Canadian Mineralogist
Vol. 17, pp. 847-855 (1979)

PETROLOGY OF SERPENTINIZED METAMORPHIC OLIVINE, BIRD RIVER SILL, MANITOBA

C. J. A. COATS
Falconbridge Nickel Mines Limited, Winnipeg, Manitoba R3J 0M1

R. BUCHAN
Falconbridge Metallurgical Laboratories, Thornhill, Ontario L3T 4A8

Abstract

The Archean Bird River greenstone belt in southeast Manitoba includes the layered and differentiated Bird River sill. Ultramafic rocks in the basal portion of the sill at Maskwa West contain talc, magnesite, dolomite, chlorite, chrome spinel, magnetite and lizardite. Relict cumulus olivine textures preserved by magnesite are recognizable from the distribution of fine-grained magnetite inherited from the serpentinization of original olivine. Lizardite is pseudomorphic after coarse-grained regenerated olivine, with morphologies described as rosettes, blades and "veins". The sill and surrounding volcanic rocks at Maskwa are in the lower-amphibolite facies. From petrological evidence concerning the sill rocks, we infer the following sequence of events: (1) intrusion of primary peridotite, (2) serpentinization, (3) formation of metamorphic bladed olivine and (4) lizardite pseudomorphs. An integral part of this sequence is the development of magnesite, dolomite and late calcite veins during pervasive CO_2 metasomatism, replacing the early serpentine (2) and developing the bladed olivine (3). Reference to the calculated temperature–gas-composition diagram of CaO–MgO–SiO_2–H_2O–CO_2 at 2000 bars suggests that $X(CO_2)$ is limited to greater than 0.20 and maximum temperature to about 515°C.

Sommaire

Le filon-couche différencié de Bird River se trouve dans la ceinture de roches vertes archéennes du même nom, dans le sud-est du Manitoba. A Maskwa Ouest, les roches ultramafiques à la base du sill contiennent talc, magnésite, dolomite, chlorite, spinelle chromifère, magnétite et lizardite. L'olivine originelle est cumulative, à textures préservées par la magnésite. Ces dernières se reconnaissent à la distribution de magnétite à grain fin qui date de la serpentinisation. La lizardite, en rosettes, lames ou veinules, est pseudomorphe d'une olivine reconstituée à gros grain. A Maskwa, le filon-couche et les roches volcaniques encaissantes ont recristallisé dans le faciès amphibolite inférieur. Nous concluons à la chronologie suivante des événements: 1) intrusion de péridotite primaire, 2) serpentinisation, 3) formation de lames d'olivine métamorphique, 4) pseudomorphose par lizardite. La formation de magnésite, dolomite et calcite (en veinules tardives) au cours d'un métasomatisme intense à CO_2 fait partie de la séquence; cet assemblage de minéraux remplace la serpentine hâtive (2) et accompagne le développement de l'olivine en lames (3). Les relations de phase du système CaO–MgO–SiO_2–H_2O–CO_2 à 2000 bars, observées sur le diagramme (calculé) de la composition de la phase fluide en fonction de T, suggèrent que $X(CO_2)$ excède 0.20 et placent la température maximale à ~ 515°C.

(Traduit par la Rédaction)

Introduction

The Bird River greenstone belt in southeastern Manitoba comprises a suite of Archean volcanic and sedimentary rocks bounded by granitoid intrusions. It is 5-10 km wide and strikes east–west for 55 km, from Lac du Bonnet in the west to the Manitoba–Ontario border in the east. Principal geological studies of the greenstone belt are by Springer (1950), Davies (1955), Butrenchuk (1970), Karup-Møller & Brummer (1971), Juhas (1973) and Trueman (1975). The volcanic pile is composed of a lower mafic sequence consisting of pillow basalts, porphyritic flow-basalts, hyaloclastic breccias, tuffs and amygdaloidal flow-basalts, cut by stocks and sills of gabbro. An upper felsic sequence is made up of flow-banded rhyolite, breccias, tuffs and quartz porphyry, together with minor oxide-facies iron-formation. Conglomerate, containing clastic material from all the above rock-types, overlies the volcanic pile and is in turn overlain by a sequence of greywacke turbidites (Trueman *et al.* 1975).

The units of the greenstone belt, together with the bounding granitic bodies, the Maskwa Lake quartz diorite on the north side and the Lac-du-Bonnet quartz monzonite on the south side, were emplaced in the time span 2.49 – 2.65

