CO$_2$ METASOMATISM OF SERPENTINITES, SOUTH OF TIMMINS, ONTARIO

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ABSTRACT

The tectonic and metamorphic history of the ultramafic rocks is well preserved at the Slade–Forbes asbestos deposit. A north–south compression gave rise to east–west-trending folds in the area. The N–S- and E–W-trending sets of joints that developed were "healed" by chrysotile asbestos veins. A N–S-trending fault cuts through the deposit and postdates the formation of the asbestos veins. Two separate events of CO$_2$ metasomatism occurred along this fault. The first was probably associated with the development of, or an early movement along, the N–S fault, and the second event was associated with sinistral-reverse motion along the fault. The second event of CO$_2$ metasomatism was the more pervasive; the serpentinite was partly replaced by talc and carbonate. This alteration was accompanied by the addition of substantial Mg and loss of Si; the chemical exchange occurred at a constant volume. Fluid inclusion and oxygen isotope studies suggest that the metasomatizing fluid was H$_2$O-rich, with less than 0.85 mole % CO$_2$, and the salinity was 3.3 ± 0.9 wt.% NaCl equivalent. The estimated mean temperature of formation of the carbonate was 300°C (at 1 kbar); the calculated mean δ^{18}O value of fluid in equilibrium with the carbonate was +2.4‰, and the δ^{13}C value, −2.5 ± 1.3‰. Widespread CO$_2$ metasomatism in the Abitibi belt is associated with gold mineralization, some of which occurs in carbonate-altered ultramafic rocks such as at the Dome, Kerr Addison and Aquarius mines. The carbonate-altered and mineralized ultramafic rocks are characterized by complex alteration assemblages, and the carbonates formed from CO$_2$-rich fluids between +5 and +10‰. Although CO$_2$ metasomatism at Slade–Forbes may have been contemporaneous with pervasive CO$_2$ metasomatism in the Timmins camp, the differences in alteration assemblages and fluid chemistry between mineralized ultramafic rocks and the Slade–Forbes deposit suggest the existence of two significantly different environments.

Keywords: fluid inclusions, stable isotopes, ultramafic rocks, serpentine, metasomatism, CO$_2$, Timmins, Abitibi belt, Ontario.

SOMMAIRE

L'évolution tectonique et métamorphique des roches ultramafiques dans la région de Timmins, en Ontario, est bien préservée dans le gisement d'amiante de Slade–Forbes. Une compression nord–sud a causé des plis orientés est–ouest; les joints dans les deux orientations ont été cicatrisées par le chrysotile. Une faille orientée nord–sud recoupe le gisement et les fissures remplies d'amiante. La faille contient un assemblage d'altération carbonatée. Deux événements de métasomatose à CO$_2$ ont affecté ces roches. Le premier était probablement associé au développement de la faille nord–sud, ou à un mouvement précoce le long de celle-ci. Le second, le plus répandu des deux, a causé un remplacement partiel de la serpentinite par talc + carbonate. Une addition substantielle de magnésium et une perte de Si sont le résultat de cette altération; l'échange chimique a eu lieu à volume constant. Les résultats d'une analyse des inclusions fluides et des isotopes d'oxygène font penser que la phase fluide responsable de la métasomatose était aqueuse, avec moins de 0.85% de CO$_2$ (base molaire). Sa salinité était de 3.3 ± 0.9% en poids de NaCl (ou équivalent). Le carbonate se serait formé à 300°C, en moyenne (à 1 kbar). La valeur moyenne de δ^{18}O calculé était de +2.4‰, et la valeur de δ^{13}C, −2.5‰ ± 1.3‰. On associe couramment un épisode de métasomatose à CO$_2$ à la minéralisation en or dans la ceinture de l'Abitibi. Dans certains cas, cette métasomatose peut causer la carbonatation des roches ultramafiques, comme c'est le cas dans les mines Dome, Kerr Addison et Aquarius. Ces roches contiennent un assemblage minéralogique complexe dû à l'altération, et les carbonates se sont formés à partir de fluides riches en CO$_2$ dont le rapport δ^{18}O s'étalait entre +5 et +10‰. Quoique la métasomatose à Slade–Forbes aurait pu être contemporaine de la métasomatose répandue dans le camp de Timmins, les différences dans les assemblages et la composition des fluides responsables entre ces roches ultramafiques minéralisées et celles du gisement de Slade–Forbes font penser qu'il s'agit de deux milieux très différents.

(Traduit par la Rédaction)

Mots-clés: inclusions fluides, isotopes stables, roches ultramafiques, serpentine, métasomatose, CO$_2$, ceinture de l'Abitibi, Timmins, Ontario.

INTRODUCTION

The carbonate–gold association in the Timmins area, Abitibi Subprovince, Ontario, has been well documented in the past decade, but the literature on unmineralized, carbonate-altered rocks in the area is limited. Because of this selective reporting of the effects of CO$_2$ metasomatism on various lithologies, it is difficult to assess the significance

of carbonates with respect to mineralization. This paper represents an in-depth study of carbonate-altered serpentinite at an unmineralized location, the Slade–Forbes asbestos deposit. The data were obtained from mineralogical, geochemical, fluid inclusion and stable isotope studies. The Slade–Forbes deposit is located close to the Timmins gold camp, in which some of the gold is hosted by carbonate-altered ultramafic rocks (*i.e.*, at the Dome mine). There are apparent differences in mineral assemblages between the carbonate-altered ultramafic rocks at Slade–Forbes and the carbonate-altered ultramafic rocks hosting gold deposits. In order to compare and contrast the effects of CO_2-rich fluids in the case of mineralized rocks *versus* unmineralized equivalents, we must have a better understanding of chemical processes operating during CO_2 metasomatism in general. Therefore, in the context of this study, we describe the chemical and mineralogical changes that accompanied CO_2 metasomatism of a serpentinite, and characterize the chemical and isotopic composition of the CO_2-bearing fluid at an unmineralized location, using Slade–Forbes as a case study.

Regional setting

The Slade–Forbes asbestos deposit is located in the Abitibi greenstone belt, in Deloro Township, 11 km southeast of Timmins, Ontario (Fig. 1). Metavolcanic rocks of Archean age characterize the area. The rocks are divided into the Deloro and the Tisdale groups. The Deloro Group is the older, and consists of ultramafic flows at the base, but is composed predominantly of calc-alkaline basalts, andesite, rhyolite and dacite flows capped with rhyolite pyroclastic rocks (Pyke 1982). The emplacement of large sill-like bodies of ultramafic intrusive rocks in central Deloro and in Shaw and Langmuir townships is confined to the Deloro Group. Compositionally, these bodies range from dunite to lherzolite, and occasionally have upper layers of pyroxenite and gabbro. Pyke (1982) suggested that some of these ultramafic bodies may represent the magma reservoirs that produced the ultramafic flows in the overlying Tisdale Group.

Basaltic and ultramafic rocks in the Deloro Group typically form large dome-like structures, such as the Shaw and Pamour domes. The Slade–Forbes deposit, located in a dunitic sill, occurs within the Shaw Dome, in the east-central part of Deloro Township. Several similar occurrences of ultramafic bodies, such as the Canadian Magnesite deposit (Griffis 1972) in the south-central part of the Deloro Township, the Daffodil asbestos mine 3 km northwest of the Slade–Forbes deposit, and the Allerston magnesite deposit in Whitney Township (Bowen *et al.* 1976) occur in the area.

Ultramafic and basaltic komatiite flows at the base of the Tisdale Group show that the character of volcanism changed markedly with time. The komatiites are overlain by tholeiitic basalts and volcaniclastic rocks of dacite composition (Pyke 1982). A large east–west-trending break, the Destor – Porcupine fault, is the major structural feature in the area. Komatiitic flows are recognized on both sides of the fault.
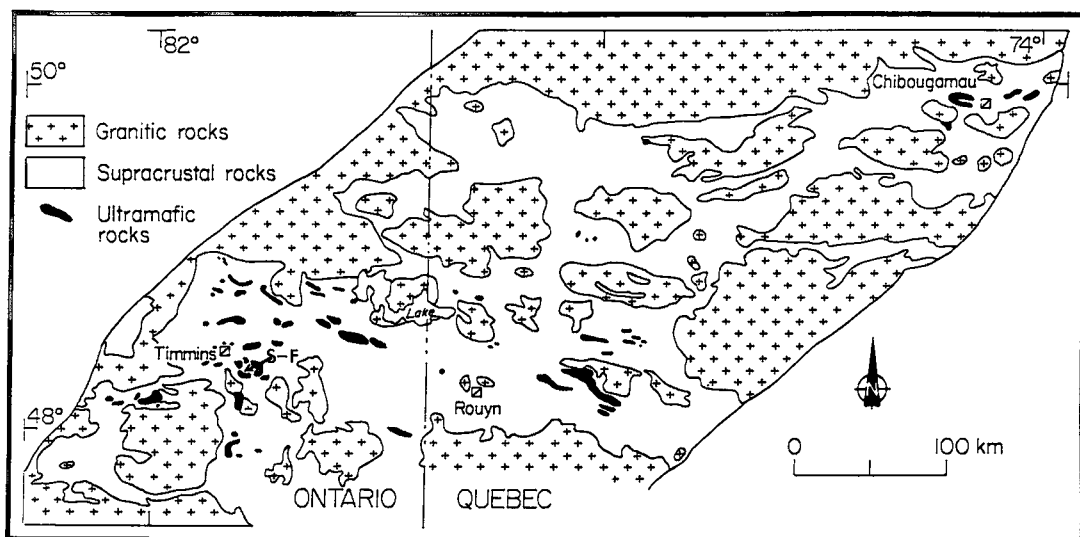

FIG. 1. Geological map of the Abitibi belt. S–F: Slade–Forbes (after Goodwin & Ridler 1970).

