

CHLOROPHAEITE, SIDEROMELANE AND PALAGONITE
FROM THE COLUMBIA RIVER PLATEAU

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SUMMARY

The three mineraloids, chlorophaeite, sideromelane and palagonite are characteristic of Kainozoic basaltic fields. From a new analysis of chlorophaeite from Oregon and existing analyses of materials from Scotland and India the approximate formula: $(\text{Fe,Al})_2\text{O}_3 \cdot 2(\text{Mg,Fe,Ca})\text{O} \cdot 4\text{SiO}_2 + 10\text{H}_2\text{O}$ is derived. It is urged that the definition of chlorophaeite be extended to cover all hydrous, amorphous, pitch-like materials of deuteritic origin, some of which have been named palagonite, in basalts and dolerites.

An argument is advanced supporting the continued use of

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sideromelane, as distinct from tachylyte, as a specific name for ideal basaltic glass formed under conditions of specially rapid cooling.

It is shown that a chemical and genetic distinction exists between chlorophaeite and palagonite; and that palagonite should properly be restricted to its original significance, namely a gel produced essentially in the hydration of sideromelane by water or water vapor of exotic origin.

INTRODUCTION

The terms chlorophaeite, sideromelane and palagonite were all proposed before the petrographic microscope was in common use, and consequently the original descriptions of these materials lack the precision now desirable. Subsequent descriptions are few and the localities to which they refer are widely scattered. As, in addition, none of these three materials possesses the constancy of chemical composition and the habit of crystalline growth proper to mineral species in the strictest sense, it is thus small wonder that their respective definitions in the works of reference are not wholly adequate, and that writers are not entirely in agreement in their acceptance and usage of the terms.

As far as we are aware chlorophaeite and sideromelane have not been previously reported from America; palagonite has occasionally been mentioned in a general sense. The recognition of the three materials typically developed in the eruptives of the Columbia River Plateau is due to one of us (Fuller) who also supplies the notes on the field relations; the other, having had previous experience with these materials, is chiefly responsible for the laboratory study and the discussion.

The main object of this communication is to record new occurrences of chlorophaeite, sideromelane and palagonite; and, from a study of this favorable material in relation to some existing descriptions, to suggest natural definitions for these materials, and thereby, if possible, to stabilize the usage of the three terms.

CHLOROPHAEITE

OCCURRENCE. Chlorophaeite occurs in a Kainozoic dyke, 55 feet in thickness, cutting Columbia River Basalt in the Grande Ronde Valley just south of the town of Anatone in southeast Washington.

HAND-SPECIMEN. A specimen from the center of the dyke is a dark, compact, medium-grained, apparently fresh rock in which

small feldspar tablets are the only recognizable primary minerals. Conspicuous on the broken surface are many circular or ovoid areas representing sections of spheroidal bodies ranging from 1 mm. to 8 mm. in diameter, with an average of about 5 mm., and constituting about 10 per cent. of the bulk of the rock. A few of these amygdales are composed of a very thin lining of an essentially black, pitch-like material and a filling of quartz or of quartz and calcite; the great majority, however, are composed wholly of the black material which also occurs in thin films along joint planes in the rock.

Another specimen from the dyke, taken at about three feet from the margin, has a finer texture than the above specimen. This rock carries about the same proportion of the black material which in this case appears in a swarm of pellicles averaging about 1 mm. in diameter.

When freshly fractured in the field the pitch-like amygdale material is green; on exposure the color rapidly darkens to a deep orange which is nearly black.¹ This color change is characteristic of chlorophaeite and is denoted by the roots from which the name is derived. In small chips the chlorophaeite is opaque with a slight deep-brown translucency at thin edges. The lustre is jet-like to pitch-like; the fracture is conchoidal, and the material may be crumbled with the fingers due to pre-existing networks of fine cracks. The hardness is usually between 2 and 3, but sometimes a fragment will just scratch calcite. The streak of the powder is brown. The specific gravity measured by suspending fragments in suitable mixtures of carbon tetrachloride and bromoform is not quite constant; the majority of fragments, however, remained suspended in a liquid whose specific gravity was found to be 2.267 at 28°. In the reducing flame the material loses its lustre and changes with some decrepitation into a black, readily crumbled, magnetic mass.

MICROSTUDY. In thin section² the coarser phase of the chlorophaeite-bearing rock is seen to be essentially an aggregate of tabular andesine and subhedral brown augite of coarse inter-

¹ The green color is well preserved in the dense, chilled border phase; in the coarse, central portion of the dyke the dark color has already developed.

² We are indebted to Mr. Aaron C. Waters of Yale University, for kindly preparing the thin sections studied in this paper. Mr. Waters also offered helpful comments on the finished manuscript.

granular texture enclosing earlier needles of apatite and irregular grains of titaniferous magnetite as rather abundant accessories. Between the larger components there is a scanty mesostasis of similar constitution.

Chlorophaeite occurs filling the larger circular cavities, and also as a thin impregnation intimately penetrating the body of the rock. In the cavities the chlorophaeite is orange-brown and totally isotropic with a refractive index lower than that of balsam. Small grains tested separately give indices varying widely from just below 1.500 to nearly 1.540; many grains lie close to 1.530 which may therefore be taken as a mean value. Within the chlorophaeite fine networks of minute cracks have developed; and occasionally incipient crystallization of the gel material has resulted in the development of minute fibres of an indeterminable birefringent mineral arranged in spherulitic fashion.

Closer study of the chlorophaeite disseminated through the rock shows that whereas some of the material occurs in quite irregular films indicating deposition from travelling solutions, much of it is present in areas with definitely rectangular outlines suggesting pyroxene pseudomorphs. As the brown monoclinic pyroxene in the rock is perfectly fresh the pseudomorphosed mineral must have been distinctly more susceptible to alteration than augite. Rhombic pyroxenes such as hypersthene are particularly unresistant to alteration, and the inference that the chlorophaeite pseudomorphs represent completely altered rhombic pyroxenes is fully in accord with the forms of the pseudomorphs and with the chemical composition of the rock to be given below.

