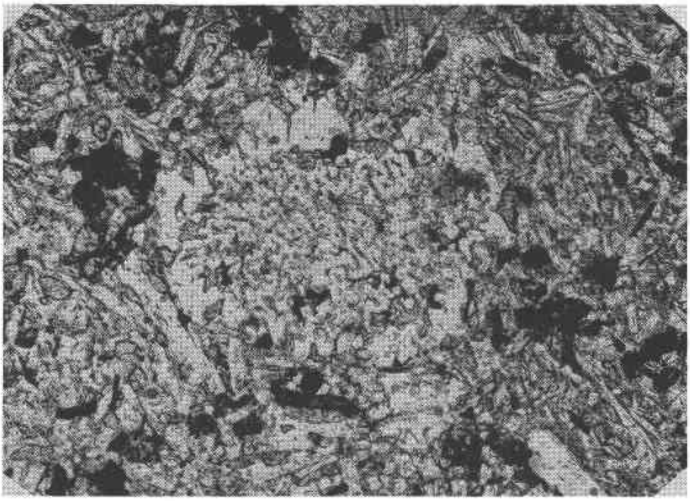

FIG. 10. Resorbed plagioclase with sieve structure due to enclosed clinopyroxene and iron oxide. Plane polarized light. ×95.

Specimens of basalt flows containing optically isotropic alteration products (chlorophaeite) were obtained from the Grande Ronde dike, Oregon (Peacock and Fuller, 1928) and from several Tertiary lavas in eastern Washington and Oregon near Walla Walla, Washington.

Grande Ronde dike

In view of some discrepancies between the author's observations and those of Peacock and Fuller, specimens from this locality will be described in detail.

In the chilled margin a few olivine phenocrysts (Fo_{87}) partly altered to chlorophaeite and anisotropic smectite-chlorite, a few plagioclase aggregates which are corroded and have a sieve structure enclosing clinopyroxene and iron oxide grains (Fig. 10), and rare quartz grains with clinopyroxene halos are set in an intergranular groundmass composed of olivine partly or completely altered to both red and green smectite-chlorite and chlorophaeite, plagioclase, clinopyroxene and iron oxide microlites with accessory apatite. There are a number of chlorophaeite amygdules some of which contain carbonate. Amygdules in which the chlorophaeite is bright orange are connected by a delicate network of veinlets which consist of chlorophaeite films coating the groundmass minerals. These stringers form a crudely polygonal or rectangular pattern. Amygdules which are not so connected contain green chlorophaeite.

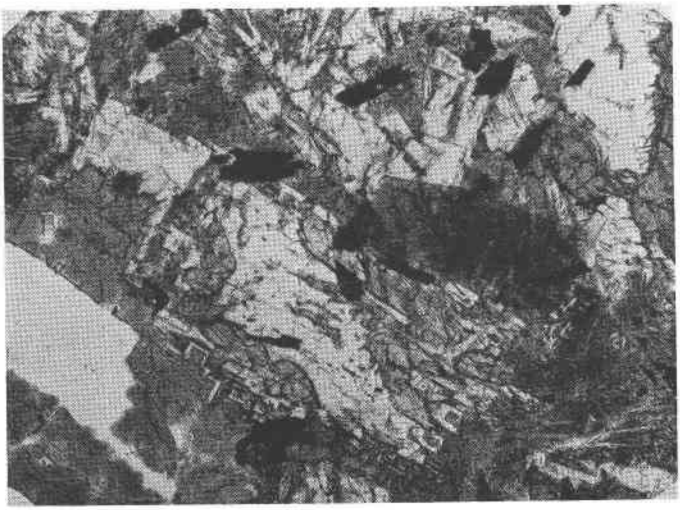

Fig. 11. Peripheral alteration of plagioclase resulting in formation of skeletal plagioclase grains. Areas of high relief within the plagioclase are clinopyroxene. Plane polarized light. ×55.

