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PARAGENESIS OF CLINOHUMITE AND ASSOCIATED MINERALS FROM WOLF CREEK, MONTANA[1]

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ABSTRACT

The Wolf Creek ultramafic pluton, in the southern Ruby Mountains in southwestern Montana, intrudes Prebeltian metamorphic rocks and is itself late Prebeltian in age. It consists chiefly of coarse-grained harzburgite which has been partly altered, chiefly to serpentinite, anthophyllite rock, actinolite rock and clinohumite-bearing rock. Along the contacts the wall rocks have undergone extensive exomorphic changes that include various recrystallizations and the formation of metasomatic actinolite and anthophyllite.

The sequence of replacement minerals involves progressive linkage of SiO_4 tetrahedra in the series: clinohumite, anthophyllite, actinolite and chlorite, serpentine and talc. It is concluded that crystallization of the peridotite was accompanied and closely followed by the two types of wall-rock changes and that the solutions producing the wall-rock metasomatism effected similar reactions locally within the peridotite itself.

INTRODUCTION

The Wolf Creek pluton is the largest of seven Prebeltian ultramafic intrusives exposed in the southern Ruby Mountains in southwestern Montana. The writer first examined it in 1947 and mapped it in 1949, 1950 and 1951 while engaged in a general study of the Montana Prebeltian rocks for the Montana Bureau of Mines and Geology. The writer gratefully acknowledges the assistance of E. S. Perry, who guided the writer to many of the localities; J. E. Bever in the mapping; M. E. Hilmy and C. A. Salotti in several laboratory aspects of the study; and especially that of the late John C. Rabbitt, who first directed the writer's attention to the occurrence, participated in critical discussions, and performed the first field studies there.

The Wolf Creek intrusive is about 23 miles airline southeast of Dillon, Montana, largely in Beaverhead County but extending for a short distance northeast into Madison County (Fig. 1), near the southeastern corner of the southern Ruby Mountains.

The Ruby Mountains form a broad, northeast-southwest trending range from whose southwestern end the southern Ruby Range extends as a short arm southeastward. This range is bounded on the southwest by the Black Tail Creek drainage, to which Elk and Moose Creeks are tributary (Fig. 1) and on the northeast by the Sweetwater Basin. Access to the intrusive body is over the Black Tail Creek road from Dillon to a point northwest of Jake Canyon and thence over ranch roads and poor jeep trails northeast and north to the top of the range.

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Much of the southeastern end of the southern Ruby Mountains is a broad, gently rolling upland, 7000–8000 feet above sea level, which breaks away sharply on both flanks, especially on the Sweetwater Basin side, where the range boundary is a prominent fault line scarp with a relief of several thousand feet.

General Geology

The southern Ruby Mountains consist entirely of Precambrian (Prebeltian) metamorphic and igneous rocks. The sequence of units is given in Table 1. Most of the southeastern end of the range is underlain by rocks of a pre-Cherry Creek group age, whereas Cherry Creek group rocks predominate at the northwestern end. This older unit has previously been referred to as Pony or its correlative (Heinrich, 1948), but since it is now known that the type Pony is not older than Cherry Creek (Reid, 1957), this older unit is called simply pre-Cherry Creek group (Heinrich and Rabbitt, 1960). Between the two a large sheet-like mass of Dillon granite (Heinrich, 1953) has been intruded, generally parallel with the regional attitude of the metamorphic layering and foliation, which trend usually northeast and dip steeply northwest.

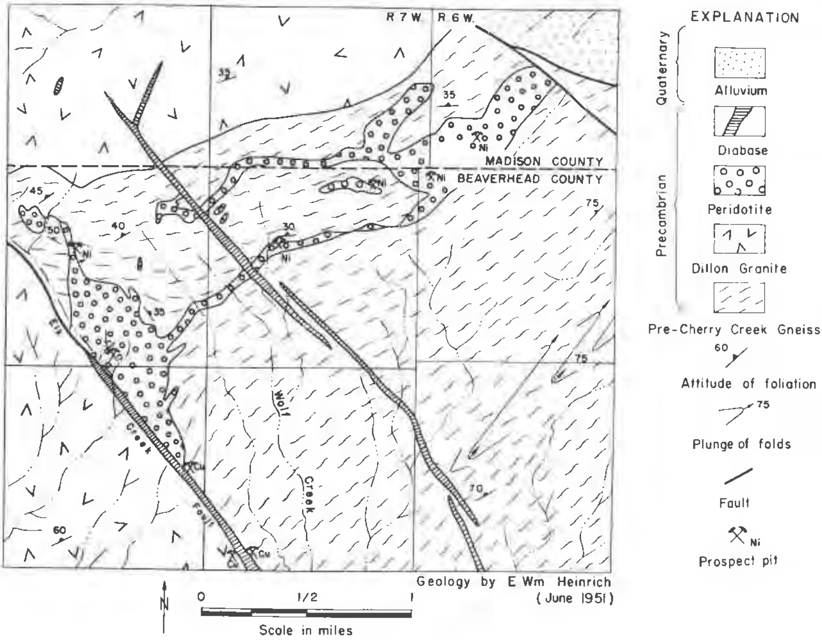

Fig. 1. Geologic map of the Wolf Creek ultramafic pluton, Montana.

