The Canadian Mineralogist
Vol. 37, pp. 431-442 (1999)

GEOCHEMISTRY AND TEXTURES OF METASOMATIC COMBS AND ORBICULES IN ULTRAMAFIC ROCKS, NAMEW LAKE, MANITOBA

THOMAS MENARD[1], CHRISTOPHER K. RIDGWAY,
HAROLD H. STOWELL AND C. MICHAEL LESHER[2]

Department of Geology, University of Alabama, Tuscaloosa, Alabama 35487-0338, U.S.A.

Abstract

Metasomatic alteration of ultramafic rocks with igneous orbicular textures from the Namew Lake Ni–Cu mine 60 km south of Flin Flon, Manitoba, has produced metamorphic comb and orbicular textures. These textures occur in a 3-m-thick concordant layer of ultramafic rock that occurs within polymetamorphic Early Proterozoic gneisses. The ultramafic rocks were fractured into blocks and altered during amphibolite-facies metamorphism, producing talc + dolomite in the cores of blocks, a 2-cm-thick layer of tremolite displaying comb textures perpendicular to boundaries of the blocks, and a rind of phlogopite. Trends of gain or loss of elements vary from zone to zone and were controlled in part by the minerals in the zone. For example, the *REE* were removed during the alteration of igneous minerals to talc + carbonate, whereas heavy *REE* were preferentially enriched in the tremolite zone and subsequently depleted in the phlogopite zone. The original igneous orbicules are elliptical, 2–4 cm in size, and have rinds with thin, concentric shells of fine-grained chromian magnetite. The orbicules originally had a core of olivine and pyroxene and a rim of olivine, now partially replaced by metamorphic tremolite, phlogopite, and serpentine. The matrix between these orbicules now contains metamorphic tremolite and phlogopite, and minor serpentine, magnetite, and sulfide. In the centers of some blocks, orbicules and their matrix have been replaced by talc + dolomite. Near the edges of these blocks, however, the cores of orbicules contain talc + dolomite, the rims have radiating tremolite, and the matrix is phlogopite. Thus, the orbicules were apparently a barrier to fluid flow, possibly the consequence of textural differences between the orbicules and the matrix.

Keywords: metasomatism, comb, orbicule, compositional alteration, fluid flow, ultramafic, metapyroxenite, Namew Lake Ni–Cu deposit, Manitoba.

Sommaire

Nous décrivons l'altération métasomatique de roches ultramafiques contenant une texture ignée orbiculaire et provenant du gisement à Ni–Cu de Namew Lake, situé à 60 km au sud de Flin Flon, au Manitoba, et leurs textures métamorphiques en peigne et orbiculaires. Ces textures se trouvent dans une couche ultramafique concordante de 3 m d'épaisseur dans des gneiss polymétamorphiques d'âge protérozoïque précoce. Les roches ultramafiques ont été coupées en blocs et altérées au cours d'un métamorphisme au faciès amphibolite, ce qui a produit talc + dolomite dans le coeur des blocs, un liseré de 2 cm d'épaisseur de trémolite ayant une texture en peigne perpendiculaire à la bordure des blocs, et une couche externe de phlogopite. Les bilans d'enrichissement ou d'appauvrissement d'éléments varient d'une zone à l'autre, et auraient été régis en partie par l'assemblage de minéraux. Par exemple, les terres rares ont été lessivées au cours de la transformation des minéraux primaires à l'assemblage talc + carbonate, tandis que les terres rares lourdes ont été enrichies de préférence dans la zone à trémolite et par la suite appauvries dans la zone à phlogopite. Les orbicules originelles sont elliptiques, entre 2 et 4 mm de diamètre, et ont des bordures faites de minces couches concentriques de magnétite chromifère à grains fins. Les orbicules contenaient à l'origine un coeur d'olivine et de pyroxène et une bordure d'olivine, maintenant partiellement remplacés par l'assemblage trémolite + phlogopite + serpentine. La matrice entre ces orbicules contient maintenant trémolite et phlogopite, et un peu de serpentine, magnétite, et sulfures. Au centre de certains blocs, les orbicules et leur matrice ont été remplacées par l'assemblage talc + dolomite. Près des bordures de ces blocs, par contre, les coeurs des orbicules contiennent talc + dolomite, les bordures contiennent des amas fibroradiés de trémolite, et la matrice est phlogopitique. Les orbicules auraient donc créé une entrave au flux de fluide, peut-être à cause de différences texturales entre les orbicules et la matrice.

(Traduit par la Rédaction)

Mots-clés: métasomatose, texture en peigne, orbicule, altération de la composition, flux de fluide, ultramafique, métapyroxénite, gisement de Ni–Cu de Namew Lake, Manitoba.

---

[1] Present address: Department of Geology and Geophysics, University of Calgary, Calgary, Alberta T2N 1N4. *E-mail address*: tmenard@geo.ucalgary.ca

[2] Present address: Mineral Exploration Research Centre, Department of Earth Sciences, Laurentian University, Sudbury, Ontario P3E 2V7.

Introduction

Igneous comb and orbicular textures are uncommon, but are well documented (Knopf 1908, Eskola 1938, Leveson 1966, Moore & Lockwood 1973, Papunen 1985, Yazgan & Mason 1988, Symes & Bevan 1987, Sinclair & Richardson 1992, Ort 1992). Although there was some debate about the origin of combs and orbicules, including a possible metamorphic or metasomatic origin (Leveson 1963, Thompson & Giles 1974), current opinion is that they reflect igneous crystallization processes (Enz *et al.* 1979). In this paper, we describe ultramafic rocks from Namew Lake, Manitoba, that originally contained igneous orbicules. The rocks were altered during metasomatism, which produced metamorphic comb textures that cross-cut the igneous orbicules and intensified compositional differentiation of the orbicules. Metasomatic reaction-zones in the ultramafic rocks are used to assess the compositional changes that occurred during metamorphism.