The center of the dike consists of plagioclase phenocrysts and aggregates (An_{12-44}) and olivine phenocrysts which are partly or completely altered, set in an intersertal groundmass composed of skeletal plagioclase grains, iron oxide microlites and glass or chlorophaeite with accessory apatite. Plagioclase is commonly intergrown with clinopyroxene and is peripherally altered, the alteration being controlled by cleavage planes resulting in skeletal plagioclase grains (Fig. 11). Chlorophaeite amygdules have a halo extending into the groundmass in which plagioclase has been partly altered to chlorophaeite (Fig. 12).

MODE OF ORIGIN

When the oxidized alteration product (iddingsite) was first named (Lawson, 1893) it was considered to be a primary mineral precipitated directly from basaltic magma. Other investigations showed that residual olivine is commonly present within pseudomorphs and this hypothesis was abandoned in favor of Iddings' (1892) suggestion that it formed by weathering of iron-rich olivine. Since the work of Ross and Shannon (1926) on iddingsite and that of Peacock and Fuller (1928) on chlorophaeite, both of these have been generally accepted as products of deuteric alteration of primary mafic minerals in basaltic lavas, iddingsite being a distinct mineral species, chlorophaeite being an amorphous substance of variable composition. Green alteration products, whether they are called bowlingite or any of their other names, are also widely thought to arise by the same process.

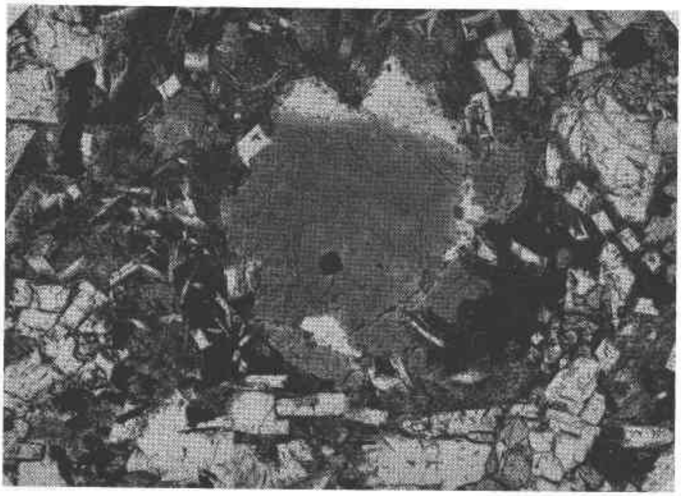

FIG. 12. Chlorophaeite amygdule with alteration halo. Plane polarized light. ×40.

Ross and Shannon presented convincing arguments favoring a deuteric origin which have been substantiated by subsequent investigations (e.g., Edwards, 1938; Fuller, 1938). However, Ming-Shan Sun (1957) has suggested that identical alteration may be continued in weathering. This conclusion is based on the identity of deuteric alteration products (only goethite was identified) with weathering products and similarity of chemical changes involved in both processes. The occurrence of both green and red varieties of alteration products at Carmel Bay, California, Orange, New South Wales, and Prospect Hill, New South Wales where oxidized material is present only in the weathered horizon clearly indicates that weathering may change the original deuteric alteration products rather than simply continue the same process. It was shown from *x*-ray data that both alteration products from Carmel Bay are composed of the same structural types except that the oxidized variety contains goethite. Conversion of green smectite-chlorite (sometimes mixed with magnetite) to red smectite-chlorite plus goethite can be effected either by leaching iron and recombination as goethite or by weathering of included magnetite, in either case the goethite acting as a pigment. Weathering of the Orange, New South Wales material resulted in formation of goethite, but the smectite-chlorite did not survive and in its place kaolinite is present. As will be shown later, the additional constituent, smectite-chlorite, of "iddingsite" identified in this study may also form by weathering of mafic minerals. However, the weathering products differ in being dioctahedral while oxidized smectite-chlorite in the same rocks is usually intermediate.

