MINERAL ASSEMBLAGES AND LOW-GRADE METAMORPHIC-METASOMATIC ALTERATIONS IN AN ARCHEAN GREENSTONE BELT, MALARTIC, QUEBEC

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ABSTRACT*

The metamorphosed volcanics, sediments and basic intrusives of the Archean Greenstone Belt are composed of secondary minerals amphibole, mica, chlorite, serpentine, accessory epidote, apatite, sphene, calcite and sulphides, and variable quantities of interstitial quartz and feldspar. The greenschists are locally sheared, brecciated and affected by metasomatic and hydrothermal alterations which produce local recrystallization and diverse chemical and mineralogical changes. Chemical analyses of minerals from selected relatively fresh and altered rock and massive sulphides were made in an attempt to study chemical changes during progressive alteration of silicates. The analytical results infer the following chemical changes:

With progressive chloritization, the biotite loses more Si, Al^{VI}, Ti, K, Na, F, and Cl and gains Al^{IV}, Mg and OH.

With progressive bleaching and recrystallization, the amphibole changes from hornblende to actinolite and tremolite whereby Fe, Al, K and Ti decrease and Si, Mg and Ca increase.

*Unedited author's abstract. The paper is condensed from a larger version available from the author upon request. All analyses in the original paper are included here.

Colour and texture of serpentine are correlative with chemical composition. Serpentine granules which retain the original olivine textures contain more iron than the white fibres from late serpentine veins, and coloured granules contain more Fe and Ni than colourless granules.

Fractured serpentinites are affected by subsequent low-grade metamorphism whereby fine-grained serpentine alters to coarse-grained talc and/or chlorite, and recrystallizes to long fibres which grow perpendicular to fracture walls or fill the fractures with felty aggregates. Secondary serpentine veinlets contain thin seams of calcite and magnesite.

INTRODUCTION

Minerals in six assemblages representing relatively fresh and altered rocks have been studied in material from the Marbridge nickel deposits, Malartic -La Motte area, Quebec (Fig. 1). The ore deposits consisted of massive and disseminated sulphides of which a high proportion at the No. 2 mine was primary millerite. Cross-sections of the ore zones and the location of the specimens studied (mainly drill cores) are shown in Figure 2.
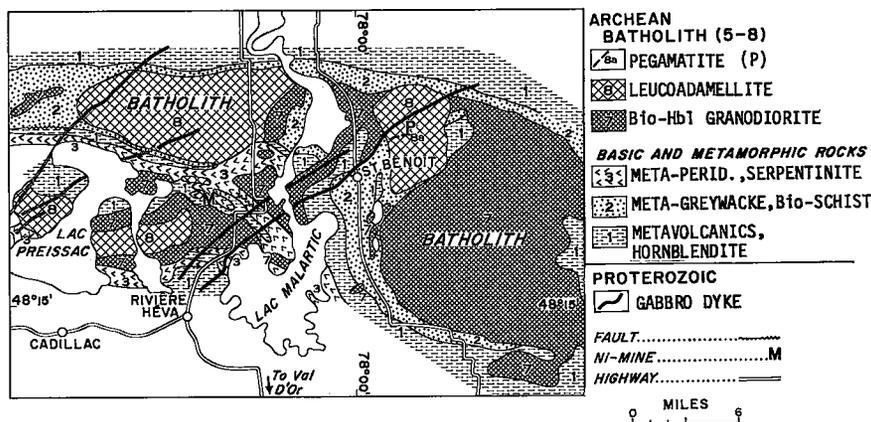

