THE ORIGIN, OCCURRENCE, COMPOSITION, AND PHYSICAL PROPERTIES OF THE MINERAL IDDINGSITE

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INTRODUCTION

Dr. A. C. Lawson,[1] while studying the volcanic rocks in the vicinity of Carmelo Bay, Calif., in 1893, found an undescribed mineral in the rocks called carmeloites, to which he gave the name iddingsite; that, however, the mineral was a distinct species was not generally recognized and it is still described in the textbooks as a variety of serpentine.[2] Subsequent study has shown this to be a widespread and, at times, an abundant mineral in basaltic rocks, but its chemical composition and real nature have long remained matters of speculation. It is a secondary mineral, rarely entirely free from the olivine from which it is derived; it is rather finely disseminated among other minerals of nearly the same specific gravity, and so investigators have been deterred from making the tedious efforts required for its separation and analysis.

The chemical portion of the following paper is based upon eight analyses of iddingsite from six localities, and while the results of these analyses do not give a complete understanding of the chemical composition of iddingsite, they show that it is not serpentine and establish it as a distinct mineral species. All the analyzed iddingsites, and additional materials from widely separated localities from the western United States, have been examined; the physical properties have been determined; its relations to the associated minerals have

[1] Lawson, Andrew C., Univ. of Calif. Bull. of Dept. of Geol., No. 1, p. 31, 1893.

[2] Johannsen, Albert, Determination of rock-forming minerals, p. 361, New York, 1908. Iddings, Joseph P., Rock minerals, p. 381, New York, 1911. Winchell, N. H., and A. N., Elements of optical mineralogy, p. 360, New York, 1909.

been studied; and conclusions as to the genesis of iddingsite have been reached. This paper is presented in the belief that the available data on the composition, and a detailed study of the origin of this long discussed mineral will prove to be of interest, as the results are distinctly at variance with previous views about iddingsite.

REVIEW OF PREVIOUS INVESTIGATIONS OF IDDINGSITE

In a discussion of the rocks of the Eureka district, Nevada, Iddings[3] says of the mineral later named iddingsite: "There commences from the surface and from fractures (in olivine) as in the ordinary process a fibration, not in directions always normal to the surface, but in lines parallel throughout the crystal, and parallel also to some direction in the plane of the more perfect cleavage. The fibers have a light yellow color at first, which deepens into a reddish brown or blood red as the decomposition proceeds; they polarize light brilliantly and show parallel extinction and sometimes faint pleochroism. The resultant mineral is evidently not a compound aggregate, but a crystallographic individual, with parallel orientation in all its parts, for the extinction of light is the same throughout, and the interference figure is that of a doubly refracting crystal." Iddings observed occasional well crystallized hexagonal plates in the less altered olivine and found that on treatment with hot concentrated hydrochloric acid the mineral lost color without changing its optical properties. This induced him to think that: "The substance is in this case a nearly colorless micaceous mineral, colored red by iron oxide." He concludes:

> That the mineral is a foliated, crystallized form of serpentine seems probable from the fact that most of the basalts are so fresh, with the decomposition of the olivine frequently confined to the weathered surface, that a very radical change is not likely to have taken place, and that simple hydration and oxidation of a very ferruginous olivine would supply all the chemical elements necessary to transform it into anhydrous unsilicate of magnesia and ferric iron; besides which is the fact that the optical properties of the mineral in question correspond to those given by Miller for thermophyllite.

Describing the "Potlach pseudomorphs after olivine" in the Carboniferous tuffs and dolorite of Derbyshire, Arnold-Bemrose[4] says:

> The plane of the optic axes is at right angles to the length of the original crystal, the angle between the optic axes is very small, and the double refraction negative. As a rule the pseudomorphs behave as a crystallographic individual, and not as an aggregate. The traces of the cleavage are generally parallel to the length of the crystal. * * * When mounted, the thin flakes appear brown or brownish-yellow by transmitted light. In convergent light they show a biaxial figure, with a small angle between the axes and negative double refraction. They are sometimes almost uniaxial. When a fragment does

[3] Iddings, Joseph P., Appendix B, Mono. 20, U. S. Geol. Survey, pp. 388–390, 1892.

[4] Arnold-Bemrose, H. H., Quart. Journ. Geol. Soc., p. 603, London, 1894.

not lie on the cleavage plane it shows dichroism, the greatest absorption taking place when the short axis of the polarizer is parallel to the trace of the cleavage.

In his investigation of iddingsite, Lawson[5] made qualitative chemical tests and says:

Chemically therefore iddingsite is a hydrous nonaluminous silicate of iron, magnesia, and soda. * * * The extraction of iron by acids without decomposition of the mineral indicates that a considerable proportion of that element is present, not as a part of the silicate molecule, but as a pigment in the form of hematite or limonite, probably the latter.

Of the optical properties Lawson says:

Under the microscope the cleavage plates prove to be biaxial, and yield with great definiteness a figure which shows that the plane of the optic axis is at right angles to the cleavage and parallel to the *c* axis, and that the acute bisectrix is perpendicular to the cleavage, being coincident with the *a* axis. In these plates and in all sections transverse to the cleavage in the slides the extinction is strictly parallel to the cleavage, to the fibrous structure, and to the trace of the pinacoids. This shows that the three axes of elasticity are parallel to the three crystallographic axes, respectively, and that the mineral is therefore orthorhombic. * * * In thin section iddingsite becomes transparent in colors which range from a deep chestnut brown to citron yellow, or occasionally a clear greenish yellow. The pleochroism is strongly marked in sections transverse to the cleavage, particularly so in those parallel to the axial plane, but usually very feeble in sections parallel to the cleavage. The absorption formula is $\mathfrak{c} > \mathfrak{b} > \mathfrak{a}$.

The double refraction (not given) low. The other properties determined by Lawson may be summarized as follows: Hardness 2.4; Specific gravity variable, maximum 2.893; Infusible before the blowpipe, and not perceptibly altered. Yields water in the closed tube. He concludes:

It is evidently not the form of crystallized serpentine thermophyllite, since it differs from the latter in physical appearance, in behavior before the blowpipe, in density, in luster, and in color: neither does it correspond optically with serpentine. Moreover, the development of serpentine from olivine by hydration is accompanied by a swelling of the mass. In the case of iddingsite, on the contrary, there is very frequently excellent evidence of shrinkage. * * * There appears to be no good reason for regarding the mineral as a crystallized variety of serpentine.