Time of Alteration

Edwards (1938) and Ross and Shannon (1926) presented textural evidence which suggests that alteration takes place after the enclosing lava ceased to flow, but sometimes prior to completion of crystallization of primary minerals. Fresh olivine rims surrounding altered olivine cores suggested to Edwards a sequence in which crystallization of olivine was followed by hydration-oxidation alteration, which in turn was followed by renewed crystallization of olivine. To Ross and Shannon, the same relationships suggested zonal replacement of olivine which had completed crystallization before alteration commenced.

Ross and Shannon further state that "The magma must have come to rest before iddingsite formed for though it is a very brittle mineral it is never fractured, or distorted by flow." Descriptions of the Carmel Bay, California and Santa Rosa, California basalts showed that, in these rocks, distortion of pseudomorphs is common, but restricted to narrow bands parallel to the flow banding (Figs. 2 and 3). These data are interpreted as indicating at least partial alteration of olivine prior to cessation of flow, followed by distortion in shear zones developed when laminar flow is interrupted by consolidation.

Chemical and Physical Properties and Their Implications

It is evident from the *x*-ray data that the formula of "iddingsite" represents at least two minerals and possibly as many as three or four, and that, in general, none of these are optically distinguishable.

Notwithstanding mineralogical difficulties, bulk chemical compositions are important, for they represent alteration products of primary minerals whose composition can often be determined from relicts. It is, however, still a matter of conjecture whether or not relicts are representative of the entire original crystal. Most of the chemical data now available are of "iddingsite," chlorophaeite, and associated olivine. By comparison of these analyses it is seen that, although a broad range of compositions occurs, they are characterized by high Fe/Mg ratios, the lowest being about 2/1 while the average is about 8/1. Of all associated olivines reported in the literature, the highest Fe/Mg ratio is 1/2 and most are lower. It was by similar interpretation of data that Ross and Shannon (1926) were led to state, "the proportion of silica has remained nearly constant . . . , the iron has all been changed from the ferrous to the ferric state and its proportion has greatly increased, water has been added in large amount, and magnesium has been largely abstracted. It is clear that in the change of olivine to iddingsite there has been a metasomatic replacement . . . ," In addition Ross and Shannon, noting the occurrence of fresh olivine rims surrounding altered olivine cores and fresh olivine microlites with altered olivine phenocrysts, state that alteration is partly dependent on composition of the olivine. Although these relations indicate selective replacement of magnesian olivine (assuming normal zoning), some authors (e.g., Tomkeieff, 1934) have interpreted this ambiguous statement to mean selective alteration of fayalitic olivine. Typically the initial stages of alteration are characterized not by zonal replacement of olivine, but by replacement along fractures randomly cutting the phenocrysts. Since textural relationships indicate either no zonal preference or preference for magnesian zones, composition differences between olivine and its alteration products are best explained by Ross' and Shannon's conclusion that Mg is leached. The common occurrence of iron oxides with the clay minerals and the not rare complete replacement of olivine by iron oxides indicates addition of iron as well as removal of magnesium. It is of course clear that the alteration cannot be simply a process of hydration and oxidation, for the proportions of FeO (recalculated from Fe_2O_3), MgO and SiO_2 do not approach those of olivine. It is not, therefore, unreasonable to suppose that compositions of relicts are representative of the entire original phenocryst subject to zoning fluctuations no more severe than found in unaltered olivine.

These changes in bulk composition and structure have resulted in alteration products which are considerably less dense (see Table 4A) than the minerals they replace. Since the alteration is pseudomorphic, volume relations require removal of material, which, according to the above arguments, involves selective leaching of Mg. Ross and Shannon do not consider the ultimate disposition of the extracted material, but Peacock and Fuller (1928) clearly state their belief that chlorophaeite