FIG. 1. Location of the Marbridge deposits in the Malartic - Val d'Or area, Quebec. (Geological map from Dawson 1966).
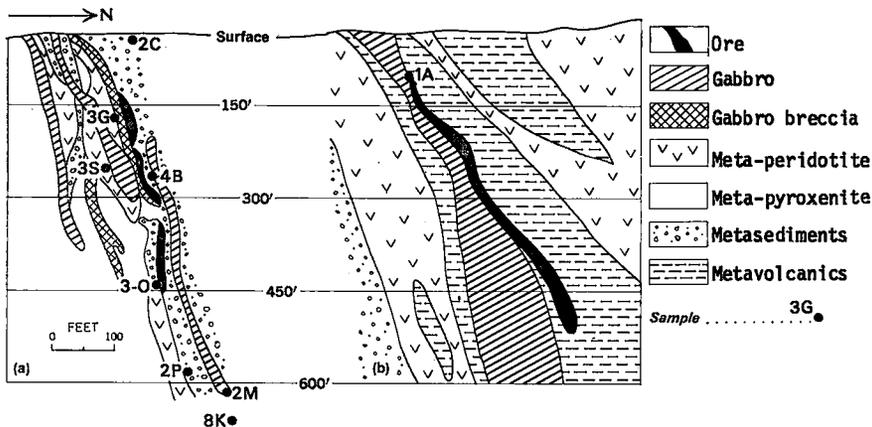
FIG. 2. Vertical cross-sections of the Marbridge 1 and 2 deposits showing the locations of the ore lenses and the samples studied; (a) Marbridge 2 mine (after Buchan & Blowes 1968), (b) Marbridge 1 mine (after Clark 1965).

The geological history of the Malartic - Val d'Or district is summarized in Table 1, which is based on data from Tremblay (1950), Snelling (1962), Fairbairn et al. (1965), Reesman (1968), Steiger & Wasserburg (1969), Douglas (1970), and Gates & Hurley (1973). It is evident that the four lithological units that were sampled may have been affected by one or more periods of alteration. The occurrence of "bleached" hornblende (Tremblay 1950), and the presence of the lithian amphibole, holmquistite (Nickel et al. 1960) have been attributed to metasomatism related to intrusive rocks; Clark (1965) and

Buchan & Blowes (1968) found marked chemical differences between the relatively fresh rocks and their altered equivalents. Thus, in order to further study the chemical and mineralogical differences, fresh and altered specimens were collected from the same rock unit. The specimens are numbered to correspond with the rock units shown in Figure 1, and special characteristics, such as massive sulphide ore and specific minerals, are designated by letters (Table 2). Thus "2Ob" is biotite "b" from massive sulphide ore "O" in mineralized meta-greywacke from rock unit 2. Specimens from late granitic rocks and transecting pegmatites (units 8 and 8P in Fig. 1) have been described previously (Rimsaite 1968).

As the metamorphic history of the area is complex, the emphasis in the present paper is documentation rather than interpretation; detailed analyses are given for specific minerals and mineral groups, such as serpentines and amphiboles, in order to show their variability and, in some cases, the compositional trends during retrograde and contact metamorphism.

TABLE 1. TIME-STRATIGRAPHIC SEQUENCE AND LITHOLOGICAL UNITS, MALARTIC AREA, QUEBEC

Time-Stratigraphic Sequence	Lithological Units (Tremblay 1950)	Mineralization	Mineral Specimen Nos.
HELIKIAN ERA KEWEENAWAN			
Gabbro dykes 1.2 b.y. (GSC 1970)	Gabbro dykes		
APHEBIAN ERA			
Carbonate veins 1.6 b.y. (MIT 1968)		Carbonatization, dissem. Py,Po,Pn,Sp	2A,2P
POST-TIMISKAMING	Pegmatite and crushed granite		
Micas 2.24-2.65 b.y. (Dawson 1966)	Batholith		
	Quartz porphyry Diorite		
	Meta-pyroxenite, breccia, alt. peridotite		4B,4BF
		Massive sulphides	
		Sulphide-peridotite	3S,30, 3G
TIMISKAMING & KEEWATIN	Peridotite; serpentinite		
K/Ar biotite 2.46 b.y. altered biotite 2.38 b.y. (Snelling 1962)	Kewegama Group Biotite-hblde schist Greywacke cut by peg.		2C,2F 2A,2P 2M
Rb/Sr isochron (MIT 1965) Kirkland Lake Timiskaming Series 2.38 b.y. Keewatin 2.57 b.y.	Malartic Group Biotite-hblde schist, amphibolite derived from volcanics		1A,1B
KEEWATIN	Kinojevis Group D:rhyolite C:agglomerate		
	B:altered basic volcs. A:basaltic, andesitic lavas	Py,Po,Pn fragments	