CHEMICAL COMPOSITION. An analysis of the tachylytic phase of the dyke, free from chlorophaeite, gave the following values, from which was deduced the appended mineral constitution:

SiO ₂	48.90	Orthoclase.....	16.68
TiO ₂	1.86	Albite.....	16.77
Al ₂ O ₃	12.70	Anorthite.....	17.51
Fe ₂ O ₃	2.82	Diopside.....	24.52
FeO.....	12.93	Hypersthene.....	13.56
MnO.....	.73	Magnetite.....	4.18
MgO.....	2.65	Ilmenite.....	3.65
CaO.....	9.30	C. I. P. W. Symbol. III. 5.3.3.	
Na ₂ O.....	1.97		
K ₂ O.....	2.83		
Ignition.....	3.11		
	<u>99.80</u>		

Tachylytic phase of trachydolerite, free from chlorophaeite; 55 foot dyke cutting Columbia River basalt, Grande Ronde Valley, just S. of the town of Anatone, S.E. Washington. Analysts, Ledoux & Co.

In the main the analysis and the derived mineral constitution accord well with the mode of the coarser rock described above. Potash, and consequently normative orthoclase, is surprisingly high; and as orthoclase was not found in the section it is evident that potash has partly entered the plagioclase molecule, and is partly occult in the groundmass. The low value for magnesia is unusual, and this constituent was therefore redetermined with concordant results. The ores are notably titaniferous, as expected, and the ferromagnesian are wholly metasilicates supporting the conclusion that the chlorophaeite pseudomorphs are replaced pyroxenes and not olivines. In view of the alkalic character of the feldspar and the relatively low silica-content this rock has been classed with the trachydolerites.

TABLE I. ANALYSES OF CHLOROPHAEITE

	I	II	III	IV
SiO ₂	38.67	36.00	32.95	35.15
TiO ₂	0.24	.....	0.62	.....
Al ₂ O ₃	1.54	.....	5.40	1.00
Fe ₂ O ₃	26.14	22.80	12.37	21.77
FeO.....	2.06	2.46	9.18	2.18
MnO.....	0.31	0.50	0.33	0.35
MgO.....	6.77	9.50	4.75	5.02
CaO.....	1.72	2.52	3.05	2.51
Na ₂ O.....	0.00	} trace	1.68	} trace
K ₂ O.....	0.10		0.36	
H ₂ O+.....	9.56	7.23	5.20	4.98
H ₂ O-.....	12.54	19.23	23.90	27.44
	99.65	100.24	99.79	100.40
G.....	2.267	2.020	1.81±	1.83-84

I. Grande Ronde Valley, near Anatone, S. E. Washington. Analysts, Ledoux & Co.

II. Sgurr Mor, Rum, Scotland (type locality). Analyst, M. F. Heddle. Ref. Heddle, 1880, p. 87.

III. Ravelrig Quarry, Dalmahoy near Edinburgh, Scotland. Analyst, W. H. Herdsman. Ref. Campbell and Lunn, 1925, p. 438.

IV. Nagpur, India. Analyst, B. P. C. Roy. Ref. Fermor, 1925, p. 127.

In TABLE I is given an analysis of clean fragments of the amygdale-filling chlorophaeite from the Grande Ronde dyke together with Heddle's analysis of the type material from Rum,

Scotland, and two recent analyses of chlorophaeite from Scotland and India respectively. These represent all the available chemical data of reliable quality. The new analysis exhibits the characteristic features of the previous ones. Water is a large component, and the bulk of it is liberated at 100°. Ferric oxide is also large and strongly dominant over ferrous oxide. Alumina and the divalent bases are subordinate, and the alkalis are vanishingly small.

A complex gel-mineral cannot, of course, be expected to yield a definite constant molecular formula; in TABLE II, however, an attempt is made to derive a general molecular expression which will approximately embrace the four analyses. In a hydrous, amorphous mineral a distinction between combined and hygroscopic water does not exist; therefore total water has been included in the derived formula.

TABLE II. MOLECULAR CONSTITUTION OF CHLOROPHAEITE

	Grande Ronde	Rum	Dalmahoy	Nagpur	Average
SiO ₂	.645	.600	.549	.586	.598 = 4(.149)
TiO ₂	.003	....	.008	....
Al ₂ O ₃	.015	....	.053	.010	.146
Fe ₂ O ₃	.163	.142	.078	.136	
FeO	.029	.034	.128	.031	.275 = 2(.138)
MnO	.004	.007	.004	.005	
MgO	.169	.237	.119	.125	.206
CaO	.030	.045	.055	.045	
Na ₂ O	.000	.000	.027	.000	1.801
K ₂ O	.001	.000	.004	.000	
H ₂ O+	.531	.402	.289	.277	1.529 = 10(.153)
H ₂ O-	.697	1.068	1.328	1.524	

From these figures we obtain the expression: $R_2O_3 \cdot 2(R,R_2)O \cdot 4SiO_2 + 10H_2O$, with some constancy of factors in the average column; or, neglecting TiO₂, MnO and the alkalis, and grouping the bases of similar valencies in order of decreasing abundance: $(Fe,Al)_2O_3 \cdot 2(Mg,Fe,Ca)O \cdot 4SiO_2 + 10H_2O$. Considering the nature of the material the four analyses conform to this formula reasonably well.³

THE IDENTITY OF CHLOROPHAEITE AND CERTAIN MATERIALS DESCRIBED AS PALAGONITE. In 1887 McMahon observed an

³ Professor Larsen has drawn our attention to the similarity between the composition of chlorophaeite and that of hisingerite, a hydrated ferric silicate found associated with pyrites.

abundant isotropic or feebly birefringent, orange-colored substance in "ball trap" from the Deccan. Of this material and a similar associated green substance McMahan wrote: "On the whole, then, I have come to the conclusion that the bright-orange and dull-green substances represent the original magma or glassy base of the rock" (1887, p. 108).