TABLE 4A. CHEMICAL ANALYSES*

	A		B		C	
	Average	Range	Average	Range	Average	Range
SiO_2	41.20	22.08–48.36	44.79	42.68–46.32	45.11	43.42–48.17
TiO_2	0.14	0.12– 0.26	0.22	0.00– 0.46	0.29	0.00– 0.82
Al_2O_3	3.81	0.00– 5.09	8.24	5.87–10.62	3.91	1.37– 7.12
Fe_2O_3	35.42	25.48–60.13	8.90	6.33–12.30	22.13	12.37–30.02
FeO	0.38	0.00– 1.97	4.77	2.70– 7.98	6.66	2.36–12.10
MnO	0.05	0.00– 0.11			0.47	0.35– 0.62
MgO	6.85	0.60–12.71	22.50	21.71–23.29	8.16	6.26–11.73
CaO	2.35	1.72– 3.26	1.96	0.32– 3.29	3.13	1.97– 4.02
Na_2O	0.12	0.12– 0.13			0.55	0.00– 2.21
K_2O	0.10	0.09– 0.10			0.14	tr – 0.47
H_2O^+	9.30	5.74–11.00	8.84	7.47–10.00	8.39	6.83–10.97
Total	99.54		100.22		98.94	
H_2O^-	9.84	4.76–22.85	10.72	7.69–13.52	20.78	12.54–27.44
Density		2.5 – 2.8		2.24– 2.30		1.81– 2.23

* Column A (iddingsite) represents 10 analyses, 2 from Tomkeieff (1934), 8 from Ross and Shannon (1926). Column B (saponite) represents 4 analyses from Caillere and Henin (1951). Column C (chlorophaeite) represents 4 analyses from Peacock and Fuller (1928).

All analyses were recalculated to 100% excluding H_2O^- before averages were computed.

vesicle-filling and veinlets result from an alteration of mafic minerals. In the same manner, it is believed that material extracted from mafic minerals during alteration to anisotropic varieties is recombined in the same structural types (principally smectite-chlorite) in joints and vesicles.

The limited chemical data presented in Table 4 may now be divided into two groups: 1) those representing extracted material in motion at the time of consolidation (columns B and C, Table 4A; specimens 6, 8, and 10, Table 4B), and 2) those representing alteration residues (column A, Table 4A). It is clear by comparison of these groups that, in basalt lavas, both are characterized by high Fe/Mg ratios. It is reasonable to ask, then, why pseudomorphs are retained at all if the material which precipitates from the final solutions is of the same composition as that in pseudomorphs. This is probably largely due to concentration of iron in the altering solutions; as the mafic minerals break down, Mg passes into solution over a concentration gradient while iron is recombined in place in a solid phase appropriate to the environment. It is presumed that Mg

TABLE 4B. CHEMICAL ANALYSES

[illegible] sill N.S.W. [illegible] filling [illegible] N.S.W.

	8*	10	6
SiO_2			49.48
Al_2O_3	12.80	7.14	5.85
Fe_2O_3	0.43	0.80	18.86
FeO	6.67	6.09	3.90
MgO	25.24	31.80	12.66
CaO			2.13
TiO_2	nd	0.37	0.35

Rock Analyses†

100 cc. 100 cc.

	Unaltered	Altered	gms/m³ Unaltered	gms/m³ Altered
SiO_2	51.66	51.51	140.0	134.5
Al_2O_3	15.88	16.98	43.0	44.4
Fe_2O_3	0.76	5.49	2.1	14.4
FeO	9.70	4.82	26.3	12.7
MgO	7.35	5.26	19.9	13.7
CaO	8.07	8.56	21.9	22.4
Na_2O	2.81	2.17	7.6	5.7
K_2O	1.52	1.05	4.1	2.7
TiO_2	1.60	1.68	4.3	4.0
CO_2	nd	nd	0.0	0.0
H_2O^+	0.65	2.48	1.8	6.5
Total	100.00	100.00		
H_2O^-	0.09	3.08		
Density	2.71	2.61		

* Numbers correspond to same samples in other tables. See Table 1 for descriptions.

† Olivine basalt near Orange, New South Wales. See text for description. Analyses recalculated to 100% excluding H_2O^-.

Analysts: Avery and Anderson, Melbourne.

added to the solutions is outweighed by Fe, the final crystalline product still being Fe-rich. Since the structural groups represented by the alteration products can accommodate any variation in Fe, Mg and Al, the presence of these minerals in joints and vesicles does not imply alteration of mafic minerals, but the two usually occur together. When this material is accommodated interstitially, its composition can have only an indirect bearing on the nature of liquid residues formed by fractional crystallization.