ANALYSES

Electron microprobe analyses of 49 fresh and altered minerals (Table 2) were obtained using an energy dispersive spectrometer and procedures described by Lachance & Plant (1973). Element distributions in altered and zoned minerals were studied in x-ray scanning images. Four minerals were concentrated for partial chemical analyses.

The identification of all analyzed altered grains was confirmed by x-ray powder diffraction patterns.

TABLE 2. ELECTRON MICROPROBE ANALYSES OF Fe-Mg MINERALS IN SIX MINERAL ASSEMBLAGES, MALARTIC AREA, QUEBEC

Assem-blage	Rock unit or association	Mineral number	Mineral description	weight %											Ni
				SiO_2	Al_2O_3	TiO_2	FeO	MgO	CaO	MnO	Cr_2O_3	Na_2O	K_2O	
1 a	Meta-greywacke	2Mb	Biotite in quartz	37.3	18.3	1.1	22.8	11.1	0.0	0.1	0.0	0.0	9.8	
			in ore	35.6	17.3	1.2	24.1	9.5	0.0	0.2	0.0	0.2	9.6	
			in muscovite	34.3	17.1	1.0	29.6	8.6	0.0	0.2	0.0	0.0	7.7	
		2M	Muscovite	45.4	32.2	0.5	4.5	1.2	0.0	0.0	0.0	0.7	10.0	
		2Msg	Serpentine granule in muscovite	38.4	11.2	0.0	20.7	25.5	0.0	0.1	0.0	0.0	0.0	
b	Meta-pyroxenite	3Gh	Hornblende dark green	37.8	11.6	0.5	19.3	8.7	11.9	0.3	0.0	1.3	0.3	
			pale green	41.1	11.6	0.4	16.7	10.3	11.3	0.0	0.0	1.4	0.3	
		3Gb	Biotite	33.5	14.3	1.8	29.1	7.2	0.2	0.1	0.0	0.0	8.5	
		3Gl	Serp granule in hornblende	36.8	7.2	0.0	26.1	15.5	0.6	0.1	1.1	0.2	0.0	
		3Gbr	Brown serp granule in hblde	41.9	9.4	0.0	20.2	21.2	0.5	0.0	0.0	0.4	0.0	
		3GS-2	Serp pseudo after olivine "islands"	34.0	7.6	0.0	22.3	16.4	0.5	0.1	0.1	0.1	0.0	
		3GS-1	Serp veinlet in serp granule	33.5	7.8	0.0	35.9	9.1	1.0	0.1	0.1	0.1	0.0	
2 a	Gabbro breccia-fragments	4Bh	Green hornblende	50.5	7.2	0.5	13.9	14.3	12.2	0.4	0.1	1.1	0.3	
		4Bb*	Biotite	36.9	15.4	1.9	16.6	13.7	0.1	0.1	0.2	0.1	9.6	
		4BSp	Spinel in biotite	18.5	6.1		31	6.8		1.4	31			
b	Gabbro breccia-veins	4BFh	Hornblende in feldspar	47.0	8.3	0.4	14.4	13.2	11.7	0.3	0.4	1.4	0.3	
		4BFb	Biotite in hornblende	37.8	16.8	1.0	17.3	16.2	0.2	0.0	0.0	0.2	8.3	
		4BFc	Chlorite in feldspar	26.4	20.6	0.0	19.7	20.6	0.0	0.3	0.0	0.2	0.0	
		4BFm	Muscovite in feldspar	46.4	39.8	0.2	0.3	0.2	0.1	0.0	0.0	1.3	10.6	
3 a	Altered biotite-hornblende schists	1Ah**	Hornblende, dark center	45	8.5	0.7	15.8	11.8	11.7	0.3	0.1	1.5	0.4	
		1Aa	Actinolite rim	51	4.4	0.2	12.1	16.3	12.0	0.3	0.1		0.1	