Two years later Middlemiss redescribed material similar to that studied by McMahan, and closed his paper thus: "In conclusion, I would state that though I consider these substances described in this paper as undoubtedly belonging to what has been called palagonite, I would not absolutely bind myself to the view either that they are metamorphosed or zeolitized portions of the original glassy magma (though I lean to this view), or that they are pseudomorphs after olivine" (1889, p. 234).

In 1916 Fermor and Fox described abundant shot-like spherules of glassy aspect in basalt from the Deccan, and suggested that the material is either identical or very similar to the chlorophaeite of MacCulloch (1916, p. 95). They also observed that much of the material was formed at the expense of the augite in the rock.

In 1925 Fermor described and discussed in detail palagonitic materials in specimens from the core of a deep boring through Deccan trap at Bhusawal. Observing that the description and illustrations of Middlemiss would apply closely to the Bhusawal material, Fermor follows Middlemiss in his use of palagonite as a comprehensive term denoting brown and green, mostly isotropic, hydrous materials of secondary origin. After careful study Fermor concludes, however, that the brown and orange varieties of palagonite are identical with chlorophaeite (1925, pp. 125, 130-131); and that the green variety, when anisotropic, is very probably delessite or celadonite (1925, p. 133). Just as in the present instance the Indian chlorophaeite, delessite and celadonite occur both in vesicles and distributed through the body of the rock; and Fermor concludes that while the major portion of these materials has been formed by hydration at the expense of the original glass of the rock, augite, olivine and iron-ores have contributed to their formation.

In the same year Wadia described a palagonite-dolerite from Nagpur, the type locality for Indian chlorophaeite. Wadia's material occurs in shot-like spherules and amoebiform chambers in the dolerite, and has clearly been formed at the expense of augite

in the rock (1925, pl. ii). As the material described by Wadia does not exhibit the color change shown by chlorophaeite, and occurs only to a minor extent as true vesicle-fillings, Wadia named his material palagonite in preference to chlorophaeite.

Also in 1925 Campbell and Lunn reported typical chlorophaeite in the dolerites (tholeiites) of Dalmahoy and Kaimes Hills near Edinburgh. This material occurs in vesicular patches, in veins, in association with areas of intersertal mesostasis, and pseudomorphic after olivine (1925, p. 436).

The following year one of us (Peacock) adopting the current usage, described and figured as a palagonite-olivine-dolerite a rather coarse-grained basic intrusive rock forming a massive sill on the island of Videy, near Reykjavík, Iceland (1926 A, pp. 457-458, fig. 9). In this rock the palagonitic material occurs in irregular areas some of which appear to be altered vitreous mesostasis, while others are undoubtedly altered olivine. Later in the same year the same author completed a study of the palagonite tuffs of Iceland, the type locality for palagonite, and arrived at a definite conception of the properties of the material to which Sartorius von Waltershausen gave the name palagonite. For reasons to be developed later the writer regarded the application of the term palagonite to the chlorophaeite-like bodies under discussion as undesirable and recommended that the usage be discontinued (1926 B, pp. 72-74).

From these brief excerpts it will be clear that chlorophaeite and the brown or orange-colored palagonitic materials in basalts and dolerites are either identical, or so closely similar that to sustain a distinction is impracticable. Indeed the only points of difference appear to be: first, that the palagonitic material in dolerites sometimes does not exhibit the color change of chlorophaeite; and second, that much of the palagonitic material occurs in the body of the rock, and not in true vesicles. Although the color change of chlorophaeite is a useful field characteristic, and is given special importance in the name itself, the systematic significance of the change appears to be rather trifling. Of the several attempts which have been made to ascertain the cause of the color change that of Campbell and Lunn seems to have been the most successful. These authors were able to inhibit the change from green to brown by placing the freshly broken material in an atmosphere of carbon dioxide, thus indicating that surface oxidation was concerned in

the change (1925, p. 439). The green condition is thus a very unstable phase of a typically brown material; and therefore, if a material shows all the properties of chlorophaeite except the color-change on fresh exposure, this change has undoubtedly already been undergone due to oxidizing conditions, and it seems unreasonable not to admit such a material as chlorophaeite, especially as all the data of chlorophaeite have of necessity been obtained from exposed material.

Again, the second distinction emphasized by Wadia, is unreal. While chlorophaeite occurs conspicuously in cavity-fillings the available descriptions of indisputable chlorophaeite all contain references to the occurrence of the material in the body of the rock. Indeed, so consistently has chlorophaeite been formed at the expense of pyroxene or olivine, or at the cost of the basic constituents of the mesostasis or vitreous base of the rocks in which it occurs, that we incline strongly to the belief that the chlorophaeite forming the conspicuous shot-like spherules in the hand-specimens has been formed by late-magmatic hydrothermal action on the basic constituents of the rock resulting in the production of a fluid product which intimately penetrated the rock and was deposited in cavities if such existed.

Our material contains the green phase only in small amount; in thin section it is partly isotropic and partly individualized as birefringent chloritic fibres. Campbell and Lunn unhesitatingly class their green isotropic material as chlorophaeite, and in view of the green color exhibited by perfectly fresh chlorophaeite there can be no doubt that the green material represents areas of chlorophaeite which have escaped oxidation with the consequent color change to orange-brown.

We therefore conclude that both the green and the orange-brown isotropic materials may be properly classed as chlorophaeite, and that the term palagonite is thus free to describe the material for which it was designed, namely the hydro-gel of sideromelane.