The data on alteration products from shallow intrusions indicate that the material in motion is rich in Mg and relatively poor in Fe. Since associated Fe-bearing minerals are rare in joint-filling, this is taken to indicate a lack of iron enrichment in the residual solutions. Since neither Mg nor Al can be expected to be concentrated in the altering solutions, complete solution of mafic minerals susceptible to the alteration is possible. Where pseudomorphs are retained, duration of alteration may be more important than composition of solutions, but additional factors of structural inheritance in alteration products and heat supply provide problems for which there are no quantitative data. The markedly higher alumina may be attributed to contributions from altered Al-bearing minerals such as plagioclase which is much more extensively altered in these rocks than in typical altered basalt lavas.

Mechanisms of Movement of Extracted Material

Since there is good evidence that alteration takes place, at least in some lava flows, at a late stage of consolidation, some mechanism for rapid removal of material extracted during alteration is required. Occurrence of alteration products as delicate networks of veinlets connecting pseudomorphs and vesicles, as veinlets parallel to flow banding, and, principally, along major joints all suggest operation of a pressure gradient. Smedes and Lang (1955) appealed to jointing to provide low pressure areas towards which altering solutions moved. If alteration precedes jointing, extracted material could be removed in this manner. Polygonal networks of veinlets may be interpreted as micro-joints and may have served the important function of cleaning out on a small scale. Veinlets parallel to flow banding could be caused by shearing along irregular flow planes resulting in dilated areas of low pressure. Curtis (1954) utilized the last proposal in interpreting autobrecciation of lavas. Whatever the mechanism of cleaning out on a small scale, the major joint system acts as a permanent low pressure area until pressures are equalized, and it is towards these that the altering fluids tend to move. In shallow intrusions, low pressure areas are probably created chiefly by jointing, the location of much of the smectite-chlorite, but this will depend greatly on the nature of the wall rock.

Effects of the Alteration on Bulk Chemical Composition of Some Basaltic Rocks

It is clear from the conclusions drawn above that alteration of mafic minerals results in selective leaching of Mg which, in lavas, is later combined with iron and silica presumably derived from the altering solutions. If these components are not recombined within the rock, but escape into joints or wall rock, the composition of the rock no longer represents the composition of the magma from which it crystallized. The quantitative effects of the alteration can be assessed only where fresh and altered equivalents occur. The effects of loss of Fe, silica and other components concentrated in solution prior to alteration cannot be quantitatively assessed.

In Table 4B are given chemical analyses of altered and unaltered portions of the Orange, New South Wales basalt. These differ only in nearly complete alteration of olivine and minor alteration of glass in the altered phase. Since density changes have taken place, comparison of weight per cents does not give a true picture of composition changes and these have been recalculated to gms./m^3. Specimens were collected from several columns and combined to reduce sampling error. The most significant changes are loss of MgO and SiO_2, addition of H_2O and change of ferrous to ferric iron in the altered rock. Total iron and alkalis show a small loss and alumina a small gain in the altered phase, but, in view of sampling and analytical error, these cannot be safely interpreted. The analysis of smectite-chlorite joint-filling from this locality (no. 6, Table 4B) clearly indicates the final disposition of Mg leached from olivine. It also shows that the Fe content of the fresh rock is not representative of the magma.

Data presented by Fuller (1938) indicate that opposite changes in bulk composition can take place under certain conditions. In the basalt flows described by Fuller, alteration of olivine is confined to cores of columns, residues of the alteration being accommodated interstitially. Although direct comparison of analyses shows little change between altered cores and unaltered sheaths, Fuller (Pers. comm.) believes that the porous texture of the sheaths is explained by loss of the mesostasis (formed as a crystallization residue, not by alteration). Under these conditions recalculation of weight per cent analyses to gms./$m.^3$ would probably show changes in the opposite direction from those described above.