Previous work

Previous studies on talc–carbonate alteration of serpentinized ultramafic rocks in the area include the work of Naldrett (1966) in Carman and Langmuir townships, and of Griffis (1972) on the Canadian Magnesite deposit in the Deloro Township. Both investigators concluded that CO_2 metasomatism of serpentinized ultramafic rocks is not accompanied by a significant change in volume, and that the only important chemical changes are the addition of CO_2 and the removal of H_2O.

The Slade–Forbes deposit was included in a reconnaissance survey of talc, magnesite and asbestos occurrences in the Timmins – Kirkland Lake area by Kretschmar & Kretschmar (1986). The age of the ultramafic sill that hosts the Slade–Forbes deposit, and also the Bowman asbestos mine 3 km northwest of Slade–Forbes, was determined by the U–Pb method on zircon grains recovered from a small pod of plagioclase cumulate within the ultramafic rocks. The age of the sill is 2707 ± 3 Ma (Corfu *et al.* 1989).

Rodingites occur within the serpentinized ultramafic rocks at the Bowman mine (Schandl *et al.* 1989). Fluid-inclusion microthermometry of a rodingitized gabbroic inclusion indicates that the temperature of the serpentinizing fluid was approximately 290°C, and the mean salinity of the fluid was 1.6 wt.% NaCl (equiv.). Its CO_2 content, determined by gas chromatography (Dr. Colin Bray, pers. comm.), was less than 150 ppm, and the calculated oxygen isotopic composition ($\delta^{18}O$) of the serpentinizing fluid was +2.5 to +4.2‰ (Schandl *et al.* 1990a).

The effects of regional metamorphism on serpentinized ultramafic rocks have been studied by Chidester (1962), Jahns (1967), Sanford (1982), Evans & Trommsdorff (1970, 1974) and Trommsdorff & Evans (1972, 1977), and of contact metamorphism by Frost (1975). Experimental studies of the system $MgO–SiO_2–H_2O–CO_2$ (Johannes 1969, Greenwood 1967) indicate that if a small amount of CO_2 is added to the system, serpentine will alter to talc and magnesite or quartz and magnesite. The reactions are temperature- and $X(CO_2)$-dependent.

The purpose of this study is fourfold: 1) to determine the temperature, chemistry, and isotopic composition of the fluid that gave rise to talc–carbonate alteration in the Slade–Forbes deposit, 2) to calculate the volume change and the extent of addition and removal of elements that occurred during the alteration of serpentine to talc and magnesite, 3) to identify the paragenetic sequence of the minerals by integrating field relationships and petrographic observations with mineral chemistry, and thus correlate individual

tectonic and metasomatic episodes recognized at the mine with the tectonic and metamorphic history of the region, and 4) to compare and contrast fluid composition and alteration assemblages associated with gold mineralization in the Timmins area with results obtained from the present study.

ANALYTICAL WORK

Whole rocks were fused into glass beads and analyzed for major elements by X-ray fluorescence (XRF) by X-Ray Assay Laboratories, Toronto. Powder pellets were analyzed for trace elements by XRF at the University of Toronto. Concentrations of the rare-earth elements (*REE*) were determined by instrumental neutron-activation analysis (INAA), using the SLOWPOKE reactor at the University of Toronto. Sample preparation and operating conditions followed the guidelines of Barnes & Gorton (1984). Microprobe analyses of minerals were carried out on a JEOL 733 four-spectrometer electron microprobe equipped with an energy-dispersion spectrometer at the Department of Geology, Dalhousie University, Halifax. The fluid inclusion study was carried out at the F. Gordon Smith Fluid Inclusion Laboratory, Department of Geology, University of Toronto. Freezing and heating measurements were determined on a LINKAM TH 600 fluid inclusion stage. The operating conditions and calibration methods used followed the guidelines established by MacDonald & Spooner (1981). Values of $\delta^{18}O$ and $\delta^{13}C$ were determined in eight representative carbonate-altered samples at the Stable Isotope Laboratory of the University of Waterloo. Carbonate samples were treated with phosphoric acid at 50°C for 24 hours to dissolve dolomite, and the total oxygen yields of the analyzed samples were corrected. The reference standard for oxygen is SMOW, and for carbon, PDB.

The density of samples was calculated from $S_d/(S_d - S_w)$, where S_d is the weight of the dry rock, and S_w is the weight of rock suspended in water. Measurements were repeated for increased precision.

GEOLOGICAL SETTING

The Slade–Forbes asbestos mine was in operation intermittently from 1917 to 1957 and produced approximately 600 tonnes of chrysotile asbestos (Kretschmar & Kretschmar 1986). Two open pits are to be found on the property; the main pit (No. 1) lies to the north, and a smaller pit (No. 2) is located about 100 m south of the main pit (Fig. 2). The serpentinized ultramafic rocks show the outline of medium-grained olivine replaced by serpentine. Chrysotile asbestos veins occur in roughly north–
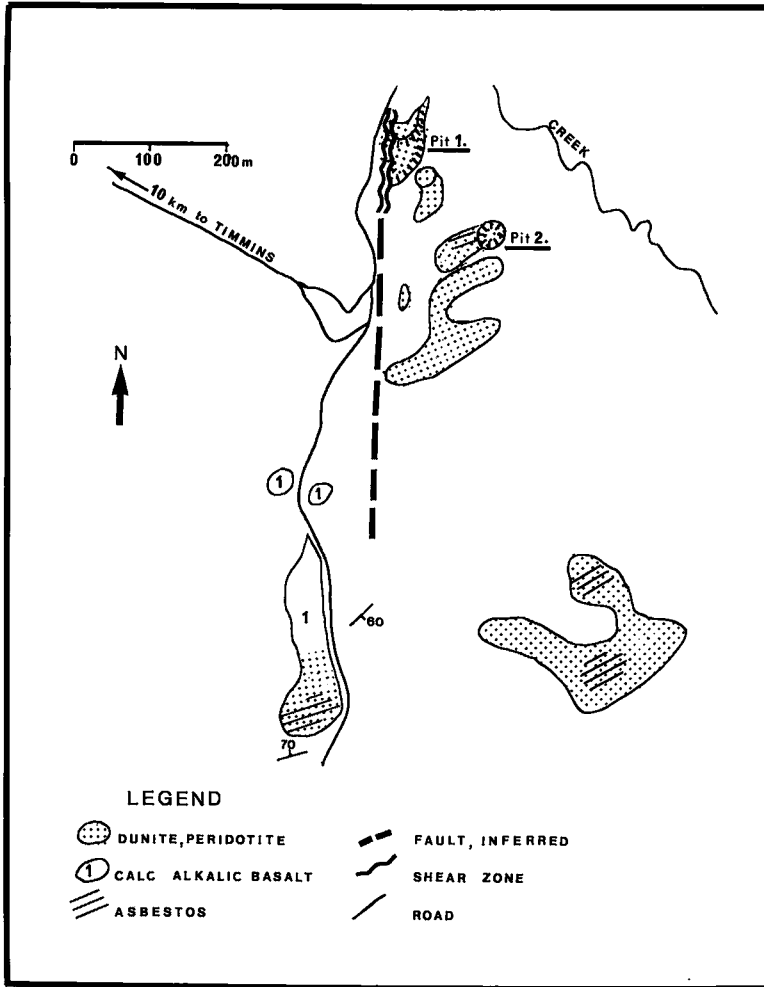
FIG. 2. Sketch map of the location of the No. 1 and No. 2 pits (modified after Kretschmar & Kretschmar 1986).

south- and east–west-trending sets of fractures. A north–south-trending fault cuts through the western part of the mine, and more or less parallels the long axis of the No. 2 pit. The surface expression of this fault is a wide shear-zone (10 m) that cuts through the western part of the No. 1 pit. Extensive CO_2 metasomatism has occurred along the fault and partly altered the serpentinized ultramafic rocks, composed of lizardite and chrysotile, to talc, magnesite ± dolomite. A progression from relatively unaltered serpentinite (3 wt.% CO_2) to extensively altered serpentinite (30 wt.% CO_2) is particularly well demonstrated in the No. 2 pit (Fig. 3). As the progression in CO_2 metasomatism is visible both on outcrop and thin section scales, this outcrop was considered a suitable target for a detailed mineralogical and geochemical study.