		1Bb	Fresh biotite	35	14.4	2.3	16.7	11.6	0.0	0.1	0.4		9.7	
		2Cl	Sagenitic biotite	35.2	18.2	1.1	17.9	18.0	0.0	0.1	0.0	0.1	5.7	
		2C2***	Chloritized biotite	26.6	21.4	0.1	15.3	23.9	0.0	0.2	0.0	0.1	0.0	
		1Bal†	Allanite in biotite	30	24.6	0.0	10.1	0.4	12.0	0.4	1.3	0.0	0.0	
		1Bep	Epidote rims on allanite	38.8	21.5	0.0	15.6	0.2	23.3	0.1	0.0	0.2	0.0	
b	Fractured and hydrated serpentinite	3S-2	Green serp pseudo of ol "islands"	40.6	0.0	0.0	6.4	36	0.1	0.2	0.0	0.0	0.0	0.5
		3S-1	White serp in fractures in serp ol	39.8	0.0	0.0	2.6	38.8	0.0	0.0	0.0	0.0	0.0	
		3S-10††	Serpentine fibres	42.5	0.3	0.0	2.4	41.2	0.3	0.0	0.0	0.1	0.1	
4 a	Carbonatized serpentinite	3SCtr	Tremolite after serp "islands"	58.2	0.1	0.0	1.9	23.6	13.6	0.2	0.0	0.1	0.0	
		3SCcl	Chlorite after serp veinlets	27.7	15.8	0.0	6.2	30.4	0.2	0.3	0.0	0.0	0.0	
b	Contact metamorphic meta-greywacke	2Aa	Tremolite-actinolite	56.2	1.0	0.0	2.6	22.4	13.2	0.2	0.0	0.3	0.0	
		2Atr	Porphyroblastic tremolite	58.2	1.2	0.0	0.8	24.2	13.7	0.2	0.1	0.4	0.0	
		2P	Phlogopite	39.2	15.7	1.0	6.9	20.1	0.1	0.1	0.1	0.2	9.6	
5	Fresh silicates in massive sulphides	1AOh	Hornblende in sulphides	49	8.7	0.6	15.3	12.3	12.1	0.0	0.0	0	0.5	
		1AOa	Actinolite rims on hornblende	52	4.9	0.3	12.5	13.6	11.9	0.0	0.0		0.2	
		1BOb	Biotite in sulphides	36	13.6	2.3	17.4	13.6	0.0	0.1	0.3		9.3	
		1SO	Orange-brown serpentine granule	32	4.6	0.0	17	26.3	0.1	0.0	0.0		0.0	0.7
6 a	Meta-peridotite fragments in massive sulphides	30Sc	Chlorite in peridotite fragment	42.5	0.4	0.0	4.9	39.4	0.0	0.0	0.0	0.0	0.0	
		30St	Talc in peridotite fragment	62.6	0.0	0.0	1.6	31.8	0.0	0.0	0.0	0.0	0.0	
		30Gp	Pale green serp granule in sulphide	45.1	0.2	0.0	4.9	41.3	0.0	0.0	0.0	0.0	0.0	
		30Gbr	Orange-brown serp gran in sulphide	41.1	0.1	0.0	9.6	32.6	0.0	0.1	0.0	0.0	0.0	0.7
		30S-4	Serp rim on spinel	31.0	4.1	0.1	10.0	32.5	0.0	0.2	0.0	0.0	0.0	
		30Sp	Spinel in sulphide ore	0.0	5.8	0.0	52.4	0.0	0.0		37.0	0.0	0.0	
		30Spv	Cross-cutting secondary spinel	3.7	1.6	1.0	40.8	3.0	0.0		44.7	0.0	0.0	
b	Alt. biotite, recryst. talc & trem. in massive sulph	1Ach	Chlorite	27	17	0.0	8.5	35.0			0.3		0.0	
		1BO	Biotite in ore	34	15.8	0.8	13.2	21.4			0.4		9.8	
		1TOp	Pale green talc in ore	58	0.1	0.0	7.4	29.1	0.0	0.0	0.0	0.0	0.0	
		1TOb	Brown talc in ore	55	0.9	0.0	13	23.9	0.2	0.0	0.0	0.0	0.0	