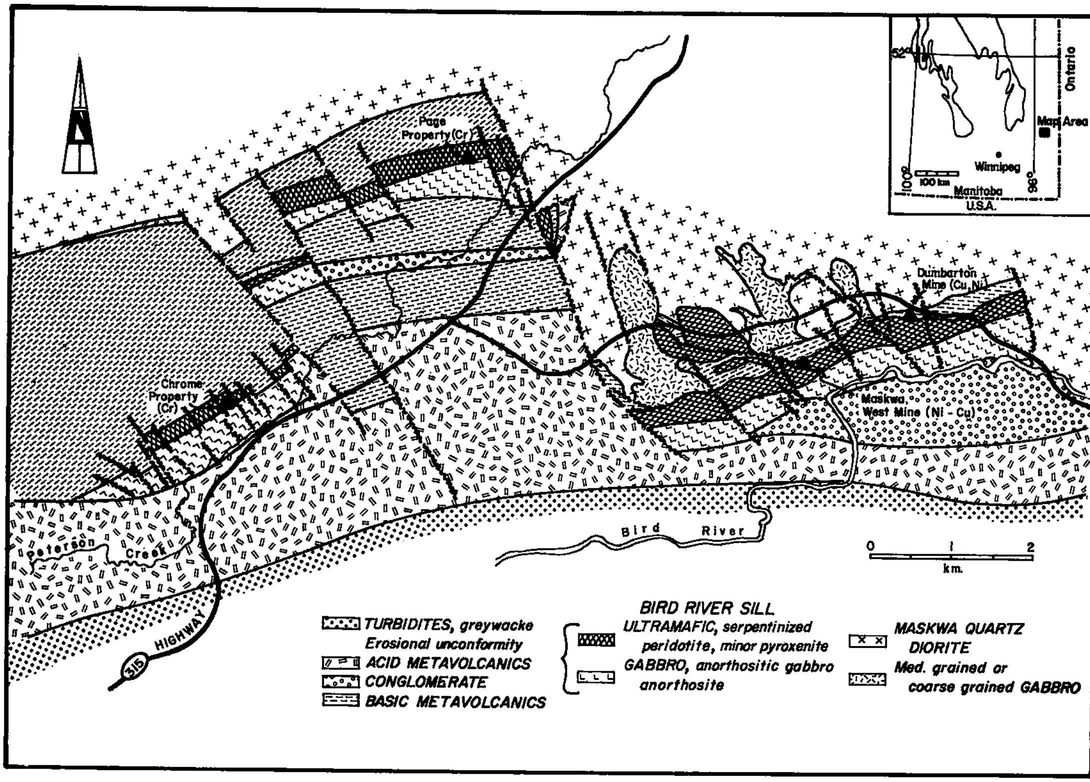

FIG. 1. Geology of the Bird River sill in the Chrome–Page–Dumbarton area and location of the Maskwa West Ni–Cu deposit.

Ga (Penner & Clark 1971). The metamorphic grade changes progressively from greenschist facies at Lac du Bonnet in the west to amphibolite facies at the interprovincial boundary. At the Maska West mine, located in an approximately central position in the belt, the metaporphic grade is in the lower amphibolite facies (Juhas 1973, Trueman & Turnock 1975).

THE BIRD RIVER SILL

The Bird River sill is a layered, differentiated ultramafic to gabbroic body emplaced within the volcanic rocks of the lower mafic sequence. Cross-faulted segments of the sill attain an outcrop length of about 30 km in the Bird River belt and the average thickness is close to 1000 m. The sill is composed principally of a lower peridotite unit and an upper hornblende-gabbro unit, with less prominent layers composed of pyroxenite, olivine gabbro, chromitite and anorthositic gabbro. The attitude of the compositional layering is conformable with south-facing pillow structures in adjacent volcanic rocks.

PETROLOGY OF THE ULTRAMAFIC ROCKS

Ultramafic rocks of the Bird River sill have previously been studied from the Chrome and Page properties (Trueman 1971) and from the area south of the Dumbarton mine (Juhas 1973). These will be reviewed briefly and compared to the ultramafic rocks forming the basal zone of the sill at Maskwa West (Fig. 1).

The Chrome and Page properties are located 8 km west and 6 km northwest of the Dumbarton mine, respectively. The grade of metamorphism is in the greenschist facies. Serpentinized peridotite near the base of the sill at both the Chrome and Page properties consists of oval-shaped serpentine pseudomorphs after olivine grains poikilitically enclosed in clinopyroxene, which constitutes approximately 30% of the rock. The pyroxene exhibits extensive alteration to tremolite, but this decreases in intensity at higher stratigraphic levels. Subhedral grains of chromite are incorporated in both tremolite and relict pyroxene. Chromiferous peridotite and chromitite form 18 persistent layers within the serpentinized peridotite near its upper contact with the overlying anorthositic gabbro.

Regional metamorphism increases in grade eastward; rocks at the Dumbarton mine are in the lower amphibolite facies. Mineral assemblages in the ultramafic portion of the sill, south of the mine, are recorded by Juhas (1973) as follows: (1) antigorite + chlorite ± tremolite ± carbonate; (2) antigorite + chlorite + talc ± tremolite ± carbonate; (3) olivine + tremolite ± talc ± carbonate ± chlorite ± antigorite; (4) tremolite ± carbonate ± chlorite; (5) diopside + olivine + tremolite ± chlorite.

The assemblages occupy the full width of the ultramafic unit, with assemblage 5 in the centre grading laterally outward in both directions, successively through zones 4, 3, 2 and 1. Their formation is attributed to contact-thermal metamorphism of the sill by the Maskwa quartz-diorite pluton. The thermal-metamorphic effects are superimposed on regional metamorphism and are apparently restricted to a limited area. Textural criteria indicate that all the assemblages were derived from an initial serpentinite.

Petrology of the ultramafic rocks at Maskwa West

Little evidence of magmatic layering is present in the ultramafic unit of the sill at Maskwa West. Rocks exposed in the Maska open pit and intersected by exploration diamond-drill holes consist of dark green to black serpentinite in a dense, light grey matrix of talc, carbonate and chlorite (Fig. 2). Serpentine content ranges from zero to a maximum of approximately 60%, in irregularly shaped patches up to 3 cm across. Massive talc–carbonate zones within the sill seem to be associated with zones of intense shearing, related to prominent northwest faulting in the area and to less obvious strike faulting within the sill. The contacts of the ultramafic unit with underlying volcanic rocks and overlying anorthositic gabbro are highly carbonated, tectonized surfaces.