DEFINITION OF CHLOROPHAEITE. A study of chlorophaeite from a new locality, together with a comparative examination of existing descriptions of chlorophaeite and of palagonitic materials differing from chlorophaeite in no essential respect, show that chlorophaeite, although somewhat variable in properties, is a well-recognized petrographic entity. While such a material cannot be classed as a mineral species in the strict sense, it falls properly

into the group of *mineraloids* proposed by Niedzwiedzki (1909, pp. 661-663) to embrace all naturally occurring, homogeneous, amorphous substances.

To conclude the discussion of chlorophaeite it may be of value to offer a condensed definitive description which will embrace authoritatively reported variations of this material.

Chlorophaeite, Macculloch, 1919, p. 506; derivation, $\chi\lambda\omega\rho\acute{o}s$, *green*, and $\phi\alpha\acute{i}\acute{o}s$, *brown*. Color, deepest brown, or olive-green changing rapidly on exposure (oxidation) to deepest brown. Amorphous; no plane cleavage; fracture, conchoidal; lustre, jet-like, pitch-like, or dull; streak, brown; H. = $1\frac{1}{2}$ -3; G. = 1.81-2.23; infus.; gives dull black magnetic mass. Color in thin slices, pale-green, olive-green, orange-brown (commonest), red; isotropic; when birefringent, due to chloritic fibres; R.I. = 1.50-1.54. Chem. comp. approximating $(Fe, Al)_2O_3 \cdot 2(Mg, Fe, Ca)O \cdot 4SiO_2 + 10H_2O$; greater portion of H_2O liberated at 100° . Occurs in shot-like spherules up to 8 mm. diameter, filling or lining cavities, in amoebiform or irregular patches, in veinlets, pseudomorphic after olivine and pyroxene, and replacing vitreous base or mesostasis in basic extrusives or intrusives ranging from mugearite, trachydolerite, to basalt and olivine-dolerite. Origin, probably due to hydrothermal action on ferromagnesian minerals and on the basic constituents of the vitreous base or mesostasis, resulting in a fluid product which permeates the rock and is deposited in the various ways indicated. Localities, numerous in Scotland, also in England and Ireland (Campbell and Lunn, 1925, pp. 435 and 440, whom see for earlier refs. to British occurrences); Deccan Plateau (Fermor, 1925, pp. 125-135, whom see for earlier refs. to Indian occurrences); Iceland (Peacock, 1926 A, p. 458 and fig. 9; here named palagonite following usage now disapproved); Columbia River Plateau (this paper); Faeroe occurrence given by Dana discredited by Heddle (1880, p. 85).

SIDEROMELANE

OCCURRENCE. The example of sideromelane chosen for full description was taken from the nose of a basaltic flow at Columbia River, 3 miles S.W. of Moses Coulee, Douglas Co., central Washington. The field relations indicate that the flow entered a lake and consequently suffered drastic quenching.

HAND-SPECIMEN. The material consists of a number of irregularly shaped pieces of black basaltic glass, the largest unfractured piece being 4 cm. long. The individual pieces are bounded partly by somewhat rough surfaces which are parts of the original corded or ropy flow-surface of the lava; partly by smoother, curved and corroded surfaces representing original shrinkage fracture-surfaces along which volcanic vapors have slightly attacked the glass; and partly by fresh, hackly-conchoidal surfaces of vitreous lustre produced in detaching the material. The glass contains large, distorted steam-cavities reaching a length of 2 cm., and numerous minute vesicles. Apart from a slight development of white and rusty corrosion products along incipient cracks and in some of the steam-cavities, the glass appears homogeneous and perfectly fresh. Small fragments examined without a lens are translucent at thin edges, and the powdered material is faintly greenish, notably translucent, and similar to powdered bottle-glass in appearance. The powder gives no streak; the hardness of the glass is $5\frac{1}{2}$; and the specific gravity of a clean fragment about 1 cub. cm. in volume and sensibly free from vesicles is 2.74.

MICROSTUDY. Crushed samples temporarily mounted in standardized immersion liquids consist essentially of glass shards typically bounded by smooth, curved fracture-edges. In terms of Ridgway's *COLOR STANDARDS* (1912) these fragments range from "pale olive-buff" in the smallest pieces to "citrine drab" in the largest ones. Except for a few tabular microlites of sodic labradorite ($ab:an=45:55$) and of faintly colored rhombic and monoclinic pyroxene the glass is perfectly clear, fresh, homogeneous and isotropic with a refractive index of 1.583.

In addition to the dominant olive-buff shards a few colorless fragments and still fewer yellow fragments are seen. The colorless grains represent the white corrosion product already mentioned, and the yellow grains are probably related to the rusty films; both materials have the vitric structure of the fresh glass. The colorless material has acquired barely perceptible aggregate birefringence with marked reduction of refractive index to 1.44-1.45. The yellow grains are still perfectly isotropic with a refractive index similar to that of the fresh glass. From these characters and the appearance of the hand-specimens it is conjectured that the colorless fragments are essentially hydrated silica and alumina produced by the corrosive action of acidic volcanic vapors travelling along

fractures in the newly consolidated glass and removing the more soluble and strongly refringent components, principally iron and magnesia; and that the yellow particles are derived from surfaces of the fresh glass which have suffered no alteration beyond some hydration and oxidation.

CHEMICAL COMPOSITION

SiO ₂	51.30	Orthoclase.....	6.12
TiO ₂	1.40	Albite.....	24.10
Al ₂ O ₃	18.54	Anorthite.....	34.47
Fe ₂ O ₃	0.26	Diopside.....	6.80
FeO.....	11.21	Hypersthene.....	23.84
MnO.....	0.35	Olivine.....	1.06
MgO.....	4.03	Magnetite.....	0.46
CaO.....	8.55	Ilmenite.....	2.74
Na ₂ O.....	2.83		
K ₂ O.....	1.05		
H ₂ O+.....	0.30		
H ₂ O-.....	trace		
P ₂ O ₅	0.05		
CO ₂	none		
S.....	none		
	99.87		

C.I.P.W. Symbol...II (III). 5. "4. 4.

