THE MINERALOGY OF METAMORPHOSED SERPENTINE AT HUMPHREYS, FRESNO COUNTY, CALIFORNIA

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ABSTRACT

Nodules of metamorphosed serpentine which were described by MacDonald[1] have been reexamined. New observations have shown that several minerals not recognized by MacDonald exist in these nodules. Their presence largely explains some of the inconsistencies of his description.

Careful examination of the succession of metamorphic zones about several nodules shows that the changes varied greatly from nodule to nodule, and even in different parts of the same nodule. It is impossible to summarize these changes in a single scheme or graph.

INTRODUCTION

Last year there appeared in this journal a discussion of "progressive metasomatism of serpentine"[1] by G. A. MacDonald in which the mineralogy of the materials considered aroused the interest of the writer. MacDonald described certain zoned nodules of serpentine in a rock which he called biotite schist. The nodules occur in a roadcut on California State Highway 168, just west of Humphreys, Fresno County, California. MacDonald has described the locality and the geologic setting at length.[2]

For a better understanding it is necessary to repeat some of the main features of MacDonald's description of the nodules. He states that they vary "in diameter from about 10 cm. to over a meter." They are spherical to flattened ellipsoidal and consist of a "core of massive grayish-green serpentine" entirely enclosed in several zones of varying composition. The thickness of these zones does not increase with the size of the nodule. The boundaries between the zones are, in part, rather sharp. *The serpentine core*[3] is essentially antigorite. It is surrounded successively by *the talc zone*, composed largely of talc with some serpentine, chlorite and "ore minerals"; *the talc-actinolite zone*, the "inner part" consists of felty talc in which lie needles of actinolite with 18° extinction angle, making up 5 per cent of the rock; "middle," similar to the inner part, but with 40 per cent actinolite; and an "outer part" consisting largely of actinolite in long blades with $\gamma = 1.646$ ($\pm .003$). The extinction angle is not men-

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[1] MacDonald, G. A., Progressive metasomatism of serpentine in the Sierra Nevada of California: *Am. Mineral.*, **26**, 276–287 (1941).

[2] *Op. cit.*, and Geology of the western Sierra Nevada between the Kings and San Joaquin Rivers, California: *Univ. Calif. Publ., Bull. Dept. Geol. Sci.*, **26**, 215–286 (1941).

[3] The italics in this paragraph correspond to those of MacDonald.

tioned. Rosiwal analysis of a section shows "actinolite = 89.1 per cent, talc = 7.9, chlorite = 2.6, ore = 0.4." *The biotite zone* is "composed largely of biotite, generally with about 10 per cent of actinolite and a little chlorite."

All this may seem plausible, but MacDonald also published and discussed three analyses which furnish evidence of the misidentification of some of the more important constituents. Moreover, he drew a graph to represent the "compositions of successive zones" based on these three chemical analyses and on "two micrometric analyses." As will be shown this diagram is misleading because it omits from representation certain parts of the zones which were not properly covered by the analyses.

THE ANALYSES

MacDonald's first analysis is of the serpentine and requires no comment. The other two contain evidence of misidentification of principal constituents.

TABLE 1

SiO_2	54.14	Na_2O	0.19
TiO_2	0.19	K_2O	0.08
Al_2O_3	2.52	H_2O-	0.07
Fe_2O_3	3.42	H_2O+	3.34
FeO	7.17	CO_2	none
MnO	0.22	P_2O_5	none
MgO	25.35	S	0.03
CaO	2.82	Cr_2O_3	0.28
			99.82

The second analysis (see Table 1) is of the "outer part of the radial talc-actinolite zone," for which the Rosiwal analysis is quoted above. The material is described as largely "actinolite" and MacDonald calculated the composition of this mineral, giving it only 3.2 per cent CaO. No actinolite analysis has thus far been published which showed so little lime. In 29 analyses tabulated by Doelter, the minimum CaO content is 10.50 per cent, and most of the values lie between 11 and 14 per cent. This is in excellent accord with the theoretical composition of $(OH)_2Ca_2(Mg,Fe)_5(Si_8O_{22})$ which would permit variation between 11.44 per cent CaO for the magnesian end-member, and 16.68 per cent for the ferrous end-member, the name actinolite being applied to only a portion of this range. The limits of its application need not concern us here. In any case the material analyzed lies well outside the limits and is *not* actinolite.