The phases comprising the matrix to the serpentine patches in the ultramafic rocks include magnesite, dolomite, calcite, talc, chlorite, magnetite, hematite and chrome spinel (14.7% Cr_2O_3). Magnesite forms pseudomorphs after equant and close-packed cumulate olivine grains, with fine-grained magnetite outlining the margins of, and the fractures within, the original olivine grains (Fig. 3). This cellular distribution of magnetite is inherited from a precursor of serpentinized primary olivine and indicates the existence of an olivine-rich ultramafic cumulate zone in the lower part of the sill. Sulfides present in a zone close to the sill base occupy the interstices between the pseudomorphed olivine grains, in a poorly defined net-texture. There is no remaining textural evidence indicating the former presence of primary pyroxene in these rocks. Estimates of initial pyroxene content will be discussed in a later section on the chemistry of the rocks.

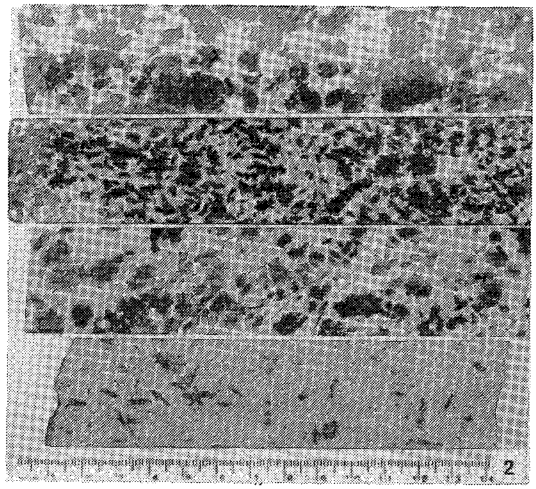

FIG. 2. Lizardite pseudomorphs after olivine (dark) in talc–carbonate (light). Diamond-drill-core samples. Scale in centimetres.

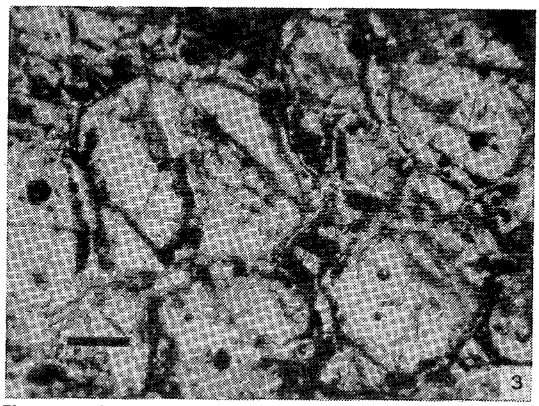

FIG. 3. Photomicrograph of magnesite pseudomorphs after equant primary olivine. Very fine-grained magnetite occupies fractures and outlines the margins of the original olivine grains. Sample 65-302. Scale bar 0.1 mm.

Talc is a ubiquitous phase, occurring both as scattered flakes and in a fine-grained aggregate with dolomite. The latter association makes up the bulk of the massive talc–carbonate rocks

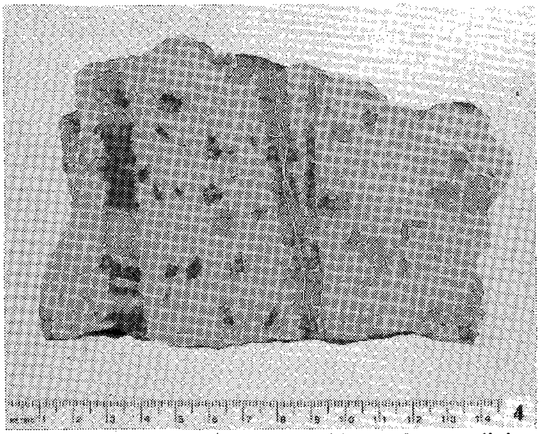

FIG. 4. Lizardite pseudomorphic after olivine (dark) in talc–carbonate matrix (light). Rosette, blade and "vein" morphologies are present. Hand specimen, Maskwa open pit. Scale in centimetres.

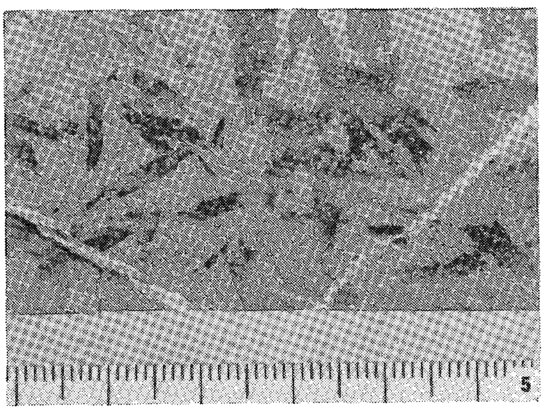

FIG. 5. Lizardite pseudomorphic after olivine blades (dark) in talc–carbonate matrix. White veins are calcite. Scale in centimetres.