Review of the Literature

Igneous combs and orbicules

Comb textures in igneous rocks occur at the margins of some magma chambers, in which alternating layers of crystals oriented perpendicular or parallel to the chamber wall resemble combs in cross section (Moore & Lockwood 1973, Donaldson 1977, Berg 1980). Comb textures are locally associated with orbicules, in which similar patterns of crystal growth occurred around a core of some material. The cores of the orbicules may be single crystals, rock fragments, or comb fragments, and the type of core material may vary within a group of orbicules (Eskola 1938). Thus, the type of core material was unimportant because it apparently only provided a surface for nucleation. Orbicules have been reported in plutonic igneous rocks ranging from felsic to ultramafic in composition (Leveson 1966, Papunen 1985, Yazgan & Mason 1988, Symes & Bevan 1987, McKinney & Mugler 1992), but are rare in volcanic rocks (Ort 1992).

Combs and orbicules indicate preferential growth of crystals on pre-existing surfaces, in contrast with homogeneous growth throughout a magma chamber. One mechanism that could lead to their formation is superheating of the magma by the addition of fluid or other contaminant that would lower the liquidus temperature of the magma and melt existing crystal nuclei (Donaldson 1977, Vernon 1985, Ort 1992). Subsequent supercooling at the edge of the magma chamber would cause rapid nucleation and growth of crystals on the few available surfaces (Moore & Lockwood 1973, Donaldson 1977).

Metasomatism of ultramafic rocks

Many metamorphosed ultramafic rocks were serpentinized early in their metamorphic history, and reactions during subsequent metamorphism liberated fluids (Evans 1977). In contrast, ultramafic rocks at the Namew Lake mine were not serpentinized during early metamorphism, and the reactions of primary minerals to talc, carbonate, tremolite, and phlogopite progressed only where and when fluids had access (Menard *et al.* 1996). Ultramafic rocks emplaced in crustal settings are usually significantly different in composition than surrounding rocks, and consequently are commonly altered during metamorphism. This alteration produces a series of metasomatic reaction-zones on both sides of the contact, containing mineral assemblages that vary with metamorphic grade (Philips & Hess 1936, Chidester 1962, Jahns 1967, Frost 1975, Evans 1977, Sanford 1982, Dymek *et al.* 1988). Metasomatic alteration of ultramafic rocks has been treated theoretically and experimentally by Korzhinskii (1970), Brady (1977), Balashov & Lebedeva (1991), and Zharikov & Zaraisky (1991). The individual reaction-zones may be monomineralic if local equilibrium is attained and reactions proceed to completion. The production of reaction zones containing only one or two minerals requires and demonstrates transport of most elements.

Geological Setting

The Namew Lake Fe–Ni–Cu sulfide deposit is located 60 km south of Flin Flon, Manitoba (Fig. 1). The Namew Lake mine operated from 1988 to 1993, during which time 2.57 million tonnes of Fe–Ni–Cu sulfide ores grading 1.79% Ni and 0.63% Cu were mined. The ore is hosted by a metapyroxenite sill enclosed in Early Proterozoic orthogneisses, which are nonconformably overlain by Ordovician sediments (Pickell 1987). The geology of the Early Proterozoic basement near Namew Lake has been discussed by Leclair *et al.* (1993) and Menard *et al.* (1996). In addition to orthogneisses and minor metapyroxenites exposed in the mine, intermediate to mafic metavolcanic rocks and minor metasedimentary rocks occur within a few kilometers of the mine below the Ordovician cover. The nearest outcrop of Early Proterozoic rocks is the Flin Flon greenstone belt (Fig. 1), which includes Amisk Group volcanic rocks and Missi Formation sediments (Bruce 1918, Stauffer *et al.* 1975, Bailes & Syme 1989, Stauffer 1990, Syme & Bailes 1993).

The petrology, geochemistry, and structural geology of the Namew Lake deposit have been described by Menard *et al.* (1996). The Namew Lake pyroxenite host unit is a sill 8 to 25 m thick and 250 m long that contains cumulus olivine + orthopyroxene + spinel + sulfide and intercumulus clinopyroxene. The footwall ultramafic sill, *ca.* 200 m structurally below the Namew Lake pyroxenite, is 0.5 to 5 m thick, more than 1200 m long, and contains mineral assemblages similar to the Namew Lake pyroxenite, as well as the comb and orbicular textures described here. The difference in thickness and possible difference in cooling history between