There are several amphiboles that are very low in calcium. The monoclinic cummingtonite series tends to be richer in ferrous iron, whereas the orthorhombic anthophyllite series is richer in magnesium. The analysis suggests anthophyllite and this is in harmony with the optical data quoted above. Reexamination of many specimens confirms this interpretation.

TABLE 2

SiO_2	37.46	Na_2O	0.53
TiO_2	0.87	K_2O	0.19
Al_2O_3	14.64	H_2O-	6.89
Fe_2O_3	7.57	H_2O+	8.89
FeO	1.22	CO_2	none
MnO	0.09	P_2O_5	0.06
MgO	19.66	S	0.04
CaO	1.66	Cr_2O_3	0.07
			99.93

MacDonald's third analysis is of the "biotite rim" (see Table 2). The sample is said to contain "about 95 per cent biotite," whose optical properties were given as "small negative optic angle, $\beta=1.565$ ($\pm .003$), and X = nearly colorless to very pale yellow, Y and Z = yellowish-brown." The analysis must have seemed unusual, for he says "it shows the mineral to be a phlogopitic variety, low in iron and alkalies, especially K_2O, and fairly high in magnesia." The analysis shows only 0.19 per cent K_2O, less than one-fiftieth the amount required by the formula and far below the range, 6 to 10 per cent, common for biotite, including even the most "phlogopitic." On the other hand, MacDonald paid little attention to the high water content (total 15.78 per cent), nearly four times that required by the phlogopite formula. In this case the interpretation again is not far to seek. The biotite-like material, which must have made up most of the analyzed samples, was in all probability vermiculite. Such optical properties of this mineral as are given by MacDonald might apply equally well to vermiculite or to phlogopite. An explanation of the slightly low water content for vermiculite, and the rather high lime, will be suggested in the conclusion. Many vermiculite analyses, however, show a small CaO content and it will be fruitless to try to determine, in this particular case, just how much of it is due to contamination. The analysis as a whole suggests vermiculite and reexamination has shown that this is the chief constituent of the micaceous crust of some of the nodules.

THE REEXAMINATION

The writer was not acquainted with the locality, or the material, at the time MacDonald did his work. The reexamination was begun on a suite of specimens collected in February 1940 by Dr. Richard Merriam and Mr. A. L. Repecka, and kindly made available to the writer by the latter. One of these specimens is almost identical in size and appearance with that shown in MacDonald's Fig. 2 *A*, which seems to have formed the basis for much of his discussion. In April 1942 the writer visited the locality. Though the exposure had suffered slightly from rain wash, the nodules were easily located and the relations could be seen very clearly. Many specimens were collected, including one very much like MacDonald's Fig. 2 *B*.

The material collected by the writer was mostly taken from the cut on the south side of state highway 168, about 140 paces west of the intersection at Humphreys. Here the nodules are embedded in a fine grained friable rock called "mica schist" by MacDonald. They can be seen at intervals in the cut for a distance of at least sixty feet. Several score of feet to the east, serpentine makes the entire walls of the cut and extends to the above mentioned intersection, whereas granitic rocks are found a few hundred feet to the west and extend westward for some distance as indicated on the map, MacDonald's Fig. 1. Small irregular patches of quartz, aplite, serpentine and granitic rock are interspersed with the "mica schist," their contacts being obscure.

MacDonald states that "the mica schist in which the zoned nodules are enclosed is composed largely of brown biotite, with a smaller amount of quartz and a little orthoclase and oligoclase." The writer collected several specimens of this rock adjoining and within a few feet of the metamorphosed serpentine nodules. A bromoform separation of the heavy minerals for the purpose of securing a sample of the biotite in this rock for comparison with the micaceous minerals of the nodules, yielded a concentrate consisting mostly of dirty green hornblende. This seemed unusual and so extra large thin sections were made from two specimens of this rock. The maximum grain dimensions do not exceed 1 mm. and the average dimensions are of the order of one or two tenths of a millimeter. The texture is granular with only a slight orientation of some of the minerals; an ideal case for micrometric analysis. The results for the two slides were:

	Plagioclase	*Hornblende*	*Biotite*	*Quartz*	*Magnetite*
I	55%	27	16	1	1
II	54	24	20	1	1

The plagioclase is mostly oligoclase. Apatite is conspicuous but was not included in the micrometric analysis. The composition is that of an igneous rock. It hardly seems proper to call it a mica schist and its mineral composition is quite different from that given by MacDonald.