TABLE 1. SEQUENCE OF MAIN PREBELTIAN ROCK UNITS IN THE SOUTHERN RUBY MOUNTAINS, MONTANA

Name	Principal Rock Types
Diabase dikes	Fine- to coarse-grained diabase, quartz diabase, diabase with granophyre
Major faulting	
Ultramafic intrusives	Harzburgite, serpentinite
Dillon granite gneiss	Granite, gneissic granite, aplite, pegmatite, quartz veins
Cherry Creek group	Marble, Ca-Mg silicate gneiss, quartzite, mica schists and gneisses, sillimanite schist and gneiss, ironstones, hornblende gneiss, amphibolite
Pre-Cherry Creek group rocks	Biotite-garnet gneiss, quartz-feldspar gneisses, hornblende and hornblende-garnet gneiss, amphibolite, epidote gneiss

GEOLOGY OF THE PLUTON

The intrusive (Sinkler, 1942) is extremely irregular in shape, trending in general N. 55° E. It is bounded on the northeast by the Sweetwater fault and on the southwest by the Elk Creek fault, both of which truncate it (Fig. 1). Close to each of the faults the pluton forms a thick mass, with thin connecting branches (Fig. 1). Along its axis the pluton is about 2½ miles long.

The body has been intruded into pre-Cherry Creek group gneisses, generally in a concordant manner, just south of the pre-Cherry Creek–Dillon granite gneiss contact. Near the contacts of the pluton the foliation has been markedly disturbed, deviating considerably from the regional attitude.

Where the Elk Creek fault chops off the pluton a sheared zone, 200 feet wide, is characterized by slickensided serpentine and abundant quartz. Two diabase dikes (the "gabbro" of Sinkler, 1942), which trend northwest across the pluton, are post-Elk Creek faulting in age. The diabase dike emplaced along the Elk Creek fault also is younger than the faulting.

PETROLOGY

The pluton consists of fresh and altered peridotite, most of the latter occurring near the contacts or along fracture or fault zones. Although there is some variation in composition and texture in the unaltered rocks, mineralogical banding is absent, and the variations are not obviously related to distances from contacts or to changes in thickness. The predominant rock is harzburgite, containing essential orthorhombic pyroxene, olivine and spinel. Outcrops display conspicuous rounded crystals of pyroxene, ranging in size from ⅛ inch to nearly two inches, set in a subordinate, finer-grained matrix. Upon weathering the pyroxene anhedra stand out in relief (Fig. 2).

Much of the orthopyroxene is optically (−) and should be called hypersthene. Enstatite, optically (+), occurs in some specimens, but hypersthene is apparently more common. The pink-green pleochroism not uncommonly characterizing hypersthenes in norites is not present, but in one specimen optically (+) orthopyroxene (enstatite) shows pale pink–pale green pleochroism. This demonstrates again, as has been pointed out by Quensel (1951, p. 248), that pleochroism in the orthopyroxene series does not increase with increasing Fe^{2+} but may depend on the presence of minor elements, perhaps Mn or Ti.