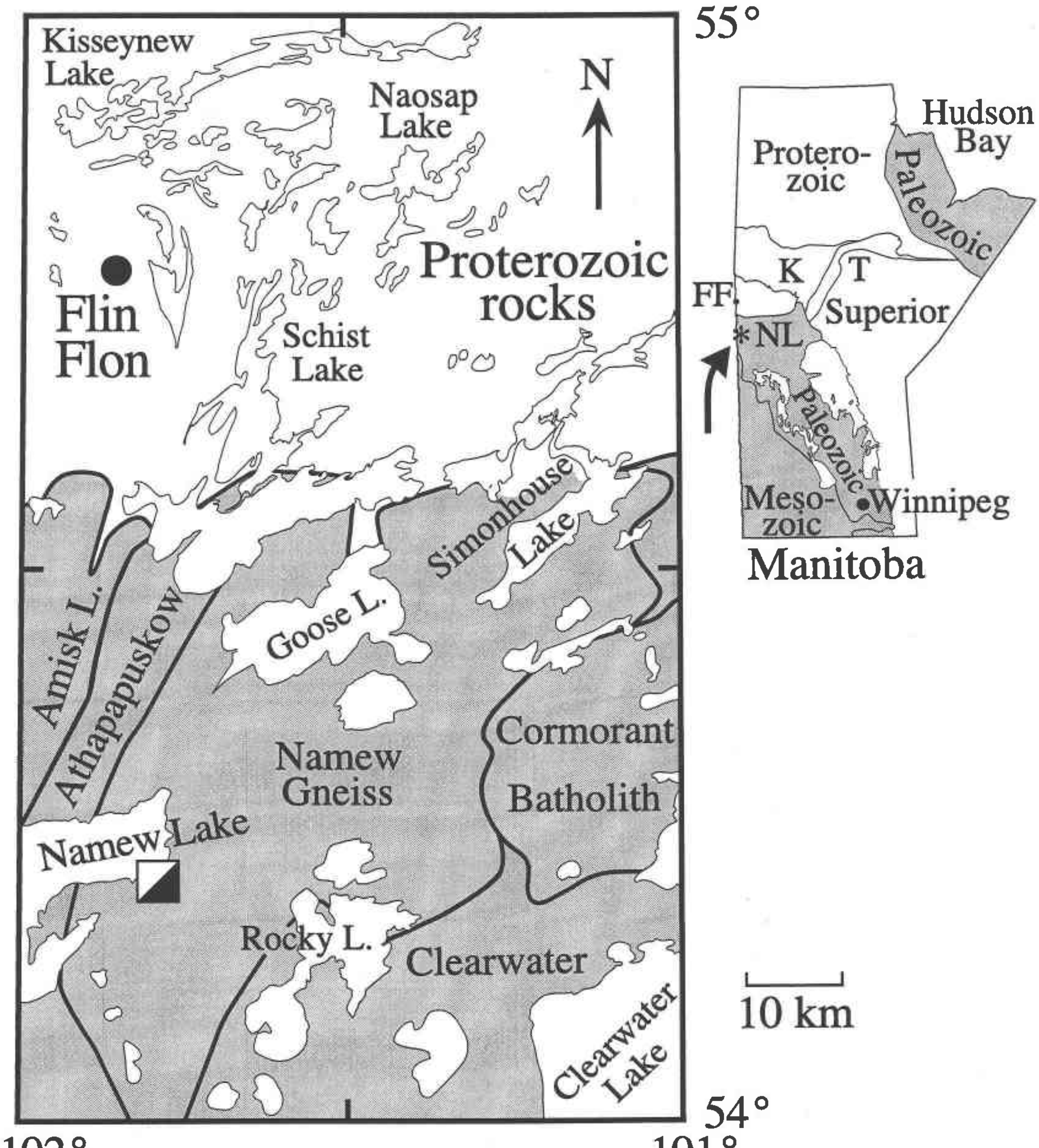


FIG. 1. Location map of the Namew Lake mine in northern Manitoba. Subdivision of the basement into terranes in the area covered by Ordovician sediments (shaded) is from Leclair *et al.* (1993).

these two units may explain why orbicules are found only in the footwall ultramafic sill.

Structure and metamorphism

Five events of deformation and three events of metamorphism have been recognized in the Namew Lake area (Menard *et al.* 1996). The footwall ultramafic sill and sheets of tonalite and granodiorite were emplaced prior to or during D_1 and were deformed into gneisses at upper-amphibolite-facies conditions during D_1. D_2 produced broad, upright synforms, antiforms, and domes of the interlayered tonalitic, granodioritic, and metavolcanic gneisses. D_3 involved boudinage of ultramafic rocks at middle-amphibolite-facies conditions and emplacement of granitic pegmatite dikes. D_4 was a ductile shearing event recognized at the edge of the orebody, and D_5 was a minor event that involved brittle faulting. Some of these events may be phases of a continuous event.

The three metamorphic events each produced distinct assemblages and mineral compositions in the ultramafic rocks (Menard *et al.* 1996). The earliest recognized metamorphism, M_1, produced pargasitic amphibole that partially replaced the igneous minerals during D_1. The second-recorded metamorphism, M_3, occurred during D_3 and produced alteration to talc + carbonate, to tremolite, and subsequently to phlogopite. In the Namew Lake pyroxenite, these stages involved partial replacement of older igneous and metamorphic assemblages, whereas in the footwall ultramafic sill, these stages involved nearly complete replacement, producing a set of monomineralic or bimineralic zones. M_5 metamorphism produced minor serpentine in the ultramafic rocks. Because of the poor preservation of M_1 assemblages, we concentrate here on M_3 assemblages.

Methods

Samples were collected at two locations from underground exposures of the footwall ultramafic sill in the Namew Lake mine. These locations are along strike from one another and differ mainly in the degree of metasomatic alteration. Selected whole-rock samples were analyzed at X-ray Assay Labs in Don Mills, Ontario, by a combination of wavelength-dispersion X-ray-fluorescence spectrometry (for major and minor elements), inductively coupled plasma – optical emission spectrometry (ICP–OES: Li, Sc, Co, Ni, Cu, Zn, Sr, Y, Mo, Ag, Pb), direct-coupled plasma – optical emission spectrometry (DCP–OES: Be, B, V, Ge, Sc), inductively coupled plasma – mass spectrometry (ICP–MS: Ga, rare-earth elements), instrumental neutron activation gamma-ray spectrometry (INAA: Au, Cr, As, Se, Br, Cs, Hf, Ta, W, Th, U), wet chemistry (Hg), atomic absorption spectrophotometry (AAS: Cd, In), and inductive-combustion titration (S). Selected minerals were analyzed using a JEOL 8600/5 electron-probe micro-analyzer at the University of Alabama with 15 to 120 nA specimen current, 15 kV accelerating voltage, and 20 to 60 s count times. Analytical precision at the 1σ level is of the order of 2% for most major elements and 10% for most minor elements. Recent studies (*e.g.*, Xie & Kerrich 1995a, b) have shown that mixed acid dissolutions prior to ICP–MS may not completely dissolve zircon, so the Hf data reported here may be less accurate than the other data. Samples of known composition were submitted to check accuracy of data.

Blocks and Combs

During D_3 deformation and metamorphism, the footwall ultramafic sill was fractured into blocks bounded by dikes and veins, and was variably altered. In location 1 (on the –320 m level), the blocks have a core of talc + dolomite, a 1- to 2-cm-thick rim of comb-textured amphibole, and 1- to 3-cm-thick rinds of phlogopite foliated parallel to the contact (Figs. 2, 3). The zone boundaries migrated toward the center of the blocks, as shown by overgrowth textures at the boundaries between zones (Fig. 3).