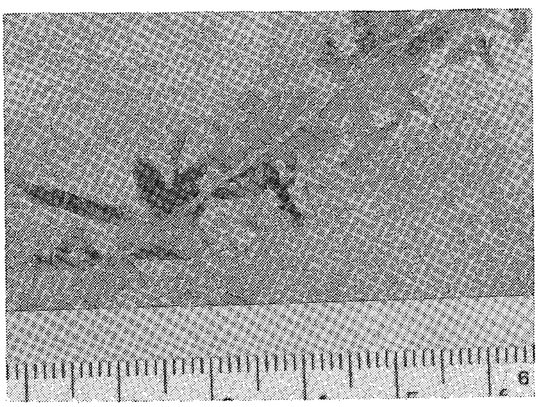

FIG. 6. Lizardite pseudomorphic after olivine blades (dark) adjacent to fracture in talc–carbonate matrix. Sample 65-263. Scale in centimetres.

previously described. Calcite is present in late-stage cross-cutting veins which range in width from less than 1 mm to a maximum of about 15 cm. Pyrite, marcasite, millerite and sepiolite have been identified with calcite in some veins. Chlorite occurs as fine-grained, scaly patches associated with magnetite and primary chrome spinel and as streaks along shears. Magnetite is present in all rock types.

The serpentine variety in the Maskwa rocks is mesh-textured lizardite 1*T*, identified by X-ray microbeam diffraction-patterns in the manner described by Wicks & Zussman (1975). Textural features and habit displayed by the lizardite indicate that it is not remnant serpentine after the primary olivine which has escaped the talc–carbonate alteration process, but rather that it replaces coarse-grained regenerated olivine blades. A single isolated remnant of this olivine has been detected, despite the examination of a large number of samples. For descriptive purposes, the regenerated olivines and their lizardite pseudomorphs are termed rosettes, blades and "veins", examples of which are present in the hand specimen illustrated in Figure 4.

Rosettes, consisting of a series of spike-like blades radiating outward from a central core, are the most common form of regenerated olivine, but they have been replaced by mesh-textured lizardite. Rosettes with dimensions of a few mm best display the radiating structure, whereas larger ones tend to be more lobate or scalloped in shape, although still retaining highly serrated margins. Central cores to the rosettes consist of dolomite tinged red with hematite, forming a pseudomorphic cellular texture. The single occurrence of unaltered olivine noted in the Maskwa rocks (Fo_{88} by electron-microprobe analysis) is preserved within a small rosette.

The habit of regenerated olivine consists of randomly oriented bladed crystals up to 1 cm in length, pseudomorphically replaced by mesh-textured lizardite, enclosed in the talc–carbonate matrix (Fig. 5). These have sharp prismatic faces and, in some instances, display partial euhedral terminations which are preserved by the lizardite pseudomorphs. For the most part, however, alternation by talc–dolomite has progressed extensively in from the extremities of the blades and has commonly disrupted them into a number of separate segments. Veins of white calcite cross-cut both the matrix talc–carbonate and the lizardite pseudomorphs and represent a final carbonatization event (Fig. 5).

"Veins" refer to discontinuous, fracture-controlled zones of olivine blades, with a variety of configurations, all of which are pseudomorphically replaced by lizardite. Discrete blades may project outward at varying angles from a central fracture (Fig. 6) and may develop on one or both sides of the fracture, exhibiting highly serrated margins against the surrounding talc–carbonate (Fig. 4). Zones of fine-grained disseminated magnetite in a predominantly carbonate matrix constitute the fracture-filling material.

The lizardite of all morphologies displays a series of prominent, subparallel α-serpentine rims, derived from preferential serpentinization of partings in the regenerated olivine. This direction is normal to the axis of elongation in blades and individual segments of rosettes, and parallel to the controlling central fracture of "veins". The prominent α-serpentine mesh-rims form part of a more-or-less symmetrical mesh-texture with isotropic mesh-centres, an example of the type-3 pseudomorphic texture described by Wicks & Whittaker (1977).

Composition of the ultramafic rocks

When rocks that have been altered metasomatically are compared, two major questions must be considered. Were the original rocks chemically homogeneous prior to the alteration? Was there any addition or removal of material other than the volatile constituents H_2O and CO_2? The original ultramafic rocks at Maskwa were presumably mineralogically layered, in a manner similar to those at the Chrome and Page properties (Trueman 1971). As the layering is defined by variation in the proportions of primary olivine and clinopyroxene, local differences in SiO_2, MgO, FeO and CaO content can be assumed. Where sufficient magnetite was generated during the first serpentinization and preserved during the later talc-carbonate alteration, residual textures of an olivine-rich cumulate are outlined by magnetite in the serpentine–talc–carbonate rocks at Maskwa. Relict magnetite would be considerably less plentiful in those layers initially richer in primary clinopyroxene. As a large proportion of the Maskwa talc–carbonate rocks (mostly dolomite) are devoid of such relict textures, it may be inferred that some of these originally contained a considerable proportion of primary pyroxene.

Chemical studies of serpentinized peridotites from near Timmins, Ontario (Naldrett 1966) show that bulk-chemical changes involved in talc–carbonate alteration lead to the addition of CO_2 and the removal of H_2O. The alteration process did not significantly alter the Si, Mg, Fe or Ni contents of the rocks. The Ca content of these serpentinites was extremely low, and CO_2 metasomatism resulted in the generation of magnesite as the only carbonate phase. Magnesite, dolomite and calcite are present in the Maskwa rocks, again suggesting the probability that these ultramafic rocks were rich in primary clinopyroxene.

