Mineralogy and Genesis of the Vermiculite Deposits at Libby, Montana

Raymond Kujawa

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MINERALOGY AND GENESIS OF THE VERMICULITE DEPOSITS
AT LIBBY, MONTANA

A Thesis
Submitted to the Department of Geology in
Partial Fulfillment of the Requirements
for the Degree of Bachelor of Science
in Geological Engineering

by
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15501

Montana School of Mines
Butte, Montana
May, 1942

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**CONTENTS**

<table>
<thead>
<tr>
<th>Topic</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>Introduction</td>
<td>1</td>
</tr>
<tr>
<td>General</td>
<td>1</td>
</tr>
<tr>
<td>Location and Accessibility</td>
<td>2</td>
</tr>
<tr>
<td>Geography</td>
<td>4</td>
</tr>
<tr>
<td>History and Production</td>
<td>5</td>
</tr>
<tr>
<td>Preparation of Specimens</td>
<td>6</td>
</tr>
<tr>
<td>General Geology</td>
<td>7</td>
</tr>
<tr>
<td>Sedimentary Rocks</td>
<td>7</td>
</tr>
<tr>
<td>Igneous Rocks</td>
<td>8</td>
</tr>
<tr>
<td>General</td>
<td>8</td>
</tr>
<tr>
<td>Pyroxenite</td>
<td>9</td>
</tr>
<tr>
<td>Syenite</td>
<td>12</td>
</tr>
<tr>
<td>Pegmatite</td>
<td>13</td>
</tr>
<tr>
<td>Geologic History</td>
<td>14</td>
</tr>
<tr>
<td>Ore Deposits</td>
<td>15</td>
</tr>
<tr>
<td>Structure</td>
<td>15</td>
</tr>
<tr>
<td>Size and Pattern of Deposits</td>
<td>16</td>
</tr>
<tr>
<td>Mineralogy</td>
<td>16</td>
</tr>
<tr>
<td>Diopside</td>
<td>16</td>
</tr>
<tr>
<td>Microperthite</td>
<td>18</td>
</tr>
<tr>
<td>Tremolite and Asbestos</td>
<td>19</td>
</tr>
<tr>
<td>Vermiculite</td>
<td>19</td>
</tr>
<tr>
<td>Quartz</td>
<td>20</td>
</tr>
<tr>
<td>Apatite</td>
<td>20</td>
</tr>
</tbody>
</table>
ILLUSTRATIONS

<table>
<thead>
<tr>
<th>Plate I</th>
<th>Aerial photograph of a portion of the area on Rainy Creek.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Plate II</td>
<td>1. View of the upper bench of the Lewis pit.</td>
</tr>
<tr>
<td></td>
<td>2. Close-up of a portion of the pit.</td>
</tr>
<tr>
<td>Plate III</td>
<td>1. Panorama of the Climax pit</td>
</tr>
<tr>
<td></td>
<td>2. View of a small portion of the Climax pit.</td>
</tr>
<tr>
<td>Plate IV</td>
<td>1. Partly altered crystal of diopside.</td>
</tr>
<tr>
<td></td>
<td>2. Coarsely crystalline syenite.</td>
</tr>
<tr>
<td></td>
<td>3. Altered pyroxenite.</td>
</tr>
<tr>
<td></td>
<td>4. Basic pegmatite.</td>
</tr>
<tr>
<td>Plate V</td>
<td>1. Weathered pyroxenite cut by a small granite pegmatite.</td>
</tr>
<tr>
<td></td>
<td>2. Weathered pyroxenite from Bobtail Creek.</td>
</tr>
<tr>
<td></td>
<td>3. Alteration of pyroxenite to tremolite asbestos.</td>
</tr>
<tr>
<td></td>
<td>4. Specimen of high grade vermiculite ore.</td>
</tr>
<tr>
<td>Plate VI</td>
<td>1. Photomicrograph of typical syenite</td>
</tr>
<tr>
<td></td>
<td>2. Photomicrograph of a more basic portion of the syenite.</td>
</tr>
</tbody>
</table>
3. Photomicrograph of a more basic portion of the syenite.

4. Photomicrograph of a more basic portion of the syenite, showing resorption.

Plate VII ............................................. 19

1. Transformation from colorless diopside to green diopside.

2. Further alteration of green diopside to tremolite asbestos.

3. Continued alteration.

4. Final obliteration of the diopside.

Plate VIII ............................................. 22

1. Section of the unaltered magnetite segregation.

2. Partly altered magnetite rich rock.

3. Photomicrograph showing the nearly complete destruction of the diopside grains.

4. Photomicrograph of almost pure vermiculite ore.

Geologic map of the Rainy Creek Intrusives ---- In pocket
INTRODUCTION

General.-- This thesis contains the results of a survey of the vermiculite deposit near Libby, Montana, and laboratory investigations conducted at the Montana School of Mines. The survey, completed in August, 1941, was essentially one of collection of hand specimens from critical locations. Using a road and claim map, prepared by Mr. John B. Meyers of the Universal Zonolite Insulations Company, specimens were obtained from the major portion of the area. The laboratory work consisted of the preparation and study of thin sections for the purpose of ascertaining the paragenetic relationship of the original minerals of the rock and the result of the alteration of these rock-forming minerals.