It is evident from MacDonald's paper that he worked mostly with thin sections showing only fragments of the zone succession. In fact, several paragraphs of his paper begin with references to thin sections cut from a certain zone or part of a zone. It has long been the writer's conviction that effective petrographic study requires, among other things, the use of large sections and low magnifications in order that microscopic petrography may be more than mere mineral determination. Only in this way can the relations of several minerals, the texture and structure of the assemblage and, as in the present case, the transition from one zone to another, be properly observed.

Accordingly a pair of thin sections measuring about 20 by 40 mm. each were prepared from each of six specimens. The core and the enclosing rock are not cut by these sections, but every one shows the entire succession of zones from the micaceous crust to the talc zone. The innermost shell breaks away from the core easily in many specimens and no sections show this sharp boundary between the massive gray-green antigorite and its mantle of felted white talc. The nature of the contact between the micaceous crust and the "schist" matrix cannot even be observed well in the field, or in the hand specimen, since the matrix is very friable and the micaceous crust tends to fall away from materials on either side of it. Nevertheless, all sections show at least a little of this crust.

In order to observe the complete thin sections, whose area is many times that visible under even the lowest magnification of any petrographic microscope, they were also studied between polaroid sheets and one of each pair (i.e., six sections) were photographed full size between crossed polaroids at 4 diameters. The observations thus gained, together with immersion study of all constituents in each of these and several other specimens and auxiliary experiments mentioned below, yielded a rather detailed picture of the mineralogy and succession of zones.

MacDonald recognized that the zones are not uniformly developed about all of the specimens, or even about an entire nodule. Nevertheless he emphasized and discussed at length the particular zone succession whose description is briefly given in the first part of this paper. My observations do not warrant such a procedure, but two features seem constant in all the specimens:—

A. The innermost zone is always dominantly felted talc with only minor amounts of other minerals which may include chlorite, magnetite, and monoclinic amphibole.
B. The outermost zone is always micaceous, but the character of the micaceous minerals varies.

The mineralogy and succession of the intermediate zones are highly diverse. Some samples of this diversity are recorded in Table 3 which gives the complete zone successions found in several sections.

TABLE 3. SUCCESSION OF ZONES OBSERVED IN SEVERAL SECTIONS NORMAL TO CRUST OF METAMORPHOSED SERPENTINE NODULES

I	II	III*a*	III*b*
7 mm. Chlorite	2 mm. Chlorite	1 mm. Vermiculite	4½ mm. Coarse chlorite
33 mm. Talc with some chlorite	4 mm. Tremolite partly changed to talc	3 mm. Coarse tremolite	33 mm. Felted and radial talc containing chlorite and magnetite with pressure shadows
	6 mm. Felted and radial talc	20 mm. Radial anthophyllite with some talc	
	15 mm. Radial tufty anthophyllite		
	10 mm. Talc with nests of magnetite and chlorite	8 mm. Talc with some tremolite	

The recorded thickness of the micaceous crust is in all cases less than its total thickness. MacDonald mentions 7 mm. as a maximum thickness for this zone. This may be correct for those places where it consists largely of vermiculite, but chlorite crusts locally reach a thickness of 30 mm. or more. The recorded thickness of the innermost zone is, of course, likewise less than its total, but the figures given for the intermediate zones indicate their true thickness, as all sections were cut carefully at right angles to the zone boundaries.

The zone successions recorded in Table 3 as III*a* and III*b* were observed on different parts of the same large nodule. The only correspondence in the mineralogy of the zones is in the predominance of talc in the inner part. If suitable allowances are made for the misdetermination of minerals mentioned above, III*a* corresponds roughly to the succession discussed in detail by MacDonald. Figures 1 and 2 show the greater part of each of these successions. The difference between the two amphiboles in III*a* is readily apparent.