Ransome[6] studied iddingsite in the eruptive rocks of Point Bonita and has the following to say of the mineral:

Iddingsite is present in many of the slides of the diabase, in rounded ideomorphic crystals of various sizes up to about 2 millimeters in length, whose outlines are strongly suggestive of olivine. The color varies from light greenish yellow to dark dingy green. * * * These sections are pleochroic, being dark yellowish green parallel to the cleavage, and light greenish yellow at right angles to that position. Under crossed nicols the undecomposed portions show brilliant mottled polarization colors, crimson and green predominating,

[5] Lawson, Andrew C., Univ. of Calif. Bull., Dept. of Geol., No. 1, pp. 31–36, 1893.

[6] Ransome, F. L., Bull. Dept. Geol., Univ. Calif., No. 1, pp. 90–92, 1894.

and the double refraction is therefore strong. The mean index of refraction (not given) is rather low. The distinctly terminated prismatic sections are but slightly pleochroic and show no cleavage. The interference colors are moreover low. In general they give a distinct biaxial figure, with a small angle. * * * The plane of the optic axes lies parallel to the longer axis of the prism, and is, therefore, perpendicular to the cleavage planes. * * * The mineral was ascertained to be optically negative.

OCCURRENCE

Iddingsite is widely distributed in the basaltic rocks of the San Juan region of southern Colorado and northern New Mexico, and, indeed, throughout the western United States. Petrographic studies [7] of these rocks show conclusively that the red or red-brown alteration product of olivine is not serpentine and indicate that it is a definite mineral as suggested by Lawson.

Iddingsite nearly always gives clear evidence of its derivation from olivine, since the outlines of the original olivine crystals are often beautifully preserved. All degrees of alteration have been observed from perfect, homogeneous crystals of iddingsite to olivine crystals with the merest film of iddingsite between cleavage cracks. Usually the outer zone is changed to iddingsite where the alteration is incomplete, but in one large group of rocks the central area is usually iddingsite with an outer zone of fresh olivine. The manner of alteration appears to depend upon some property inherent in the original olivine itself, which allows some parts to be more easily altered than others. Much of the iddingsite seems at first glance to be fibrous, and it has been so described. Close study, however, shows that this effect in the material investigated is the result of minute inclusions of spinels, magnetite, or hematite. High magnifications of small grains of iddingsite reveal a clean fracture with no indication of fibers. The photomicrographs in Plates 1 and 2 show the relationships between olivine and iddingsite in a number of different rocks. In many specimens (pl. 1, fig. 1, and pl. 2, fig. 4), there is an outer zone of iddingsite surrounding a core of olivine with a ragged area between the two, with shredlike masses of iddingsite extending into the olivine. In other specimens (pl. 1, figs. 3, 4) there is alteration along cracks in the olivine with the same shredlike masses of iddingsite extending into olivine. In some specimens (pl. 1, fig. 3) there is an outer zone of iddingsite around olivine with a sharp contact between the two. In many specimens the large phenocrysts are completely changed to iddingsite, while small groundmass grains of olivine of a later generation show little alteration. In one large group of rocks (pl. 1, fig. 3; pl. 2, figs. 5, 6) there is an inner core of iddingsite surrounded by fresh olivine. In some specimens (pl. 1,

[7] Larsen, Esper S., Bull. 679, U. S. Geol. Survey, p. 90, 1921.

fig. 4) alteration has occurred along cracks with very sharp contacts between iddingsite and olivine. Much of the iddingsite investigated contains very small grains of magnetite and other spinels arranged in minute lines parallel to the crystallographic axes of the mineral.

A pale brown or yellow material is associated with iddingsite in some rocks and this material is represented by analyses 3 and 5. This is usually cryptocrystalline and has a lower index of refraction than normal iddingsite and a small axial angle where it is possible to determine it. It forms a rim around iddingsite in some specimens and a core in others. The contact between the two types of material is sharp in some specimens and transitional in others. The evidence does not clearly indicate whether this pale material is impure, imperfectly crystallized iddingsite or a different but closely related mineral.

Usually there is evidence that there was a very marked loss of volume during alteration of olivine to iddingsite, as the cleavage planes (pl. 2, fig. 1) are marked by widely gaping cracks that occupy 10 to 20 per cent of the volume of the original olivine.

ORIGIN

Iddingsite has usually been described as a weathering product of olivine. Its origin through the processes of weathering can not be summarily rejected for all occurrences, but in the material studied in the preparation of this paper an origin through weathering seems to be extremely improbable. In the basaltic rocks of southern Colorado and northern New Mexico there is no observable relation between the occurrence of olivine or iddingsite in a rock and the amount of weathering that rock has undergone. In general, there is little weathering in these rocks and iddingsite occurs in the freshest of them, in association with unaltered augite, feldspars that are not even clouded, and basaltic glass (a very unstable material) that is unchanged. It has been observed evenly distributed from top to bottom of a basaltic sill 50 feet in thickness where no trace of weathering could be found. Its occurrence bears no relation to exposure of surface, proximity to joint cracks or relative age of the various beds. It may be abundant in one flow and be absent in any one or all of either higher or lower flows of a series. Several flows have been identified where iddingsite of similar characteristics is present over very wide areas, showing that the characteristics of the iddingsite are inherent in the rock.

In rocks that do show extensive alteration, serpentine and not iddingsite has developed from olivine. Some basalts show a narrow leached zone at the surface, and here impure amorphous aggregates of hydrous iron oxides have formed from the olivine crystals and not iddingsite.

In many of the rocks studied the relation of fresh olivine and iddingsite present pecularities that appear to give a clew as to the mode of origin. The presence of small grains of ground-mass olivine remaining nearly fresh in the presence of large phenocrysts that have been completely changed to iddingsite suggests that the processes involved in the change are partly dependent on the original composition of olivine. The basalt of the Hinsdale volcanic series of the Rio Grande Valley of northern New Mexico has been traced for 80 miles, and wherever observed it shows cores of iddingsite surrounded by fresh olivine (see pl. 1, fig. 2, and pl. 2, figs. 5, 6). Similarly, rocks from many other sources show a very distinct zonal relationship in the development of the iddingsite. It seems very difficult to explain such relationships on the basis of weathering, especially as these phenomena are characteristic of single flows or single groups of flows over wide areas. On the other hand, these facts suggest very strongly that the alteration was partly dependent upon zonal variations in the original olivine from which the iddingsite was derived. This led to an investigation of the olivines of iddingsite-bearing rocks. The basalt of Cerro Mohera, New Mexico, is of the same age and type as that giving rise to the sharp zones of olivine around iddingsite shown (pl. 1, fig. 2, and pl. 2, figs. 5, 6), but is itself little altered. A careful study of the optical properties of this olivine showed that the index of refraction for β varied from $n=1.711$ to $n=1.722$, and the optical character varied from + to —, indicating an appreciable variation in the proportion of iron silicate (Fe_2SiO_4) in the olivine molecule. These facts, supported as they are by the mineral relationships, seem to show that the formation of iddingsite from olivine is partly dependent upon the chemical composition of the olivine.