The selected study area consists of the 25 × 25 m outcrop containing the No. 2 pit, and a few smaller outcrops to the west (Fig. 3). On the northeastern face of the outcrop, where 1- to 2-cm-wide chrysotile asbestos veins cross-cut the thoroughly serpentinized dunite, a gradual alteration of serpentine to talc + carbonate is observed. The large outcrop has a roughly north–south trend, and displays a system of closely spaced joints; all joint sets are filled with chrysotile asbestos. Two set of joints, one at 090–110°, dipping 60°N–90° and one at 340–360°, dipping vertically, define a closely spaced (1 ± 0.5 m) rectangular grid (Fig. 4A). A set of conjugate shear-fractures at 310–320°
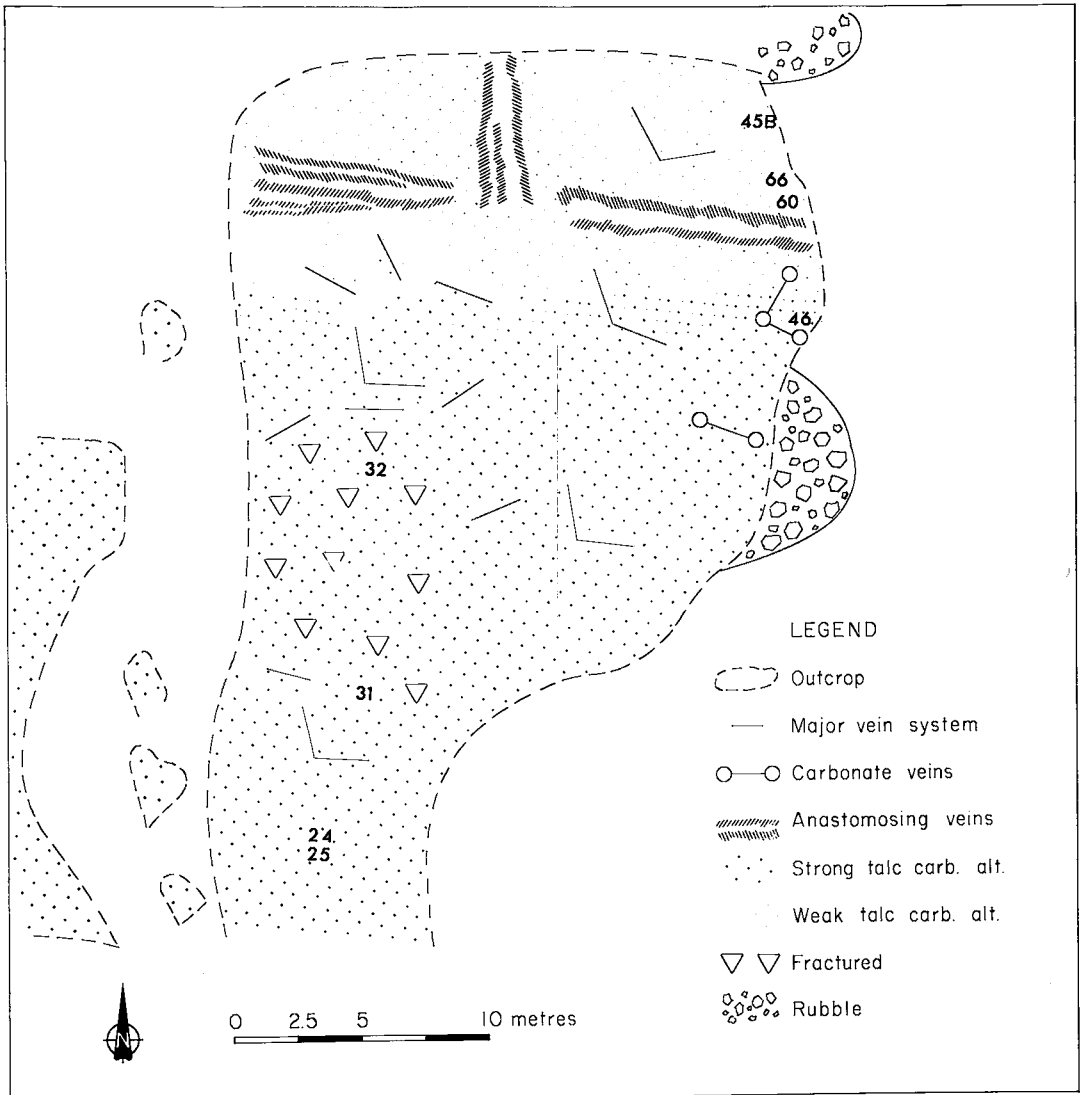
FIG. 3. Detailed map of the No. 2 pit. Numbers represent sample numbers from Table 4.

and 90° obliquely intersect the two sets of joints. The shear-fractures were associated with fracturing and brecciation, and were filled and healed by cross-fiber asbestos so that they appear as a set of anastomosing veins. The orientation of the sets of asbestos veins suggests that the joints formed as the result of the north–south compression that gave rise to the approximately east–west-trending folds in the area, as described by Pyke (1982).

Two episodes of carbonate alteration occurred at the Slade–Forbes deposit. Both events postdated the formation of asbestos veins, and both are spatially related to a north–south-trending fault. The first episode of CO₂ metasomatism was a minor event, and it is characterized by the replacement of serpentine pseudomorphous after olivine, and by the partial breakdown of serpentine to quartz and magnesite (Fig. 4E). The second phase of CO₂ metasomatism accompanied NW–SE compression, and subsequent sinistral-reverse motion along the fault (O'Hanley et al. 1988). As a result of this NW–SE compression, tension gashes were developed in one set of joints that host the asbestos veins, and these reopened fractures were
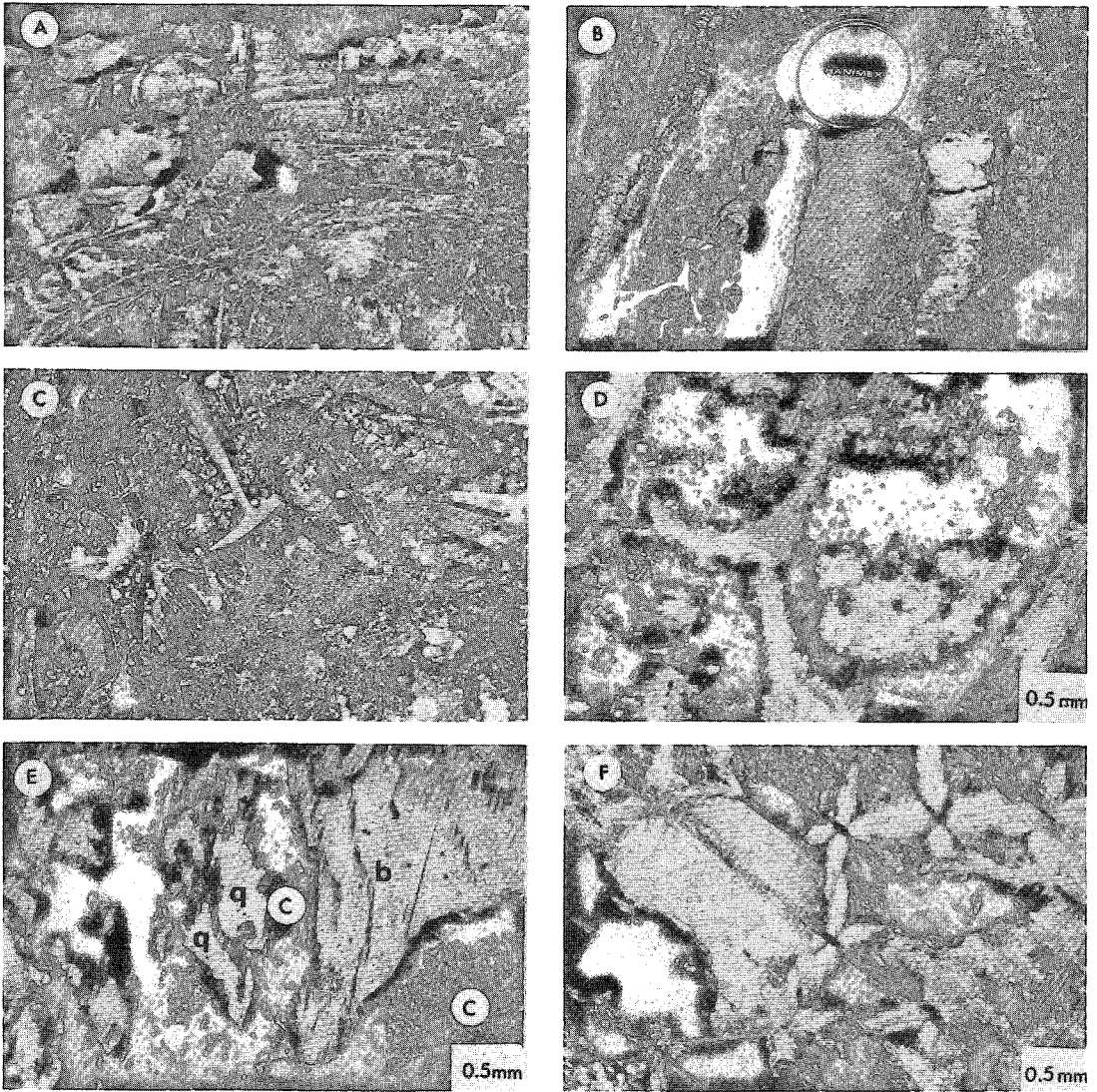
FIG. 4. A. Joint sets in serpentinized and talc–carbonate-altered ultramafic rocks at the No. 2 pit (scale used: black field book and pen). B. Light magnesite vein occupies a tension gash (at right), and light-colored magnesite replaces chrysotile asbestos vein (at left) in talc–carbonate-altered serpentinite. C. Fracture pattern resembling "polyhedral joints" developed in carbonate alteration of chrysotile asbestos in anastomosing veins. D. Olivine is replaced by mesh-textured lizardite (dark, fine-grained) and carbonate + talc (light rim on lizardite aggregates). E. Quartz (q) and carbonate (c) replacing serpentine bastite (b). F. Radiating rosettes of antigorite nucleating from magnesite in the NW-oriented cleavages. Dark area at left is another magnesite grain (at extinction).

filled by carbonate veins up to 8 to 10 cm in width (Fig. 4B). Slip-surface picrolitic serpentine (apple green, slickenside serpentine: field term) occurs between the vein carbonate and the walls of the fractures that host the veins. The effect of the motion on the fault is visible in thin section as fragmentation and offsets of relict chrysotile veins.

The joints that host the asbestos veins were conduits for the CO_2-bearing metasomatizing fluid. This is evident from the preferential alteration of the chrysotile asbestos veins to carbonate, relative to the lizardite and chrysotile in the enclosing wallrock. The intensity of carbonate alteration appears to increase from north to south; this is

probably a function of the distance between the joints, which also decreases from north to south. Weathering of the anastomosing chrysotile asbestos veins that have been replaced by carbonate gave rise to irregular ridges on the rock surface, and produced a pattern that superficially resembles polyhedral joints, similar to those in komatiite flow-tops (Fig. 4C). These ridges are commonly wider than the original vein, as they include carbonate-replaced wallrock.