Electron microprobe analyses by G.R. Lachance. Total Fe as FeO. Chemical analyses below are by J.-L. Bouvier and J.G. Sen Gupta.
*H_2O 2.9, F 0.39, Cl 0.18, Li_2O 0.04, FeO 13.65, Fe_2O_3 3.23   **H_2O 2.1, F 0.14, Cl 0.18, Li_2O 0.01, FeO 14.43, Fe_2O_3 3.93
***H_2O 10.9, F 0.11, Cl 0.13, Li_2O 0.02, FeO 13.53, Fe_2O_3 0.45 wt %.   †Also contains about 10% CeO and rare earths.
††H_2O 12.82, F 0.11, Cl 0.16, Li_2O 0.00, FeO 0.45, Fe_2O_3 1.89 wt %.

DISCUSSION OF PARAGENESES IN SIX ASSEMBLAGES

From a microscopic study, the minerals studied were grouped into the six "assemblages" listed in Table 2. The term assemblage in this paper does not denote mineral associations characteristic of a rock; rather, the term indicates the presence of a characteristic feature, such of the preservation of original peridotitic textures, the presence of "bleached" amphibole, or the occurrence of alteration such as hydration or recrystallization. In the treatment below, assemblages 1 and 2 are considered as "primary" in that the first contains relict peridotitic textures, and the second has not suffered retrograde alteration. These are used for comparison with the other four assemblages which have been subjected to various alterations such as hydration and carbonatization. Most important is that, regardless of the type of alteration, "peridotite relics" have been traced through all the altered assemblages to show the various chemical changes that have occurred.