Iddingsite is confined almost exclusively to extrusive or hypabyssal rocks and is practically absent from deep-seated rocks, but if iddingsite were derived from olivine by ordinary weathering there is no reason why it should not occur in abyssal rocks. The restriction in occurrence shows that specialized conditions are required for the formation of the mineral and that these conditions are most often realized in a cooling extrusive. This restriction in occurrence and the relationships described indicate that the development of iddingsite is definitely associated with magmas that cooled near the surface.

In discussing iddingsite, Iddings[8] says:

> There remained in the portion (iddingsite) subjected to acid, well developed, nearly opaque octahedrons, most likely picotite.

[8] Iddings, Joseph P., U. S. Geol. Survey, Mono. 20, p. 390.

Ransome[9] says:

> It (iddingsite) includes abundant grains of iron ores, and frequently dark brown microscopic crystals of chromite or picotite. * * * In the Point Bonita iddingsite the limonitic pigment is entirely absent.

The writers have found very large amounts of magnetite in the iddingsite from Race Creek, Colo., and spinels in that from Brazos River, N. Mex. Small amounts of magnetite or related minerals seem to be almost always associated with iddingsite. These associated minerals that have clearly developed by the same processes as iddingsite contribute a very convincing line of evidence that iddingsite is not the result of ordinary rock weathering. Weathering would produce hydrous iron oxides probably in the form of limonite and would be very unlikely to yield magnetite and other minerals of the spinel group. On the other hand these would be the very minerals to form if the alteration of olivine to iddingsite were the result of magmatic or deuteric[10] processes.

Sederholm says:

> I think that it would be advisable to discriminate between such metasomatic changes which belong to a later period of metamorphism, i. e. are secondary in the strictest sense of the word, and those which have taken place in the direct continuation of the consolidation of the magma of the rock itself. I propose to call the later deuteric, as distinct from secondary changes.

This strongly confirms the evidence presented by the restriction in occurrence and suggests that *iddingsite is a deuteric mineral*; that is, it has been produced by processes largely inherent in the magma itself, probably brought about by gases during final cooling.

The conclusion that iddingsite is a deuteric mineral first based purely on petrographic evidence is strongly supported by the chemical analyses. The ordinary agents of weathering would be extremely unlikely to produce an homogeneous crystal with definite optical properties and the chemical composition of iddingsite. On page 8 is given a typical analysis of iddingsite and the analysis of an olivine from rocks of the same region.

A comparison of these analyses shows that the proportion of silica has remained nearly constant, a little aluminum and calcium appear to have been added, 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, and the only stages through which these rocks have passed where forces seemingly capable of performing such work have been active are those

[9] Ransome, Frank L., Univ. of Calif. Bull. of Dept. Geol., No. 1, p. 92, 1893.
[10] Sederholm, J. J., Com. Geol. de Finlande, Bull. No. 48, pp. 141–142, 1916.

associated with magmatic cooling. It is, therefore, concluded that iddingsite is most probably a deuteric mineral formed in the presence of heat, water, and gases after the magma has reached a horizon near enough the surface to give oxidizing conditions. 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.

A similar result may have been produced in other ways. Thus it is quite probable that the heat and gases given off by one lava flow would have a metasomatic action on a previous flow, and iddingsite might be the result of this action. It is doubted, however, if this effect could be widespread, and it could not produce a uniform distribution of iddingsite from top to bottom of a thick flow.

A comparison of the chemical composition of iddingsite and serpentine shows how different are the processes involved in the development of the two minerals.

Comparative analyses of iddingsite, serpentine, and olivine

	(1)	(2)	(3)	(4)
SiO_2	38. 63	42. 17	44. 1	38. 76
Al_2O_3	1. 78	. 30		
Fe_2O_3	32. 49	1. 57		
FeO		. 64		22. 55
CaO	2. 79			trace.
MgO	6. 64	41. 33	43. 0	38. 52
H_2O	17. 70	13. 72	12. 9	. 09
	100. 03	99. 73	100. 0	99. 92

(1) Iddingsite from La Jara Creek, Conejos quadrangle, Colo.
(2) Serpentine from Fort Henry, New York,[11] analysis No. 19.
(3) Serpentine ideal composition.
(4) Olivine from Cerro Mohera near Tres Predias, N. M.

In analyzed serpentine aluminum peroxide (Al_2O_3) and iron peroxide (Fe_2O_3) reach a maximum of 6 per cent, and a variable amount of iron monoxide (FeO) replaces magnesium oxide (MgO), but no serpentine even remotely resembling iddingsite has ever been described. Serpentine is generally believed to have been the result of metasomatic changes at some depth and seldom, if ever, the result of surface weathering, and yet its chemical composition is not very different from that of the olivine from which it is derived. The changes in the ratios of the chemical components involved in the derivation of serpentine from olivine are very much less than the changes in ratio when iddingsite is derived from olivine. It is also

[11] Dana, James D., Descriptive mineralogy, p. 672, 1909.

evident that serpentine forms under conditions where reducing conditions prevail, and most of the iron remains in the ferrous condition, while iddingsite forms where oxidizing conditions produce ferric iron.

PETROLOGY OF IDDINGSITE-BEARING ROCKS

RACE CREEK, COLO., OCCURRENCE

The rock containing the material represented by analysis (1) is and andesite of basaltic habit of late Tertiary age collected from a peak at the headwaters of Race Creek near the south edge of the Creede quadrangle, Colorado, and about 11 miles south of South Fork on the Creede branch of the Denver & Rio Grande Western Railroad. The rock is gray and somewhat vesicular and in the hand specimen shows phenocrysts of oligoclase, quartz, and iddingsite. The modal composition of the rock is as follows:

Mineral composition of andesite from Race Creek, Colo.