Olivine occurs in nearly all varieties, being altered in varying degrees

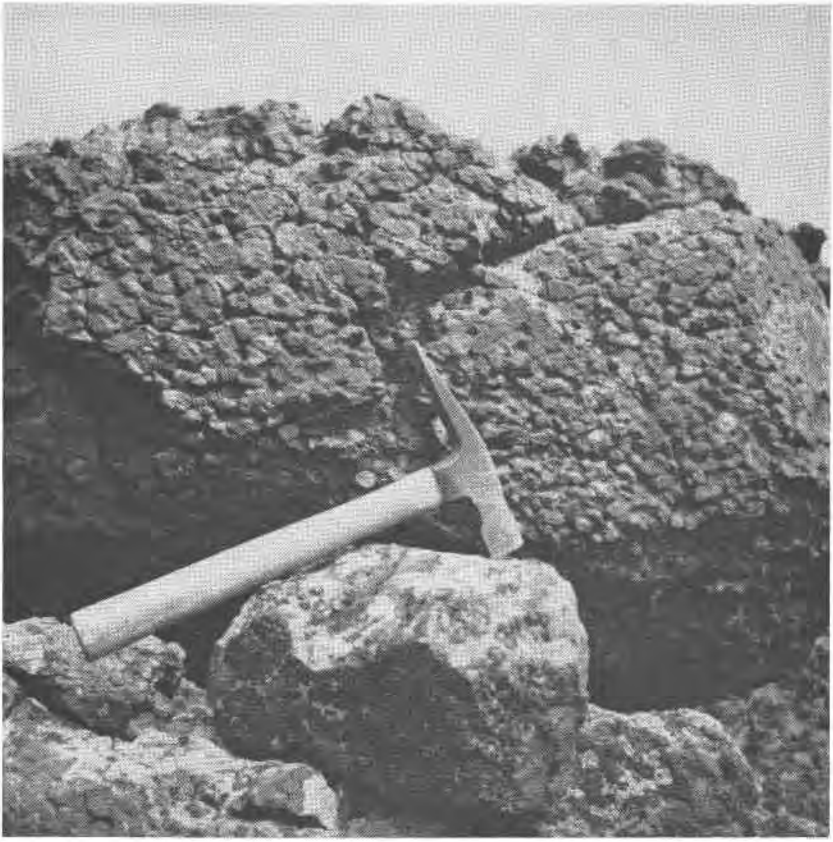

Fig. 2. Weathered outcrops of unaltered harzburgite, showing poikilitic hypersthene or enstatite anhedra in relief. Wolf Creek ultramafic pluton, Montana.

TABLE 2. ANALYSES OF ANTHOPHYLLITE

	1	2
SiO_2	45.98	57.14
TiO_2	0.53	tr.
Al_2O_3	14.92	1.94
Fe_2O_3	0.62	—
FeO	17.42	11.12
MnO	0.04	0.11
MgO	18.27	26.82
CaO	0.07	0.64
Na_2O	0.47	0.27
K_2O	—	0.06
F	—	—
H_2O	1.51	2.06
Ag	0.002	0.002
Ba	—	0.006
Co	0.006	0.006
Cr	0.02	0.03
Cu	0.005	0.003
Li	0.03	0.02
Ni	0.008	0.06
V	0.03	0.001
Zr	0.002	0.002

1. Anthophyllite from exomorphic zone around Wolf Creek pluton. Rabbitt (1948), No. 9, Table 2.
2. Anthophyllite from altered peridotite, Wolf Creek pluton. Rabbitt (1948), No. 30, Table 2.

chiefly to serpentine and dusty magnetite. Locally the harzburgite grades into pyroxenite, commonly a hypersthene-spinel rock, less commonly into an enstatite-spinel rock.

The orthopyroxene forms large stubby poikilitic anhedra enclosing numerous rounded olivine and smaller rounded spinel grains. Some of the pyroxene anhedra have cores rich in minute specks of an iron ore mineral, and some also contain very thin exsolved clinopyroxene lamellae (Bushveld-type pyroxenes).

Olive green to brown spinel varies in amount from 1 to about 15%. The color usually is constant in a single specimen, but some spinels are zoned with darker cores and light margins. One unusual type of green spinel forms large anhedra choked with dusty magnetite pinpoints. Chromite and ilmenite were noted in a few rock specimens. Small amounts of primary magnetite occur in most types. Apatite and sphene are rare accessories.

EXOMORPHIC EFFECTS

Most of the pre-Cherry Creek group rocks into which the pluton has been intruded are hornblendic types (hornblende schist, gneiss and amphibolite) or quartz-feldspar gneisses (± garnet and biotite). The quartz-feldspar gneisses have been little affected by the intrusion except very locally near the contacts, where they have been converted to coarse garnet-sillimanite gneisses with strongly sericitized plagioclase. The hornblendic rocks have been extensively and variously altered. Varieties occurring marginal to the pluton are:

1. Coarse-grained hornblende amphibolite with randomly oriented hornblende blades, up to several inches long, that display a brilliant blue schiller. The schiller results from the presence of very thin, irregular plates of a dark brown mineral arranged parallel with the *c* axis of the hornblende. This amphibole was called ferroanthophyllite by Sinkler (1942)
2. Hornblende gneiss with garnet porphyroblasts as large as five inches in diameter
3. Diopside gneiss with garnet, sericitized plagioclase, abundant sphene and minor chlorite and serpentine
4. Anthophyllite-actinolite schist
5. Anthophyllite-rich schist with minor quartz and cummingtonite and accessory magnetite, spinel and zircon

The anthophyllite of rock type 4 has been analyzed (No. 1, Table 2) and its optical properties have been determined (No. 1, Table 3).