The problem considered in this report is one of the mineralogy and mode of formation of the extremely pure, large bodies of vermiculite. Mineralogically the ultrabasic intrusive, with which the economic mineral is associated, presents an array of rather unusual minerals. The determination of these minerals, their associations, and the sequence of alteration that lead to the formation of the vermiculite bodies, constitutes the problem.
The chief mineral of the vermiculite deposits has been identified by some as hydrobiotite*. Other specialists** have given this material the name jeffersite. These minerals are classed under the group name vermiculite. The term vermiculite is used in this report, as the correct name is still disputed, and because that name is more widely recognized and associated with this type of mineral.

For some years, prior to 1940, the commercial name "Zonolite" was extensively used for the expanded Libby vermiculite. At about this same time the name "Unifil" became prominent. At present this latter term is the sole trade name for Libby vermiculite.

Location and Accessibility.—The vermiculite deposit is located on Rainy Creek north of Libby, Montana, approximately ten miles by road. Libby, situated on the south bank of the Kootenai River, is 95 miles west of Kalispell, Montana, on the Great Northern Railroad.


and on U. S. Highway No. 2. The deposit itself, on the opposite side of the river from Libby, is reached by road, seven miles of which is now being reconstructed as a state highway. For the most part, the rest of the road is kept in good repair by Lincoln County and the mining company. It is necessary to truck the concentrated vermiculite from the mill, at the mine, to storage bins at the edge of Libby.

The town of Libby affords a sufficient labor supply for the few men needed to operate the property. The Rainy Creek deposit is, at present, controlled by the Universal Zonolite Insulations Company which owns all but a few claims lying along the edge of the intrusive. These outlying claims are on quartz veins associated with the intrusive.

The operating company, using open pit mining methods, does extensive development work by building roads, in a regular pattern over the mountain that contains the ore. Experience has shown that road cuts disclose changes in soil and rock character that can be interpreted to show possible commercially exploitable deposits.
Geography.—Lying within the western fringe of the Rocky Mountains, the area under discussion has a relief of from 3000 to 5000 feet. The mountains rise abruptly from the stream valleys to the peaks at the level of an old Tertiary penéplane. There are few inaccessible spots as the ranges are well dissected by large streams. The entire region is heavily timbered with stands of fir, pine, and hemlock that extend to the top of most of the mountains. All the streams in the area drain into the Kootenai River that enters Montana from Canada, passes with a sharp curve into Idaho, and flows into Canada again where it joins the Columbia River.

Rainy Creek, to the northeast of Libby, drains southwestward into the Kootenai River. The stream cuts a narrow canyon for a few miles into the mountains of the Purcell Range. The upper branches of the stream, dry for several months of the year, drain into a small basin at the foot of Zonolite Mountain. Most of the ridges are partly open on the south and west slopes, but heavily timbered on the north and east (Plate I).

The rainfall is rather high with an annual average of from 40 to 60 inches. This is slightly higher than the usual precipitation for northwestern Montana. The snowfall is heavy, and may stop work in the open pits for short periods. The precipitation
PLATE I

Aerial photograph of a portion of the area on Rainy Creek, showing changes in the types of vegetation and the major pits of the Universal Zonolite Insulations Company.
accounts for the dense pine and hemlock jungles that interfere with the mapping and prospecting.

**HISTORY AND PRODUCTION**

There was considerable prospecting in this area prior to the first World War. Exploration was mostly along the quartz veins that contain small amounts of copper, manganese and vanadium. However, the vermiculite was not definitely recognized until about 1917. At this time Mr. E. N. Alley, prospecting for ores of vanadium, noticed the expansive qualities of the vermiculite. He experimented with the mineral, identified it, and formed the Zonolite Company for the exploitation of the substance as an insulating material. Other companies, the Micalite and the Vermiculite Company, were formed. The Micalite Company, a promotion scheme, did not function long. There remained two operating companies until 1940 when they merged to form the Universal Zonolite Insulations Company. Since its discovery, vermiculite has been developed for many purposes. Among these are insulating material, acoustic board, refractory and insulating brick, plaster filler, coloring for gilt paints, and as a substitute for graphite in lubricants. Production has risen gradually until, in 1940, the Libby deposits produced about 20,000 short tons with a value of $12.00 per ton at the mine.
PREPARATION OF SPECIMENS

It was found that, due to the altered condition of the majority of the specimens, thin sections could not be made directly from the rock as it occurred in the field. In order to overcome this difficulty, a portion of the sample to be sectioned was first impregnated with lucite.

The lucite was prepared from monomeric methyl methacrylate. The inhibitor, in the methacrylate, was first removed with a 3% aqueous solution of potassium hydroxide. This solution was added in small portions until, after shaking, the hydroxide solution remained colorless, and was not tinged brown by the inhibitor. The water remaining in the liquid was then removed with dehydrated calcium chloride, by adding in several small amounts of about one gram each, agitating with the mixture and the collected water drained off. This was repeated until the liquid lucite became clear. A small amount of benzoyl peroxide was added, about 0.1 gram per 200 cc. of liquid. When this had dissolved, the liquid was poured over the specimen and the material, in a covered beaker was kept at 35°C. until the lucite had solidified. This last step, taking about 48 hours, was of sufficient duration to allow complete impregnation of the sample.