Quartz	0.5
Plagioclase (oligoclase)	60.0
Augite	18.7
Iddingsite	8.5
Olivine	3.8
Magnetite	8.0
Apatite	0.5
Total	100.0

This rock contains augite and magnetite in notable proportions, but the feldspars are sodic and like the Brazos River Rock it would be classed as an andesite. The iddingsite occurs in euhedral pseudomorphs after olivine reaching 3 millimeters in length and in subhedral aggregates. The alteration from olivine to iddingsite is not complete in all grains, but the large difference in specific gravity of olivine and iddingsite allowed its elimination. Part of the material was rich in particles of magnetite, but this was separated magnetically and eliminated before analysis. The particles of magnetite are arranged in lines parallel to the crystal axes of the original olivines. In thin section the iddingsite shows very distinct open shrinkage cracks, and the iddingsite occupies from 15 to 20 per cent less volume than the olivine from which it was derived.

LA JARA CREEK, COLO., OCCURRENCE

The iddingsite of analysis (2) was concentrated from a nearly normal olivine basalt of late Tertiary age collected near the base of a cliff on La Jara Creek, 19 miles northwest of Antonnito, Conejos quadrangle, Colorado.

The rock is medium-grained, dark gray, and very coarsely vesicular. The modal composition is as follows:

Mineral composition of basalt from La Jara Creek Colo.

Plagioclase (oligoclase)	60.0
Augite	28.6
Olivine	1.3
Iddingsite	3.8
Magnetite	6.6
Total	100.0

The iddingsite occurs in masses of a maximum diameter of 4 millimeters, whose outlines are those of olivine. The olivine is only partly altered to iddingsite, but the greater specific gravity of olivine allows an almost complete separation of the two minerals. Part of the alteration product of olivine was a lemon yellow material, which under the microscope appeared to be cryptocrystalline. This material has a lower specific gravity than crystalline iddingsite and is represented by analysis No. 3. It contains many minute, highly magnetic black inclusions arranged in lines running parallel to the crystallographic axes, which are undoubtedly magnetite.

BERNARDS FERRY, IDAHO, OCCURRENCE

A specimen of basalt from Bernards Ferry, Silver City quadrangle, Owyhee County, Idaho, contained in Lindgren's[12] studied series of rocks yielded the iddingsite used in analysis No. 4. The rock contains abundant reddish brown iddingsite, although Lindgren does not mention olivine or iddingsite in his brief description of the basalts of the region. The rock is coarse-grained, slightly vesicular, and dark gray. The modal composition is as follows:

Mineral composition of the basalt from Bernards Ferry, Idaho

Plagioclase $Ab_{38}An_{62}$	46.0
Augite	43.3
Olivine	2.6
Iddingsite	5.9
Magnetite	2.2
Total	100.0

The iddingsite is dark reddish brown and occurs as pseudomorphs after olivine. The larger grains are completely altered to iddingsite, but some of the smaller ones show outer borders of olivine around cores of iddingsite.

As in the occurrence previously described, the Bernards Ferry rock contains a cryptocrystalline substance derived from the olivine in the same manner as the deeper red crystalline material which is

[12] Lindgren, Waldemar, U. S. Geol. Surv. Ann. Rept. 20, pt. 3.

represented by analysis No. 5. In some specimens this forms at the core and in others as a border around the crystalline part. It seems clear that the two types of material were not the result of different conditions during formation but are dependent upon variations in the composition of the olivine from which they were derived.

SOUTH ELK CREEK, COLO., OCCURRENCE

The rock containing the iddingsite represented by analysis 6 was collected at the cliffs surrounding a cirque at the head of South Elk Creek in the southwest part of the Conejos quadrangle, Colorado. The rock is of the same age as the La Jara Creek and Gato Creek occurrences. It is a nearly black basalt with conspicuous red areas of iddingsite reaching a maximum diameter of 2 millimeters. The mineral composition of the rocks is as follows:

Mode of basalt from South Elk Creek, Colo.

Labradorite	52
Augite	20
Iddingsite	19
Magnetite	9
Total	100

GATO CREEK, COLO., OCCURRENCE

The iddingsite represented by analysis 7 was secured from a dike occurring on Gato Creek, 2 miles above Tipton's ranch in the north central part of the Conejos quadrangle, Colorado. The rock is a fine-grained, porous gray andesite with about the following mineral composition:

Mode of andesite from Gato Creek, Colo.

Andesine	71
Augite	15
Iddingsite	10
Magnetite	4
Total	100

The iddingsite occurs in rounded grains about 0.5 millimeter in diameter and is clearly derived from olivine.

BRAZOS RIVER, N. MEX., OCCURRENCE

Analysis No. 8 is an iddingsite in an andesite occurring one-half mile east of the Brazos River in the Rio Ariba County, N. Mex., and about 15 miles south of Osier on the Durango branch of the Denver & Rio Grande Railroad. The rock appears to be an instrusive sill of Miocene age that forms a sheer 50-foot ledge at this place. A microscopic study showed that it contained a red material derived from olivine, but with no residual olivine. It is rather coarse-grained andesite, is light gray in color, and is very fresh, showing no indications of weathering. Its modal composition is as follows:

Mineral composition of andesite from Brazos River, N. Mex.

Plagioclase ($Ab_{60}An_{40}$)	82.9
Augite	8.7
Iddingsite	4.6
Magnetite	3.8
Total	100.0

This rock contains rather sodic feldspars and is unusually low in femic minerals to be olivine bearing, but the form of the red alteration product shows that it was derived from that mineral, and other specimens from the same horizon in the region show olivine in all degrees of alteration to iddingsite. The alteration mineral occurs in irregularly rounded grains, in aggregates of several grains, and as perfectly bounded, pseudomorphs after olivine, varying in size from 0.05 to 2 millimeters. Many of the grains contain minute particles distributed in lines that run parallel to one of the crystallographic axes of the original olivine. In partly altered olivine, between iddingsite and colorless olivine, may be seen a brown zone which is filled with lines of inclusions that continue into homogeneous iddingsite. These inclusions are dark brown in color and very small. They are isotropic and have an index of refraction a little lower than 1.74. Their specific gravity is greater than that of iddingsite, since it was possible to separate and reject that part of the iddingsite containing them in greatest amount. These things make it seem probable that they are iron-magnesium spinel.