Xenoliths of formerly hornblendic wall rock are common and may be large; some reaching 4×50 feet in plan. Both large and small xenoliths show alterations that are usually even more extensive and varied than

TABLE 3. OPTICAL PROPERTIES OF ANALYZED ANTHOPHYLLITES AND OF CLINOHUMITE

1. (Na)	2. (Na)	3. (Na)
$\alpha=1.6520$ pale tan	1.6162 colorless	1.655 orange
$\beta=1.6603$ pale tan	1.6290 colorless	1.678 pale orange
$\gamma=1.6695$ smoky gray	1.6410 colorless	1.700 yellow
(+) 2V=87°	(+) 2V=88°	(+) 2V=90° r>v extreme

1. Exomorphic anthophyllite. Rabbitt (1948).
2. Anthophyllite from altered peridotite. Rabbitt (1948).
3. Clinohumite from altered peridotite. In part from Lindberg (1947).

those produced in similar wall rocks. Altered rock types represented in xenoliths are:

1. Anthophyllite-hornblende rocks
2. Anthophyllite-cummingtonite-quartz rocks
3. Schistose cummingtonite-quartz rocks with minor serpentine
4. Schistose biotite rock composed chiefly of subparallel biotite flakes as much as ½ inch across

ALTERATION OF THE PERIDOTITE

General. Many of the peridotite specimens examined show at least some minor alteration microscopically, and over relatively large areas various intensive alteration products also are megascopically recognizable. The alterations have produced a variety of secondary rock types that occur as irregular, gradationally bounded masses within the pluton, in some places located marginally, elsewhere more centrally. The main secondary rocks are relatively distinct types, but gradations also occur. In order of abundance they are

1. Serpentinite
2. Anthophyllite rocks
3. Actinolite rocks
4. Clinohumite-bearing rocks

It is estimated that the total outcrop area of secondary rock types is about 10% of the entire area underlain by peridotite. In addition, fracture-filling veins and sharply-bounded fracture-controlled, tabular replacement masses also are common:

1. Serpentine veins, both aphanitic, brown material and golden yellow, cross-fiber chrysotile
2. Banded veins in which one-inch chromite layers alternate with serpentine-chromite bands
3. Cross-fiber veins of olive brown anthophyllite in blades as much as 1¼ inches long
4. Actinolite replacement bodies
5. Veins of chlorite
6. Talc veinlets
7. Garnetiferous carbonate veins
8. Garnet veinlets

In harzburgite, orthopyroxene is replaced chiefly by anthophyllite or actinolite, to a much lesser extent by serpentine or talc. Olivine alters principally to serpentine plus dusty magnetite in a variety of patterns. This serpentine is chiefly antigorite; chrysotile is present locally. Less commonly olivine also is replaced by anthophyllite and rarely by actinolite, these replacements being restricted to rocks that are strongly altered. Magnetite may be replaced by pyrite.

Clinohumite rocks. Clinohumite, the rarest of the secondary minerals, is restricted to rocks that show relatively little alteration. Clinohumite-bearing rock (Lindberg, 1947) is exposed in a small pit in the SE $\frac{1}{4}$, NE $\frac{1}{4}$, sec. 1, T. 9 S., R. 7 W. The deep red mineral occurs as scattered, irregular to rounded grains and grain clusters as much as two inches across. Megascopically the host peridotite shows mainly stubby pyroxene crystals cut by veinlets of green serpentine, $\frac{1}{4}$ to one inch thick. Microscopically the rock is seen to consist chiefly of enstatite, olivine, and dark greenish brown spinel and lesser amounts of anthophyllite, actinolite, chlorite, phlogopite, magnetite and antigorite. The clinohumite forms subrounded grain clusters enclosing spinel (Fig. 3) as well as irregular relicts of both enstatite and olivine. Anthophyllite replaces clinohumite marginally and also lies across its aggregates as subhedral blades. A pale green chlorite with bright green margins replaces enstatite and clinohumite peripherally. Phlogopite and actinolite replace both enstatite and olivine, and minor serpentine is localized along enstatite-clinohumite contacts.