MINERALOGY AND TEXTURE

The presence of mesh-textured *lizardite*, which formed after cumulus olivine (Wicks *et al.* 1977) in the Slade–Forbes asbestos mine, suggests that the original rock was a dunite. Magnetite was a common product of the serpentinization of olivine. The presence of some primary pyroxene is indicated by large plates of lizardite, pseudomorphic after pyroxene (Wicks & Whittaker 1977). In some lizardite plates, fine, rod-shaped grains of magnetite lie along the cleavage traces. One- to 2-cm-wide veins of chrysotile asbestos, with elongate grains of magnetite between fibers, cross-cut olivine and pyroxene that had been replaced by lizardite.

The addition of CO_2 to the rock caused the breakdown of serpentine minerals to *talc, magnesite ± dolomite + quartz* in two stages. The first metasomatic event produced minor fine-grained quartz and magnesite after lizardite plates (Fig. 4E), a magnesite + talc rim on the mesh-textured lizardite (Fig. 4D), and partial replacement of some chrysotile asbestos veins by magnesite. The magnesite that was identified as belonging to the first generation is relatively pure $MgCO_3$ ($0.005 < X_{Fe} < 0.007$) (Table 1). The first-generation magnesite

is corroded and rimmed by second-generation magnesite. The second event was more pervasive, and produced coarse-grained magnesite ± dolomite up to 4-5 mm in diameter, and coarse-grained talc, up to 2 mm across. Both talc and the carbonates occur in veins, and as a replacement of the fragmented veins of asbestos. Some of the carbonate grains are strained and have undulose extinction. In the second-generation magnesite, X_{Fe} has a value between 0.04 and 0.07 (Table 1). The chemical composition of selected grains of serpentine and talc is shown in Table 2.

Coarse-grained blocky *magnetite* grains (Table 2) are a common product of serpentinization, but decrease in abundance and size in the talc–carbonate rocks. *Quartz* is rare relative to talc and magnesite, and has poorly defined grain-boundaries. It occurs with lizardite plates (Fig. 4E), or is interstitial to magnetite. It is associated with first-generation magnesite, with which it appears to have reacted to produce talc.

Rutile is a minor phase within and close to the north–south shear zone. It coexists with small crystals of hematite. Rutile appears to have formed from the breakdown of magnetite.

The final episode of alteration observed at Slade–Forbes was the breakdown of carbonate and talc to interpenetrating-texture *antigorite*. The

TABLE 2. REPRESENTATIVE COMPOSITIONS OF SELECTED MINERALS FROM THE SLADE-FORBES DEPOSIT

	Srp	Srp	Srp	Srp	Srp	Tlc	Tlc	Mag	Mag
Sample	64-4	40-6	81-1	81-2	81-3	40-4	34-2	63-3	31-1
SiO₂	41.57	41.58	42.49	43.16	41.86	63.33	61.54	0.10	0.09
TiO₂	0.00	0.00	0.04	0.03	0.11	0.00	0.05	0.02	0.15
Al₂O₃	1.88	0.99	1.32	0.62	0.38	0.12	0.10	0.06	0.06
Cr₂O₃	0.31	0.09	0.27	0.22	0.08	0.07	0.07	0.15	0.60
Fe₂O₃								69.54	69.04
FeO	3.77*	3.09*	4.24*	3.01*	3.35*	0.92*	0.83*	31.29	31.08
NiO	0.35	0.59	0.42	0.30	0.33	0.24	0.33	0.00	0.00
MgO	37.81	38.57	38.80	37.45	39.13	31.45	31.37	0.17	0.08
TOTAL	85.69	84.61	87.58	84.79	85.24	96.13	94.29	101.33	101.08
			Structural formulae						
Si	1.985	2.003	1.991	2.069	2.007	7.998	7.911	0.020	0.021
Ti	0.000	0.000	0.002	0.001	0.005	0.000	0.005	0.000	0.026
Al	0.106	0.056	0.073	0.012	0.021	0.018	0.015	0.022	0.019
Cr	0.011	0.003	0.010	0.003	0.003	0.007	0.008	0.030	0.107
Fe³⁺								11.910	11.847
Fe²⁺	0.151*	0.124*	0.166*	0.120*	0.134*	0.097*	0.090*	5.961	5.024
Ni	0.014	0.011	0.016	0.012	0.013	0.009	0.034	0.000	0.000
Mg	2.691	2.769	2.709	2.671	2.796	5.919	6.010	0.060	0.027

* total iron expressed as FeO. Srp serpentine, Tlc talc, Mag magnetite. The Tracor Northern Matrix Correction Program was used for ZAF matrix corrections; accelerating voltage 15 kV, take-off angle 40°, and specimen current 5 nA. Standards used: olivine and jadeite for talc; olivine for serpentine; magnetite for magnetite; calcite and hornblende for carbonate. The structural formulae are based on 7 atoms of oxygen for serpentine, 22 for talc, and 24 for magnetite. Oxides are reported in wt.%.

TABLE 1. REPRESENTATIVE COMPOSITIONS OF MAGNESITE FROM THE SLADE-FORBES DEPOSIT

Sample	24-2	24-1	24-4	24-3	63-2	63-2	40-2	40-1
FeO wt%	0.54	5.31	0.60	5.92	0.53	3.49	0.42	3.59
MnO	0.45	0.05	0.63	0.51	0.03	0.10	0.70	0.06
MgO	47.27	44.09	46.63	43.57	48.26	46.49	46.63	44.90
CaO	0.05	0.10	0.00	0.05	0.05	0.09	0.02	0.10
TOTAL	48.31	49.55	47.86	50.05	48.87	50.17	47.79	48.65
		Structural formulae on the basis of 6 atoms of oxygen						
Fe	0.012	0.126	0.014	0.140	0.012	0.081	0.010	0.084
Mn	0.010	0.001	0.014	0.012	0.001	0.002	0.010	0.001
Mg	1.975	1.890	1.962	1.845	1.985	1.914	1.973	1.910
Ca	0.001	0.003	0.009	0.001	0.001	0.003	0.000	0.003
X_Fe	0.006	0.063	0.007	0.071	0.006	0.070	0.005	0.043

X_{Fe} = Fe/(Fe+Mg).

elongate blades of antigorite occur as small rosettes in the center of magnesite grains (Fig. 4F), and they are most common along cleavage traces, generally radiating outward from the cleavage traces of the carbonate.

STUDY OF THE FLUID INCLUSIONS

The data-set for primary fluid inclusions in the Slade–Forbes ultramafic rocks is relatively small, as the size of the inclusions is generally less than 5 μm; as a result, phase changes during freezing and heating are difficult to observe. Reliable microthermometric measurements were obtained from thirty primary fluid inclusions in coarse-grained second-generation carbonates. The inclusions have an equant, regular shape (Figs. 5A, B) and consist of a vapor (bubble) and a fluid phase. Single inclusions are isolated or occur in small clusters. The criteria of Roedder (1984) were used to distinguish between primary and secondary fluid inclusions.

The fluid composition was determined from heating and freezing measurements. Inclusions were cooled with liquid N_2 below 120°C, in order
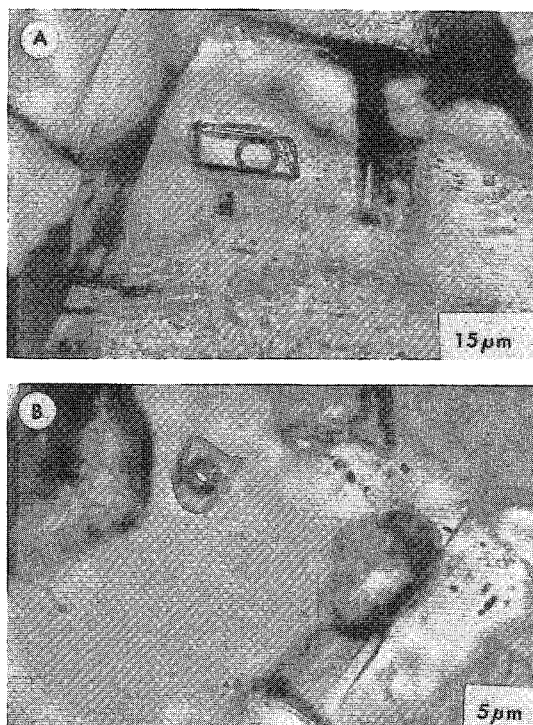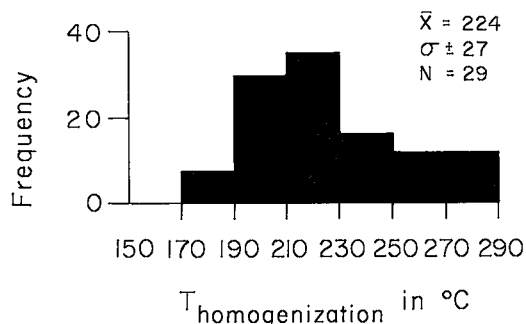

FIG. 6. Frequency histogram of temperatures of homogenization of primary fluid inclusions.

to determine the presence of CO_2. Freezing of the fluid between –40° and –50°C, and the lack of double freezing (clathrate) when the inclusions were cooled to –120°C, indicate that the fluid does not contain an appreciable amount of CO_2. The absence of clathrate suggests that CO_2 is less than 0.85 mole % (Hedenquist & Henley 1985). The first appearance of liquid at the eutectic point (T_e) during the heating of ice (between –21° and –22°C) suggests that the composition of the liquid is in the system H_2O–NaCl or H_2O–NaCl–KCl (Crawford 1981). The salinity of the fluid was calculated from (T_m), the temperature of final melting of the ice, using the equation of Potter et al. (1978). The range of final melting of ice, –0.8° to –3.1°C, gives a salinity range of 0.9 to 5.7, and mean salinity of 3.3 ±0.9 wt.% NaCl equivalent (Fig. 6).