Sideromelanc (Ideal Basaltic Glass), from the lake-quenched nose of a flow at Columbia River, 3 miles S.W. of Moses Coulee, Douglas Co., Washington. Analysts W. H. & F. Herdsman.

The analysis and mineral composition are those of a slightly undersaturated basalt. The only striking feature is the very low value for Fe₂O₃. Previous sideromelane analyses show the same feature (Peacock, 1926 B, p. 57), and thus a relation between the pale color and low tenor of ferric oxide suggests itself.

THE NOMENCLATURE OF BASIC GLASSES. Various terms have been proposed and employed to designate basaltic glasses and dominantly vitreous basalts. The older texts give the following: tachylyte⁴ (Breithaupt, 1826); hyalomelane (Hausmann, 1846); sideromelane (Sartorius von Waltershausen, 1853); basalt-obsidian (Cohen, 1880); and hyalobasalt (Rosenbusch, 1887). Breithaupt's original description of tachylyte (1826) is brief and lacks micro-

⁴ From *ταχύς*, quick, and, *λυτός*, dissolved, in the sense of fused. The second "y" in tachylyte being thus demanded by the derivation, the spelling tachylite is not recommended.

scopical criteria. The material occurs in basalt at Säsebühl between Dransfeld and Göttingen; it is described as opaque, similar to obsidian, and readily fusible, this last property being expressed in the name. In 1847 Hausmann distinguished the basaltic glass from Bobenhausen with the name hyalomelane although even then the grounds for the distinction were not apparent. In 1872 Rosenbusch (1872, p. 147) suggested the arbitrary separation of basaltic glasses according to their solubility in HCl, and proposed that tachylyte be reserved for glasses soluble with some readiness, and hyalomelane for insoluble glasses. But this distinction attached the meaning "rapidly soluble" to the word tachylyte, which was not intended by Breithaupt, and classed as insoluble the Bobenhausen material which is in fact more soluble. Penck was inclined to attach little weight to this distinction (1879, p. 521), and Judd and Cole clearly showed that "the supposed distinction between tachylyte and hyalomelane, founded on their behavior with acids, altogether fails in practice as a means of discrimination between the different varieties" (1883, p. 461). Rosenbusch, however, had already abandoned the solubility-distinction (1877, p. 445), and the term hyalomelane has since become obsolete.

In 1853 Sartorius von Waltershausen described as sideromelane⁵ basaltic, vitreous chips in the palagonite-tuffs of Sicily and Iceland. The following properties were given: color, lustre and fracture, like obsidian; hardness barely that of labradorite; sp. gr. 2.531; dull-black on weathered surfaces; amorphous, without trace of outward form or cleavage; wholly dissolved in warm, concentrated HCl; composition similar to basalt (1853, pp. 202-204). In their report on the basic volcanic material dredged from the bottom of the Pacific Ocean during the voyage of H. M. S. "CHALLENGER" Murray and Renard described and figured fragments of fresh, basaltic glass from the nuclei of manganese nodules; this glass is clear and olive-buff in color in thin sections, and carries only a small microlitic content composed of olivine and plagioclase (1891, pp. 299-311), pls. xvi, xvii). The authors identified this material with the sideromelane of von Waltershausen. In a recent study of the basic tuffs of Iceland one of us (Peacock) found that fragments of fresh, basaltic glass, pale apple-green in thin sections and precisely similar to the "CHALLENGER" material, form an im-

⁵ Sideromelan in German. In English sideromelane is preferred and used throughout the paper.

portant component of the tuffs of Glacial and Recent Age (1926 B, pp. 56-60, pl. i). As this material contrasts so strikingly with the deep-brown, almost opaque appearance of thin sections from the tachylytic margins of basic intrusive bodies; and as, furthermore, this difference between the two types of basaltic glass seems to be directly related to the different cooling conditions attending their formation, it was deemed desirable to revive von Waltershausen's obsolescent term sideromelane to denote the rather uncommon, clear, pale-colored basaltic glass produced by drastic chilling of basalt magma (subglacial extrusion in Iceland, and submarine eruption in the case of the shell-bearing tuffs of Sicily and the non-pumiceous deep-sea examples), as distinct from the less rapidly chilled vitreous selvages of basaltic intrusions which are typically deep-brown or nearly opaque in thin sections due to incipient or advanced separation of turgid or opaque bodies consisting mainly of magnetite. As a sufficiently distinct petrographic entity it was further suggested that sideromelane might be classed with the mineraloids of Niedzwiedzki⁶ (Peacock, 1926 B, pp. 66-67).

Our attention has been drawn to the fact that the standard lexicons identify tachylyte with basalt glass; and as sideromelane is simply ideal basalt glass the question of the validity of von Waltershausen's term is reopened. An examination of all the descriptions of analyzed basaltic glasses collected by Washington (1917) and listed under the rock names chosen by the respective authors, and of some further relevant descriptions, shows however that with only one exception tachylyte has been used consistently and exclusively to describe deep-brown, turgid, dohyaline, chilled selvages of basic intrusive bodies; and that basalt glass has invariably been reserved for the pale-colored, clear material forming surface films on rapidly cooled lavas and occurring in small and consequently quickly chilled fragmental basaltic ejecta. To describe sideromelane as tachylyte would thus be misleading; and to describe it simply as basalt glass would, through the nominal identity of tachylyte and basalt glass given in the works of reference, lead to the same misconception. And therefore, while admitting the necessity of reducing nomenclature to a working minimum, we believe that there is still room for sideromelane as a specific name to denote ideal basaltic glass.

⁶ Adopting Niedzwiedzki's definition of mineraloid, Rogers had already urged that natural glasses be classed as mineraloids (1917, p. 540).