Permout was used to cement the slices to the glass
plates, and to seal on the cover glasses. This material was used, in preference to Canada Balsam, as it did not require heat that might have affected the lucite, the lucite-mineral bond, or the vermiculite in the sample.

GENERAL GEOLOGY

Sedimentary Rocks

The sedimentary rocks of the area are entirely Proterozoic in age with the exception of a small remanent of middle Cambrian shale about 20 miles to the south of Rainy Creek. Great thicknesses of Belt sandstones, shales, limestones, and argillites are exposed. These Belt formations, from the Pritchard to the Striped Peak, have an exposed thickness of from 12,000 to 15,000 feet. These sedimentary rocks are identified solely on lithologic character. The only fossil types are algal colonies, family Collenia, in the Wallace limestone. The beds, in this locality, show a regional dip to the southwest. Near the Rainy Creek intrusives the entire Belt sequence has been tilted to almost vertical. Little contact metamorphism is noticeable along the boundaries of the igneous bodies. The Belt section in the Libby quadrangle
is as follows:*

Striped Peak Shale --------------- 2000-6000 ft.
Wallace Limestone --------------- 16,500 ft.
Ravalli Group (Shale and Sandstone) -- 7000-10,000 ft.
Pritchard Argillite --------------- 9700 ft.

Igneous Rocks

General.--Rainy Creek is located in the Libby, unorganized, mining district. The older intrusive, pyroxenite, is roughly rectangular in outline, about two miles wide by 3 miles long. The pyroxenite lies mostly in sections 14, 15, 22, 23, 26, 27 of T. 30 N., R. 31 W., M. P. M. The syenite, very irregular in outline, adjoins the pyroxenite, lies in sections 21, 22, 27, 28, and has a surface exposure of about 2½ square miles.

The Rainy Creek area was intruded first by a stock-like body, extremely basic in character. Upon partial cooling small bodies of magnetite separated from the intrusive. It is these bodies, of unknown size, that so greatly disturb a compass needle and thus prevent its use in surveying. Slightly later pegmatites, and some high temperature veins, were formed. The veins frequently contain small amounts of.

copper, vanadium, and manganese. The pegmatites show, from their basicity, their origin in the first intrusive. Segregation may, also, have been responsible for the formation of almost pure bodies of diopside, and, subsequently, the vermiculite (Plate II).

The syenitic masses appeared somewhat later. They may have been from a later rejuvenation of the same magmatic reservoir as the ultramafic mass. Syenite and granite pegmatites were injected some time after the solidification of this igneous body. When viewed from the top of Zonolite Mountain, near the center of the intrusive, these pegmatites display a somewhat radial character from the syenitic intrusion (Plate III).

Pyroxenite.--The ultramafic intrusive is composed almost entirely of diopside. In the majority of exposed areas, however, it is so intensely altered that only scattered crystals of the mineral, in its original state, are found (Plate IV, 1). The diopside varies from colorless to green, depending upon the intensity of the uralization, or alteration to hornblende and tremolite. Usually all of the visible pyroxenite has a definite green color. Colorless, or light green, diopside is megascopically noticeable only in the deeper portions of tunnels. Frequently the diopside has altered to asbestiform tremolite, particularly along fractures and near the surface (Plate V, 3).
PLATE II

1. View of the upper bench of the Lewis pit with a cut of 75 feet, a lower, 25 foot cut is not shown. The relation of relatively pure vermiculite (a), granite pegmatite (b), syenite pegmatite (c), and altered pyroxenite (d) is generally shown.

2. Close-up of a portion of the pit, showing the complexity of the dikes, and the megascopic relationship of vermiculite (a), granite pegmatite (b), syenite pegmatite (c), altered pyroxenite (d), and syenite (e).
1. Panorama of the Climax pit, showing vermiculite (a), granite pegmatite (b), syenite pegmatite (c), altered pyroxenite (d), syenite (e), and basic pegmatite (f). The vertical striations are marks from a power shovel teeth.

2. View of a small portion of the Climax pit as seen from the entrance. The vertical distance to the next bench is 40 feet.
The rock varies from almost pure pyroxenite to olivine. The rock always contains some olivine, which is present in crystals that are without magnification. Small amounts of pyroxene are usually present in xenonite microgranular.

The magnesite is in part visible, and the rock is almost entirely of magnesite. The rock is so fine-grained that magnesite and olivine can not be preserved in a thin section (Plate 2, 1 and 2). Along veins, an inclusion of almost pure tremolite asbestos, 2 feet in width, can be seen. Although the amphibole of the pyroxenite has been altered, the rock of the serpentine has kept its identity. The graph shows the best grade of serpentine at the right.
In composition the rock varies from almost pure pyroxenite to near gabbroic. The rock always contains some titanite that may increase to as much as 10%, in crystals that become visible without magnification. Small amounts of feldspar are usually present as microcline micropetthite, but some labradorite, An$_{49}$, is occasionally observed.