Assemblage 1

Original peridotitic textures are preserved in fragments in two different rock units — meta-greywacke and "meta-pyroxenite". The meta-
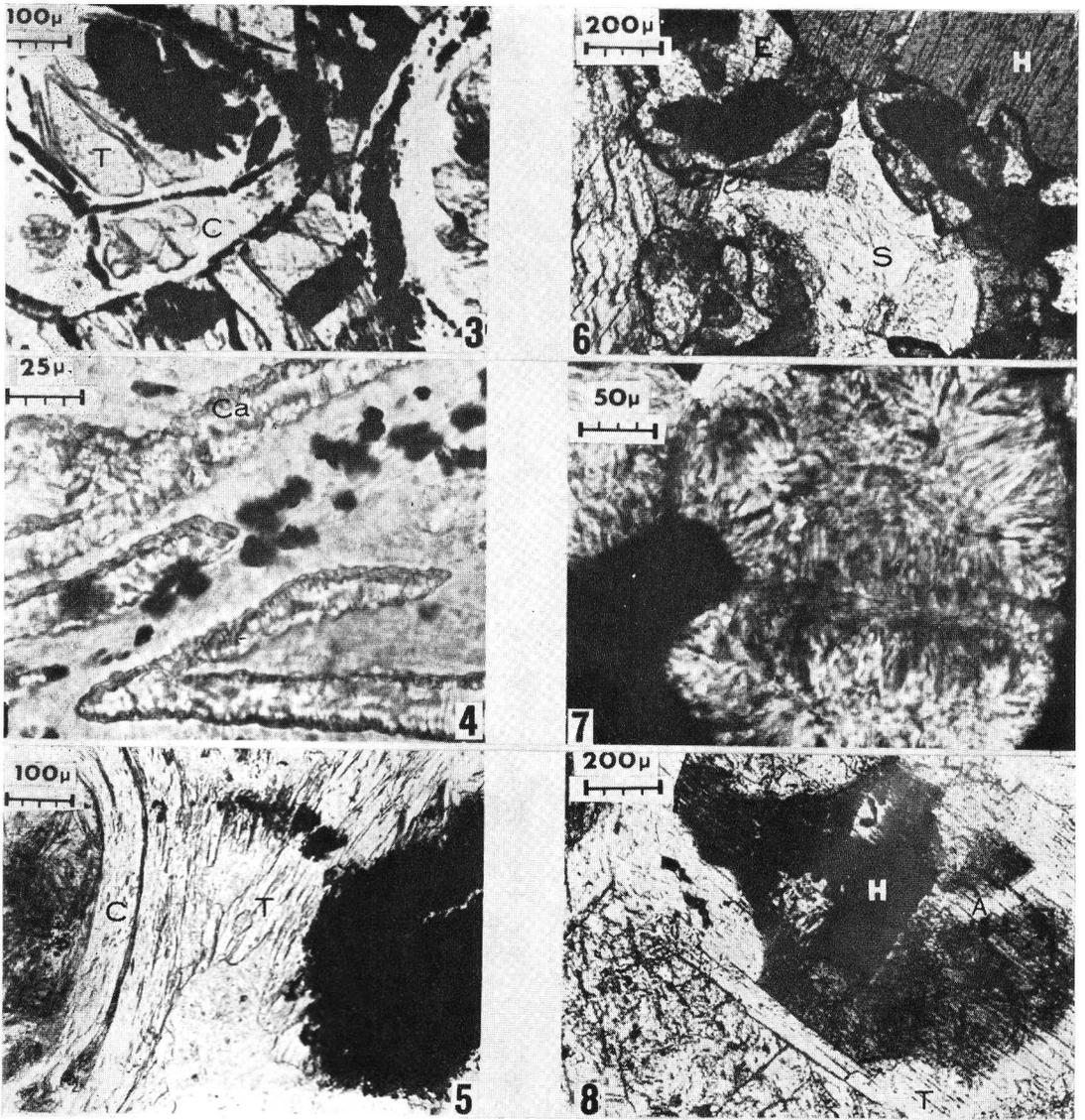
FIG. 3. Photomicrograph showing altered olivine granules in carbonatized serpentinite of assemblage 4. Serpentine veinlets are replaced by chlorite (C), and carbonate and oxides; olivine "islands" are replaced by tremolite (T) and sulphides (opaque).

FIG. 4. Enlargement of Figure 3 showing secondary oxides (opaque) and carbonate (Ca) in serpentine veinlet.

FIG. 5. Deformed olivine pseudomorphs, replaced by chlorite (C) and opaque sulphides, in massive serpentine recrystallized to antigorite and tremolite (T).

FIG. 6. Porphyroblastic hornblende of assemblage 1 with enclosed patch of mineralized serpentinite (S). Olivine granules are replaced by epidote (E) and sulphides.

FIG. 7. Same thin section as Figure 6, showing recrystallized serpentine granules enclosed in sulphides.

FIG. 8. A porphyroblast of "bleached" amphibole consisting of hornblende (H), and patches of actinolite (A) that grade into tremolite (T). Assemblage 3a.

greywacke is a schist composed of quartz-oligo-clase and biotite bands, the latter containing sulphide fragments with adhering recrystallized serpentine granules. The biotite bands, which contain accessory epidote, allanite, sphene, and apatite, are partly replaced by coarse-grained muscovite porphyroblasts that crystallized along the serpentine-sulphide fragments. Microprobe analyses (Table 2) indicate that all biotite in the meta-greywacke is relatively high in Al, that the muscovite is phengitic, and that biotite associated with muscovite is highest in iron. Green serpentine granules partly enclosed in Fe-Ni sulphides and within muscovite porphyroblasts apparently recrystallized *in situ*: their relatively high Al and Fe contents differ markedly from the composition of colourless granules in the periditote host (assemblage 3b, Table 2).