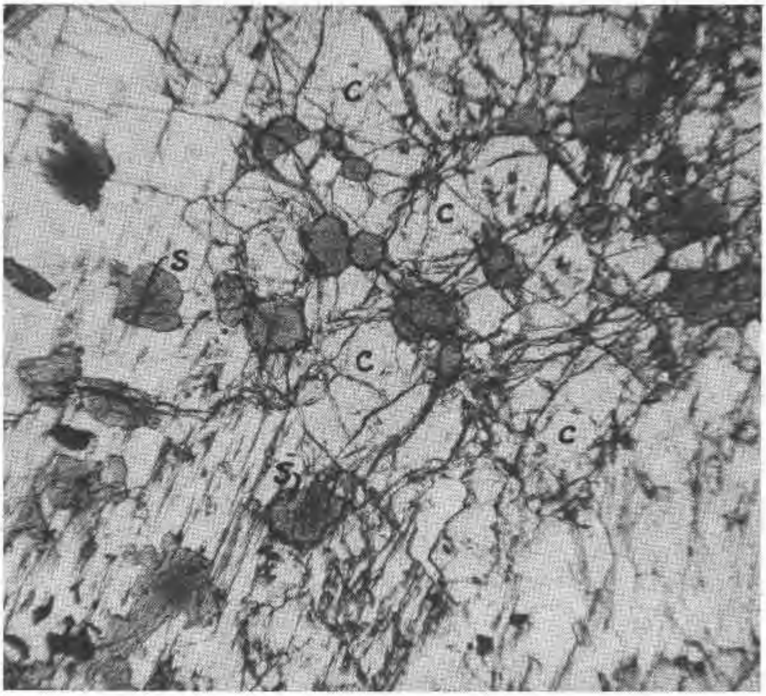

FIG. 3. Photomicrograph of clinohumite (c) rock with spinel (s) and anthophyllite (upper left and lower right). Wolf Creek ultramafic pluton, Montana. ×40, polars not crossed.

The optical properties of the clinohumite are given in Table 3, No. 3. The dispersion is exceptionally strong, with conspicuous abnormal interference colors. This and the high birefrigence indicate the mineral is the titanian variety.

Annabergite in thin, fine-grained, yellow-green crusts occurs as fracture coatings in the clinohumite-bearing rocks and in nearby harzburgite. Sinkler (1942) has presented a partial analysis:

As_2O_5	44.11%
NiO	28.71
MgO	2.19
H_2O	0.06

A check by Fleischer (Sinkler, 1942) on purified material gave 34% NiO. Under the microscope the annabergite appears as felted aggregates of very fine-grained needles, the largest of which measure only about 0.008 by 0.032 mm. The aggregates have a mean index of refraction near 1.670. The needles are very weakly pleochroic from colorless to pale green and show an extinction angle, $\gamma \wedge c = ca.\ 15°$.

Anthophyllite and actinolite rocks. Locally, particularly in the southwestern part of the intrusive, anthophyllite and actinolite rocks are common and conspicuous, forming masses as much as 50 feet long and 4 to 8 feet thick. They consist of golden-brown anthophyllite blades up to an inch long, either in subparallel or semi-radial groups, and glistening bright green blades and needles of actinolite. There is a complete series between anthophyllite-rich and actinolite-rich rocks.

The anthophyllite-rich types contain 50–75% anthophyllite with variable but subordinate amounts of actinolite and minor relict enstatite, green spinel and magnetite and minor chlorite, talc and serpentine. In some examples the anthophyllite blades have cores packed with small magnetite inclusions. An analysis of this anthophyllite has been presented by Rabbitt (1948) (Table 2, No. 2). A comparison of the compositions of the two genetically distinct anthophyllites emphasizes the differences in their origin. Number 1 (Table 2), which is exomorphic and was formed at the expense of hornblende in hornblende gneiss and amphibolite, is an aluminian anthophyllite, rich in Fe^{2+}; whereas the anthophyllite formed within the peridotite (No. 2, Table 2), largely at the expense of orthopyroxene, is low in Al but rich in Mg. It is noteworthy that this latter anthophyllite also contains about eight times as much Ni as the exomorphic type, which is not of peridotitic ancestry.

Optical properties of the analyzed anthophyllites are given in Table 3 (No. 2). That the intraplutonic anthophyllite varies somewhat in composition is shown by the following index values obtained on unanalyzed specimens from different parts of the intrusive:

$$\alpha = 1.632,\ 1.635,\ 1.636,\ 1.639,\ 1.644$$
$$\gamma = 1.652,\ 1.648,\ 1.647,\ 1.651,\ 1.660$$

Thus the range in weight % $FeO+Fe_2O_3+TiO_2+MnO$ for these anthophyllites (which will be mainly FeO since the other constituents are low) can be estimated as 11–18% (Rabbitt, 1948). Index measurements on the exomorphic anthophyllites indicate a range of $FeO+Fe_2O_3+TiO_2+MnO$ (again largely FeO) of 18–27%.

The actinolite rocks contain also variable amounts of anthophyllite, subordinate serpentine, talc and chlorite, and relicts of all the magmatic species. Like some anthophyllite, actinolite blades may be inclusion-zoned, with cores rich in magnetite specks. Actinolite, which commonly shows multilamellar twinning, replaces chiefly orthopyroxene, but also olivine and anthophyllite, and is itself replaced by chlorite. From the variation in refractive indices ($\gamma = 1.635$, 1.637, 1.645) it contains an estimated 7–21% of the iron-actinolite molecule.