In the northwestern part of the pyroxenite there is a considerable of magnetite. Here the rock, dark grey and aphanitic, contains up to 35% magnetite. This magnetite, evidently a segregation product, contains very little of the visible titanite so common in the rest of the pyroxenite. The magnetite lens, in its narrower portions, grades into an altered diopside, vermiculite, magnetite rock that shows an increase in vermiculite with a decrease in diopside.

It is the prevalent surface feature of the pyroxenite to be altered to hornblende, tremolite, and tremolite asbestos. The asbestos, of good quality near the surface, becomes less fibrous with depth, and, at 25 or 30 feet, passes into tremolite and diopside. The rock is so soft that good hand specimens can not be preserved in their natural state (Plate V, 1 and 2). Along veins and pegmatites bodies of almost pure tremolite asbestos, four and five feet in width, are found. Although the entire surface of the pyroxenite has been altered, the area at the head of Kearney Creek displays the best grade of asbestos at the surface.

Vermiculite is scattered within the tremolite
1. Partly altered crystal, $x_2^4$ of diopside that has partly altered to tremolite and to hornblende.

2. Coarsely crystalline syenite, $x_2^3$, composed entirely of large crystals of microcline microperthite.

3. Altered pyroxenite, $x_2^3$, showing introduced apatite (a), hornblende and diopside (b), and vermiculite (c).

4. Basic pegmatite, $x_2^3$, with large crystals of hornblende (a) in a groundmass of pyroxenes and microcline microperthite.
zone, over the same area. In this zone the vermiculite usually constitutes from 2% to 35% of the rock (Plate IV, 3). It ordinarily is in small grains that frequently show a rather poor power of exfoliation. In some localities the entire rock is composed of large books of vermiculite. These occurrences, as large lenses, contain only 5% to 20% of other minerals, mainly partly altered diopside, hornblende, tremolite asbestos, microperthite, apatite, and titanite (Plate V, 4).

An analysis of Rainy Creek pyroxenite, by George Steiger in the U. S. Geological Survey laboratory, shows the following composition:

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<th>Percent</th>
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<tr>
<td>SiO₂</td>
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<tr>
<td>Al₂O₃</td>
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<tr>
<td>Fe₂O₃</td>
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<td>FeO</td>
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<tr>
<td>MgO</td>
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<tr>
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<tr>
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<tr>
<td>H₂O⁺</td>
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</tr>
<tr>
<td>TiO₂</td>
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<tr>
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</tr>
<tr>
<td>CO₂</td>
<td>0.36</td>
</tr>
<tr>
<td>P₂O₅</td>
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<tr>
<td>S</td>
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Specific Gravity 3.417

From this analysis it is apparent that the intrusive is highly calcic, and contains high percentages of vanadium and titanium.

1. Weathered pyroxenite (a) cut by a small granite pegmatite vein (b), x\(\frac{1}{2}\), and showing small amounts of tremolite asbestos (c) and vermiculite (d) disseminated through the rock.

2. Weathered pyroxenite from Bobtail Creek, demonstrating similarity of this deposit to the one on Rainy Creek, and showing disseminated vermiculite (a) and apatite (b).

3. Alteration of pyroxenite (a) to tremolite asbestos (b). Sample was obtained at considerable depth from near a pegmatitic dike.

4. Specimen of high grade vermiculite ore showing small amounts of microcline microperthite (a) and tremolite asbestos (b). The vermiculite shows the prominent cleavage planes.
Syenite.--Syenite enters the area from the south and stops near the top of Zonolite Mountain, within the pyroxenite zone. The rock, varying in texture from fine grained to pegmatitic, is mainly microcline microperthite, with a few scattered crystals of laboradorite. In places the syenite contains considerable quantities of diopside and titanite. These areas may be due to partial remelting of pieces of the pyroxenite. On rare occasions the syenite has been partly kaolinized. More commonly, however, the small percentages of iron in the rock have oxidized to give the syenite a rusty or dark brown color. In such cases the grains are so loosely joined that the rock may disintegrate with very little pressure (Plate IV, 2). This gives outcrops of the coarser syenite a very rough surface. Surface exposures are often typified by sericite and muscovite, as on the north slope of Keeney Creek. The syenite has a dark green, greasy appearance in the finer grained portions. These zones also contain greater percentages of the pyroxenes and titanite. The wide difference in color, grain size, and accessory minerals of the syenites may be due to different intrusive waves from the same magmatic source. This appears to be supported by the fact that the finer grained syenites are usually more dike like in character.
Pegmatite.--Within the pyroxenite are some pegmatite dikes that cut only the pyroxenite. These rare bodies, one found near the top of Zonolite Mountain, have such a basic character that they are definitely of a class quite different from the usual pegmatite. The minerals of these dikes correspond to the minerals of pyroxenite. Pyroxene crystals, several inches in length and large hornblende crystals are common. Feldspars, as microperthite, form the major part of the groundmass (Plate IV, 4).