The "meta-pyroxenite" studied consists predominantly of hornblende and about 20% sulphides enclosing recrystallized serpentine granules (Figs. 6, 7). These and minor biotite, ilmenite, and spinel, alternate with lighter, narrower bands composed of oligoclase-andesine, epidote, and minor quartz.

The hornblende varies from dark blue-green to pale green, with the lighter, "bleached" grains being actinolitic (Table 2). Most of the serpentine granules have recrystallized to brown and dark reddish brown acicular and felty aggregates, but relict textures are represented by pseudomorphs formed from residual "olivine islands", and by veinlets characteristic of initial serpentinization along olivine fractures. Analyses of these are given in Table 2, and a more detailed description of the relationships between parent olivine and the various serpentine types is given by Rimsaite (1973).

Assemblage 2

Assemblage 2 is an example of brecciation without accompanying hydration. The gabbro breccia studied (Fig. 2) consists of dark fragments of "meta-pyroxenite" (mainly hornblende) in white "veins" of patchy, porphyroblastic oligoclase. Biotite and Fe-Cu sulphides occur along the vein margins. The feldspathic portions of the rock also contain small quantities of ferromagnesian minerals and vice versa.

Colour variation in the green hornblende in the breccia fragments is not prominent. The few grains of biotite that occur along hornblende cleavage planes and fractures contain inclusions of spinel and allanite crystals rimmed with epidote and prominent pleochroic haloes.

The oligoclase veins in the gabbro breccia also contain hornblende, biotite, and traces of chorite and muscovite. The ferromagnesian minerals contain more Al than their counterparts in the breccia fragments (Table 2).

The "gabbro breccia" may be an example of mineral segregation formed from an originally homogeneous mafic rock.

Assemblage 3

Assemblage 3a, an altered schist, is an example of chemical and mineralogical changes that occur in fractured meta-sediments and meta-volcanics of rock units 1 and 2 (Fig. 1). Amphibole in the altered schist occurs as porphyroblasts with actinolitic patches and rims (Fig. 8). Biotite has altered to sagenitic biotite-chlorite, and to chlorite free of rutile. Relatively fresh residual biotite contains abundant inclusions of Ce-rich allanite with epidote rims (Table 2).

In biotite-hornblende schists at the contact with massive sulphides, x-ray scanning images show relics of the original minerals in newly-formed overgrowths. Biotite has been partly replaced by chlorite and small prismatic crystals of tremolite.

As a second example showing the changes effected by fracturing and hydration, serpentinite assemblage 3b (Table 2) was chosen. In fractured serpentinite breccia, serpentinized olivine granules and associated magnetite veinlets are deformed, stretched, and locally replaced by coarse-grained chlorite. Some fine-grained serpentine aggregates recrystallized to coarse-grained chlorite-antigorite flakes which are compositionally similar to the original serpentine, and some fractures and veins are filled with serpentine fibres (Table 2), with iron oxides, calcite, dolomite, magnesite, stichtite, and sjogrenite along the fracture walls.

Notable is the low Al_2O_3 content of these serpentines compared to that of recrystallized material within hornblende in assemblage 1.

Assemblage 4

Some brecciated rocks are locally replaced by patches of coarse-grained carbonates. The carbonate-rich rocks, which have a pitted, crumbly appearance, have been observed in drill-core samples a few feet from their contact with massive sulphides. Buchan & Blowes (1968) reported that meta-peridotites locally contain 30% carbonates. The carbonatization is apparently related spatially and temporally with late fracturing and brecciation. The carbonate patches and veins transect and replace earlier minerals.

Carbonatized serpentine and contact metamorphic meta-greywacke were examined in the present study. The serpentinite consists of vari-

able proportions of serpentine, chlorite, tremo-
lite, calcite and other carbonates, epidote, oxides,
and sulphides. Serpentinized olivine granules
have retained their original textures despite par-
tial to complete replacement by calcium-bearing
minerals (Fig. 3). Serpentine formed from oli-
vine "islands" is usually replaced by tremolite,
magnetite, or remobilized sulphides; "rim" and
veinlet serpentines are replaced by calcite and
chlorite $\pm$ magnetite. Analyses for these types
of tremolite and chlorite are given in Table 2.