TABLE 1. WHOLE-ROCK COMPOSITIONS OF COMBS, ORBICULES, AND THE NAMEW LAKE PYROXENITE, MANITOBA

Analysis	1		2		3		4		5	
	TM94679		TM94760T		TM94760A		TM94760B		TM94517	
	ign orb		Tlc + Crb		Tr		Bt		NL pxite	
	analy	recalc	analy	recalc	analy	recalc	analy	recalc	analy	recalc
SiO_2	40.0	45.3	50.5	55.4	51.9	54.7	39.3	41.24	41.5	48.27
TiO_2	0.12	0.14	0.13	0.14	0.08	0.08	0.64	0.67	0.25	0.29
Al_2O_3	2.39	2.7	3.04	3.33	3.05	3.2	14.9	15.65	6.14	7.15
Cr_2O_3	0.45	0.52	0.29	0.32	0.51	0.54	0.16	0.17	0.32	0.38
Fe_2O_3	11.20	0	9.47	0	7.21	0	12.2	0	12.6	0
MnO	0.15	0.18	0.07	0.08	0.23	0.24	0.19	0.20	0.14	0.16
MgO	31.1	35.2	28.0	30.7	22.5	23.7	18.3	19.2	21.8	25.3
FeO	0	10.9		9.16		6.46		11.5	0	9.26
CaO	3.67	4.17	0.19	0.21	9.58	10.07	0.61	0.64	7.27	8.46
Na_2O	0.35	0.38	0.18	0.2	0.31	0.33	0.41	0.43	0.39	0.45
K_2O	0.33	0.38	0.33	0.36	0.58	0.6	9.70	10.2	0.20	0.23
LOI	7.95	0	5.75	0	2.05	0	0.85	0	3.60	0
P_2O_5	0.11	0.13	0.09	0.10	0.08	0.08	0.10	0.1	0.04	0.05
S	0.30	0	0.12	0	0.21	0	0.01	0	2.33	0
Total	98.1	100	98.2	100	98.3	100	97.4	100	96.6	100
V	61	69.1	42	46.1	42	44.2	133	139	127	147
Co	97	0	84	0	66	0	61	0	194	0
Ni	1360	0	717	0	596	0	414	0	11100	0
Cu	304	0	70	0	250	0	4	0	4420	0
Zn	96	0	79	0	114	0	230	0	65	0
Rb	9	10.2	11	12.1	21	22.1	265	278	3	3.5
Sr	55	62.3	2	2.2	20	21.1	45	47.2	51	59.3
Y	7	7.9	1	1.1	12	12.6	3	3.2	6	7.0
Zr	31	35.1	34	37.3	28	29.5	123	129.0	28	32.6
Nb	5	5.7	6	6.6	5	5.3	32	33.6	2	2.3
La	8.9	10.1	1.5	1.6	2.7	2.8	15.3	16.1	2.4	2.8
Ce	21.2	24.0	3.6	4.0	7.2	7.6	32.6	34.2	5.7	6.6
Pr	2.7	3.1	0.5	0.6	1.1	1.2	3.6	3.8	0.9	1.1
Nd	11.7	13.3	2.4	2.6	6	6.3	13.7	14.4	4.4	5.1
Sm	2.7	3.1	0.5	0.6	2.1	2.2	2.1	2.2	1.2	1.4
Eu	0.66	0.75	0.08	0.09	0.47	0.49	0.46	0.48	0.41	0.48
Gd	2.2	2.5	0.5	0.6	2	2.1	1.6	1.7	1.4	1.6
Tb	0.3	0.3	<0.1	<0.1	0.3	0.3	0.2	0.2	0.2	0.2
Dy	1.3	1.5	0.3	0.3	1.9	2	0.7	0.7	1.4	1.6
Ho	0.22	0.25	<0.05	<0.05	0.35	0.37	0.1	0.1	0.28	0.33
Er	0.6	0.7	0.1	0.1	1	1.1	0.3	0.3	0.8	0.9
Tm	<0.1	<0.1	<0.1	<0.1	0.2	0.2	<0.1	<0.1	0.1	0.1
Yb	0.6	0.7	0.1	0.1	1	1.1	0.3	0.3	0.8	0.9
Lu	0.08	0.09	<0.05	<0.05	0.15	0.16	0.05	0.05	0.1	0.1
Hf	<0.2	<0.2	0.5	0.6	0.6	0.6	5.3	5.6	0.4	0.5
Th	1.2	1.4	0.5	0.6	<0.2	<0.2	3.3	3.5	<0.2	<0.2
U	0.8	0.9	0.6	0.7	<0.1	<0.1	2.9	3.0	<0.1	<0.1

analy = raw analytical values; recalc = values recalculated to 100% oxides; ign orb = orbicular ultramafic rock with igneous textures (Fig. 6); Tlc + Crb = talc + carbonate zone of ultramafic block where it displays comb textures (Fig. 3); Tr = tremolite zone of same block; Bt = biotite zone of same block; NL pxite = least altered Namew Lake pyroxenite (Menard et al. 1986). Concentrations of major elements (oxides, S) are reported in wt.%, whereas those of the trace elements are reported in ppm. LOI: loss on ignition.

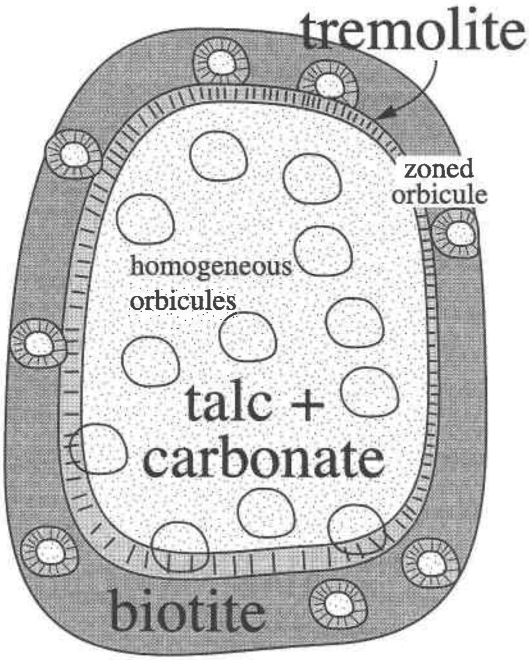


FIG. 2. Sketch of a block of the footwall ultramafic sill showing the distribution of metasomatic reaction zones. The sketch is not to scale: blocks are 1–2 m wide, and orbicules are *ca.* 2 cm wide. The geometry and mineral textures show that these zones progressed in toward the center of the block. Material was transferred in both directions across zone boundaries. Orbicules in the block contain mineral assemblages that vary with position in the block.