Syenitic pegmatites, that is pegmatitic bodies composed largely of crystals of microcline microperthite, cut both the pyroxenite and the syenite. There is usually considerable apatite associated with these dikes. There is no free quartz. Along the strike some of these dikes grade into a material with a texture approximately the same as the major body of syenite.

There are numerous quartz pegmatites that cut the entire district. Locally these dikes are composed solely of quartz, orthoclase, and microperthite phenocrysts in a groundmass of feldspar. In many exposed places this feldspathic groundmass has been completely kaolinized. All that remains are large quartz crystals in a clay matrix. Some of the quartz pegmatites grade into hypothermal veins that contain small amounts of copper, lead, and manganese. The majority of these veins are composed entirely of white, massive to glassy, quartz.
Geologic History

This area is within the bounds of a Proterozoic synclinal basin in which was deposited a great thickness of shaly and sandy sediments, now somewhat metamorphosed into argillites and quartzites, and known as the Belt series. After the deposition of the Beltian sediments, the district became a part of the persistent early Paleozoic island, Montania. The majority of Paleozoic sediments deposited in this area were eroded by Tertiary time. There was little deformation of the sedimentary rocks until the Laramide orogeny when mountain building activity caused the uplift and gentle folding of the Belt formations. The only major fault, the Moyie or Snowshoe, is about ten miles to the west, and it had no effect upon the Rainy Creek area. Ultrabasic rocks were intruded into the Belt sediments relatively early during this diastrophism, and this intrusion was followed by syenitic magmas. After all of the present rock types had formed, the region was eroded to its present relief and the igneous bodies were exposed.
Structure.—The vermiculite occurs both as lens-like bodies, and as disseminations throughout the exposed portions of the pyroxenite.

The lenses are generally irregular in outline, conforming roughly to the areas of more intense fracturing and possible solution penetration. Wherever found, these bodies show minor slip planes at the edge of the deposits, or just within the mineral body. Secondary crystallization has obscured many of these fractures within the ore body. Because of the extremely altered condition of the rock, and also because of its homogeneity, it is impossible to determine the extent of movement along these faults. Many of the fractures have acted as channels for ascending solutions. It is noticeable that the area of greatest fracturing and introduction of new material is also the zone that always contains the highest grade vermiculite ore. Minor faults transgressing the ore bodies are often noticeable over a considerable distance. There appears to be no simple fracture system; the faults tend to radiate from a center near the top of Zonolite Mountain, although many show some tendency towards an easterly strike. It is possible that the majority of these fractures are tension cracks resulting from the cooling of the intrusives.

Over the entire district, wherever the pyroxenite
is exposed, the rock contains small percentages of disseminated vermiculite. This dissemination is slightly deeper along cracks and dikes. However, where adits have penetrated below the zone of weathering, the disseminated vermiculite disappears.

Size and Pattern of Deposits.—The high grade deposits of vermiculite are from 100 to 1000 feet in length, range greatly in width from a few feet to perhaps 300 feet, and are of unknown depth. The Climax body apparently has been cut at about 300 feet beneath the surface by an adit from the Kearney Creek slope. There are many tongues branching from the main ore bodies along pegmatites or faults, which give the deposits in such places an extremely irregular shape.

The main portion of the ore bodies on the Lewis and Climax claims has an easterly trend, but on the Longmont and Vermiculite No. 8 claims the lenses appear to be oriented more northeasterly.

MINERALOGY

Diopside.—As most commonly observed in the ultrabasic rock, this mineral appears in grass-green, subhedral crystals with prominent cleavage. Some colorless grains of diopside may be observed, generally, however, the
colorless variety has altered, thereby resulting in green colorations. The green diopside is distinguished from pseudomorphic hornblende by its lack of pleochroism under the petrographic microscope. The uralitic variety of hornblende preserves the crystalline outline of the diopside to an excellent degree. Altered diopside constitutes up to 80 percent of some of the pyroxenite (Plate VII, 4). In some cases the diopside crystals attain great size. Euhedral crystals, four to five inches in length, are conspicuous, particularly in adits near the magnetite body shown on the accompanying map.

Individual crystals of diopside occasionally have cores of titanite, however the titanite does not exert any apparent influence upon the growth of the diopside. In some crystals the outer layer of silicate is very thin, but it still develops the crystal habit of diopside.

In the syenite diopside composes but a small part of the total mineral assemblage. It appears as small euhedral crystals scattered within large microcline microperthite grains (Plate VI, 2, 3). Diopside, generally uralitized, occurs also in more concentrated segregations within the syenite. Individual crystals normally do not exceed five millimeters in length, and commonly show evidence of resorption (Plate VI, 4).
Microperthite.—This mineral substance is a graphic intergrowth of microcline and albite. At Libby the perthitic intergrowth is commonly megascopically visible, and the crystals display a strong tendency toward idiomorphism. Within the coarse grained syenite, where microperthite may compose 90 percent of the rock, the grains are poorly interlocked, and a small amount of weathering will cause the particles to separate. The fine textured mineral substance may compose rock of such firmly interlocked grains as to be exceedingly tough.