PHYSICAL PROPERTIES

Iddingsite from many localities has been studied, but the material from Brazos River, N. Mex., is the most homogeneous and shows the physical properties in greatest perfection. For that reason the Brazos iddingsite will be described in detail and that from other localities more briefly.

The iddingsite of the Brazos River rock is very brittle. The hardness is about 3.5 and the specific gravity 2.80. In small grains the cleavage is somewhat imperfect, but four cleavages can be recognized. If the orientation X=a, Y=b, Z=c ($\mathfrak{a}=a$, $\mathfrak{b}=b$, $\mathfrak{c}=c$), proposed by Lawson, is retained, there is one cleavage (100) perpendicular to the acute bisectrix; a second (001) is perpendicular to the obtuse bisectrix; a third (010) is parallel to the plane of the optic axes; and the fourth (101) is nearly perpendicular to an optic axis. That is, a cleavage parallel to the macropinacoid, one parallel to the basal pinacoid, one parallel to the brachy-pinacoid, and one parallel to the macrodome. In thin sections three cleavages (100) (001) and

(010) can easily be recognized, and (101) is seen less frequently. The indices of refraction are:

$\alpha=1.792\pm0.003$ β is variable, 1.827 to 1.840 ± 0.003
$\gamma=1.864\pm0.003$ $\alpha-\gamma=0.072$

The axial angle is variable, the extreme values of 2V ranging from 60 to 90°, but most of the grains have 2V=80 to 90°. The optical character is usually negative, but in some of the grains the optical angle passes through 90° and the mineral becomes positive. The dispersion is strong: $\rho<\upsilon$ when the character is negative and $\rho>\upsilon$ when it is positive. The color is deep reddish brown to brownish-ruby red, and the pleochroism is distinct in all but basal sections. The indices of refraction of the iddingsite from the Brazos River rock are rather high but the other optical properties are similar to those of other occurrences.

The iddingsite from Race Creek, Colo., is brittle. The hardness is about 3.2, and the specific gravity about 2.54. In small grains the color is dull dark brown. Three mutually perpendicular cleavages (100), (001), and (010) are very good and a less perfect one (101) gives plates that are nearly perpendicular to an optic axis. X=a is the acute bisectrix. The indices of refraction are somewhat variable $\alpha=1.608\pm.005$ $\beta=1.646\pm.005$, $\gamma=1.655\pm.005$ $\alpha-\gamma=.047$ 2V=20°—50°, but a large proportion of the grains have 2V= 35°—42°, and only a few reach the maximum values given. The optical character is negative. The dispersion is strong $\rho<\upsilon$. In thin section the color is golden yellow to golden brown, pleochroism slight.

The iddingsite from Bernards Ferry, Silver City quadrangle, Idaho, is deep reddish brown in color. It has very perfect cleavage, but the great brittleness prevents a good development of the cleavage. Cleavages parallel to the planes of the three crystal axes are well developed, and the large number of plates approximately perpendicular to an optic axis indicate a fourth. Cleavages (100), (001), (010), and (101). Optical orientation $X=a$, $Y=b$, $Z=c$.

The indices of refraction are: $\alpha=1.710\pm.005$, $\beta=1.722\pm.005$, $\gamma=1.754\pm.005$, $\alpha-\gamma=.044$. The optical angle is variable 2V=20° to 65°. most of the grains about 50°. The optical character is negative, dispersion strong. The color is deep brownish red, pleochroism slight.

For purposes of comparison the optical properties of iddingsite from other localities are given below:

1. Type material from carmeloite, Carmelo Bay, Calif.; reddish brown; extinction parallel to cleavage; X is normal to cleavage plates. Optically negative. Dispersion $\rho<\nu$ (strong). Pleochroic. $\alpha=1.723\pm.003$. $\beta=1.745\pm.003$. $\gamma=1.765\pm.003$. $\alpha-\gamma=0.42$. 2V large.

2. Head of Mill Gulch, south central part of Uncompahgre quadrangle. Gabbro inclusion in basalt. Deep reddish brown grains. X is normal to cleavage plates. Extinction parallel to cleavage. 2V=40° estimated. Optically negative. Dispersion $\rho<\upsilon$ (strong). Pleochroic. Indices $\alpha=1.724\pm.003$. $\beta=1.745\pm.003$. $\gamma=1.768\pm.003$. $\alpha-\gamma=.044$.

3.[13] Pyroxene latite, Wicher Mountain knoll, Pikes Peak quadrangle. Reddish brown grains. Optically—. 2V large. $\rho<\nu$ (strong). X normal to the plates. Indices vary somewhat $x=1.71\pm 0.01$. $\beta=1.74\pm0.01$. $\gamma=1.76\pm0.01$. $\alpha-\gamma=.05$.

4. Uncompahgre quadrangle, Colorado. In thin section clear pale reddish brown. Optical properties vary a little. Optically+. 2V large. $\rho>\nu$ (strong). Faintly pleochroic. $\alpha=1.70\pm0.01$. $\beta=1.72\pm 0.01$. $\gamma=1.74\pm0.01$. $\alpha-\gamma=.04$.

5. La Jara Creek, Conejos quadrangle, Colorado. Bright reddish brown. Optical properties vary a little. Optically—. 2V=25° to 45°. $\rho<\upsilon$ (strong). Pleochroic. X perpendicular to plates. $\alpha= 1.674\pm0.0004$. $\beta=1.710\pm0.004$. $\gamma=1.718\pm0.004$.

Table of optical properties of iddingsite

Locality	Optical angle 2V	Indices of refraction			$\gamma-\alpha$	Optical character
		α	β	γ		
Race Creek, Colo	35°–42°	1. 608	1. 650	1. 655	0. 047	—
La Jara Creek, Colo	25°–45°	1. 674	1. 715	1. 718	0. 044	—
Bernard's Ferry, Idaho	50°	1. 710	1. 746	1. 754	0. 044	—
South Elk Creek, Colo	[a] 60°	1. 710	1. 735	1. 745	0. 35	+
Gato Creek, Conejos quadrangle, Colorado	20°–25°	1. 70	1. 73	1. 74	0. 040	—
Brazos River, N. Mex	60°–90°	1. 792	1. 827–1. 846	1. 864	0. 072	—
Mill Gulch, Colo	40°	1. 724	1. 763	1. 768	0. 044	—
Uncompahgre quadrangle Colorado	Large.	1. 70	1. 72	1. 74	0. 04	+
Wicher Mountain, Colo	Large.	1. 71	1. 74	1. 76	0. 05	—
Carmelo Bay, Calif	Large.	1. 723	1. 745	1. 765	0. 042	—
Daton Peak, Routt County, Colo	35°–42°	1. 720	1. 725	1. 760	0. 040	—
Death Valley, Calif	42°	1. 730	1. 725	1. 765	0. 035	—

[a] About.