Composition of the least-altered footwall ultramafic sill

Compositions of the relatively unaltered footwall ultramafic sill from location 2 (on the –262 m level) and of the metasomatic reaction-zones from location 1 are listed in Table 1. Continuity of the unit and similarity of textures suggest that the original composition of the rock was the same in the two exposures. Loss on ignition (LOI) is highest in samples with the least M_3 amphibole and phlogopite, and reflects abundant M_3 talc or M_5 serpentine (or both). The complete replacement of previous minerals by the M_3 assemblages suggests that M_1 alteration can be safely ignored. The primary igneous compositions were modified by amphibolitization during M_1, steatization, carbonatization, amphibolitization, and biotitization during M_3, and by serpentinization during M_5. The major oxides and minor and trace elements have been recalculated to 100% volatile-free in order to compensate for variable hydration and carbonatization. Comparing the least-altered samples, which best preserve the original igneous composition (Table 1; Menard *et al.* 1996), the footwall ultramafic sill contains lower Si (42–44 wt % SiO_2 recalculated), Ti, Al, Fe, S, Cu, and Ni than the Namew Lake pyroxenite, and higher Mg (33–35 wt% MgO recalculated), Ca, Cr, and Sr.

Compositions of alteration zones

Figure 4 shows compositional changes in the alteration zones as the ratios of the volumes of elements in one assemblage to the volume in the preceding assemblage. The volumes are obtained by dividing the compositions by the density of the sample (Gresens 1967). The diagrams showing enrichment or depletion show apparent relative mobilities among elements, plotted in groups with geochemical similarities. If alteration proceeded at a constant volume, immobile elements would plot at a ratio of 1. On the other hand, if the volume changed during alteration, immobile elements would have ratios greater than 1 (volume decrease) or less than 1 (increase). We make no *a priori* assumption that alteration must have proceeded at constant mass or constant volume, but examine the relative differences among the elements.

Aluminum, Ti, and Zr exhibit relatively constant interelement ratios and are distributed in different phases, so they are interpreted to have been among the least-mobile elements in the alteration zones (Fig. 4). Alteration to talc + carbonate changed Al, Ti, and Zr by a factor of 1 to 1.3 times, suggesting minor loss in volume of up to 23%. Alteration to tremolite changed them by a factor of 0.5 to 0.8 times, suggesting a gain in volume of 25 to 100%. Alteration to phlogopite changed them by a factor of 5 to 9 times, suggesting major loss in volume of 80–89%.

Alteration of the igneous assemblage to talc + carbonate involved gain of Si and loss of Na, Sr, Ca, Cu, Ni, and approximately 90% of the rare-earth elements (*REE*) (Fig. 4A). In addition, the mineral assemblage demonstrates addition of H_2O and CO_2. The *REE* likely were hosted by igneous minerals, which were completely removed, and apparently talc, carbonate, and accessory phases could not accommodate the *REE*. Interpretation of the *REE* as immobile would lead to inference of dramatic changes in mass and volume (and mobility of Al, Ti, and Zr). Instead, it appears that the small amounts of *REE* in the rock were mobilized during metasomatism. Figure 5 shows a chondrite-normalized plot of the *REE* in the various alteration-zones for comparison with other data sets.

Alteration of talc + carbonate to tremolite (Fig. 4B) involved addition of K, Na, Ca, Mn, Cu, Cr, and the *REE* (especially the heavy *REE*). It also involved loss of CO_2, as required by the mineral assemblages. The elements added to the tremolite zone are mainly those that could be incorporated in tremolite. Mobility of Cr is consistent with petrographic observations of chromite

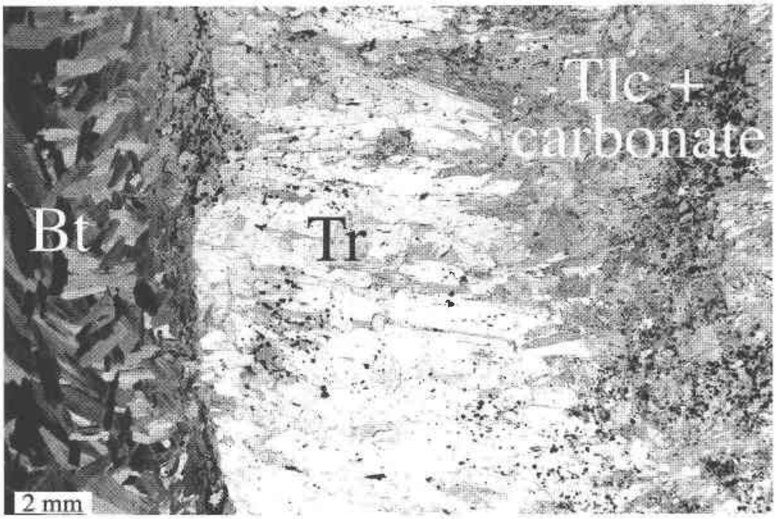


FIG. 3. Photomicrograph of the edge of an ultramafic block displaying talc + carbonate in the core, a zone of tremolite with a comb texture, and phlogopite at the edge. Tremolite is interpreted to have overgrown talc + carbonate, and phlogopite, to have overgrown tremolite. In some other samples, the boundary between zones is gradational. Plane-polarized light.

recrystallization in the M_3 tremolite zone in the Namew Lake pyroxenite (Menard *et al.* 1996).

Alteration of amphibole to phlogopite (Fig. 4C) involved addition of Rb, K, and Ba, and loss of Ca, Mg, Mn, Fe, S, Cu, Ni, and the middle and heavy *REE*. The large loss in volume involved in replacing amphibole by phlogopite (interpreted above) implies substantial dehydration. The elements added to the phlogopite zone are mainly those that could be incorporated in phlogopite. Other elements, especially Ca and the heavy *REE* that had been incorporated in tremolite, were removed. Interpretation of the direction in which elements moved is somewhat uncertain, but an interpretation for some elements is shown in Figure 4D. Material may have been transported through the zones, but was added or removed at reaction fronts, which moved inward toward the center of blocks. CO_2 and H_2O added at the igneous rock – talc + carbonate boundary must have come from outside the system, and CO_2 removed at the talc + carbonate – tremolite boundary was removed from the system. The Cr and middle and heavy *REE* added to form the tremolite zone may have been transported inward from the tremolite – phlogopite boundary. Ca, Sr, Cu, and Zn added to the tremolite zone may have been mobilized from the igneous rock – talc + carbonate boundary, whereas K and Rb were brought in from outside the ultramafic block. This transport of elements in both directions is termed bimetasomatism. K and other alkali metals in phlogopite must have come from outside the system, because they generally have very low concentrations in ultramafic rocks. The Cu and S lost from the ultramafic rocks likely were deposited in chalcopyrite veins observed to cross-cut the gneissosity.