Serpentinites. Serpentinites, the most abundant and widespread of the secondary rocks, are particularly common in the northeastern part of the pluton. Although megascopically they vary considerably in color, texture and grain size, mineralogically they are similar. The main colors are gray-white, gray-green and greenish black, with many mottled greenish white–greenish black. Microscopically most show a fibro-lamellar or felted arrangement of antigorite cut by veinlets of fibrous or flaky serpentine (Fig. 4). Some varieties have a mosaic arrangement of individual lamellar serpentine aggregates, separated from one another by cross-fiber veinlets along contacts. In types that contain numerous relicts of orthopyroxene, olivine and amphibole, pseudobreccia textures are conspicuous.

Serpentine replaces mainly olivine but also veins or replaces orthopyroxene, spinel, anthophyllite, actinolite and chlorite. In some cases the cleavage surfaces of orthopyroxene or amphibole are preserved pseudomorphously. Microscopically most of the serpentine shows wavy extinction and varies in color from neutral to pale green and tan. The mean refractive index varies considerably; $n = 1.555$, 1.557, 1.582, 1.595, probably reflecting mainly variation in Fe^{2+} content inherited from different parent minerals. The subordinate tan type, interleaved with the green, has the same refractive index but shows slightly higher birefringence.

Chlorite and garnet veins. In general, the mineralogy of veins of serpentine, anthophyllite and actinolite is similar to that of their replacement

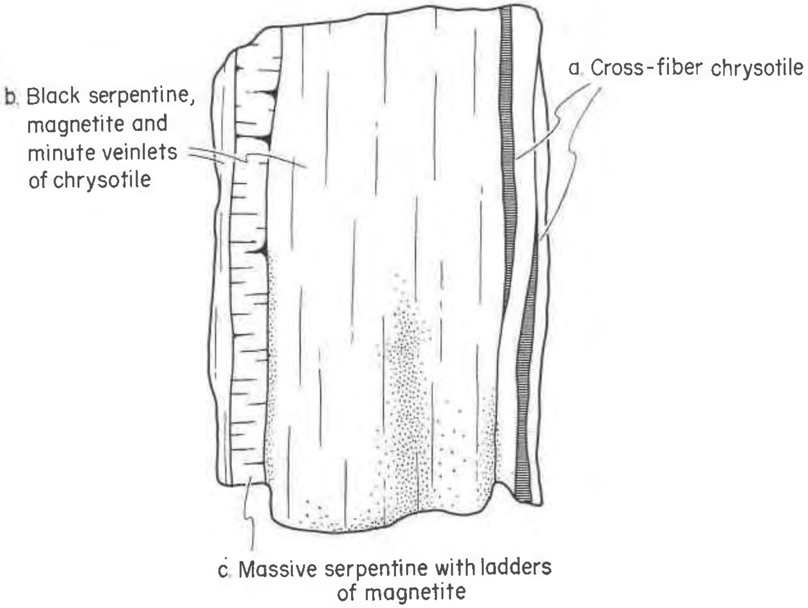

FIG. 4. Serpentine veinlets of two types cutting massive serpentinite. Wolf Creek ultramafic pluton, Montana. ×½.

bodies, but chlorite, calcite-garnet and garnet are represented only in fracture-filling vein assemblages.

Chlorite forms veinlets in which it is the sole mineral, occurring as flakes as much as ¾ inch wide. This chlorite is light green with $\gamma=1.585$, $2V=15°$, $r>v$, and contains Cr as a minor constituent. A similar variety occurs in the calcite-garnet veins.

The calcite-garnet veins are restricted to the southernmost corner of the pluton (SE¼, NE¼, sec. 11, T. 9 S., R. 7 W.), occurring in serpentinite. They are irregular in shape, anastamosing, and generally less than one foot thick, consisting mainly of coarse white calcite, fine-grained dark green serpentine and coarse dark red garnet in anhedral grains and clusters as much as several inches long. The garnet, some of which is slickensided, has $n=1.778$ and is magnesium-rich. Minor vein constituents are magnetite and chlorite. The latter occurs in two varieties: a dark green type (I) with abnormal interference colors, (+), $2V<10°$, $\gamma=1.625$; a lighter type (II) with $\alpha=1.586$, $\gamma=1.591$, $\gamma\wedge c=3°$, (+), $2V=25°$, $r<v$ distinct. Sphene occurs in two generations: as anhedra (I) as much as ½ inch long with brown cores and buff margins and as small granules (II) intergrown with chlorite.

Disseminated chalcopyrite is common in the serpentinite and altered peridotite in the vicinity of the garnet veins near the diabase-peridotite contact along Elk Creek. Since similar copper mineralization also occurs in pre-Cherry Creek group rocks near the diabase south of the peridotite and in Cherry Creek group rocks near diabase dikes elsewhere in the area, this metallization is unrelated to either the peridotite intrusion and/or its hydrothermal alteration.