Small quantities of microperthite, of the same composition as in the syenite, are found in the pyroxenite. Here the microperthite forms the interstitial material. It is present only as irregular masses, no crystals being observed.

Upon long exposure, in the zone of oxidation, the microperthite disintegrates to exceptionally plastic kaolin. Kaolinization is most noticeable in the coarse grained syenite and granite pegmatite (Plate VI, 1).

There is extensive sericitization of the microperthite, it being a more widespread type of alteration than the kaolinization. Sericite replaces entire crystals of the microperthite. In places muscovite may form small books that seldom exceed one centimeter in diameter.
Tremolite and Asbestos.--The formation of asbestiform tremolite is the most common surface indication of alteration in the entire area (Plate VII, 2). Tremolite close to the water table occurs chiefly in rather massive bunches. In areas close to pegmatites the tremolite has been converted into asbestos. In such places it may form vein-like bodies four and five feet in width. Where the tremolite asbestos has been produced solely by weathering, the quality is good at the surface, but the fibrous character decreases rapidly with depth (Plate VII, 4).

Vermiculite.--This mineral is a micaceous material, having the same general appearance as biotite, but differs in that it is less elastic. Like biotite the mineral may be light brown, but where the brown colorations of biotite no doubt result from weathering, the brown coloration of vermiculite may result from some condition of primary or deep seated alteration.

Vermiculite, varying from light brown to black in color, is always present as subhedral or anhedral grains, and is found in particles that range from microscopic size to one or two feet in diameter. Apparently there is little difference between the exfoliating power of normal light and dark colored vermiculite, however, some of the dark material having a slightly more glossy appearance, is more flexible and expands only slightly
PLATE VII

1. Transformation from colorless diopside (a) to green diopside (b) with the start of the formation of tremolite asbestos (c).

2. Further alteration of green diopside (a) to tremolite asbestos (b) and vermiculite (c).

3. Continued alteration that has left only a few unaltered islands of diopside (a) in vermiculite (b) and tremolite asbestos (c).

4. Progressive step from figure 3, showing final obliteration of the diopside.
on heating. In these cases the dark mineral is not
true vermiculite, but is phlogopite or biotite that
has only partially altered to vermiculite.

The disseminated vermiculite, particularly the
smaller grains, is generally lighter colored. Some of
these grains, apparently having formed from the ferro-
magnesian minerals, may show a poor expansive quality.
The mineral in the high grade bodies often shows markings
or rulings apparently cleavage lines on the prominent
basal cleavage planes. These lines intersect to form
nearly equilateral triangles and rhombohedrons.

In thin section all vermiculite also appears
light brown (Plate VIII, 2, 3). Within individual crys-
tals there are commonly darker portions that blend into
the more pure vermiculite. These may be remnants of
an earlier biotite stage (Plate VIII, 4).

Quartz.--The only quartz found is in the granite pegmatites.
It forms excellent, doubly terminated crystals, and con-
stitutes the greater portion of some of the vein filling.
The quartz is generally clear and glassy, but may be
dark gray, especially the crystals.

Apatite.--Crystals of apatite are scattered through
portions of the pyroxenite, syenite, pegmatites, and
vermiculite bodies. In the syenite apatite is not
visible megascopically, but it may comprise up to
five percent of the total minerals present. It is readily identified by its moderate relief in 1.544 oil, its low birefringence, and by the hexagonal cross-section of the crystals. Apatite, although often present in large amounts, does not appear as a mineral of the original pyroxenite. In the pyroxenite it may be found as irregular masses and bunches, with almost no tendency toward idiomorphism. The pegmatites contain euhedral crystals of apatite in vugs, as inclusions in the phenocrysts, and as a small portion of any finer grained matrix.

From microscopic examination it is apparent that apatite is a primary part of the syenite and pegmatite, but a secondary constituent of the pyroxenite and vermiculite. It is a good indicator of hydrothermal alteration of these rocks. The apatite, through replacement and the filling of small cavities, amounts to from 10 to 15 percent of some of the pyroxenite occurring adjacent to pegmatite.

Titanite.—In most igneous rocks titanite is found only as scattered microscopic grains that seldom exceed 1 to 2 percent of the rock. In the case of the Rainy Creek intrusives, however, titanite is found in crystals ranging from 1 to 2 millimeters in length, and composing up to 10 percent of the rock. It is found in both the pyroxenite and the syenite, but is much more abundant in the former. The crystals are invariably euhedral,
and under the microscope range from gray to brownish. Twinning is common.

**Magnetite.**—The few occurrences of magnetite are solely in the pyroxenite. The mineral forms irregular masses interstitial to the diopside grains, and commonly cuts into crystals of the diopside along crystal planes (Plate VIII, 1). The magnetite is non-crystalline, and occasionally occurs as particles that exceed 5 millimeters in length. The dissemination is usually fine, however, and apparently represents a late injection into the partially cooled diopsidic mass.