ORBICULES

Orbicules occur in the footwall ultramafic sill in both locations where the sill was exposed in the Namew Lake mine. We distinguish three types of orbicules on the basis of their mineral assemblages: 1) orbicules that preserve some igneous minerals, 2) homogeneous orbicules that contain only metamorphic minerals, and 3) zoned orbicules that contain only metamorphic minerals.

Orbicules with igneous textures

The footwall ultramafic sill at location 2 (on the –262 m level) preserves some igneous minerals and contains randomly distributed orbicules (Fig. 6). The sill is similar in this location to that at location 1 (described above), but displays less intense alteration. The orbicules are ellipsoidal, 2–4 cm in diameter, and have a distinct core, mantle, and rind. The core of the orbicules contains small (0.3 mm) grains of olivine (Fo_{88-90}, 800–1200 ppm Ni) partially altered to M_5 serpentine and M_1 amphibole (see below). The mantle of the orbicules contains olivine (Fo_{88-90}) partially altered to M_5 serpentine. Serpentine preferentially replaced olivine along cracks, but olivine grains are optically con-

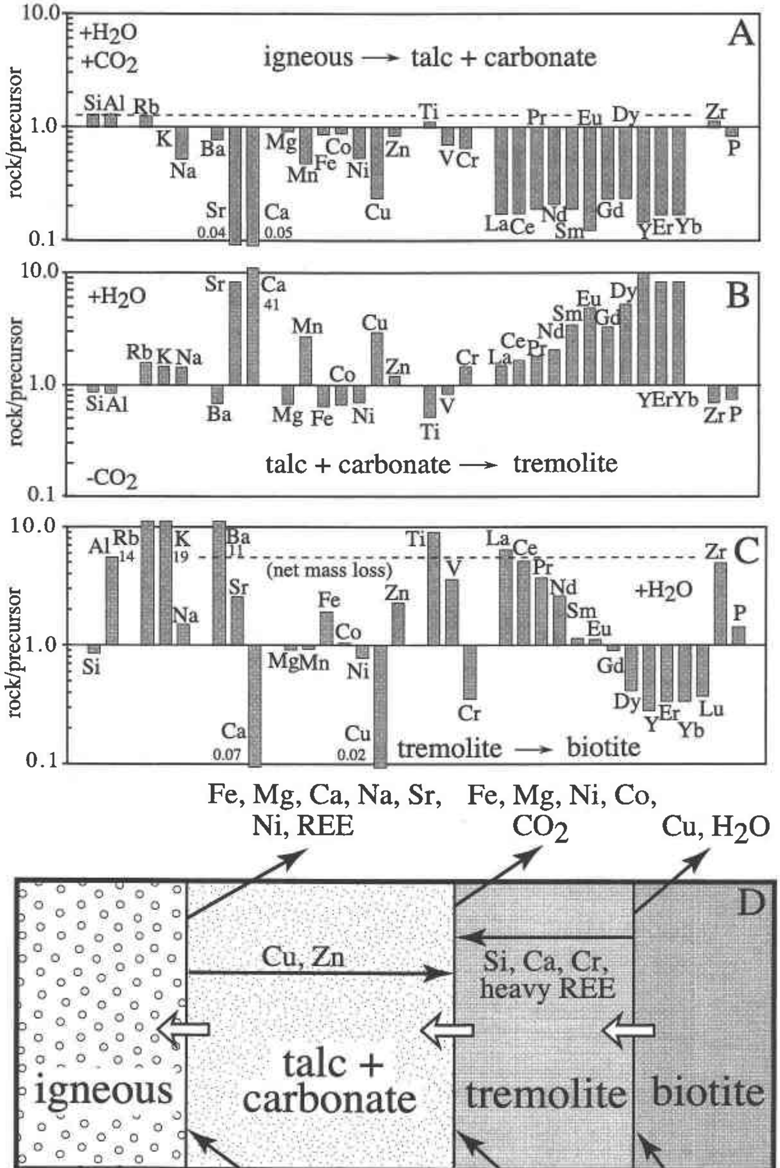


FIG. 4. Enrichment or depletion diagrams showing compositional alteration as ratios of the composition of one zone to that of the previous zone (corrected for density). The elements are grouped by charge and ordered according to decreasing ionic radius. Dashed lines indicate zero change in mass, assuming that Al, Ti, and Zr were immobile. A. Alteration from the least-altered sample to talc + carbonate. B. Alteration from talc + carbonate to amphibole. C. Alteration from amphibole to phlogopite. D. Sketch showing interpreted movement of elements in the alteration zones (not to scale). Material is added or removed (black arrows) from the reaction-zone boundaries, which moved in the direction of the white arrows.

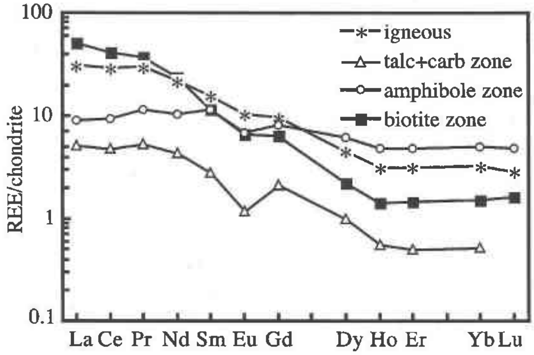


FIG. 5. *REE* normalized to chondrites (Taylor & McLennan 1985) showing loss of *REE* from the inner talc + carbonate zone, addition of heavy *REE* in the amphibole zone, and loss of heavy *REE* in the phogopite zone. The upturn of Lu in the talc + carbonate zone may be within analytical uncertainties associated with the detection limit.

tinuous across the cracks. Thus, olivine grains were originally 3-mm-long crystals arranged radially in the orbicules. Similar textures have been described in igneous orbicules from other locations, in which olivine grains in the orbicule mantle grew outward from the core (Eskola 1938, Thompson & Giles 1974). The rind of the orbicules contains M_5 serpentine and concentric shells of fine-grained chromian magnetite and chromite (Fig. 6). Faint pseudomorphic textures suggest that the serpentine likely replaced olivine that appears to have been oriented tangentially to the edge of the orbicules. Some shells of oxide grains continue around the orbicules, but others merge with each other. The thickest portions of the shells likely indicate that the orbicules grew faster on those sides. The matrix between orbicules consists of metamorphic amphibole + phlogopite with minor chlorite and serpentine and igneous chalcopyrite and magnetite (Fig. 6B).