CHEMICAL COMPOSITION

Iddingsite has not heretofore been analyzed because of its mode of occurrence, always as small grains, as a rock constituent which made the obtaining of pure material, in amount sufficient for quantitative chemical examination, exceedingly difficult. In the course of

[13] 4, 5. Larsen, Esper S., U. S. Geol. Survey Bull. 679, p. 91, 1921.

the present work there were purified and analyzed, more or less completely, six samples of clean crystalline iddingsite from as many localities together with cryptocrystalline materials associated with two of the crystalline materials analyzed.

In most cases the samples of purified material available amounted to only 0.25 gram. These samples were separated by the use of a powerful electromagnet and heavy solutions from igneous rocks in which the iddingsites formed grains seldom exceeding 2 millimeters in diameter. In general the practice was to crack the iddingsite-bearing rock into small pieces with a hammer and gouge out the visible iddingsite with a sharp steel point yielding a product of high iddingsite content for subsequent treatment. This was crushed and screened to uniform size, the dust removed, and the material separated magnetically and with methylene iodide gravity solutions.

The mineral, as established by previous investigators, is insoluble in acids, but upon digestion in hot hydrochloric acid yields up its iron and probably its other bases, leaving decolorized scales. This phenomenon has been interpreted as evidence indicating that the iron is not essential to the composition but is present as staining films of limonite or hematite. The fallacy of this reasoning is patent when it is recalled that many minerals behave thus, even so common a substance as biotite leaving decolorized scales of silica retaining the original form and optical properties of the mineral, when digested in hot concentrated sulphuric acid. Few would venture to suggest, from this observation, that the iron of biotite is nonessential or extraneous.

The analytical results on the iddingsites are given in the following tables:

1. Crystalline iddingsite from Race Creek, Colo.

2. Crystalline iddingsite from La Jara Creek, Colo.

3. Cryptocrystalline material associated with the iddingsite from La Jara Creek of the preceding analysis.

4. Crystalline iddingsite from Bernards Ferry, Owyhee County, Idaho. Specimen collected by Lindgren.

5. Cryptocrystalline material associated with the preceding iddingsite from Bernards Ferry, Idaho.

6. Crystalline iddingsite from South Elk Creek, Colo.

7. Crystalline iddingsite from Gato Creek, Conejos quadrangle, Colo.

8. Crystalline iddingsite of high index from Rio Brazos, N. Mex. Original analysis.

9. Iddingsite from Rio Brazos. Preceding analysis corrected for impurities and recalculated to 100 per cent.

	(1)	(2)	(3)	(4)	(5)
SiO_2	42. 12	38. 63	44. 38	40. 28	44. 40
TiO_2	--------	. 24	. 11	. 12	. 16
Al_2O_3	--------	1. 78	2. 65	3. 16	2. 28
Fe_2O_3	34. 16	32. 49	26. 87	29. 76	29. 00
FeO	None.	Trace.	--------	--------	--------
CaO	1. 72	2. 79	2. 54	3. 00	2. 20
BaO	--------	Trace.	Trace.	--------	--------
MgO	6. 40	6. 64	5. 13	10. 36	7. 12
H_2O+110° C.	8. 84	9. 24	10. 09	5. 28	6. 96
H_2O−110° C.	7. 20	8. 46	8. 64	8. 12	8. 40
Total	100. 44	100. 27	100. 41	100. 08	100. 52

	(6)	(7)	(8)	(9)
SiO_2	35. 60	38. 94	23. 22	21. 02
Al_2O_3	3. 60	4. 62	3. 18	2. 18
Fe_2O_3	31. 24	29. 78	53. 88	57. 27
FeO	--------	. 96	. 72	. 67
CaO	1. 64	2. 26	2. 36	1. 64
MgO	11. 92	4. 96	3. 01	2. 50
H_2O+110° C.	9. 80	9. 30	9. 36	9. 96
H_2O−110° C.	6. 72	8. 40	4. 48	4. 76
Total	100. 52	99. 22	100. 21	100. 00

Excluding from consideration, for the moment the cryptocrystalline materials, columns 3 and 5, and the Brazos River sample, columns 8 and 9, the remaining analyses are decidedly similar as shown by the following comparison and average:

	(1)	(2)	(4)	(6)	(7)	Average
SiO_2	42. 12	38. 63	40. 28	35. 60	38. 94	39. 11
TiO_2	--------	. 24	. 12	--------	--------	[a] . 18
Al_2O_3	--------	1. 78	3. 16	3. 60	4. 62	3. 29
Fe_2O_3	34. 16	32. 49	29. 76	31. 24	29. 78	31. 49
FeO	None.	Trace.	--------	--------	. 96	[a] . 96
CaO	1. 72	2. 79	3. 00	1. 64	2. 26	2. 28
MgO	6. 40	6. 64	10. 36	11. 92	4. 96	8. 05
H_2O+110° C.	8. 84	9. 24	5. 28	9. 80	9. 30	8. 49
H_2O−110° C.	7. 20	8. 46	8. 12	6. 72	8. 40	7. 78
Total	100. 44	100. 27	100. 08	100. 52	99. 22	101. 63

[a] The amounts here indicated are probably about what the averages would be were these constituents accurately determined on each sample. In most of the analyses, owing to scarcity of material TiO_2 is included with SiO_2 and the FeO—, always very small in amount, is included with Fe_2O_3. This explains the high summation of the average column.