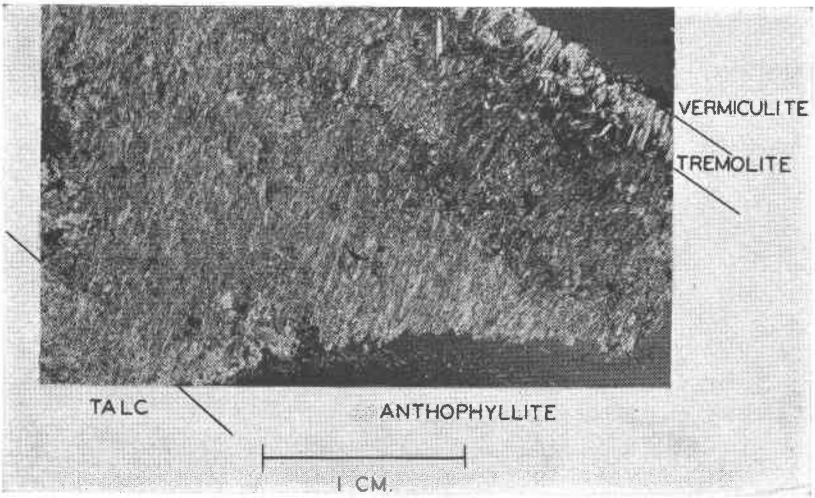

FIG. 1. Thin section normal to surface of nodule between crossed polaroids.

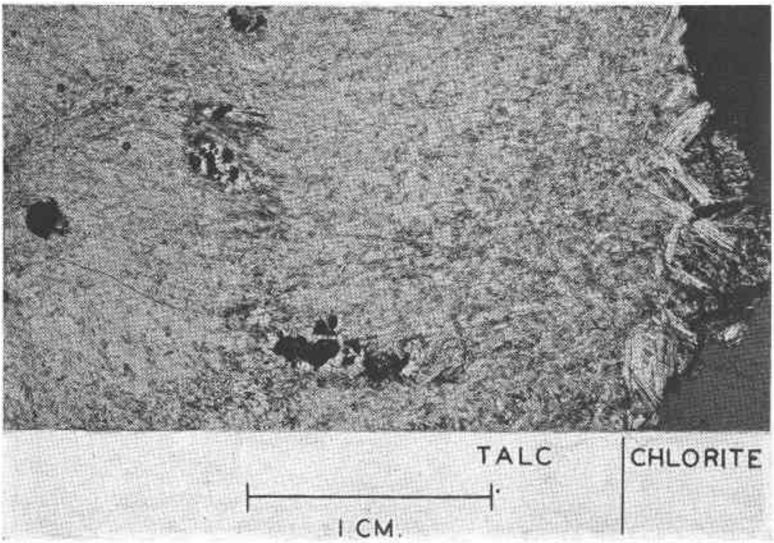

FIG. 2. Thin section normal to surface from another part of the same nodule shown in Fig. 1. Between crossed polaroids.

Since there is such variability in the zones it may be more satisfactory to discuss the mineralogy of the nodules, mineral by mineral rather than zone by zone.

Vermiculite. This mineral was found to constitute most of the micaceous crust of several specimens. In these specimens the crust is only a few millimeters thick. The properties of the vermiculite vary slightly and it is most easily identified by its very low specific gravity, near 2.3, which clearly distinguishes it from all other constituents. In every case where the micaceous crust is composed of vermiculite, it directly overlies a zone of tremolite and some prisms of tremolite are embedded in the vermiculite. It was also seen in streaks or nests in a specimen closely resembling MacDonald's Fig. 2 *B*. These streaks are doubtless identical with what he called "dark veinlets of biotite."

A detailed examination of the vermiculite was carried out on the specimen, collected by Merriam and Repecka, which closely resembles MacDonald's Fig. 2 *A*. The properties of this vermiculite are:—

G. (Berman balance) = 2.29
G. (suspension) = 2.27
Optically negative, moderate birefringence,
$\beta = 1.552 \pm 0.003$
$2V$ = ca. 20°, (Mallard's method)
Pleochroism:
Z and *Y*, yellowish brown;
X, nearly colorless
Ignition loss = 19.1%
Loss at about 650° C. = 15.1%

This leaves no doubt as to the identity of the mineral. The specific gravity is higher than the value for ideal vermiculite given by Gruner,[4] but is close to that reported by him for a vermiculite from near Pilot, Md., having nearly the same water content.