The amphibole in the orbicule cores and in the matrix contains abundant inclusions of fine-grained magnetite and chromite. Similar amphibole was found in the Namew Lake pyroxenite, where M_1 pargasitic amphibole replaced clinopyroxene that surrounded olivine (Menard *et al.* 1996). Thus, the orbicule core may have been a fragment of pyroxenite prior to metamorphism. Likewise, the phlogopite displays compositions and textures similar to those in M_3 phlogopite in the Namew Lake pyroxenite.

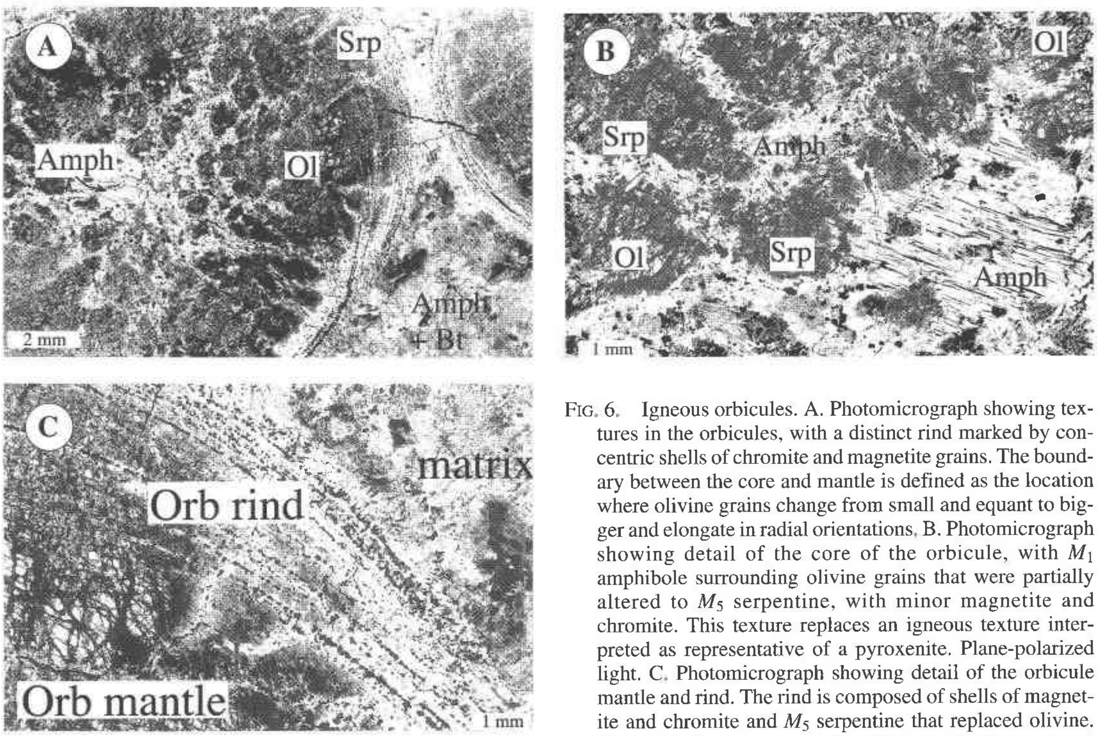


FIG. 6. Igneous orbicules. A. Photomicrograph showing textures in the orbicules, with a distinct rind marked by concentric shells of chromite and magnetite grains. The boundary between the core and mantle is defined as the location where olivine grains change from small and equant to bigger and elongate in radial orientations. B. Photomicrograph showing detail of the core of the orbicule, with M_1 amphibole surrounding olivine grains that were partially altered to M_5 serpentine, with minor magnetite and chromite. This texture replaces an igneous texture interpreted as representative of a pyroxenite. Plane-polarized light. C. Photomicrograph showing detail of the orbicule mantle and rind. The rind is composed of shells of magnetite and chromite and M_5 serpentine that replaced olivine. The matrix is now composed of M_1 tremolite that replaced pyroxene, M_3 phlogopite, and minor chlorite, serpentine, sulfides, and oxides. Plane-polarized light.

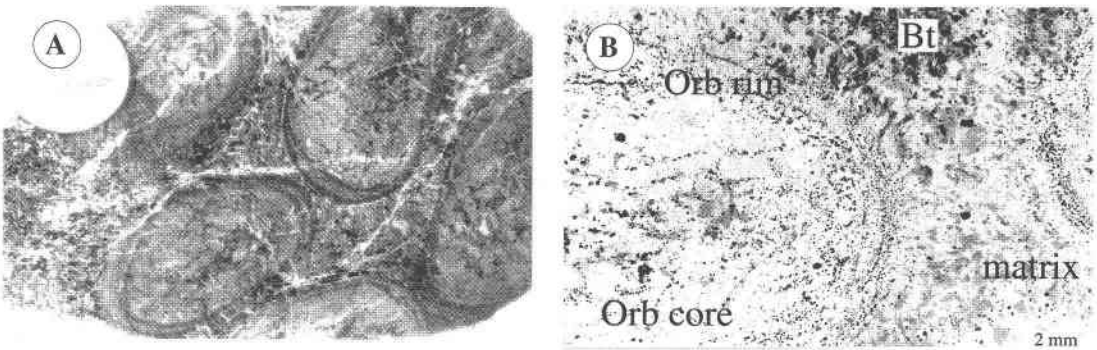
The above features suggest that olivine + chromite in the mantle and rim crystallized on fragments of olivine-bearing pyroxenite. The resulting orbicular textures suggest heterogeneous crystallization and a lack of other sites of crystallization in the magma. Subsequent crystallization of pyroxene and accumulation of minor sulfide between orbicules suggest that crystallization continued at lower temperatures and that sulfide saturation occurred after growth of the orbicules. The origin of the cores of the orbicules remains enigmatic, however. They may be exotic fragments transported from elsewhere by the magma, but this seems unlikely because there are few other ultramafic rocks nearby. Alternatively, they may have crystallized from the same magma that later produced the rest of the footwall ultramafic sill. In the second scenario, an early pulse of flow in the magmatic conduit could have crystallized olivine and then accumulated pyroxene along the walls, and a later pulse could have brought fresh magma that tore fragments off the conduit wall. Cooling of this second pulse would have crystallized olivine + chromite as mantles and rinds of orbicules, followed by pyroxene + sulfides in the matrix.