The average column gives the following ratios:

SiO_2	39.11	0.649	0.651	0.217 × 3	0.96 × 3
TiO_2	.18	.002			
Al_2O_3	3.29	.032	.229	.229 × 1	1.01 × 1
Fe_2O_3	31.49	.197			
FeO	.96	.013	.254	.254 × 1	1.11 × 1
CaO	2.28	.041			
MgO	8.05	.200			
H_2O+	8.49	.471	.899	.225 × 4	.99 × 4
H_2O-	7.78	.428			
Total	101.63				

The formula derived from the ratios is:

$$MgO \cdot Fe_2O_3 \cdot 3SiO_2 \cdot 4H_2O.$$

with the magnesia replaced in part by CaO which is in the ratio, approximately, of CaO : MgO = 1 : 4. The calculated composition for this formula is as follows:

SiO_2	39.66
Fe_2O_3	35.01
CaO	2.46
MgO	7.07
H_2O+	7.90
H_2O-	7.90
Total	100.00

In view of the agreement of the above analyses with each other and with the theoretical composition, this formula may be confidently quoted as that of the normal iddingsite. This is especially true since a comparison of optical properties indicates that the above are typical of 95 per cent of all iddingsites studied by the writers or reported by others. Nearly all of the red-brown material secondary to olivine is shown by its refractive indices and other properties to be of this type and presumably of this composition.

The cryptocrystalline materials represented by analyses 3 and 5 give the same formula as the crystalline iddingsites. They are distinguished by pale yellow color, low refractive indices, and very small extinction angle. Often there is a sharp contact between the iddingsite and the cryptocrystalline material while the latter grades almost imperceptibly into the residual olivine. This cryptocrystalline material may represent a transition stage in the alteration of olivine to iddingsite. While of the same composition, it is sufficiently distinct optically to suggest that it is a distinct mineral—possibly a variety of chloropal. It is certainly not the material commonly called iddingsite.

One disturbing factor is introduced into otherwise consistent data by the Brazos River material represented by the anlaysis given in columns 8 and 9 of the above tabulation. This analysis, which differs strikingly from all the others, gives the formula (Mg.Ca) $O.5Fe_2O_3.4SiO_2.10H_2O$. This sample was the first one studied and about 1 gram of material which was separated for analysis was estimated to contain 2 per cent of augite and 4 per cent of plagioclase of the composition $Ab_{60}An_{40}$. The figures given in column 9 have been recalculated after correcting for these impurities. The loss of water below 110° C. was determined on two portions yielding 4.40 and 4.48 per cent, respectively, with one hours heating while several hours continued exposure to this temperature occasioned no further loss. The dehydrated powder showed no change in any of its optical properties. A gain of 2.28 per cent of the original weight was acquired by a dried sample upon standing overnight in a dessicator over sulphuric acid.

While this material is chemically very unlike the others the optical properties, other than refractive index, are those typical of iddingsite. The refractive indices are very high as would be expected from the high content of ferric iron, and no other occurrences of such high refractive index have been recorded. Optically it seems to be a true iddingsite but until similar materials from other localities have been analyzed no conclusions can be drawn with regard to its relationship to the ordinary iddingsites of the above group.

SUMMARY

Iddingsite is a red-brown mineral that is widespread, and often an abundant mineral in basaltic rocks.

It occurs as cores in fresh olivine, as rims around olivine, or where cleavage cracks in olivine have formed a locus for its development. Therefore it is clearly a secondary mineral derived from olivine.

Iddingsite is not confined to weathered surfaces; its development shows no proximity to joint cracks and evidences of weathering in associated minerals are entirely absent. Normal products of weathering such as limonitic pigment are absent, but spinels (minerals not produced by weathering) are abundant and almost invariable associates. Thus it is concluded that iddingsite is not a product of ordinary weathering but is a deuteric mineral; that is, it is the result of metasomatic processes associated with the later stages of a cooling magma.

Iddingsite does not commonly occur in abyssal rocks, but is confined to extrusive and hypabyssal rocks. The relations indicate that it is formed near or just after the close of crystallization, and after the magma came to rest. The factors necessary for the formation are an olivine of suitable composition, a concentration of mineralizers (principally water), oxidizing conditions and heat.

The changes involved are principally abstraction of magnesium oxide (MgO), oxidization of ferrous oxide (FeO) to ferric oxide (Fe_2O_3) and addition of water (H_2O).

Iddingsite has a composition and optical properties distinct from any described mineral, and it is not related to serpentine in mode of origin, in chemical composition, or in physical properties. Thus it appears to be a distinct mineral species.

The normal type of iddingsite is represented by the formula: $MgO . Fe_2O_3 . 3SiO_2 . 4H_2O$ where MgO is replaced by CaO in the ratio 4:1, and varying proportions of Fe_2O_3 are replaced by Al_2O_3.

EXPLANATION OF PLATES

PLATE 1

FIG. 1. Iddingsite from andesite collected at the headwaters of Race Creek near the south border of Creede quadrangle, Colorado. Open cracks show the loss of volume on alteration of olivine to iddingsite. Alteration is complete.

2. Iddingsite in andesite from 1 mile west of Osier, N. Mex., near Colorado-New Mexico State line. Shows characteristic outline of olivine crystals. Alteration nearly complete.

3. Iddingsite in basalt from Santa Clara Creek, 13 miles west of Espanola, N. Mex. Iddingsite forming sharp outer borders around unaltered olivine.

4. Andesite from southeast flank of Green Mountain, northern part of Conejos quadrangle, Colorado. Euhedral phenocrysts of olivine with very narrow outer border of iddingsite.

5 and 6. Basalt from cliff on north side of Los Magotes, southeast part Conejos quadrangle, Colorado. Iddingsite core with narrow sharp outer border of olivine.

PLATE 2

FIG. 7. Basalt with iddingsite collected 4 miles south of the crest of San Antonio Peak and 8 miles north of Tres Piedras, N. Mex. Large phenocrysts of olivine with core of iddingsite and outer rim of olivine.

8. Basalt from cliffs on north side of Los Magotes, Conejos quadrangle, Colorado. Many small grains of iddingsite with sharp outer rim of olivine. Large crystal on upper border shows core of olivine.

9. Basalt from mouth of Rito de los Frijoles Canyon, 10 miles southwest of San Ildefonso, N. Mex. Phenocryst of olivine showing alteration to iddingsite along border and cracks.

10. Basalt dike in Cerro Negro volcanic cone about 10 miles east of Tres Piedras, N. Mex. Phenocryst of olivine with very narrow sharp films of iddingsite developing along cracks.

11. Iddingsite in Brazos River andesite from one-half mile east of Brazos River, N. Mex., about 15 miles south of Osier, Colo. Iddingsite crystal showing characteristic outline of olivine. Near the center of crystal are shown 2 cleavages parallel to crystal axes and the cleavage parallel to the macrodome (101).

12. Basalt from west slope of Mesa La Sauses, 10 miles east of La Jara, Colo. Phenocryst of olivine entirely altered to iddingsite.