The temperature T_h at which the vapor bubble disappears into the liquid represents the homogenization temperature of the fluid inclusions. Values of T_h show a relatively wide range: 184° to 285°C ($\bar{x}$ = 224° ± 27°C) (Fig. 7). Fluid

FIG. 5. A. Large primary fluid inclusion in carbonate. B. Primary fluid inclusion of typical size in carbonate.
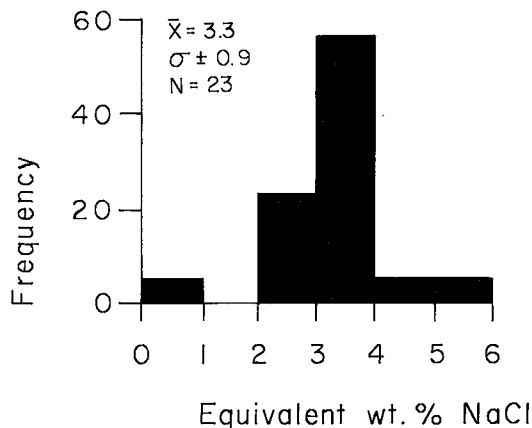

FIG. 7. Frequency histogram of equivalent weight % NaCl in primary fluid inclusions.

inclusions were selected only from second-generation carbonates; therefore, the measurements obtained are representative of the second episode of CO_2 metasomatism. One large, optically homogeneous grain of magnesite contains three primary fluid inclusions that show decreasing temperatures (258°, 225° and 202°C, respectively) from core to rim.

H_2O–CO_2 phase separation was not observed in the fluid inclusions, nor was there evidence for boiling, as the gas:liquid ratio is comparable in all the inclusions studied. Therefore, the T_h must be corrected for pressure in order to estimate the temperature of formation or of filling (T_f). An indirect estimate of pressure is possible from the assemblage of coexisting minerals. Lizardite and chrysotile are the most common serpentine minerals at Slade–Forbes, suggesting that the temperature of the CO_2-bearing fluid did not exceed 350°C, above which the lizardite and chrysotile would have been completely replaced by the high-temperature polymorph *antigorite* (Evans *et al.* 1976, Chernosky *et al.* 1988, O'Hanley *et al.* 1989). If the maximum temperature of formation is taken to be 350°C, using the H_2O–NaCl isochore of Crawford (1981), a pressure correction of 1 kbar to the maximum T_h (285°C) will yield the maximum temperature of formation (350°C) permitted by the stable serpentine minerals. Applying the 1 kbar pressure correction to the mean T_h, 224°C, yields a mean temperature of formation of 300°C for second-generation carbonate, and a range of 250°–350°C.

STABLE ISOTOPE STUDY

The $\delta^{18}O$ and $\delta^{13}C$ values of magnesite were determined from eight representative specimens (Table 3). Figure 8 shows that both parameters have a relatively wide range; $\delta^{18}O$ values range from +10 to +14‰ ($\bar{x}$ = +12.4 ± 1.2‰), and $\delta^{13}C$ values, from –0.7 to –4.8‰ ($\bar{x}$ = –2.5 ± 1.3‰). The $\delta^{18}O$ composition of the fluid was calculated using the dolomite–water fractionation curve of Northrop &
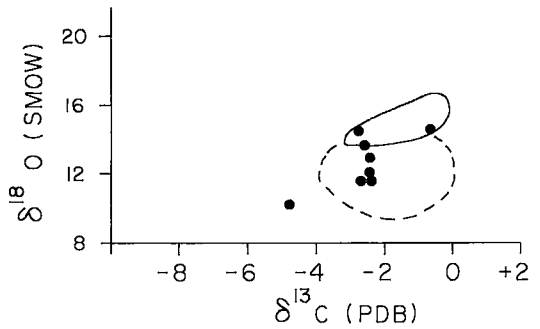

FIG. 8. Oxygen and carbon isotopic composition of magnesite. Reference standards used: SMOW for oxygen, PDB for carbon. Filled circles: this study; solid line represents basalts from the Timmins area (Fyon *et al.* 1980), and dashed line represents komatiites from the Timmins area (Fyon *et al.* 1980).

Clayton (1966). Assuming a mean temperature of formation of 300°C (1 kbar), the isotopic composition of the fluid in equilibrium with the carbonate was calculated. It is important to note here that the specimens selected for oxygen isotope analysis and microthermometric measurements were completely recrystallized during the second event of CO_2 metasomatism. Therefore, assuming equilibration, both the composition of the fluid and the temperature of formation are representative of the second event of carbonate metasomatism. The calculated $\delta^{18}O$ value of the water in equilibrium with carbonate, using the 1 kbar pressure correction for the mean T_h obtained from fluid inclusions (300°C), is +2.4‰, and the range is +0.9 to +3.5‰. Although this isotopic composition is close to somewhat modified seawater values, it has been demonstrated by Kyser & Kerrich (1990) that in tectonically active regimes, the final oxygen isotopic composition of any given fluid will depend on a number of variables. These variables include degree of evaporation, extent of isotopic and chemical exchange between water and rock, isotopic fractionation, water:rock ratio, oxidation–reduction and fluid mixing. At present, it is not possible to come to conclusions regarding the source of fluid at Slade–Forbes, based on isotopic composition alone, but it is apparent that this isotopic composition is significantly different from those obtained from quartz and carbonate veins at lode gold deposits in the area, which range from +5 to +10‰ (Colvine *et al.* 1984, Roedder 1984).

The $\delta^{13}C$ value of magnesite at Slade-Forbes ranges from –0.7 to –4.8‰. These values are not diagnostic of any one particular environment, as Kerrich (1987) demonstrated that carbon isotope

TABLE 3. STABLE ISOTOPIC COMPOSITION OF MAGNESITE FROM THE SLADE-FORBES DEPOSIT

Sample No.	$\delta^{18}O$	$\delta^{13}C$
ES84-66	+14.07	-2.90
ES84-66b	+11.89	-2.83
ES84-28	+10.05	-4.75
ES84-23	+11.86	-2.27
ES84-23 (duplicate)	+11.89	-2.37
ES84-62	+12.98	-2.28
ES84-31	+12.15	-2.26
ES84-20	+12.93	-0.69

Values are expressed in ‰.

composition of metamorphic fluids, for example, can range from −46 to +4‰, depending on redox conditions during their precipitation. We can only say at present that the $\delta^{13}C$ value of carbonate at Slade–Forbes is comparable to other data reported from the Timmins area, including those obtained at lode gold deposits (Fyon *et al.* 1980, 1981, Kerrich 1987).

GEOCHEMISTRY

Forty samples were collected for major- and trace-element analyses along a cross-section of the No. 2 pit. Eight representative samples from the least and most extensively carbonatized serpentinite are plotted on Figure 3, and the bulk-rock chemical compositions are shown in Table 4. Chemical data for the other samples are available from the Depository of Unpublished Data CISTI, National Research Council, Ottawa, Ontario K1A 0S2.

The low Al_2O_3, TiO_2 and Zr contents support the petrographic observations that the Slade–Forbes rocks are olivine cumulates (Table 2). They are also extremely depleted in *REE* (Fig. 9), a usual feature of cumulus rocks due to the removal of *REE* with the intercumulus liquid. The analytical errors are high for a number of *REE* because they are present in low concentrations; for example, Nd values are not reliable below 5 ppm (M.P. Gorton, pers. comm. 1991). The chondrite-normalized *REE* pattern of both the serpentinized (SF series) and talc–carbonate-altered (84 series) ultramafic rocks are shown in Figure 9. We contend that the *REE* were not mobilized during CO_2 metasomatism. Both the serpentinite and the carbonate-altered equivalents have relatively flat patterns characteristic of ultramafic rocks.

The large outcrop in the No. 2 pit shows a gradation from serpentinized to talc–carbonate-altered equivalents. The gradual progression from serpentinite to talc + magnesite makes this an ideal outcrop for calculations of the addition and

TABLE 4. BULK-ROCK CHEMICAL COMPOSITION OF SERPENTINITES, SLADE-FORBES DEPOSIT

Sample	84-32	84-45B	84-66	84-60	84-31	84-25	84-46	84-24
SiO_2 (wt.%)	45.10	43.20	36.40	36.10	38.30	33.50	28.10	28.20
TiO_2	0.04	0.04	0.06	0.05	0.05	0.06	0.03	0.04
Al_2O_3	0.62	0.59	0.54	0.54	0.73	0.98	0.44	0.72
Fe_2O_3*	6.17	6.02	5.20	5.92	6.04	6.05	6.59	4.60
MgO	34.50	35.30	38.70	37.80	35.00	36.20	38.50	38.30
CaO	0.02	0.04	0.31	0.05	0.06	0.05	0.07	0.13
MnO	0.01	0.04	0.04	0.09	0.07	0.07	0.13	0.13
Na_2O	0.05	0.08	0.03	0.07	0.03	0.04	0.04	0.05
P_2O_5	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01
LOI	12.60	14.10	17.90	19.60	19.70	23.40	26.20	28.50
TOTAL	99.12	99.42	99.19	100.23	99.99	100.36	100.11	100.68
CO_2	6.00	6.50	9.10	13.40	15.70	19.70	22.40	25.80
s.g.	2.56	2.79	2.76	2.80	2.87	2.90	2.85	2.94
Co ppm	59	57	68	72	44	42	66	48
Cu	2	2	2	2	1	1	2	1
Zn	12	11	17	18	15	11	14	15
Pb	8	12	20	16	18	12	18	18
Zr	3	1	2	1	4	4	1	2
Ni	3260	2968	2501	3007	2961	2617	3193	2226
Cr	1356	1668	598	927	1329	1356	972	903

* Total Fe is expressed as Fe_2O_3; CO_2 was determined by wet chemistry; LOI: loss on ignition, s.g.: specific gravity of rock. Composition determined by X-ray fluorescence spectroscopy.