Chemical data for the ultramafic rocks of the

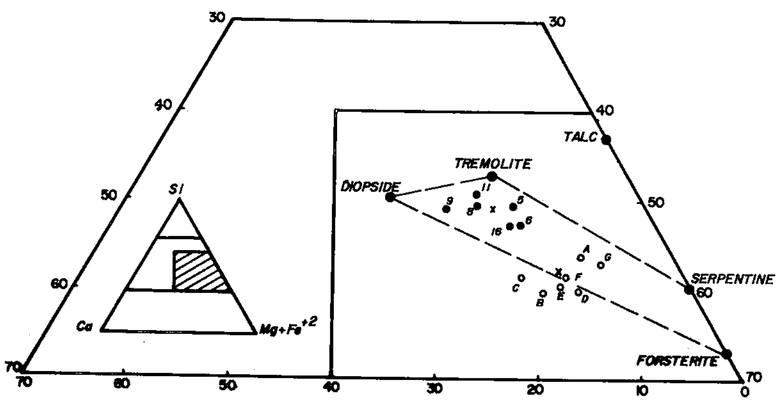

FIG. 7. Compositions of Bird River sill ultramafic rocks plotted in the triangular diagram Si–Ca–Mg+Fe^{2+} (atomic ratios). Black dots: diopside–olivine–tremolite assemblages (Nos. 5, 6, 8, 9, 11 and 16) from Juhas (1973). Analyst: K. Ramlal, Univ. of Manitoba. Open circles: talc–carbonate–serpentine rocks from Maskwa West (Nos. A, B, C, D, E, F and G, unpublished analyses, courtesy of P. Theyer). Analyst: J. Gregorchuk, Manitoba Dep. Mines. *X*s are the arithmetic means of the two groups.

Bird River sill are restricted to the area south of the Dumbarton mine and to the Maskwa West open-pit area. As the bulk composition lies within the system $CaO–MgO–SiO_2–H_2O–CO_2$, rock compositions can best be illustrated on a triangular diagram as atomic percentages of Si, Ca and $Mg+Fe^{2+}$ (Fig. 7). The dashed line joining the compositional points diopside, tremolite, serpentine and forsterite encloses the field of ultramafic rock compositions from the sill south of Dumbarton (Juhas 1973). Six analyses (Nos. 5, 6, 8, 9, 11 and 16) of assemblage-5 rocks (diopside + olivine + tremolite ± chlorite) are plotted, together with their arithmetic mean. These recrystallized rocks contain minimal amounts of carbonate and serpentine minerals, and if they resulted from essentially isochemical metamorphism (apart from the loss of CO_2 and most H_2O), their compositions must closely represent those of the primary rocks. The mean composition plots at 15 at. % Ca, which equates to 65% diopside, close to the 70% diopside content estimated from petrological studies (Juhas 1973). Seven analyses (Nos. A, B, C, D, E, F and G) of the Maskwa talc–carbonate–serpentine rocks are also plotted in terms of $Si–Ca–Mg+Fe^{2+}$ on Figure 7. Each sample point represents the bulk composition of about 4 m of diamond-drill core. The range in Ca content is quite large, whereas the $Si/Mg+Fe^{2+}$ ratio is more restricted. The arithmetic mean for the Maskwa group plots at 11.5 at. % Ca, which can be translated into an original average diopside content of about 50%. This approach probably gives the most reliable estimate of the overall olivine–clinopyroxene content in the primary rock. Since the presence of an olivine-rich cumulate zone is inferred from relict textures, stratigraphically higher portions of the sill presumably contained primary clinopyroxene in amounts greater than 50%.

Metamorphic Olivine and Talc–Carbonate Metasomatism

The association of metamorphically generated olivine, talc, magnesite and dolomite and the absence of enstatite, anthophyllite and cummingtonite at Maskwa West indicate a grade of metamorphism in the amphibolite or hornblende-hornfels facies. The talc-olivine paragenesis of regional metamorphic origin is common to ultramafic rocks in the staurolite and kyanite zones of the Central Alps (Trommsdorff & Evans 1974, Evans & Trommsdorff 1974), where some elongate olivines attain impressive lengths and the textures suggest growth in a relatively static environment. The assemblage is stable over a temperature range of about 150°C, between 500 and 650°C, depending on pressure and $X(CO_2)$ conditions (Greenwood 1967, Johannes 1969).

Metamorphic olivine derived from rocks that previously were partly serpentinized, with the production of much magnetite, can have diagnostically higher forsterite compositions than the primary olivine (Morgan 1978). Most studies of secondary olivine in metamorphosed alpine-type ultramafic bodies, however, show a considerable range in forsterite compositions (*e.g.*, Wolfe 1967, Trommsdorff & Evans 1972, Springer 1974, Pinsent & Hirst 1977, Vance & Dungan 1977). The forsterite contents of olivines in the ultramafic bodies examined by these authors fall within an overall range of Fo_{85-98}. In the case of the Blue River ultramafic body at Cassiar (Pinsent & Hirst 1977), the metamorphic olivine compositional range (Fo_{86-97}) straddles the mean value determined for primary olivine (Fo_{91}). Iron-rich metamorphic olivines (Fo_{63}) are recorded from spinifex-textured Archean ultramafic volcanic rocks in Western Australia (Oliver & Ward 1971, Oliver *et al.* 1972). Thus the amount of iron incorporated into olivine during metamorphism is highly variable and, as noted by Evans (1977), is determined by the Fe/Mg ratio of the rock, $f(O_2)$, the nature and amounts of coexisting phases. The forsterite content of the Maskwa olivine (Fo_{88}) is therefore not unusual, nor is it diagnostic of a metamorphic origin.