The carbonatized meta-greywacke contains
calcite patches, minor diopside, porphyroblastic
tremolite and epidote, and remnant phlogopite
partly replaced by pyrite, pyrrhotite, pentlandite,
and tremolite. Fine-grained quartz in the ground-
mass is clouded by iron oxides and sphalerite.
The original banded appearance of the meta-
greywacke has been obliterated by patches of
calcite and porphyroblastic tremolite, which re-
placed all minerals, including the older actino-
litic tremolite. Analyses of both types of tre-
molite are given in Table 2. Note also that the
porphyroblasts contain slightly more Al and Na,
and less Fe than the tremolite pseudomorphs
in the carbonatized serpentinite described above,
thus indicating that the secondary tremolites re-
flect their environment of crystallization and
the compositions of the minerals they replaced.

Assemblage 5

Assemblage 5 consists of about 90% massive
sulphides (pyrite-pyrrhotite-chalcopyrite) and
about 10% hornblende rimmed by actinolite,
biotite, and serpentine. Although both amphi-
boles are chemically similar to those in unmin-
eralized assemblage 3 (Table 2), the actinolite
rims here are narrower and the contrast in Si
and Mg from cores to rims is less pronounced.
At the contact between massive sulphides and
hornblende-biotite schist, some of the rimmed
hornblende crystals also contain overgrowths of
a dark green alkali amphibole.

Biotites and serpentines from this assemblage
are chemically similar to those in equivalent un-
mineralized host rocks. An exception is an ap-
parently recrystallized orange-brown serpen-
tine granule with 0.7% Ni (Table 2).

Assemblage 6

The previous assemblage was considered to
be representative of fresh silicates in massive
sulphides; assemblage 6 consists of (a) recrystal-
lized meta-peridotite, and (b) altered minerals,
both of which are also enclosed in massive sul-
phides.

The specimens of assemblage 6a consist of
about 90% sulphides, with meta-peridotite in-
clusions ranging from a few mm to a few cm
in size. The sulphides also contain serpentine
granules, thin serpentine veinlets, and serpen-
tine rims on fractured spinel grains cut by sec-
ondary spinel. The meta-peridotite fragments
are recrystallized to coarse-grained acicular
chlorite-antigorite and talc. Analyses for all these
minerals are given in Table 2. X-ray scanning
images confirmed that the spinel veinlet con-
tains more Cr and Fe than its host, and that in-
clusions account for the anomalous analysis.

In assemblage 6b, the massive sulphides
enclose long, intersecting actinolite-tremolite
prisms, biotite partly replaced by chlorite, and
serpentine granules partly altered to pale green
and brown talc. Analyses of chlorite, biotite, and
talc are given in Table 2.

SUMMARY AND CONCLUSIONS

Mineralogical and chemical changes have been
studied in specimens representing four lower
lithological units in the Archean greenstone belt
in the Malartic area, Quebec. The rocks have
been affected by regional and local retrograde
metamorphisms, and by local alkali metaso-
matism, hydration, and carbonatization.

Six mineral assemblages characterized in this
study consist largely of hydrous ferromagnesian
minerals, with variable quantities of altered oli-
goclase, quartz, and massive sulphides. Although
much of the original rock texture and mineralogy
has been obliterated by porphyroblasts, ser-
pentinized olivine granules have been traced
from meta-pyroxenites to serpentines embedded
in massive sulphides and metamorphic silicates.

Chemical changes in heterogeneous serpen-
tines, in zoned amphiboles and epidotes, and in
chloritized micas have been documented. In
some cases, such has been shown for the micas,
the type of host rock seems to have had a de-
monstrable effect on composition. The over-all
chemical and mineralogical trends established
in the present study confirm and support the
petrological and chemical trends reported by
Buchan & Blowes (1968).

The assistance of Falconbridge Nickel Mines Limited in obtaining specimens from the Marbridge nickel deposit is very much appreciated.

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