removal of elements during CO_2 metasomatism. The method of Gresens (1967) was used to calculate the gains and losses of elements and the volume changes that accompanied the recrystallization of serpentine to talc + magnesite. This method requires that the specific gravity of the parent rock (A) and the product rock (B) be known, as well as the chemical compositions of both A and B. In order to solve the equation and compare the chemistry of A and B, it is neccessary to know either the behavior of one component (X_n) or the volume factor (f_v) to solve the equation. In the absence of textural evidence for either one of these parameters, a composition – volume diagram can be constructed. The gains and losses of various components are plotted on this diagram, using a
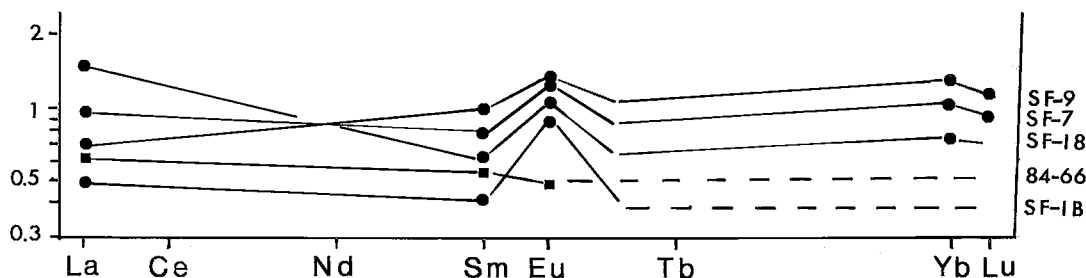

FIG. 9. Chondrite-normalized concentrations of the *REE* in the Slade–Forbes dunite. Filled squares represent the carbonate-altered serpentinite, and filled circles, the relatively unaltered serpentinite. The slope for the *HREE* was obtained by interpolating between Sm and Yb, making an allowance for a Eu anomaly.

series of volume factors (Gresens 1967, Fig. 3). The volume factor to be used in the following calculations is selected at the point where a number of components simultaneously cross the zero gain–loss line. The gains and losses of other components are calculated using the volume factor chosen in the following equation of Gresens (1967):

$$100 \left[f_v \left(\frac{g^B}{g^A} \right) c_n^B - c_n^A \right] = x_n$$

where x_n is the component to be calculated, A is the parent, and B is the altered product, g is the specific gravity of the rock, c_n^B is the weight fraction of an element in rock B, and 100 represents the sum of elements (wt.%) in the rocks analyzed.

One serpentinite (84–32) was selected as the parent (3.0 wt.% CO_2), and seven others, containing from 9.0 to 25.8 wt.% CO_2, were selected as the products. Although Ti, Zr and Al are considered to be relatively immobile during alteration processes, in the Slade–Forbes rocks these elements commonly gave inconsistent volume-factors. The following reasons are suggested for their erratic behavior: a) the concentrations of Ti and

Zr are extremely low (0.02–0.07 wt.% TiO_2, 2–3 ppm Zr), which reflects the cumulus nature of the dunite. The accuracy and precision associated with such low concentrations are poor, and small changes in these concentrations would result in large changes in the calculations, b) the concentration of Al in the samples depends on the distribution of pyroxene in the rock. Because the rocks have been serpentinized, we do not have petrographic control on the original mineral assemblages in the peridotite to select rocks with comparable pyroxene distribution.

Nickel shows the most consistent behavior during CO_2 metasomatism, as it crosses the zero gain–loss line at similar volume-factors for the seven selected samples (range: 0.97 to 1.1, average: 1). Based on the f_v value of 1, we conclude that CO_2 metasomatism of the serpentinite at Slade–Forbes was not accompanied by a change in volume. Therefore, the gains and losses of various components were calculated using a f_v of 1. Figure 10 is a visual representation of the percent gain and loss for individual oxides plotted against increasing CO_2 wt.% in the rock. It appears that CO_2 metasomatism of the serpentinite was accompanied
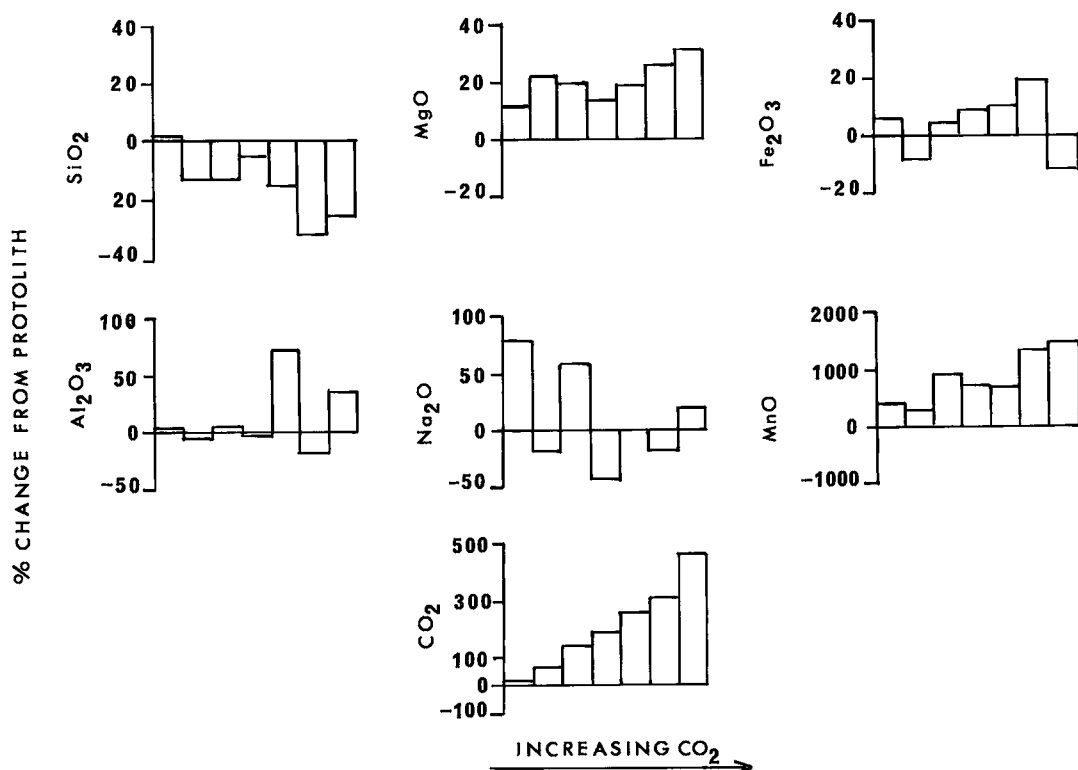

FIG. 10. Gain-loss diagram of chemical components in the Slade–Forbes dunite (after Gresens 1967).

by loss in SiO_2 and gain in MgO and MnO, whereas other components were redistributed. Apparently, the alteration of serpentine to talc and magnesite involved volume-for-volume replacement, but it was not an isochemical process.

DISCUSSION

Textural evidence suggests that during the first episode of CO_2 metasomatism at the Slade–Forbes deposit, a minor rim of talc + magnesite formed on the serpentinized olivine, and minor quartz + magnesite replaced serpentine pseudomorphous after pyroxene. During the second episode, the quartz–magnesite assemblage became unstable and recrystallized to talc, magnesite ± dolomite. Measurements on fluid inclusions, coupled with data on the upper stability of chrysotile, suggest that the temperature regime for the second episode of CO_2 metasomatism was 250°–350°C ($\bar{x}$ = 300°C). Carbonate alteration was followed by the partial breakdown of magnesite to rosette-shaped minor antigorite. This reaction marks the last episode of metasomatism at the Slade–Forbes deposit.

Microthermometric measurements on fluid inclusions show that the CO_2-bearing fluid was H_2O-rich; it contained less than 0.85 mole % CO_2, and the mean salinity of the fluid was 3.3 wt.% NaCl (equiv.). Combining isotopic and geochemical data, we suggest that the calculated $\delta^{18}O$ composition of the fluid in equilibrium with the magnesite (+ 2.4‰), and the addition of Mg to the rocks during CO_2 metasomatism, are consistent with seawater as a possible source. The Mg gain supports the experimental work of Hajash & Chandler (1981), who measured substantial Mg loss from seawater during the interaction of peridotite and seawater. Fixation of Mg in basalts by heated seawater is a common phenomenon in the temperature range of 200°–300°C (Bischoff & Dickson 1975).

The $\delta^{13}C$ values of carbonates at Slade–Forbes (–0.7 to –4.8‰) correspond to values obtained from carbonate-altered komatiite flows in the Timmins area (Fyon et al. 1983). As these isotopic values are not unique to any particular environment, CO_2 may have been derived from various sources. Metamorphic fluids, for example, can have a wide range in $\delta^{13}C$, from –46 to +4‰ (Kerrich 1987), and small positive or negative shifts in $\delta^{13}C$ values can also occur as a result of oxidation–reduction reactions (Kerrich 1987). A positive identification of the CO_2 source is not possible at present; as the talc–carbonate alteration occurs along a north–south-trending shear zone, it seems that the fault acted as a plumbing system for the CO_2-bearing fluid. The ascending fluid migrated through the pile of ultramafic cumulates,

and discharged along the fault. The joints adjacent to the fault acted as a local system of distribution for the fluid.

One of the objectives of this study was to make a quantitative estimate of mass transfer during CO_2 metasomatism of serpentinized ultramafic rocks. Many of the elements were conserved during CO_2 metasomatism; however, the addition of substantial amounts of Mg and loss of Si occurred with increasing degree of alteration. This suggests that on the scale of the outcrop, serpentinized ultramafic rocks behaved as an open system with respect to fluids *and* certain elements during CO_2 metasomatism, although the volume remained constant during chemical exchange.