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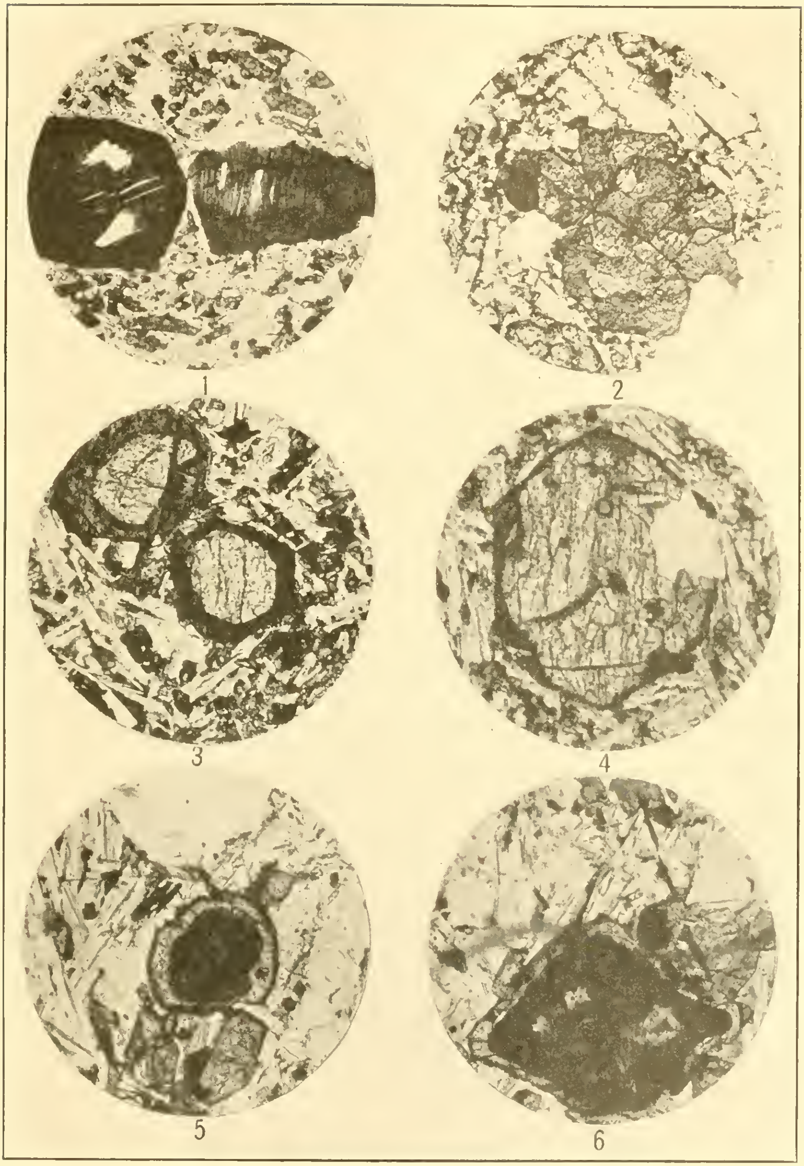
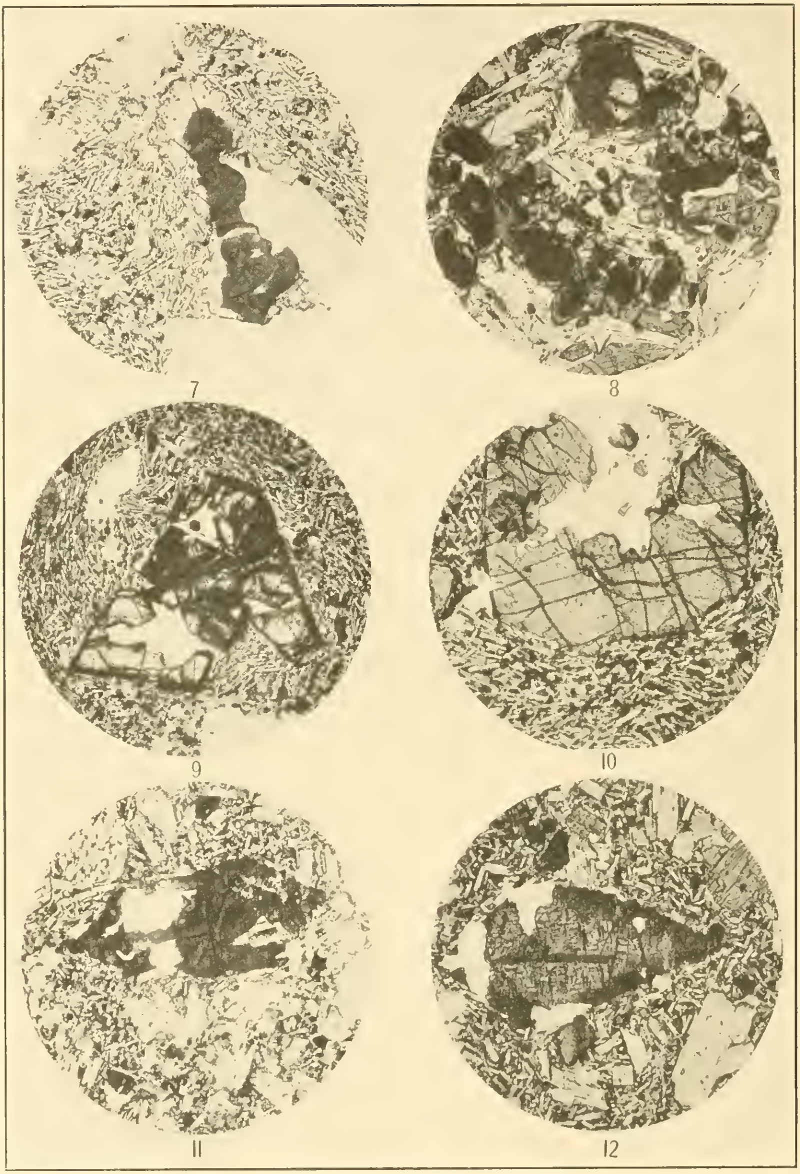


PHOTOMICROGRAPHS OF IDDINGSITE-BEARING ROCKS

FOR EXPLANATION OF PLATE SEE PAGE 19



PHOTOMICROGRAPHS OF IDDINGSITE-BEARING ROCKS

FOR EXPLANATION OF PLATE SEE PAGE 19