It is necessary to bear in mind that these minerals are only a small part of a much more complex association. This is particularly true of shallow intrusions where carbonates and zeolites are invariable associates of the clay minerals and the total secondary mineral assemblage extremely varied. Since these too are usually less dense than the primary minerals from which they are derived, their escape into joints may be expected to have a similar effect on bulk chemical composition of the altered rocks.

APPLICATION TO SOME PROBLEMS IN SOIL CLAY MINERALOGY

It is apparent from the results of this investigation that chlorites and smectites occurring in soils derived from basic volcanic rocks cannot be assumed to have originated by weathering. The possibility that these minerals remain as relicts, although probably modified depending on conditions of weathering, is strengthened by a detailed study of the

Carmel Bay, California basalts which lie in a temperate climate zone, and which are structurally disposed to allow through drainage. A section is accessible at this locality which contains rocks ranging from those whose only altered constituent is olivine to those so deeply weathered that all of the primary minerals are altered and the rock is very porous. The freshest rocks contain green alteration products which are trioctahedral smectite-chlorite aggregates, while the most highly weathered rocks contain oxidized smectite-chlorite and goethite aggregates, the smectite-chlorite of these rocks being predominantly intermediate to dioctahedral. By plotting the position of the 060 reflection against a qualitative estimate of degree of weathering of the enclosing rock it was found that the higher the degree of weathering the more closely the smectite-chlorite approached a dioctahedral structure. *X*-ray powder photographs of a colorless clay pseudomorphing clinopyroxene-plagioclase aggregates (presumed to have formed by weathering because such alteration occurs only in the weathered zone) show that it is also composed in part of smectite-chlorite aggregates, but differs in having kaolinite (?) as part of the aggregate. It might be expected, since the structural types represented by deuteric alteration products are stable in the weathering environment while pyroxene and plagioclase undergo a complete structural change, that conversion of these to dioctahedral structures will lag behind alteration of plagioclase and pyroxene. This was found to be true since pseudomorphs after olivine, even in the most deeply weathered rocks, are still composed in part of a trioctahedral structure. In addition, the occurrence of lightly pigmented (goethite) smectite-chlorite in deeply weathered, almost colorless rocks attests to continued leaching of iron. Although weathering of these rocks took place in a temperate climate with through drainage, it is obvious that weathering conditions which favor formation of trioctahedral chlorites and smectites will also favor preservation of the original trioctahedral products of deuteric alteration. It should be noted, however, that weathering of smectite-chlorite in the Orange, New South Wales basalt resulted in an aggregate of goethite, quartz and kaolinite without preservation of the smectite-chlorite.

It is believed that recognition of the abundance and character of these minerals as pre-weathering constituents of basic igneous rocks will aid in solution of some problems in soil-clay mineralogy which have heretofore been explained by complicated chemical or physical histories such as those described by Allen and Scheid (1946) and Ross and Hendricks (1945). In no case will it be a simple problem to evaluate residual contributions to the clay fraction, for these minerals are not evenly distributed through the parent rock. This is particularly true of differentiated shallow intrusions such as that at Prospect, New South Wales, where the smectite-chlorite content of different specimens ranges from practically nil to more than half by volume.

ACKNOWLEDGMENT

The author is indebted to Drs. C. D. Campbell, A. B. Edwards, B. C. King, R. L. Rose, A. C. Waters, L. Weiss and H. Williams for specimens used in the study. Members of the Geology and Physics Departments, Univ. of Technology, Sydney, are gratefully acknowledged for making equipment available for the author's use. Special thanks are due Profs. Howel Williams and Charles Meyer of the University of California for having critically read the manuscript, and to Drs. R. E. Fuller and G. F. Walker for their helpful discussion of some of the problems. Professor Pabst of the University of California kindly supplied powder photographs of iron oxides for comparison. Financial assistance was received from the University Research Grants Committee, Sydney University.

REFERENCES

ALLEN, V. T., AND SCHEID, V. E. (1946), Nontronite in the Columbia River region: *Am. Mineral.*, **31,** 294–312.

BRADLEY, W. F. (1945), Glycol-montmorillonite: *Am. Mineral.*, **30,** 704–713.