Finally, carbonate alteration of the Slade–Forbes ultramafic rocks was fault-controlled, as in a number of ultramafic-rock-hosted gold mines in the Abitibi belt, but there are fundamental differences between the two environments, such as fluid composition (mole % CO_2 and $\delta^{18}O$), and alteration assemblages. These differences are discussed in the following section.

Ultramafic rocks hosting lode gold deposits in the Abitibi belt, such as the Dome, Kerr Addison and Aquarius mines, consist of two different alteration assemblages: (a) quartz + carbonate ± fuchsite ± chlorite, and (b) talc + carbonate ± chlorite. Quartz–carbonate alteration of the serpentinite is generally more localized and less extensive than the talc–carbonate. It has been suggested by Schandl (1989) and Schandl et al. (1987) that a quartz–carbonate assemblage in the ultramafic rocks in the Timmins area may form at the locus of hydrothermal activity, whereas talc–carbonate assemblage probably represents a more distal part of the hydrothermal system. This hypothesis is based on previous work on fluid inclusions and stable isotopes in coexisting quartz–carbonate and talc–carbonate assemblages (Schandl 1989). Fluid inclusions in carbonates in quartz–carbonate rocks contain an appreciable amount of CO_2 (2–7 mole %) and show evidence of boiling, whereas in coexisting talc–carbonate rocks, CO_2 content of inclusions is less than 0.85 mole % CO_2 (Schandl 1989). In unmineralized carbonate-altered ultramafic rocks, such as in the Slade–Forbes deposit, the Munro asbestos deposit, Munro Township (Schandl & Wicks 1991), the Allerston deposit in the Whitney Township (Bowen et al. 1976) and the Canadian Magnesite deposit in the Deloro Township (Griffis 1972), the assemblage quartz + carbonate ± fuchsite ± chlorite is absent, and the assemblage talc + carbonate dominates. The absence of a quartz–carbonate assemblage at Slade–Forbes is consistent with low $X(CO_2)$ of the fluid.

At Slade–Forbes, the CO_2-bearing fluid had an

oxygen isotopic composition of $+2.4‰$. Well-documented ore-forming fluids, on the other hand, tend to have a $\delta^{18}O$ range of $+5$ to $+10‰$, and a much higher CO_2 content (Colvine *et al.* 1984, Roedder 1984). $H_2O–CO_2$ phase separation is commonly observed in gold-bearing fluids, but not in fluid inclusions in carbonates at Slade–Forbes. Finally, multiple generations of quartz veins characteristic of gold deposits (*i.e.*, at the Dome mine) are absent at the Slade–Forbes deposit, as are other minerals common at gold mines, such as sericite–fuchsite, chlorite and sulfides.

Although the precise age for carbonate alteration at Slade–Forbes or at lode gold deposits in the area cannot be determined, indirect (textural) evidence suggests that near gold deposits, pervasive CO_2 metasomatism of the ultramafic rocks predated K-metasomatism in the Abitibi belt (Schandl & Wicks 1990). Fuchsite dated from the Hollinger mine by the $^{40}Ar/^{39}Ar$ method (Masliwec *et al.* 1985) gives an age of 2617 ± 6 Ma, and from the Dome mine, 2633 ± 5 Ma. Muscovite from a gold-bearing quartz vein on the Davidson–Tisdale property yields an $^{40}Ar/^{39}Ar$ age of 2615 ± 4 Ma (Hanes *et al.* 1989). In addition, the $^{40}Ar/^{39}Ar$ age of fuchsite from ultramafic rocks at the Kidd Creek massive sulfide deposit is 2618 ± 8 Ma (Smith *et al.* 1992). The comparable ages of micas at various localities suggest widespread K-metasomatism in the area that postdated pervasive carbonate metasomatism. Fuchsite at gold deposits is associated with late quartz and carbonate veins that were emplaced into the quartz–carbonate-altered host rocks. The emplacement of some veins may have been contemporaneous with the precipitation of fuchsite and chlorite, although textural evidence suggests that a number of veins predated K-metasomatism.

We do not have a time constraint on the alteration assemblages at the Slade–Forbes deposit, as fuchsite is absent. Pervasive talc–carbonate alteration of the serpentinite, however, may have been contemporaneous with pervasive CO_2 metasomatism at various gold mines. We contend that this episode of CO_2 metasomatism predated the well-documented fuchsite- and chlorite-bearing alteration assemblages, which are thought to have been contemporaneous with gold mineralization in the Abitibi belt (Masliwec *et al.* 1985, Corfu & Muir 1989, Wong *et al.* 1991, Jemielita *et al.* 1990, Schandl *et al.* 1990b), and predated the emplacement of late quartz and carbonate veins, some of which are associated with mineralization. The absence of the quartz–carbonate $\pm$ fuchsite assemblage at Slade–Forbes, the absence of multiple-generation quartz veins, and the difference in mole % CO_2 and oxygen isotopic composition of the fluid compared to fluids at gold deposits imply

that the depositional environment at Slade–Forbes was significantly different from that of the gold-bearing carbonate-altered ultramafic rocks in the area.

SUMMARY AND CONCLUSIONS

The tectonic and metamorphic history of the ultramafic rocks is well preserved at the Slade–Forbes deposit. By integrating field observations, mineralogical, petrological and geochemical information and fluid inclusion and stable isotope results, the following processes are interpreted to have occurred:

1) The early history of the dunitic body is recorded in the mesh-textured lizardite pseudomorphous after olivine. The first tectonic event, a north–south compression gave rise to the roughly east–west-trending folds in the area. The orientation of three sets of joints in the Slade–Forbes rocks (090°, 340-360°, 310-320°) records this event. Serpentinization was coeval with or postdated the tectonic event, healing the fractures with chrysotile asbestos veins. If the fault was generated during folding, then it was contemporaneous with serpentine. The first episode of CO_2 metasomatism formed minor quartz + magnesite after lizardite, fine-grained magnesite and talc on the grain boundaries of lizardite pseudomorphous after olivine, and minor magnesite between asbestos fibers. The fault was later reactivated by a second tectonic event. A sinistral–reverse motion along the fault indicates a NW–SE compression of the rocks hosting the asbestos veins (O'Hanley *et al.* 1988). As a result, tension gashes developed in the east–west-trending joints, which were filled by magnesite veins up to 10 cm wide. This second event of CO_2 metasomatism was the more pervasive of the two, and formed the assemblage talc + magnesite $\pm$ dolomite. Slickenside-picrolitic serpentine between carbonate veins and the wallrocks, and the fragmented, offset asbestos veins are evidence for motion along the fault.

2) The CO_2 metasomatism that affected the ultramafic rocks was a relatively low-temperature process. Oxygen isotopic compositions of the fluid and the addition of Mg to the rocks during CO_2 metasomatism are consistent with seawater as a possible source of fluid. We suggest that CO_2 metasomatism of the Slade–Forbes rocks was contemporaneous with reactivation of the fault. Heated fluid was discharged through the fault; the joints hosting the asbestos veins were used as channelways. The development of antigorite rosettes at the expense of magnesite marks the end of metasomatism of ultramafic rocks at the Slade–Forbes deposit.

3) The alteration of serpentine to talc +

magnesite±dolomite was not an isochemical process, as is indicated by the loss of Si, addition of Mg and Mn during CO_2 metasomatism; the transformation of serpentine to a talc–carbonate rock involved volume-for-volume replacement.

4) Widespread carbonate alteration in the Abitibi belt commonly is associated with gold mineralization. Some carbonate-altered, ultramafic-rock-hosted deposits, such as at the Dome, Kerr Addison and Aquarius mines, consist of quartz–carbonate and talc–carbonate assemblages. In unmineralized carbonate-altered ultramafic rocks, such as at the Slade–Forbes deposit, however, the quartz–carbonate assemblage is absent, as well as the late quartz and carbonate veins and fuchsite alteration, characteristic of the ultramafic-rock-hosted gold deposits. The differences in alteration assemblages and fluid composition [$\delta^{18}O$, $X(CO_2)$] between the mineralized and unmineralized ultramafic rocks suggest two significantly different environments of deposition. If CO_2 metasomatism at Slade–Forbes was contemporaneous with early pervasive CO_2 metasomatism at mineralized localities in the area, the absence of extensive quartz–carbonate alteration of the wallrock suggests that Slade–Forbes could represent the distal part of a hydrothermal system.

REFERENCES

BARNES, S.J. & GORTON, M.P. (1984): Trace element analysis by neutron activation with a low flux reactor (SLOWPOKE II): results for international reference rocks. *Geostandards Newsletter* **8**, 17-23.

BISCHOFF, J.L. & DICKSON, F.W. (1975): Seawater-basalt interaction at 200°C and 500 bars: implications for origin of sea-floor heavy-metal deposits and regulations for seawater chemistry. *Earth Planet. Sci. Lett.* **25**, 385-397.

BOWEN, P., MIDDLETON, R.S. & FISCHER, S. (1976): Geological report on the Allerston property,

Whitney Township: unpublished report on Rosario Resources Corp. *Assessment Files, Ontario Geol. Surv., Toronto, Ontario.*

CHERNOSKY, J.V., Jr., BERMAN, R.G. & BRYNDZIA, L.T. (1988): Stability, phase relations, and thermodynamic properties of chlorite and serpentine-group minerals. *In* Hydrous Phyllosilicates Exclusive of Micas (S.W. Bailey, ed.). *Rev. Mineral.* **19**, 295-346.

CHIDESTER, A.H. (1962): Petrology and geochemistry of selected talc-bearing ultramafic rocks and adjacent country rocks in north-central Vermont. *U.S. Geol. Surv., Prof. Pap.* **345.**

COLVINE, A.C., ANDREWS, A.J., CHERRY, M.E., DUROCHER, M.E., FYON, A.J., LAVIGNE, M.J., JR., MACDONALD, A.J., MARMONT, S., POULSEN, K.H., SPRINGER, J.S. & TROOP, D.G. (1984): An integrated model for the origin of Archean lode gold deposits. *Ont. Geol. Surv., Open File Rep.* **5524.**

CORFU, F., KROGH, T.E., KWOK, Y.Y. & JENSEN, L.S. (1989): U/Pb zircon geochronology in the southwestern Abitibi greenstone belt, Superior province. *Can. J. Earth Sci.* **26**, 1747-1763.