FURTHER OCCURRENCES OF SIDEROMELANE. The specimen of sideromelane described represents the less common occurrence of this type of glass in coherent masses of some size. In our material sideromelane appears also as a thin film on the surface of a slaggy basalt from the Jordan Craters, 20 miles N. of Jordan Valley, Malheur County, Oregon; in a fresh, fragmental condition as the principal constituent of sideromelane breccias and tuffs; and in variously altered fragmental conditions in palagonitic tuffs.

A breccia associated with the end of the flow from which the typical sideromelane was collected, at Columbia River, 3 miles S.W. of Moses Coulee, Central Washington, consists essentially of black angular fragments of sideromelane cemented with abundant calcite. Examined in small grains the sideromelane is seen to be perfectly fresh except for a very slight development of the colorless and yellow corrosion products previously described.

A specimen from the top of Asotin Crater No. 2,⁷ Asotin, Washington, consists wholly of lightly-cohering fragments of sideromelane averaging about 2 mm. in diameter; the rock is almost identical to granulated slag in appearance. In thin section the sideromelane is pale brown and perfectly fresh. It carries a subordinate amount of olivine and calcic plagioclase phenocrysts which together with a refractive index of 1.597 indicates a more basic composition than that of the type sideromelane chosen for full description.

In the remaining specimens sideromelane is variously altered; the treatment of these altered sideromelane tuffs falls properly into the next section.

PALAGONITE

PETROGRAPHIC DESCRIPTIONS. In the present material the rock most closely approximating to a typical Icelandic palagonite-tuff is a specimen of "Asotin Sandstone" from the southern margin of Asotin Crater No. 12, 1½ miles north of Asotin, on the Washington side of the Snake River. The hand-specimen is a fine-grained, earthy-brown, friable rock in which a few specks of fresh black sideromelane can be discerned embedded in an abundant brown material of similar grain-size. In thin section the rock is seen to

⁷ The geological relations and volcanic mechanism of the Asotin Craters of the Columbia River basalt have recently been described by one of us (Fuller, 1928); and the craters have been given numbers (fig. 1) which are used in the present paper.

consist of olive-buff fragments of sideromelane averaging 0.5 mm. in diameter and carrying a small proportion of pyroxene and plagioclase microlites. Internally the sideromelane fragments are perfectly fresh with a refractive index of 1.592; marginally each grain is converted into yellow palagonite with a low and variable refractive index of 1.47 ± 0.01 . A small amount of the yellow palagonite is clear and isotropic, and thus exactly like the ideal "gel-palagonite" found to a limited extent in those Icelandic palagonite-tuffs in which sideromelane has suffered hydration by immersion in sea-water. The greater proportion of the palagonite margins is slightly turgid and birefringent due to incipient separation of some opaque mineral, and incipient molecular organization of the gel in obscure, fibrous, spherulitic or vermicular fashion. In this condition specific determination of the minerals commencing to separate from the gel is quite impracticable; and the obscurely birefracting palagonite is thus identical with the "fibro-palagonite" commonly found in those Icelandic tuffs which have suffered hydration at rather higher temperatures in the neighborhood of hot springs.

In the study of the Icelandic tuffs already cited it was found that the refractive index and water-content of palagonite are related roughly in an inverse linear manner (Peacock, 1926 B, p. 70 and fig. 4); in the present case, knowing the refractive index of the fresh sideromelane (1.59), of the palagonite (1.47), and of water (1.33), the water-content of the palagonite is found to be about 32 per cent. as against 28 per cent. in the most hydrated Icelandic example.

In the Icelandic palagonite-tuffs there is good evidence to show that yellow gel- and fibro-palagonite result simply from the hydration of sideromelane, this hydration being accompanied by extensive oxidation of the iron-content and some loss of lime and soda. In the present material yellow palagonite is too slightly represented to permit separation and chemical analysis; the microscopic similarity between the yellow palagonite from the Columbia River Plateau and from Iceland is so close, however, that we may infer with some assurance that the nature of the palagonitization process has been the same in both cases.

In the remaining specimens sideromelane has suffered more profound alteration. A coarse, lake-quenched breccia from Moses Coulee, about 1 mile south of Douglas Creek, Washington, con-

sists of sideromelane fragments embedded in a rusty-white, earthy matrix. In thin section this matrix is seen to consist of small sideromelane fragments wholly converted into a turgid-gray substance, almost isotropic, with a refractive index of 1.45 ± 0.01 . Around the borders of these altered sideromelane fragments, and sometimes within them, minute, colorless, fibrous, vermicular structures have developed; these are probably zeolitic in composition. Obscure chloritic and limonitic spots, representing greatly altered pyroxene microlites, are scattered through the altered glass.

A tuff from Asotin Crater No. 6 consists dominantly of earthy-gray, altered sideromelane dust. In the hand-specimen a quartz pebble 2 cm. long is seen embedded in the tuff and in the section several foreign quartz grains appear. The sideromelane fragments are somewhat vesicular, and the alteration to fibro-palagonite and to the turgid-gray product of severer alteration has taken place both around the fragments and within the steam cavities.

The last example, a white tuff⁸ from the base of Asotin Crater No. 2, consists almost wholly of sideromelane dust converted into the turgid-gray product of severer alteration. Plagioclase and pyroxene microlites have survived the alteration process with little change; abundant minute spots of iddingsite represent olivine microlites which have completely succumbed.

The very low refractive index (1.45) of the turgid-gray alteration product of sideromelane in the above three examples, and the absence of the yellow or brown color characteristic of palagonite formed under the usual mild conditions of hydration and oxidation, suggest that the turgid-gray material represents sideromelane which has suffered, in addition to hydration, a loss of iron and perhaps of other bases by solution. In Iceland hot-spring action is unable to produce so profound a change on sideromelane; and the conjecture, based on petrographic evidence, that the tuffs characterized by the turgid-gray material have been acted upon by acidic vapors, is supported by the field evidence which strongly indicates that the palagonitization of these tuffs was effected by the steam generated in the quenching of the extruded material.