As previously noted, the bulk composition of the Maskwa rocks falls within the chemical system $CaO–MgO–SiO_2–H_2O–CO_2$, and so experimental work in this and related systems can be used to determine the probable metamorphic conditions prevailing during the genesis of the observed assemblages. Major contributors to experimental and theoretical aspects of the systems $MgO–SiO_2–H_2O$, $MgO–SiO_2–H_2O–CO_2$ and $CaO–MgO–SiO_2–H_2O–CO_2$ include Greenwood (1967), Johannes (1969), Evans *et al.* (1976), Hemley *et al.* (1977) and Trommsdorff & Evans 1977).

In the ultramafic rocks at Maskwa West, petrological evidence lead us to infer the following progressive sequence: (1) emplacement of the fresh peridotite, (2) serpentinization, (3) metamorphic bladed olivine, (4) lizardite pseudomorphs. An integral part of this sequence is the development of talc, magnesite and dolomite.

The precise chronological relationship of carbonatization and metamorphism is not readily apparent, but the observed paragenesis might be produced in either of the following reaction sequences: (1) serpentine → talc + carbonate → olivine, or (2) serpentine → olivine + talc → talc + carbonate + serpentine. The first implies carbonatization during rising-temperature conditions of prograde metamorphism and the second, carbonatization during a declining-temperature regime, after the metamorphic peak has been attained. Each of these will be considered and an attempt made to trace the changing T–$X(CO_2)$ paths and mineral reactions involved. An appropriate diagram for this purpose is the temperature–gas-composition section at a total pressure of 2 kbar for stable reactions in the system $CaO–MgO–SiO_2–H_2O–CO_2$ (Trommsdorff & Evans 1977, Fig. 7, reproduced here as Fig. 8). Serpentine from the initial serpentinization of primary peridotite is not recognized at Maskwa West, but antigorite occurs as a stable phase in adjacent parts of the Bird River sill (Trueman 1971, Juhas 1973). This is in accord with the higher temperature-limit of antigorite stability during metamorphism (Evans *et al.* 1976, Dungan 1977). In case 1, involving carbonatization at an early stage of metamorphism, the conversion of serpentine to talc + magnesite requires an increase in the CO_2 content of the aqueous phase, a change which presumably could result from redistribution of H_2O and CO_2 at the onset of regional metamorphism. Under a total fluid-pressure of 2 kbar and at CO_2 contents of the fluid phase between 2 and 6 mole %, depending on the temperature, serpentine reacts with CO_2 according to the general equation: 2 serpentine + 3 CO_2 → talc + 3 magnesite + 3 H_2O.

Unless disturbed by subsequent deformation and recrystallization, this reaction can faithfully preserve the texture produced by the serpentinization of primary olivine (Willett *et al.* 1978). Most of the magnetite outlining the pseudomorphs seems to be retained, although there is good evidence to suggest that some magnetite has generally broken down, with consequent incorporation of iron in the magnesite phase (Naldrett 1966, Groves *et al.* 1974, Eckstrand 1975). At a total pressure of 2 kbar and with $X(CO_2)$ content of 0.20, the reaction talc + 5 magnesite → 4 forsterite + H_2O + 5 CO_2 takes place at a temperature slightly greater than 500°C (Greenwood 1967, Johannes 1969).

The equilibrium temperatures of this reaction at constant CO_2 content of the fluid phase increase with increasing total pressure. Under the same conditions, a somewhat lower temperature for the reaction is indicated by the calculated equilibrium-curves of Trommsdorff & Evans (1977). The substitution of some Fe for Mg in the reacting phases (including magnesite) is considered by these authors to have an insignificant effect on the location of the isobaric univariant curves.

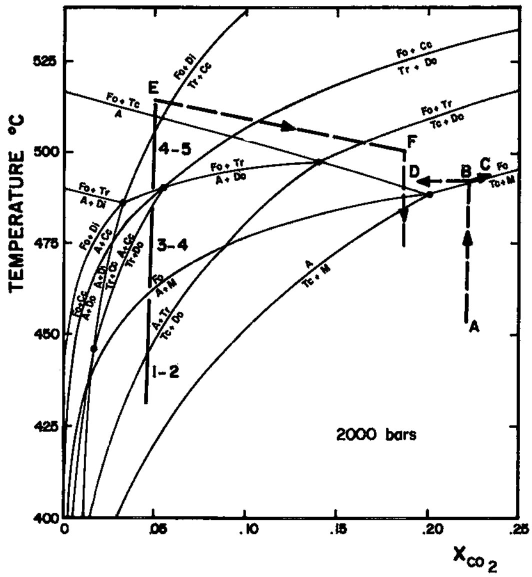

FIG. 8. Calculated T–$X(CO_2)$ phase diagram for antigorite (A), talc (Tc), tremolite (Tr), diopside (Di), forsterite (Fo), calcite (Cc), dolomite (Do) and magnesite (M) in the system $CaO–MgO–SiO_2–H_2O–CO_2$ (from Trommsdorff & Evans 1977). Vertical bars 1-2, 3-4, 4-5 are stable assemblages at Dumbarton (Juhas 1973). For points A, B, C, D, E and F, see discussion in text.