**Aegerine and Aegerine-Augite.**—Extremely small amounts of aegerine were noted. This mineral occurs in small green to black crystals in some of the basic pegmatites, late basic dikes, and along the contact of granite pegmatite with the pyroxenite. The crystals are very small, euhedral, and generally appear as slender needles. This material appears to have been formed by the pegmatitic alteration of the diopside, however it may also have been an original mineral in some of the basic dikes. Locally, the aegerine may contain some vanadium.

No aegerine-augite was noticed in any of the specimens. This mineral is found, however, to the south of the area covered by this survey, where it occurs in small basic dikes, and is associated with aegerine and vanadinite.
PLATE VIII

1. Section of the unaltered magnetite segregation showing fragments of diopside (a) in magnetite (b) which, in turn, cuts the diopside. This may indicate a late magnetite segregation.

2. Partly altered magnetite rich rock showing diopside (a), vermiculite (b), and apatite (c).

3. Photomicrograph showing the nearly complete destruction of the diopside grains (a) with remaining unaltered magnetite (b), vermiculite (c), and tremolite asbestos (d).

4. Section of almost pure vermiculite ore showing large grains of apatite (a) and dark area (b) that may represent a biotite stage.
Manganese, Copper, and Vanadium.--Manganese minerals are found in the outcrops of a few pegmatite veins. They occur in irregular masses scattered through the rock. The most plentiful mineral is probably manganite, but the original material is now altered, generally to wad.

Green stains of malachite are present in some of the quartz veins, and chalcopyrite and enargite have been identified as the primary copper minerals. However, the amount of copper present is not considered commercial by members of the staff of the United States Geological Survey, analyses showing less than two percent.*

Vanadium occurs locally in the aegerine and aegerine-augite along contacts between the pyroxenite and high temperature quartz veins. Pardee and Larsen report 3.98 percent V₂O₅ in the aegerine and 2.86 percent in the aegerine-augite, as determined by W. F. Hunt of the Geological Survey.* Although 2.86 and 3.98 percent vanadium oxide content would indeed seem to be a considerable amount, investigations indicate that it cannot be profitably mined for extraction due to its localization in small bodies.

Paragenesis.--In the typical, unaltered pyroxenite the titanite appears to be the first mineral to crystallize. It appears as euhedral crystals that often form a core for larger diopside grains. Both diopside and titanite crystals are found within single large grains of microcline microperthite. Magnetite, where found, cuts both the diopside and microperthite, and forms irregular patches between the crystals of the other rock minerals. From this evidence it appears that the magnetite is late, and was injected into the partly pyroxenite. This places the order of crystallization as titanite, diopside, microperthite, magnetite. Apatite is present as a result of the action of later solutions.

In the syenite small crystals of titanite project into pyroxene, are idiomorphic at the expense of the pyroxene. Apatite crystallized at about the same time as the titanite. All of these minerals have been engulfed in the larger grains of microperthite. This results in an order of crystallization much the same as in the pyroxenite.

The vermiculite is entirely of secondary origin. It is commonly assumed that this mineral forms from the alteration of biotite. Since no biotite is found in the original magmatic product, biotite can not be given a place in the paragenetic sequence, and, apparently, the origin of vermiculite from primary biotite is excluded.
GENERAL OF THE VERMICULITE

General.--It is generally admitted that vermiculite results as an alteration product. Two theories arise as to the mode of alteration; one by meteoric waters under surface conditions, and the other through the action of pegmatitic solutions, or alkaline juices of juvenile origin. In the case of the Libby deposits alteration must have progressed through the secondary formation of biotite which in turn altered to vermiculite. No primary biotite has been definitely identified in the unaltered pyroxenite. Libby vermiculite is a hydrous silicate, or false mica, with the general formula of \((\text{OH})_2\text{K(Mg,Fe)}_3(\text{Si,Al})_4\text{O}_{10} \cdot 4\text{H}_2\text{O}\). According to Ruthruff*, true vermiculite has the formula \((\text{OH})_2(\text{Mg,Fe})_3(\text{Si,Al})_4\text{O}_{10} \cdot 4\text{H}_2\text{O}\). This gives the Libby material the more correct name of hydrobiotite.

Meteoritic Water Theory

It is possible that biotite may alter to vermiculite by surface weathering. In all outcrops, a small amount of vermiculite is present, and these particles are conspicuously close to a grain of magnetite. In a few rare instances tremolite asbestos appears to grade into vermiculite. The possibility arises that iron is necessary for the transformation. Most of the surface

*op. cit., p. 479.
water action appears to result in the formation of asbestos, and rarely serpentine and kaolin. In one case a few grains of chlorite, possibly of different origin, were observed. However, the widespread blanket of weathered pyroxenite so persistently contains vermiculite, it appears that surface waters probably were responsible for the formation of small amounts of this mineral.

On Bobtail Creek, about six miles to the west of Rainy Creek, a pyroxenite dike occurs, and although pegmatite is present, it is far less plentiful than on Rainy Creek. Vermiculite is found only as a dissemination in the pyroxenite. Although there are no adits penetrating below the zone of weathering, a slight decrease in the amount of vermiculite in the bottom of existing pits is apparent. No high grade bodies are found on Bobtail Creek. The decrease in amount of mineral with depth suggests a formation through the action of meteoric waters.