⁸ This rock is to be distinguished from the "white tuff" recently described from the Asotin Craters by one of us (Fuller, 1928, p. 61). This white tuff consists of minute, pumiceous fragments which appear to have suffered a loss of iron by volatilization.

At the vents this steam would probably be charged with acidic volatiles. As such conditions differ from the normal, milder palagonitization conditions in degree rather than in kind, it seems necessary to extend the term palagonite to include the turgid-gray, probably iron-free product of severer alteration of sideromelane.

The present petrographic evidence thus again shows that palagonitization proceeds from hydration and alteration by water or water-vapor of exotic origin, while the formation of chlorophaeite is a deuteric process induced by endogenous fluids. This confirms the distinction between the two processes already stated by one of us in slightly different terms (Peacock, 1926 B, pp. 72-74).

THE USE OF THE TERM PALAGONITE. The term palagonite was applied by von Waltershausen in 1845⁹ to the material forming the brown groundmass of a tuff from Palagonia, Val di Noto, Sicily. The following properties were given: fully transparent; color, wine-yellow to resin-brown; lustre, vitreous; fracture, splintery-conchoidal; external appearance, like gum-arabic or brown sugar; hardness, slightly over 3; specific gravity, about 2.64; becomes opaque before the blowpipe and fuses readily to a black, lustrous, magnetic bead; soluble in HCl with residue of silica; contains 16 per cent. of water, also ferric oxide, silica and alumina (1845, pp. 402-403).

In 1846 von Waltershausen found palagonite typically developed and widely distributed in the tuffs of Iceland. At Seljadalur, near Reykjavík, he recognized a massive tuff-bed partly composed of apparently pure palagonite; to this rock he gave the name *Palagonitfels* (1847, pp. 76-79).

Although von Waltershausen's writings on palagonite are voluminous and somewhat obscured by now discarded mineralogical theory, a clear conception of what this author understood by palagonite and the manner in which he used the term can readily be gained from his three publications on the subject (1845, 1847, 1853). Firstly, palagonite was claimed as a new mineral species (1845, p. 402). Secondly, the common structural relation of palagonite to sideromelane was clearly appreciated.¹⁰ Thirdly, it was

⁹ The extract: "ein neues. . . . Mineral, dem ich den Namen Palagonit beigelegt habe" (1845, p. 402), indicates that the name was actually proposed at an earlier date. No earlier reference, however, was found.

¹⁰ Auf den Verwitterungsflächen . . . kommt der Sideromelan, vom Palagonit umhüllt, sehr deutlich zum Vorschein, . . . (1853, p. 203).

shown by analyses that palagonite is hydrated sideromelane.¹¹ And fourthly, by the frequent use of *Palagonittuff* and *Palagonitfels* it is clear that palagonite was used as a mineral qualifier and not as a rock name.

On the grounds that von Waltershausen's *Palagonitfels* proved to be an aggregate of fragments of sideromelane together with their alteration products Penck concluded: "dass ein als Palagonit zu bezeichnender Körper nicht existirt" (1879, p. 568); and thereafter, having been discredited as a mineral species, palagonite was variously used, sometimes as a synonym for palagonite-tuff, and sometimes to denote any altered basic glass. Murray and Renard, however, in their description of the palagonitic materials dredged by the "CHALLENGER," adhered strictly to von Waltershausen's original usage (1891, pp. 299-311).

A recent study of the basic tuffs of Iceland by one of us served substantially to corroborate von Waltershausen's views on the nature and origin of palagonite, and to support his usage of the term. It was found that palagonite is a well-individualized material, not a mineral, of course, in the present restricted sense, but a mineraloid in the sense of Niedzwiedzki; and that palagonite was invariably formed by the hydration of sideromelane, this hydration being accompanied by extensive oxidation of the iron-content and by some loss of lime and soda. It was furthermore suggested, in accordance with the original usage, that palagonitic tuff, palagonite-tuff and palagonite-rock be used to denote palagonitized sideromelane-tuffs according to the extent to which they had suffered alteration by hydration. And finally it was recommended that the use of palagonite to denote certain chlorophaeite-like bodies in some basalts and dolerites be discontinued (Peacock, 1926 B, pp. 56, 72-74). From a study of the present material it was found desirable to include under palagonite the turgid-gray material representing sideromelane which had undergone somewhat more intense alteration than that which affected sideromelane in the Icelandic tuffs; but beyond this, no reason has appeared for departing from the standpoint outlined above.

In a critical discussion of this standpoint expressed in a personal

¹¹ In Folge der mitgetheilten Beobachtungen steht es daher fest, dass dieser Palagonit . . . aus Sideromelan entstanden sei, dem 3 Atome Wasser hingefügt sind, . . . (1853, p. 213).

communication¹² Dr. L. L. Fermor urges that chlorophaeite and Icelandic gel-palagonite are identical on the basis of chemical composition and optical properties; that therefore the later term palagonite should be dropped as a mineral term; that palagonitization be retained for the process whereby basic glasses become hydrated; and that palagonite be retained as a rock name to signify basic glass together with hydration and other alteration products.

In the following table the values for the sesquioxides and ferrous oxide in chlorophaeite and palagonite are contrasted.

TABLE III.

	Chlorophaeite	Palagonite		
	I	II	III	IV
Al ₂ O ₃	3.6	11.2	16.26	14.64
Fe ₂ O ₃	20.1	10.3	14.57	7.93
FeO	5.7	2.2	.....	0.87

I. Average of six analyses, including two materials named palagonite, respectively from Franz Josef Land (Teall, 1897, p. 485), and Massachusetts (Emerson, 1905, p. 112), but differing from chlorophaeite in no essential respect.

II. Palagonite-rock, Iceland; representing gel-palagonite closely enough for the present purpose (Peacock, 1926 B, p. 66).