As shown in Figure 8, talc + magnesite in equilibrium with an $X(CO_2)$ in excess of 0.20 (say, point A) and with increasing temperature will react to form forsterite when reaching the forsterite curve at point B. The reaction evolves 1 H_2O + 5 CO_2 and hence the composition of the fluid phase will proceed along the curve to the right (point C). It is evident that a sudden local change in the fluid composition, caused by the injection of H_2O into fractures in the talc–magnesite rock, will induce the formation of forsterite at constant temperature (points B to D), and can account for the "vein" olivine at Maskwa. Talc, dolomite and forsterite are the principal phases present in the Maskwa rocks; these narrowly define a divariant field in the T–$X(CO_2)$ plane and limit $X(CO_2)$ to greater than ~ 0.10 and, in the absence of antigorite, to greater than 0.20. The absence of tremolite indicates that the temperature did not rise above that required for the reaction 13 talc + 10 dolomite → 5 tremolite + 12 forsterite + 20 CO_2 + 8 H_2O. In our example, the reaction curve would define an upper temperature-limit at about 515°C.

The stable mineral-assemblages present in the sill south of the Dumbarton mine (Juhas 1973) are drawn as vertical numbered bars on Figure 8. Each assemblage is stable over a limited temperature-range. As the compositions of the carbonates have not been determined, there is some uncertainty involved, but for the present purpose the bars are drawn at a constant $X(CO_2)$ of about 0.05. If the Maskwa rocks consisted of olivine, talc and diopside, they would be a stable assemblage under the same conditions as the Dumbarton group-5 assemblage (*e.g.*, point E at 515°C and an $X(CO_2)$ of 0.05). By increasing the partial pressure of CO_2 and with constant or slightly decreasing temperature, it can be seen that the talc, dolomite and forsterite field is reached at point F, by crossing three univariant reaction curves: (1) 11 diopside + 2 forsterite + 5 CO_2 + 3 H_2O → 3 tremolite + 5 calcite; (2) 8 forsterite + 13 calcite + 9 CO_2 + H_2O → tremolite + 11 dolomite; (3) 5 tremolite + 12 forsterite + 20 CO_2 + 8 H_2O → 13 talc + 10 dolomite. With a reduction in temperature at point F, and with $X(CO_2)$ constant, the stability fields of antigorite and talc + magnesite would be attained.

Of the two T-$X(CO_2)$ paths described, petrological evidence favors the first case. There is no evidence in the Maskwa rocks to suggest that tremolite was ever a significant phase, and from textural features observed in the carbonates it is evident that dolomite postdates the formation of magnesite. Magnesite replaced undeformed primary olivine pseudomorphs, a process that apparently took place under relatively static conditions. Calcite in cross-cutting fractures was the last carbonatization event.

Conclusions

Textural features in the talc–carbonate–serpentine rocks at Maskwa West resulted from metamorphic processes at a grade in the lower amphibolite facies. The original composition of the layered sill rocks is considered to have been peridotite, with an average content of ~ 50% diopside. An olivine-rich cumulate zone is evident from pseudomorph textures, but pervasive talc–carbonate metasomatism precludes the documentation of individual-layer compositions or their original stratigraphic sequence. The preferred interpretation is, first the serpentinization of the primary peridotite, followed by CO_2 metasomatism replacing the serpentine with the development of talc, magnesite, dolomite and bladed olivine. Subsequently, the bladed olivine was serpentinized to lizardite-1*T* mesh textures. The prevailing talc–dolomite–olivine paragenesis at Maskwa defines a narrow divariant field in the temperature–gas-composition plane and limits $X(CO_2)$ to greater than ~ 0.20 and maximum temperature conditions of ~ 515°C.

CO_2 metasomatism most likely began at an early stage in the metamorphic sequence with the peridotites in the stability field of serpentine. Magnesite and then dolomite were derived in a chronological sequence. The more prevalent carbonate metasomatism of the Maskwa ultramafic rocks, in comparison with other segments of the sill, suggests a restricted local source for the CO_2. The presence of local gabbroic intrusions, together with evidence from lithologies and facies changes in the layered sequence of metavolcanic rocks of the area, indicates the proximity of a volcanic-vent structure north of Maskwa. The source of the CO_2 is ascribed to this volcanic centre.

Acknowledgements

The authors are indebted to F. J. Wicks, Royal Ontario Museum, for X-ray microbeam examinations of the serpentine minerals and to R. H. Pinsent, Manitoba Mines Branch, for helpful discussion. This paper is published with the permission of G. P. Mitchell, President, Maskwa Nickel Chrome Mines Limited, and Group Vice-President, Falconbridge Nickel Mines Limited.

References

Butrenchuk, S.B. (1970): *Metamorphic Petrology of the Bird Lake Area, Southeastern Manitoba.* M.Sc. thesis, Univ. Manitoba, Winnipeg, Man.

Davies, J.F. (1955): Geology and mineral deposits of the Bird River area. *Manitoba Mines Br. Publ.* 54-1.

Dungan, M.A. (1977):Metastability in serpentine–olivine equilibria. *Amer. Mineral* **62**, 1018-1029.

Eckstrand, O.R. (1975): The Dumont serpentinite: a model for control of nickeliferous opaque mineral assemblages by alteration reactions in ultramafic rocks. *Econ. Geol.* **70**, 183-201.

Evans, B.W. (1977): Metamorphism of alpine peridotite and serpentinite. *Ann. Rev. Earth Planet. Sci.* **5**, 397-447.

———, JOHANNES, W., OTERDOOM, M. & TROMMSDORFF, V. (1976): Stability of chrysotile and antigorite in the serpentinite multisystem. *Schweiz. Mineral. Petrog. Mitt.* **56**, 79-93.

——— & TROMMSDORFF, V. (1974): On elongate olivine of metamorphic origin. *Geol.* **2**, 131-132.

GREENWOOD, H.J. (1967): Mineral equilibria in the system $MgO-SiO_2-H_2O-CO_2$. *In* Researches in Geochemistry (P.H. Abelson, ed.), **2**, 542-567.