The most unusual veinlets are parallel-walled, snow-white, aphanatic, and ½ inch or less thick, associated with the garnetiferous carbonate veins and, like the latter, transecting serpentinite. Under the microscope the white material can be resolved into a relatively uniform, fine-grained aggregate of rounded to six-sided grains set in a mosaic pattern. The colorless to light buff grains are biaxial positive with a moderate 2V; $\gamma-\alpha=0.006$, with abnormal blue interference tints, and the mean index of refraction$=1.781$. Each grain is divided into six twin sectors, and many also show zoning (Fig. 5). The mineral is an optically unusual garnet, confirmed by an x-ray powder photograph. The only other vein constituents are a few scattered flakes of chlorite and serpentine.

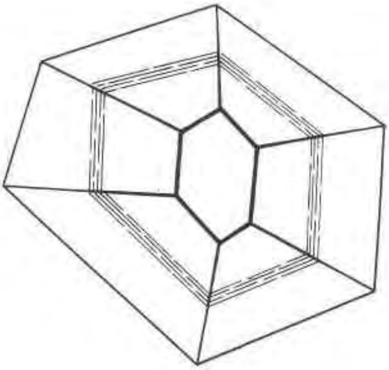

FIG. 5. Sketch of zoned anisotropic garnet grain from garnet veinlets. Wolf Creek ultramafic pluton, Montana. ×60.

PARAGENESIS

In the Wolf Creek peridotite the sequence of overlapping periods of crystallization of the magmatic constituents was 1) spinel, magnetite, chromite; 2) olivine; 3) orthopyroxene. This was followed by a series of replacements of the solidified peridotite. Some of the replacement units were formed close to the contacts; others occur within interior parts of the pluton; some appear to have been localized by single fractures or fracture sets; others show no evidence of fracture-control. The replacements and most of the veins fall into two main groups in which the sequences are:

I. Early
  1. Clinohumite
  2. Anthophyllite
  3. Actinolite
  (?)4. Phlogopite

II. Late
  5. Chlorite
  6. Serpentine
  7. Talc

The position of phlogopite in the sequence is not certain; it replaces anthophyllite and may replace actinolite, but shows no relationships to other species younger than actinolite. Similarly, the position of all of the talc is not certain; some may have formed directly after actinolite, but some talc is post-serpentine. Pyrite also cannot be placed exactly, as it replaces only magnetite. It may be relatively late, as is probably the calcite, which replaces actinolite; both occur only in strongly altered rocks.

It is noteworthy that the sequence of alteration minerals involves progressive linkage of SiO_4 tetrahedra:

Mineral	SiO_4 Linkage	Structure Type
Clinohumite	0	Nesosilicate—single tetrahedra
Anthophyllite	2.5	Inosilicates—chain
Actinolite	2.5	
Chlorite	3	Phyllosilicates—sheet
Serpentine	3	
Talc	3	

The series also shows a generally increasing H_2O content.

The position of the garnetiferous carbonate veins in the above sequence is not certainly determinable. The veins cut serpentinite and also contain some serpentine, which may be xenocrystic. The presence of serpentine within the veins, whether xenocrystic or also hydrothermal, favors a post-serpentinite formation of the veins, rather than the possibility that they originally transected unaltered peridotite, which was subsequently serpentinized. If this serpentine *is* xenocrystic, then the sequence of mineral formation in the garnetiferous carbonate veins is:

1. Serpentine
2. Calcite, garnet, magnetite, sphene I
3. Calcite, chlorites I and II, sphene II
4. Calcite

Calcite appears to have been deposited throughout the entire period, and some continued to crystallize after the silicates had been formed.

The veinlets of white birefringent garnet also appear to have been formed relatively late, this from their association with the garnetiferous carbonate veins and from their minor content of chlorite and serpentine.

The youngest mineral in the altered peridotite is annabergite. The nickel clearly was derived originally from the orthopyroxene, perhaps via anthophyllite (Table 2, No. 2). No source of the arsenic is readily apparent. It seems unlikely, however, that the annabergite was formed by hydrothermal solutions that introduced arsenic and liberated nickel from the magnesium silicates, a viewpoint favored by Sinkler (1942). Factors favoring a supergene origin are: 1) The highly oxidized state of the arsenic; 2) the very fine-grained nature of the mineral; 3) its occurrence as thin crusts along post-serpentine fractures; and 4) synthesis of the compound from aqueous solutions at room temperature and pressure.

Clinohumite and other species of the humite group are nearly entirely restricted in their occurrence to metasomatized contact marbles along silicic intrusives. Titanoclinohumite, however, occurs also in hydrothermally altered peridotites and gabbros (*e.g.* de Quervain, 1938; Huang, 1957).

GEOLOGIC HISTORY

The emplacement of the parent material for the pluton resulted from forceful injection, causing dilation, and from some stoping; for locally the wall rock foliation is markedly distorted, and xenoliths (some with foliation rotated) are not uncommon. The material apparently had not begun to crystallize appreciably prior to intrusion, for flow and autoclastic structures and banding are absent. Except for minor grain-size variations, textures are uniform throughout; there is no evidence of gravity settling.