As has been previously mentioned, the vermiculite lenses on Rainy Creek extend below the present water table, and well below any extensive indications of surface alteration. It is possible that a former lower water table may have formed vermiculite to such a depth, but this is not supported by accompanying pyroxenite alteration, and physiographic features.
Juvenile Water Theory

The contention that the vermiculite formed through the action of heated juvenile waters is supported by evidence of several types. In the field one of the most evident features is that the high grade vermiculite deposits are cut by a great number of pegmatitic dikes that completely transgress the vermiculite zone. Apatite is always associated with the higher quality deposits. This mineral is not found as a primary constituent of the ultrabasic rocks of the Rainy Creek district, hence it indicates a permeation of the area by mineralizing solutions. Examination of the pyroxenite shows no biotite. However, biotite and phlogopite are found in portions of the vermiculite bodies.

If vermiculite forms from biotite segregations of the original magma, there should be small amounts of primary biotite in the rest of the pyroxenite. No primary biotite was recognized in any of the specimens. However, from microscopic examination, the alteration of diopside to hornblende and tremolite is readily apparent. In some cases the tremolite forms asbestos. On the other hand, with sufficient iron, the alteration is to biotite. This may be seen from the gradation from amphibole to biotite, now occurring as vermiculite. In these cases the vermiculite either assumes part of the crystal shape of diopside, or the tremolite, or
grades imperceptibly into that mineral.

Objections to the fundamental idea are many. Among these is the large size that some of the vermiculite books attain. It seems improbable that crystal bodies, one and two feet across, would develop solely by alteration. However, recrystallization at the elevated temperature of the pegmatites is a possible answer to this objection. The presence of partly altered particles of pyroxenite may be used by the proponent of almost any theory. These blocks may represent pieces somewhat removed from the area of solution impregnation, or they may be included blocks in an area of segregated biotite. Descending cold waters might leave particles of the pyroxenite at a position that the solutions could not reach. However, within the zone of weathering, these blocks are altered completely to hornblende, tremolite, tremolite-asbestos, and vermiculite. The vermiculite lenses, themselves, reach well below the area of any surface alteration of the pyroxenite.

SIMILAR VERMICULITE DEPOSITS

Montana.—On the divide between Harrison, Montana, and South Boulder Creek, the Pre-Cambrian Pony gneiss, which in this area is extensively exposed, has been altered to a vermiculite-bearing rock. The gneiss, here consisting
of quartz, hornblende, biotite, and feldspar, is cut by many pegmatite stringers. Between the pegmatites, blocks of the Pony formation have been altered to rock that contains 60 to 75 percent vermiculite. The gradation from the original hornblende gneiss to the vermiculite rock is easily traced. In the most affected portions no hornblende remains. From field evidence alone it is apparent that the environment brought about by the pegmatites has been responsible for the transformation. Outside of this zone the gneiss is not altered in such a manner.

Vermiculite is found, associated with an ultrabasic intrusive in the Sapphire Mountains near Livingston, Montana. Megascopically the vermiculite appears to be the same as in the Libby deposit, and, in purer samples, is also accompanied by grains of introduced apatite. The extent of this occurrence is not known.

Another deposit of vermiculite, present under similar conditions, is situated in the Beartooth Mountains near Havre, Montana.

Georgia.—In the Kyanite deposits of Georgia, there are "veins" of vermiculite. These bodies, usually from a few inches to three or four feet in width, contain vermiculite in only the upper portions. With depth the vermiculite gradually changes to biotite. In most
cases this depth is about 50 feet, but may extend to 100 feet, which is close to the present water table.*
Such a set of conditions as this strongly points toward the formation of this vermiculite through the action of surface waters on biotite.

Other.--There are important occurrences of vermiculite elsewhere in the United States, but information is not available concerning the genesis of these deposits.

Transvaal, South Africa.--It has been reported that portions of the Bushveldt complex have been altered, by hydrothermal action, to vermiculite. These deposits, of high grade and good quality, compare favorably with the better American deposits. Development and utilization of these deposits has started.

South Madagascar.--Lacroix**, reporting on the phlogopite deposits of southern Madagascar, found that phlogopite in a pyroxenite composed largely of diopside, had been


altered to vermiculite through the action of ground waters. This, in support of the meteoric water theory, shows that vermiculite may form in this way.

CONCLUSIONS

Vermiculite is associated with rock types that contain relatively large amounts of amphibole or pyroxene. The more favorable association appears to be with minerals of the pyroxene group. Biotite, at some stage in the development, is essential to the formation of vermiculite deposits. Heated waters, usually of relatively high temperature, are necessary for the formation of the higher grade deposits. Vermiculite will form, in small quantities, through the action of meteoric waters.

In the Rainy Creek district the steps in the formation of the purer bodies were:

(1) Alteration of diopside to hornblende and tremolite.
(2) Transformation of hornblende and tremolite to biotite and/or phlogopite.
(3) Continued alteration of biotite or phlogopite by heated juvenile waters to yield vermiculite.
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