GROVES, D.I., HUDSON, D.R. & HACK, T.B.C. (1974): Modification of iron–nickel sulfides during serpentinization and talc–carbonate alteration at Black Swan, Western Australia. *Econ. Geol.* **69**, 1265-1281.

HEMLEY, J.J., MONTOYA, J.W., SHAW, D.R. & LUCE, R.W. (1977): Mineral equilibria in the $MgO-SiO_2-H_2O$ system. II. Talc–antigorite–forsterite–anthophyllite–enstatite stability relations and some geologic implications in the system. *Amer. J. Sci.* **277**, 353-383.

JOHANNES, W. (1969): An experimental investigation of the system $MgO-SiO_2-H_2O-CO_2$. *Amer. J. Sci.* **267**, 1083-1104.

JUHAS, A.P. (1973): *Geology and Origin of the Copper–Nickel Sulfide Deposits of the Bird River Area of Manitoba.* Ph.D. thesis, Univ. Manitoba, Winnipeg, Man.

KARUP-MØLLER, S. & BRUMMER, J.J. (1971): Geology and sulfide deposits of the Bird River claim group, southeastern Manitoba. *In* Geoscience Studies in Manitoba (A.C. Turnock, ed.), *Geol. Assoc. Can. Spec. Pap.* **9**, 143-154.

MORGAN, B.A. (1978): Metamorphic forsterite and diopside from the ultramafic complex at the Tuolumne River, California. *J. Res. U.S. Geol. Sur.* **6**, 73-80.

NALDRETT, A.J. (1966): Talc–carbonate alteration of some serpentinized ultramafic rocks south of Timmins, Ontario. *J. Petrology* **7**, 489-499.

OLIVER, R.L., NESBITT, R.W., HAUSEN, D.M. & FRANZEN, N. (1972): Metamorphic olivine in ultramafic rocks from Western Australia. *Contr. Mineral. Petrology* **36**, 335-342.

——— & WARD, M. (1971): A petrological study of serpentinous rocks associated with nickel sulphide mineralization at Pioneer, Western Australia. *J. Geol. Soc. Aust. Spec. Publ.* **3**, 311-319.

PENNER, A.P. & CLARK, G.S. (1971): Rb–Sr age determinations from the Bird River area, southeastern Manitoba. *In* Geoscience Studies in Manitoba (A.C. Turnock, ed.) *Geol. Assoc. Can. Spec. Pap.* **9**, 105-109.

PINSENT, R.H. & HIRST, D.M. (1977): The metamorphism of the Blue River ultramafic body, Cassiar, British Columbia, Canada. *J. Petrology* **18**, 567-594.

SPRINGER, G.D. (1950): Mineral deposits of the Cat Lake – Winnipeg River area, Manitoba. *Man. Mines Br. Publ.* **49-7**.

SPRINGER, R.K. (1974): Contact metamorphosed ultramafic rocks in the Western Sierra Nevada foothills, California. *J. Petrology* **15**, 160-195.

TROMMSDORFF, V. & EVANS, B.W. (1972): Progressive metamorphism of antigorite schist in the Bergell tonalite aureole (Italy). *Amer. J. Sci.* **272**, 423-437.

——— & ——— (1974): Alpine metamorphism of peridotitic rocks. *Schweiz. Mineral. Petrog. Mitt.* **54**, 333-352.

——— & ——— (1977): Antigorite–ophicarbonates: phase relations in a portion of the system $CaO-MgO-SiO_2-H_2O-CO_2$. *Contr. Mineral. Petrology* **60**, 39-56.

TRUEMAN, D.L. (1971): *Petrological, Structural and Magnetic Studies of a Layered Basic Intrusion, Bird River Sill, Manitoba.* M.Sc. thesis, Univ. Manitoba, Winnipeg, Man.

——— (1975): Bird River area. *Manitoba Mines Br. Prelim. Map* **1975-F-10** (West) and **1975-F-11** (East).

——— & TURNOCK, A.C. (1975): Birk Lake – Winnipeg River River Area. *Centre for Precambrian Studies (Univ. Manitoba) Ann. Rep. Pt.* **2**, *Res. Pap.* **13**, 80-84.

———, ——— & BOND, W.D. (1975): The Archean volcanic rocks of the Bird River greenstone belt, southeastern Manitoba. *Geol. Soc. Amer. Abstr. Program* **7**, 873-874.

VANCE, J.A. & DUNGAN, M.A. (1977): Formation of peridotites by deserpentinization in the Darrington and Sultan areas, Cascade Mountains, Washington. *Geol. Soc. Amer. Bull.* **88**, 1497-1508.

WICKS, F.J. & WHITTAKER, E.J.W. (1977): Serpentine textures and serpentinization. *Can. Mineral.* **15**, 459-488.

——— & ZUSSMAN, J. (1975): Microbeam X-ray diffraction patterns of the serpentine minerals. *Can. Mineral.* **13**, 244-258.

WILLETT, G., ESHUYS, E. & GUY, B. (1978): Ultramafic rocks of the Widgiemooltha–Norseman area, Western Australia: petrological diversity, geochemistry and mineralization. *Precambrian Res.* **6**, 133-156.

WOLFE, W.J. (1967): *Petrology, Mineralogy and Geochemistry of the Blue River Ultramafic Intrusion, Cassiar District, B.C.* Ph.D. thesis, Yale Univ., New Haven, Conn.

Received July 1978, revised manuscript accepted May 1979.