The refractive index is a little lower than that reported by MacDonald for what he called "biotite," but in other specimens it was found to vary to over 1.57, above MacDonald's value but still within the recognized range for vermiculite.[5]

The ignition loss indicates that the water content of this vermiculite is about normal. The water content of seven vermiculites studied by Gruner ranges from 17.80 to 21.4 per cent, averaging 19.7 per cent. The fact that about 4 per cent water is retained to a relatively high temperature is in harmony with Gruner's interpretation that vermiculite changes to a material of talc-like structure upon partial dehydration. This partly dehydrated material appears to have a very low density, but this is only because of its exfoliated condition. Under the microscope the material appears cloudy and its properties cannot be accurately determined, but the mean index remains in the neighborhood of 1.57.

The behavior of the vermiculite upon dehydration was studied with the aid of differential thermal curves.[6] Figures 3 shows such curves for

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[4] Gruner, J. W., The structure of vermiculites and their collapse by dehydration: *Am. Mineral.*, **19**, 557–575 (1934).

[5] Shannon, E. V., Vermiculite from the Bare Hills near Baltimore, Maryland: *Am. Jour. Sci.*, **15**, 20–24 (1928).

[6] Grim, R. E., and Howland, R. A., Differential thermal analysis of clay minerals: *Am. Mineral.*, **27**, 223 (1942).

the Humphreys vermiculite and several related materials. All curves were made at a heating rate of about 9¼° per minute and run from room temperature to about 1040° C.

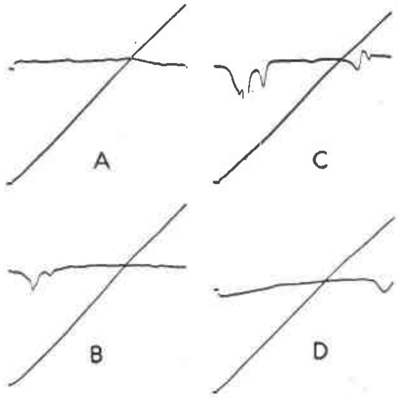

FIG. 3. Differential thermal curves. (Prepared by Dr. J. B. Page.) A. Biotite; B. Hydrobiotite; C. Vermiculite; D. Talc.

The curve for biotite (A) was made on material separated from the Half Dome quartz monzonite, Yosemite National Park. It was obtained at or near the locality where Turner[7] collected biotite for analysis. There is little doubt that this is essentially the same material. Its specific gravity was found by Berman balance to be 3.03 (Turner gave 3.05). It is nearly uniaxial and its mean refractive index is about 1.65. The water loss given in the analysis by Hillbrand is 1.03 per cent at 105° and 3.64 per cent above 105°. The curve gives no indications that there are any marked heat effects due to sudden loss. All the other curves show one or more breaks indicating water loss at a particular temperature or at a high rate over a small temperature interval.

The talc curve (D) was made on material taken from the stock of the Division of Soil Science. This talc, labelled "Providence, Rhode Island," is in large, silvery white, flakes, obviously very pure material. It is optically negative, nearly uniaxial, has a mean index of 1.582±0.003, and its specific gravity is about 2.78. Its total water content (determined by Dr. J. B. Page) is 5.38 per cent. The weight loss up to 725°, determined as the differential thermal curve was being run, was only 0.85 per cent. This shows that over 4 per cent water, essential to the structure of talc, is retained to a rather high temperature. It may be that this and the other curves give slightly high values for the temperatures at which

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[7] Turner, H. W., Some rock-forming biotites and amphiboles: *Am. Jour. Sci.*, (4) **7**, 294–298 (1899).

Table 4. Powder Pattern of Vermiculite Encrusting Zoned Nodules of Serpentine Near Humphreys, Fresno County, California