BRINDLEY, G. W. (ed.) (1951), *X*-ray identification and crystal structures of clay minerals: The Mineralogical Society, London.

BROWN, G. (1955), Report of the clay minerals group sub-committee on nomenclature of clay minerals: *Clay Mins. Bull.*, **2,** 296.

CAILLERE, S. (1935), Sur les caracteres specifiques de la bowlingite: *Compt. Rend. Acad. Sci. Paris*, **200,** 1483–1485.

CAILLERE, S. AND HENIN, S. (1951), The properties and identification of saponite (bowlingite): *Clay Mins. Bull.*, **1,** 138–144.

COATS, R. R. (1940), Propylitization and related types of alteration on the Comstock Lode, Nevada: *Econ. Geol.*, **35,** 1–16.

CURTIS, G. H. (1954), Mode of origin of pyroclastic debris in the Mehrten Formation of the Sierra Nevada: *Univ. of Calif. Pub. in Geol. Sci.*, **29,** 453–502.

EARLEY, J. W. AND MILNE, I. H. (1956), Regularly interstratified montmorillonite-chlorite in basalt: *Proc. 4th Nat'l. Conf. on Clays and Clay Mins.*, pub. **456,** 381–384.

EDWARDS, A. B. (1938), The formation of iddingsite: *Am. Mineral.*, **23,** 277–281.

FULLER, R. E. (1938), Deuteric alteration controlled by the jointing of lavas: *Am. Jour. Sci.*, **35,** 161–171.

HANNAY, J. B. (1877), On bowlingite, a new Scottish Mineral: *Min. Mag.*, **1,** 154–157.

HARGREAVES, A., AND TAYLOR, W. H. (1946), An *x*-ray examination of decomposition products of chrysotile (asbestos) and serpentine: *Min. Mag.*, **27,** 204–216.

IDDINGS, J. P. (1892), *U. S. Geol. Survey.*, Mono. **20,** Append. **B,** 388–390.

KAADEN, G. VAN DER (1951), Optical studies on natural plagioclase feldspars with high- and low-temperature optics: *Pub. van het Min. Geol. Inst. Ryks.*, Univ., Utrecht, Holland.

LAWSON, A. C. (1893), The geology of Carmelo Bay: *Univ. of Calif. Pub. in Geol. Sci.*, **1,** 1–59.

MING-SHAN SUN (1957), The nature of iddingsite in some basaltic rocks of New Mexico: *Am. Mineral.*, **42,** 525–533.

PEACOCK, M. A., AND FULLER, R. E. (1928), Chlorophaeite, sideromelane and palagonite from the Columbia River Plateau: *Am. Mineral.*, **13,** 360–382.

PRIDER, R. T., AND COLE, W. F. (1942), The alteration products of olivine and leucite in the leucite-lamproites from the west Kimberly area, Western Australia: *Am. Mineral.*, **27,** 373–384.

ROSS, C. S., AND HENDRICKS, S. B. (1945), Minerals of the montmorillonite group: their origin and relation to soils and clays: *U. S. Geol. Surv. Prof. Paper* no. **205-B,** 23–79.

ROSS, C. S., AND SHANNON, E. V. (1926), The origin, occurrence, composition and physical properties of the mineral iddingsite: *Proc. U. S. Nat'l. Museum*, **67,** Art. 7, 1–19.

SMEDES, H. W., AND LANG, A. J., JR. (1955), Basalt column rinds caused by deuteric alteration: *Am. Jour. Sci.*, **253,** 173–181.

TOMKEIEFF, S. I. (1934), Differentiation in basalt lava, Island Magee, Co. Antrim: *Geol. Mag.*, **71,** 501–512.

TROEGER, W. E. (1952), Tabellen zur optischen Bestimmung der gesteinsbildenden Minerale: E. Schweizerbartsche Verlagsbuchhandlung, Stuttgart.

TURNER, F. J. (1947), Determination of plagioclase with the four-axis universal stage: *Am. Mineral.*, **32,** 389–410.

Manuscript received June 4, 1957.