III. Palagonite, South Pacific (Murray and Renard, 1891, p. 307).

IV. Palagonitic tuff, Eden Islet, Galápagos Islands (Washington and Keyes, 1927, p. 541).

In chlorophaeite ferric oxide is strongly dominant and alumina is almost negligible; in palagonite, on the other hand, ferric oxide and alumina are present in comparable amounts by weight. In a general formula, where the sesquioxides are grouped together, this difference would not appear; and normally, such a difference is regarded as insignificant. But in the present case the strong dominance of ferric oxide in chlorophaeite and the abundance of alumina in palagonite seem to be of genetic significance. In every case chlorophaeite has apparently resulted from the action of hydrothermal solutions on olivine or pyroxene, or on the basic constituents of the vitreous groundmass of basalts or dolerites; the product of this action is thus naturally rich in iron and poor

¹² Calcutta, September, 1927. As Dr. Fermor expresses the intention of including the argument contained in this letter in a forthcoming paper in the Records of the Geological Survey of India we feel free to discuss here the questions raised.

in alumina. In palagonite, however, which results from the hydration of sideromelane, a concentration of iron or an elimination of alumina are not to be expected. Indeed the present material indicates that extreme palagonitization is actually accompanied by removal of iron. We believe, therefore, that a chemical distinction of genetic significance exists between chlorophaeite and palagonite; and thus we are unable to follow Dr. Fermor's recommendations based on their contended identity.

The difficulties attending the application of the terms chlorophaeite and palagonite seem to vanish if the definition of chlorophaeite be slightly extended, as already suggested, to embrace all those hydrous, amorphous, pitch-like materials in basalts or dolerites, whether they show the green to brown color-change or not; and palagonite be restricted to its original significance, namely the hydration product of sideromelane, by water or water vapor of exotic origin, found typically in dohyaline pyroclastics of basic composition. This distinction is based primarily not on mode of occurrence, but on a chemical difference dependent on mode of occurrence, which may therefore be taken as a reliable indirect means of distinguishing between the two materials.

Mineraloids of closely similar properties have been separated on the basis of important differences in mode of occurrence; Fermor, for example, follows Heddle and Lacroix in distinguishing between celadonite and glauconite on such a basis (1925, p. 142). With their highly distinctive megascopic and modes of origin chlorophaeite and palagonite are in no danger of confusion from the field standpoint. And therefore in view of the optical and chemical differences which in addition exist between them, we feel that the definite separation of these two basaltic mineraloids is rigorously demanded.

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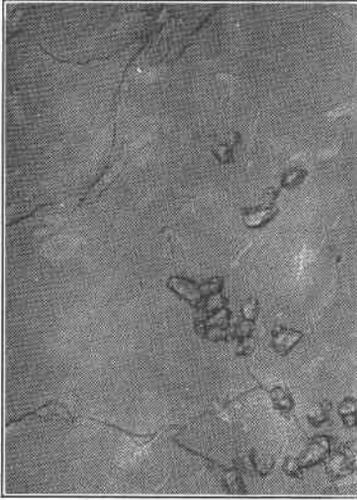


FIG. 1

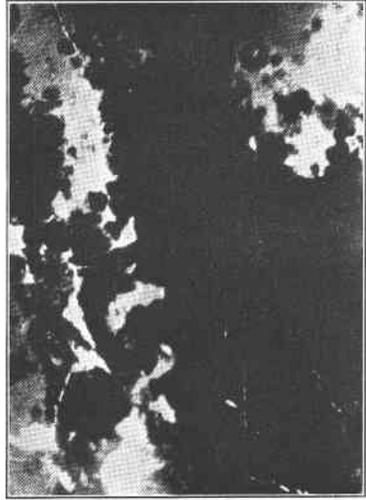


FIG. 2

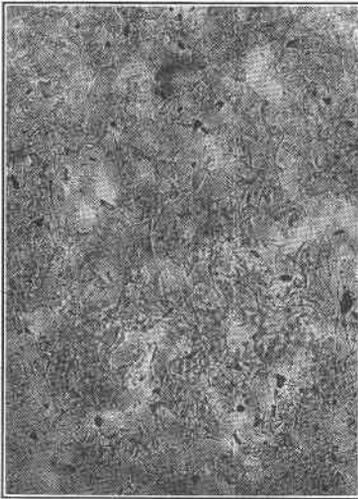


FIG. 3



FIG. 4

EXPLANATION OF PLATE XII

Fig. 1. Thin section of sideromelane (ideal basaltic glass), from the chilled nose of a basaltic flow at Columbia River, 3 miles S.W. of Moses Coulee, Washington. The glass is olive-buff in color, and carries microlites of pyroxene and labradorite. (69 diameters.)

Fig. 2. Thin section of tachylyte from the chilled margin of a basaltic dyke at Torvaig, Portree, Skye, Scotland. This is a deep-brown glass rendered largely opaque due to separation of magnetite. The specimen is a gift from Dr. Alfred Harker. (69 diameters.)

Fig. 3. Thin section of chlorophaeite in an amygdale in a trachydolerite dyke cutting Columbia River basalt in the Grande Ronde valley, just S. of Anatone, Washington. The material is orange-brown and isotropic, and is traversed by a network of fine curved cracks such as would be produced in the shrinking of a rigid gel. (159 diameters.)

Fig. 4. Thin section of palagonite-tuff from Asotin Crater No. 12 (Fuller, 1928, fig. 1), $1\frac{1}{2}$ miles N. of Asotin, Washington. The rock consists of sideromelane fragments converted marginally, by hydration, into palagonite. Some of this is clear, yellow, isotropic gel-palagonite; the bulk of it is turgid, obscurely birefringent fibro-palagonite. (69 diameters.)

Photomicrographs by M. A. P. Multiply the above magnifications by $\frac{1}{2}$.