Observations (Pabst)		Ideal vermiculite (Gruner)			Average of observations on 6 vermiculites (Gruner) Intensity
Intensity	Spacing	Indices	Spacing	Intensity	
10	13.72	002	14.12	451	10
		004	7.06	21	0.3
		006	4.71	13	0.5
4	4.583	020	4.60	55	1
3	3.545	008	3.530	137	3.5
2+	2.86	0010	2.824	106	4
		130	2.650	25	
		$20\bar{2}$	2.650	13	
		$13\bar{2}$	2.635	39	1
4 b	2.65	200	2.634	18	
		132	2.576	102	
		$20\bar{4}$	2.575	53	
6 b	2.55	$13\bar{4}$	2.534	302	1.5
		202	2.533	151	
		134	2.432	28	
		$20\bar{6}$	2.431	13	
8	2.393	$13\bar{6}$	2.374	454	3.5
		204	2.373	219	
		0012	2.353	13	
1	2.264	136	2.250	27	
		$20\bar{8}$	2.249	14	
2	2.187	$13\bar{8}$	2.186	214	1
		206	2.186	103	
2	2.078	138	2.058	92	1
		$20\overline{10}$	2.058	48	
2	2.030	0014	2.017	104	1
		$13\overline{10}$	1.996	57	1
		208	1.995	29	
		1310	1.875	19	
		$20\overline{12}$	1.875	11	
1	1.836	$13\overline{12}$	1.817	103	1
		2010	1.817	54	
		0016	1.765	6	
2−	1.732	1312	1.707	0	
		$20\overline{14}$	1.707	0	
2	1.679	$13\overline{14}$	1.656	302	2.5
		2012	1.656	151	
		0018	1.569	34	0.5
1	1.575	1314	1.559	69	
		$20\overline{16}$	1.558	34	

TABLE 4—*Continued*

Observations (Pabst)		Ideal vermiculite (Gruner)			Average of observations on 6 vermiculites (Gruner)
Intensity	Spacing	Indices	Spacing	Intensity	Intensity
9	1.533	060	1.533	205	4
		$33\bar{2}$	1.533	412	
		330	1.524	250	
		$33\bar{4}$	1.524	164	
		$13\bar{1}\bar{6}$	1.513	214	
		2014	1.513	108	
		332	1.498	35	0.5
		$33\bar{6}$	1.498	36	
2−	1.448	1316	1.428	405	1.5
		$20\bar{1}\bar{8}$	1.428	203	
		0020	1.412	62	1
		$13\bar{1}\bar{8}$	1.389	0	
		2016	1.389	0	
1	1.358	338	1.347	67	0.5
		$33\bar{1}\bar{2}$	1.347	61	
2	1.329	1318	1.314	405	2.5
4	1.321	$20\bar{2}\bar{0}$	1.314	204	
2	1.292	0022	1.284	58	1
2+	1.268				
1+	1.167				
1	1.127				
1	1.082				
2	1.048				
$d_{001}=28.46$			$d_{001}=28.24$		

significant loss occurs due to the lag attendant upon the necessarily rapid heating rate.

The vermiculite curve (C) shows two prominent breaks at rather low temperature which correspond to the loss of a large part of the water. After this loss the structure is more or less like that of talc, according to Gruner,[8] and a further break corresponding to the high temperature water loss of that mineral is to be expected. It seems, however, that in the present case at least this further water loss occurs at a slightly lower temperature than for true talc.

The curve for hydrobiotite (B) was run on the well-known material from Libby, Montana, which is commonly called "vermiculite" and whose remarkable exfoliation has led to its commercial use. It has a

[8] *Op. cit.*

water content of 11 per cent and a specific gravity of 2.64, intermediate between vermiculite and biotite. Such material is called hydrobiotite by Gruner.[9] Presumably its structure, as well as its composition, is intermediate between that of true vermiculite and biotite. This is in harmony with its thermal behavior. The low temperature breaks in the curve are less conspicuous than in vermiculite because there is less water to lose and the high temperature break is scarcely discernible because the structure is about one half like biotite which shows no breaks.

Powder diffraction patterns of the vermiculite and of the partly dehydrated material were made with molybdenum radiation and an 8 inch cassette. Observations on these two patterns are shown in Tables 4 and 5 in comparison with the results of Gruner. This leaves no doubt that the differential thermal curves, discussed above, really record the changes

TABLE 5. POWDER PATTERN OF VERMICULITE FROM HUMPHREYS, CALIFORNIA AFTER REMOVAL OF ABOUT 15% WATER

Vermiculite		Talc (after Gruner)		
Intensity	Spacing	Indices	Spacing	Intensity
6*	9.23	002	9.260	4†
7	4.57	6 planes	4.53 4.41	3 b
		6 planes	3.83	1 v.b.
6	3.044	006	3.086	5
9 b	2.63	20$\bar{2}$, 130 13$\bar{2}$, 200	2.613 2.578	1 b
9	2.473	20$\bar{4}$, 132	2.447	5
3	2.200	20$\bar{6}$, 134	2.178	2
4	2.099	13$\bar{6}$, 204	2.089	1
4	1.904	20$\bar{8}$, 136	1.897	0.5
2	1.732			
3	1.646	138 20$\overline{10}$	1.663 1.647	3 b 2 b
8	1.539	060, 33$\bar{2}$	1.517	4
2	1.513	330, 062, 33$\bar{4}$	1.499	1
			1.453	1
			1.440	0.5
5	1.374	13$\overline{12}$, 2010	1.384	4 b
2	1.324			
3	1.304	260	1.307	1
1	1.281	26$\bar{4}$, 400	1.289	2 b