_____ & MUIR, T.L. (1989): The Hemlo – Heron Bay greenstone belt and Hemlo Au–Mo deposit, Superior Province, Ontario, Canada. 2. Timing of metamophism, alteration and Au mineralization from titanite, rutile and monazite U-geochronology. *Chem. Geol.* **79**, 201-223.

CRAWFORD, M.L. (1981): Phase equilibria in aqueous fluid inclusions. *In* Fluid Inclusions: Applications to Petrology (L.S. Hollister & M.L. Crawford, eds.). *Mineral. Assoc. Can., Short Course Handbook* **6**, 75-100.

EVANS, B.W., JOHANNES, W., OTTERDOOM, H. & TROMMSDORFF, V. (1976): Stability of chrysotile and antigorite in the serpentinite multisystem. *Schweiz. Mineral. Petrogr. Mitt.* **56**, 79-93.

_____ & TROMMSDORFF, V. (1970): Regional metamorphism of ultramafic rocks in the central Alps: parageneses in the system CaO–MgO–SiO_2–H_2O. *Schweiz. Mineral. Petrogr. Mitt.* **50**, 481-492.

_____ & _____ (1974): Stability of enstatite + talc, and CO_2-metasomatism of metaperidotite, Val d'Efra, Lepontine Alps. *Am. J. Sci.* **274**, 274-296.

FROST, B.R. (1975): Contact metamorphism of serpentinite, chloritic blackwall, and rodingite at Paddy-Go-Easy Pass, central Cascades, Washington. *J. Petrol.* **16**, 272-313.

FYON, J.A., CROCKET, J.H. & SCHWARCZ, H.P. (1983): Application of stable isotope studies to gold metallogeny in the Timmins – Porcupine camp. *Ont. Geol. Surv., Open File Rep.* **5464.**

———, ———, ———, KABIR, A. & KNYF, M. (1981): Trace element and stable isotope geochemistry of auriferous iron formations in the Timmins area. *Ontario Geosci. Res. Grant Program, Summ. Res., Grant* **49**, 90-107.

———, SCHWARCZ, H.P. & CROCKET, J.H. (1980): Carbon and oxygen geochemistry of replacement carbonates from the Timmins – Porcupine gold camp. *Ontario Geol. Surv., Misc. Pap.* **72-82**.

GOODWIN, A.M. & RIDLER, R.H. (1970): The Abitibi orogenic belt. *In* Basins and Geosynclines in the Canadian Shield (A.J. Baer, ed.). *Geol. Surv. Can., Pap.* **70-40**, 1-30.

GREENWOOD, H.J. (1967): Mineral equilibria in the system MgO-SiO₂-H₂O-CO₂. *In* Researches in Geochemistry (P.H. Abelson, ed.). John Wiley and Sons, New York (542-567).

GRESENS, R.L. (1967): Composition – volume relationships of metasomatism. *Chem. Geol.* **2**, 47-65.

GRIFFIS, R. (1972): Genesis of a magnesite deposit, Deloro Township, Ontario. *Econ. Geol.* **67**, 63-71.

HAJASH, A. & CHANDLER, G.W. (1981): An experimental investigation of high-temperature interactions between seawater and rhyolite, andesite, basalt, peridotite. *Contrib. Mineral. Petrol.* **78**, 240-254.

HANES, J.A., ARCHIBALD, D.A., HODGSON, C.J. & ROBERT, F. (1989): Preliminary ⁴⁰Ar/³⁹Ar geochronology and timing of Archean gold mineralization at the Sigma mine, Val d'Or, Quebec. *Geol. Surv. Can., Pap.* **89-1C**, 135-142.

HEDENQUIST, J.W. & HENLEY, R.W. (1985): The importance of CO₂ on freezing point measurements of fluid inclusions: evidence from active geothermal systems and implications for epithermal ore deposition. *Econ. Geol.* **80**, 1379-1406.

JAHNS, R.H. (1967): Serpentinites of the Roxbury district, Vermont. *In* Ultramafic and Related Rocks (P.J. Wyllie, ed.). John Wiley & Sons, New York (137-150).

JEMIELITA, R.A., DAVIS, D.W. & KROGH, T.E. (1990): U–Pb evidence for Abitibi gold mineralization postdating greenstone magmatism and metamorphism. *Nature* **346**, 831-834.

JOHANNES, W. (1969): An experimental investigation of the system MgO-SiO₂-H₂O-CO₂. *Am. J. Sci.* **267**, 1083-1104.

KERRICH, R. (1987): The stable isotope geochemistry of Au-Ag vein deposits in metamorphic rocks. *In* Stable Isotope Geochemistry of Low Temperature Fluids (T.K. Kyser, ed.). *Mineral. Assoc. Can., Short Course Handbook* **13**, 287-336.

KRETSCHMAR, U. & KRETSCHMAR, D. (1986): Talc, magnesite and asbestos deposits in the Timmins – Kirkland Lake area, districts of Timiskaming and Cochrane. *Ontario Geol. Surv., Study* **28**.

KYSER, T.K. & KERRICH, R. (1990): Geochemistry of fluids in tectonically active crustal regions. *In* Fluids in Tectonically Active Regimes of the Continental Crust (B.E. Nesbitt, ed.). *Mineral. Assoc. Can., Short Course Handbook* **18**, 133-230.

MACDONALD, A.J. & SPOONER, E.T.C. (1981): Calibration of a LINKAM TH 600 programmable heating–cooling stage for microthermometric examination of fluid inclusions. *Econ. Geol.* **76**, 1248-1258.

MASLIWEC, A., YORK, D., KUYBIDA, P. & HALL, C. (1985): The dating of Ontario's gold deposits. *Ontario Geol. Surv., Misc. Pap.* **127**, 223-228.

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

NORTHROP, D.A. & CLAYTON, R.N. (1966): Oxygen isotope fractionation in systems containing dolomite. *J. Geol.* **74**, 174-195.

O'HANLEY, D.S., CHERNOSKY, J.V., JR. & WICKS, F.J. (1989): The stability of lizardite and chrysotile. *Can. Mineral.* **27**, 483-493.

———, SCHANDL, E.S. & WICKS, F.J. (1988): Time relationship between alteration and deformation of the Slade-Forbes asbestos deposit, Deloro Tp., Ontario. *Geol. Assoc. Can. – Mineral. Assoc. Can., Program Abstr.* **13**, 92.

POTTER, R.W., II, CLYNNE, M.A. & BROWN, D.N. (1978): Freezing point depression of aqueous sodium chloride solutions. *Econ. Geol.* **73**, 284-285.

PYKE, D.R. (1982): Geology of the Timmins area, District of Cochrane. *Ontario Geol. Surv., Rep.* **219**.

ROEDDER, E. (1984): Fluid Inclusions. *Rev. Mineral.* **12**.

SANFORD, R.F. (1982): Growth of ultramafic reaction zones in greenschist to amphibolite facies metamorphism. *Am. J. Sci.* **282**, 543-616.

SCHANDL, E.S. (1989): *Talc-Carbonate Alteration of Ultramafic Rocks at the Kidd Volcanic Complex, the Slade-Forbes and Munro Asbestos Deposits in the Abitibi Greenstone Belts, Timmins, Ontario.* Ph.D. thesis, Univ. Toronto, Toronto, Ontario.

———, DAVIS, D.W. & KROGH, T.E. (1990b): Are the alteration halos of massive sulfide deposits syngenetic? Evidence from U-Pb dating of hydrother-

mal rutile at the Kidd volcanic centre, Abitibi subprovince, Canada. *Geology* 18, 505-508.

_____, O'HANLEY, D.S. & WICKS, F.J. (1989): Rodingites in serpentinized ultramafic rocks of the Abitibi greenstone belt, Ontario. *Can. Mineral.* **27**, 579-591.

_____, _____, _____ & KYSER, T.K. (1990a): Fluid inclusions in rodingite: a geothermometer for serpentinization. *Econ. Geol.* **85**, 1273-1276.

_____, SPOONER, E.T.C. & WICKS, F.J. (1987): Carbonate alteration of ultramafic rocks in the Timmins area, Ontario. *Geol. Assoc. Can. – Mineral. Assoc. Can., Program Abstr.* **12**, 86.

_____ & WICKS, F.J. (1990): Similarities between alteration assemblages in some lode gold deposits, and the Kidd Creek deposit, Timmins, Ontario. *Geol. Assoc. Can. – Mineral. Assoc. Can., Program Abstr.* **15**, 117.

_____ & _____ (1991): Two stages of CO_2 metasomatism at the Munro mine, Munro Township, Ontario: evidence from fluid inclusions, stable isotope, and mineralogical studies. *Can. J. Earth Sci.* **28**, 721-728.

SMITH, P.E., SCHANDL, E.S. & YORK, D. (1992): Timing of metasomatic alteration of the Kidd Creek massive sulfide deposit, Ontario, using $^{40}Ar/^{39}Ar$ laser dating of single crystals of fuchsite. *Econ. Geol.* (in press).

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

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

WICKS, F.J., WHITTAKER, E.J.W. & ZUSSMAN, J. (1977): An idealized model for serpentine textures after olivine. *Can. Mineral.* **15**, 446-458.

WONG, L., DAVIS, D.W., KROGH, T.E. & ROBERT, F. (1991): U–Pb zircon and rutile chronology of Archean greenstone formation and gold mineralization in the Val d'Or region, Quebec. *Earth Planet. Sci. Lett.* **104**, 325-336.