The emplacement and crystallization of the peridotite were accompanied and closely followed by two types of wall rock changes: 1) Recrystallization at elevated temperatures without transfer of material, and 2) replacements involving exchange of materials by means of solutions moving between the pluton and the wall rocks. Recrystallization effects in amphibolite include 1) exsolution of some Fe^{3+}-Ti components in hornblende to produce schiller structure; 2) formation of very large garnet porphyroblasts; and 3) conversion of some hornblende to diopside. Since the wall rocks can in general be assigned to the intermediate part of the amphibolite facies (*i.e.* staurolite-kyanite subfacies), it can be estimated that the temperatures recreated within the contact metamorphic aureole during peridotite intrusion and crystallization ranged from slightly below those of the kyanite subfacies (exsolution effects in hornblende), through those of this subfacies (formation of coarse garnet

TABLE 4. POWDER *X*-RAY DATA FOR CLINOHUMITE

1		2	
dÅ	I	dÅ	I
5.04	s	5.02	s
4.46	s	4.44	w
3.87	w	3.86	w
3.72	s	3.70	s
3.51	m	3.48	w
3.46	m	3.44	w
3.36	w	3.35	vw
3.25	m	3.22	m
2.93	vw	2.91	vw
2.77	s	2.76	s
2.75	m	2.73	m
		2.68	vw
2.62	m	2.60	w
2.55	s	2.54	s
2.52	s	2.51	s
2.42	w	2.40	w
2.41	w	2.39	vw
2.37	m	2.36	m
2.32	vw	2.30	vw
2.26	vs	2.26	s
2.19	w	2.15	vw
2.09	w		
1.745	s	1.742	s
1.737	m	1.738	vs
1.690	w	1.681	vw
		1.624	vw
		1.612	vw
1.552	w		
		1.537	vw
1.489	w	1.488	vw
		1.479	m
1.405	w		
1.398	w	1.396	vw
1.349	vw	1.345	w

1. Titanoclinohumite, Wolf Creek peridotite, Dillon, Montana.
2. Clinohumite, Hameenkyla, Finland (Sahama, 1953).

porphyroblasts), to those somewhat above those of this subfacies (development of diopside). The exsolution intergrowth of clinopyroxene lamellae in some of the orthopyroxene grains indicates that at the time of intrusion the peridotite had a temperature of slightly over 1000° C. (Hess, 1941).

These non-metasomatic reactions were followed by replacements, both in recrystallized wall rocks and xenoliths and also in newly crystallized peridotite. Hornblende of the amphibolites was converted first to aluminous anthophyllite, which involved transfer of Mg from the peridotite to the wall rocks and the return of Ca and Fe^{2+} to the intrusive. During the second transformation, that of hornblende and/or anthophyllite to cummingtonite and actinolite, more Mg was moved to the wall rocks and Ca, Fe^{2+} and Al were transferred to the peridotitic side. The Ca and Fe^{2+} were exployed in the transformation of orthopyroxene and olivine to actinolite; Al was utilized in the formation of chlorite and minor phlogopite; and excess Ca was fixed later in calcite. Most of the mineralogical changes within the pluton, however, involved chiefly the successive rearrangement of Mg (and minor Fe^{2+}) together with Si and with increasing availibility of H_2O, into a series of hydrous silicates under continuously declining temperatures. At the lower temperatures the activities of the solutions were almost entirely restricted to the pluton itself; chlorite, serpentine and carbonate are only very minor constituents of altered wall rocks.

The hypothesis that the solutions were genetically related to the latter stages of peridotite crystallization is supported by the evidences of magnesium metasomatism in the adjoining rocks. The field evidence indicates that the formation of hydrous phases within the pluton is the result of autometasomatism involving transformation of 10% or less of the volume of peridotite. Extraneously introduced magmatic water acting on both the pluton and its wall rocks may be ruled out, for the Dillon granite, which crops out just north of the pluton, is older, being intruded by small peridotite bodies about two miles northwest of the pluton. Furthermore, many of these much smaller peridotite masses are composed entirely of unaltered harzburgite, indicating that the transformations in the Wolf Creek pluton cannot be related to any *regional* alteration.

Thus the data obtained from field observations of the pluton and a detailed microscopic study of its primary and secondary rocks as well as its wall rocks (unaltered and altered) indicate that the Wolf Creek intrusive body was forcibly implaced, probably as a largely liquid, hydrous peridotitic magma; that its *in situ*-crystallization produced exothermal wall rock effects, followed by autohydrothermal changes (under declining temperatures), generally similar mineralogically in the wall rocks, in xenoliths and in fractured parts of the pluton itself.

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