* Mo radiation.
† Fe radiation.

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[9] *Op. cit.*

Gruner postulated for vermiculite. Some of the spacings observed for vermiculite are slightly larger than those given for the ideal material, but this is due at least in part to the fact that real vermiculite always has a slightly larger *c* dimension than the ideal.

The intensity differences between the partly dehydrated vermiculite and talc shown in Table 5 are due in some measure to the fact that different radiation was used in the two cases, introducing a difference in the effect of the glancing angle. In any case exact correspondence cannot be expected. There is much variation in detail among the seven patterns of this sort tabulated by Gruner, but four of them show a line at or near the position for a spacing of 1.732Å which does not correspond to any line tabulated for talc.

Chlorite. For the most part the micaceous crust of the nodules is composed of chlorite. Generally this mineral, like the vermiculite, forms a crust of flakes parallel to the nodule surface, but in a few spots the chlorite plates show a haphazard arrangement as in Fig. 2. Chlorite is also a minor constituent of the inner zones. In these it occurs mostly in the talc-rich parts and forms aureoles or pressure-shadows about or among magnetite grains.

The properties of the encrusting chlorite were examined in detail on some material obtained from a thick portion of the crust consisting entirely of chlorite. A powder pattern of this can be fully interpreted after McMurchy[10] and shows no unusual features.

G (Berman balance) = 2.63
Optically negative, very low birefringence
$\beta = 1.580 \pm 0.003$
$2V =$ ca. 5°
Weakly pleochroic, pale dirty green to colorless
Ignition loss = 9.8%

These are the properties of clinochlore. Checks on the optical properties of the encrusting chlorite in half a dozen other specimens show that much of it has a slightly lower index, is nearly uniaxial, some negative, so that the composition is variable and lies in the range of penninite to clinochlore.

Tremolite. A layer of brittle, glassy, prisms of greenish amphibole underlies the micaceous crust in many specimens. The thickness of this layer ranges to about 6 mm. In some specimens it is very sharply defined with an excellent orientation of the crystals, as seen in Fig. 1, in others the amphibole crystals extend into the lower part of the micaceous crust and where the crust is coarse the distinctness of the layer is lost.

Some of the properties of this amphibole are:—

Brittle, perfect cleavage
$\beta = 1.626 \pm 0.003$, moderate birefringence
Optically negative
$2V =$ ca. 80° (Universal stage)
$Z \wedge c = 18°$ (Universal stage)
Pleochroism very weak
Z pale green
X and *Y* nearly colorless

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[10] McMurchy, R. C., The crystal structure of the chlorite minerals: *Zeits. Krist.*, **88,** 420–432 (1934).

These properties were determined on material taken from the specimen that yielded the vermiculite which was studied in detail. They indicate a tremolite with some slight iron content, tending towards actinolite. Tremolite in other specimens showed practically the same properties.

Occasional ragged grains of this mineral are scattered through the lower zones.

Anthophyllite. This mineral makes up the major part of the radial zone. It occurs in soft colorless fibers, which attain a length of half a centimeter or more. In general, no single fiber extends through the entire thickness of the radial zone, which consists of many tufts and slightly divergent sheaves of anthophyllite. Some of the properties of the mineral are:—

$\beta = 1.635 \pm 0.003$, moderate birefringence
$Z \wedge c = 0°$ (Universal stage)
Colorless

This is evidently an orthorhombic amphibole with moderate iron or aluminum content and may be properly called anthophyllite. Megascopically it has the typical appearance of this mineral.

Talc. This mineral is the most abundant constituent of the altered zones surrounding the serpentine nodules. Felted masses of minute talc plates or flakes make up the innermost zone which immediately overlies the serpentine. A similar zone occurs just under the micaceous crust or the tremolite zone in some cases. Talc is also interspersed with the anthophyllite of the radial zone in varying amount. A part of this talc is fibrous and in some spots this zone is largely composed of such talc. The total thickness of talc, partly fibrous and partly felted, reaches a maximum of over 6 centimeters in the specimen from which section I in table 3 was taken.

A small amount of talc occurs as a replacement of tremolite. This can be seen very clearly in several specimens in which it pseudomorphs idiomorphic tremolite projecting into the chlorite crust.

The talc is nearly colorless except where limonite stained or interspersed with grayish chlorite. Its optical properties are those normal for this mineral. It is readily distinguished from the amphiboles by its lower refraction and from the chlorite and vermiculite by its higher birefringence so that its distribution and texture can be seen with ease.

Minor constituents. Magnetite occurs in scattered grains in most specimens. It may appear in any zone and its distribution is most irregular. A very small amount of biotite was observed in the micaceous crust in one thin section and a bit of hornblende was seen just under the crust in another, but these constituents are not even discernible megascopically and are certainly not characteristic of the nodules. A little limonite stain tends to emphasize the zoning in some cases.

CONCLUSION

It is now possible to reinterpret the analyses. The analysis given in Table 2 certainly represents a part of the crust that is mostly vermiculite. Three bromoform separations of the encrusting vermiculite were made in the course of this work. The contamination with tremolite was found by weighing of clean concentrates to be 13, 29 and 39 per cent. It seems likely that most of the lime of this analysis is due to such contamination.

The analysis given in Table 1, of the "outer part of radial talc-actinolite zone," is clearly an analysis of a material rich in anthophyllite. From this MacDonald calculated what he called the "composition of actinolite," presumably using his estimate of the mineral composition of this zone. In view of the presence of two distinct amphiboles, and because of local variations in the mineralogy of the zones, this calculation has limited value. It may well be that the anthophyllite contains a lower proportion of calcium than shown in this analysis and that the calcium content is again due to the presence of a small amount of tremolite.

There is too much variation in the zone succession to allow any general statement of the sequence of changes. Nevertheless, a few points appear very clearly. Some transfer of material occurred in the formation of these zones. The amount and nature of this transfer was at least partly determined by very sharply localized conditions.

Little, if any, transfer of alkalies occurred. The small content of potash and soda shown in Table 2 may be contained in the vermiculite which is *not* the principal encrusting mineral, or may be partly in the tremolite of the crust. It seems certain that the more common, chloritic parts of the crust are even lower in alkalies.

Calcium reaches a maximum concentration in the tremolite zone *just* under the micaceous crust and, though no analysis of this exists, it is certain that this concentration greatly exceeds that shown in Table 1 or in MacDonald's Fig. 3. This maximum is reached in a narrow zone which lies between two zones very low in calcium, but this thin tremolite layer is discontinuous or wholly lacking around some nodules.

A few details of the order of crystallization can be given. The pseudomorphs of tremolite after talc in the outer parts suggest that the talc may have formed over a longer interval than some of the other constituents, possibly in several stages, and that the concentration of calcium in a narrow zone was reversed at a late stage. There is nothing to indicate that all of the talc is a replacing mineral.

It may be that the scattered magnetite is a relic embedded in all parts of the zones. It is anhedral, in clusters or remnants of broken or altered grains. Structures in the chlorite crust suggest crystallization locally influenced by preexistent grains of magnetite. Excellent pressure shadows (see Fig. 2) of chlorite occur about the magnetite of the inner zones and show very clearly that this chlorite formed *after* the adjoining talc or anthophyllite.

These observations still leave the story of the formation of the zoned nodules very incomplete, but one suggestion may not be amiss. It is that mineral occurrences of this sort can be most effectively studied by methods analogous to those that have been used with much success in the study of pegmatites, modified, of course, to suit the much finer grain of the material. As in pegmatites, it is practically impossible to get satisfactory bulk compositions of the whole or of typical parts. The history of the assemblage is best arrived at by a careful identification of all discernible minerals, the analysis of those whose composition may be especially significant, and the determination of such fragments of the sequence of crystallization as may be recognizable. Just as one would not describe a pegmatite from hand specimens, however numerous, but would examine the whole body, one must examine specimens or sections in which the structure and relations of the whole assemblage are adequately shown.

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