Homogeneous orbicules

Homogeneous orbicules occur in the centers of blocks at location 1 (Fig. 2). These orbicules and their matrix are composed of talc + dolomite and minor phlogopite, chlorite, calcite, serpentine, oxides, and sulfides (Fig. 7). In some samples, talc was partially replaced by M_5 serpentine. The orbicules are ellipsoidal, 2- to 4-cm in size, and have a rind with thin, concentric shells of fine-grained chromian magnetite. Variations on a millimeter scale of mineral modes and sizes of talc and dolomite grains replace an igneous texture similar to that displayed in the igneous orbicules (Fig. 7). These similarities indicate an igneous origin for all of the orbicules and suggest that the differences in observed assemblages of minerals reflect metasomatic alteration.

Metasomatically zoned orbicules

Compositionally zoned orbicules occur near the edges of the blocks in location 1 (Fig. 8). They contain a core of talc + dolomite and a rim of radiating tremolite within a matrix of phlogopite. Tremolite grains display metamorphic comb textures in the orbicule rims. At the inside of the tremolite zone, tremolite overgrew talc + dolomite, whereas at the outside of the zone, phlogopite partially replaced tremolite, demonstrating that the zone boundaries migrated toward the center of the orbicules. Tremolite grains display minor compositional zoning, with Al, Na, and Fe/(Fe + Mg) decreasing toward the sides of the grains and toward the center of the orbicules, which also suggests growth inward. Grains



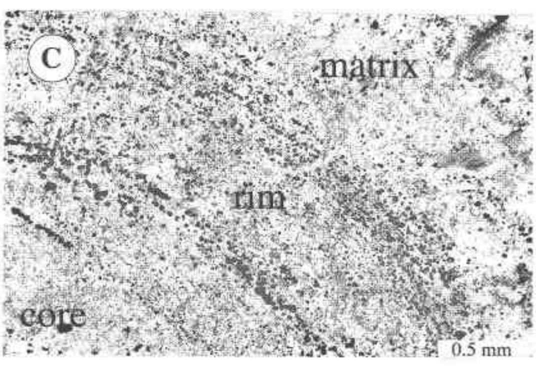


FIG. 7. Homogeneous orbicules. A. Hand sample showing orbicules with talc + carbonate in the core, rim, and matrix. The locations of orbicules are marked by relict shells of magnetite and chromite, similar to those shown in Figure 6. The texture of olivine grains in the rim of the orbicule was replaced by variations in mode of talc and carbonate. Coins for scale is 21 mm in diameter. B. Photomicrograph showing homogeneous orbicules composed of talc + carbonate in a matrix of talc + carbonate. This sample also contains minor M_3 phlogopite. Plane-polarized light. C. Photomicrograph showing detail of the rim of a talc + carbonate orbicule with shells of magnetite and chromite grains. Cross-polarized light.

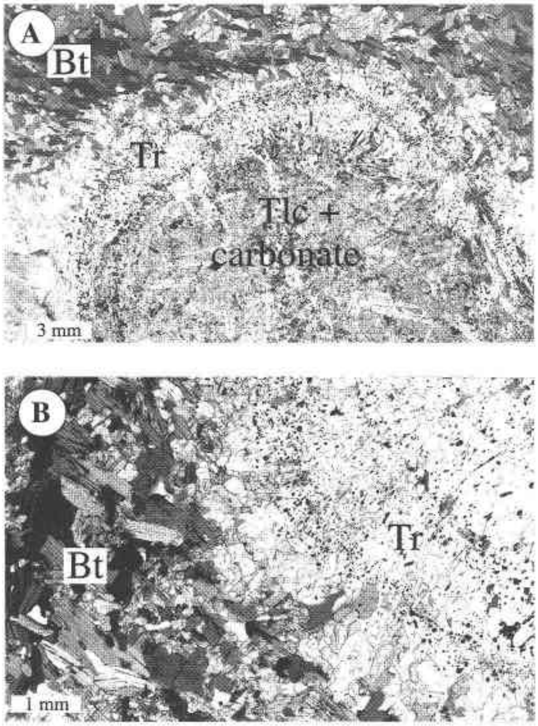


FIG. 8. Compositionally zoned orbicules. A. Photomicrograph of orbicules displaying talc + carbonate in the core, tremolite in the rim in a radial orientation, and phlogopite in the matrix. The geometry indicates that the matrix between orbicules was preferentially replaced first, and metasomatic zones progressed in toward the center of the orbicules. The orbicules apparently formed a barrier to fluid flow. B. Photomicrograph showing detail of the rim of a compositionally zoned orbicule. Relict shells of magnetite and chromite were overgrown by tremolite oriented radially around the orbicule. Plane-polarized light.

of magnetite and chromite included within tremolite preserve the pattern of shells displayed in the previous samples, and are the last remnants of the igneous texture. The matrix is composed of phlogopite in some samples and of phlogopite + amphibole in others, along with minor chlorite, magnetite, and serpentine. The textures strongly suggest that growth of tremolite and subsequent growth of phlogopite produced new compositional variation in orbicules that had been homogeneous.

Pathways of Fluid Flow

The geometry of the alteration zones and the textures of mineral overgrowths show that metamorphic fluid traveled along the edges of blocks and flowed into the blocks from all sides. In a similar manner, the matrix between orbicules was altered to amphibole and subsequently to phlogopite, and these alteration fronts progressively affected the interior of orbicules. Thus, the orbicules appear to have formed a local barrier to fluid flow during metasomatic alteration to amphibole and phlogopite. One possibility is that the shells of oxides formed the barrier, but this seems unlikely because grains of magnetite and chromite that decorate the rims of orbicules are discontinuous, and because they were overgrown by amphibole and incorporated as inclusions without apparent effect on growth of the amphibole. Another possibility is that permeability was controlled by slight differences in the size and shape of grains of talc and carbonate in the orbicules compared with those in the matrix, differences that likely were inherited from the original igneous textures.

Conclusions

Compositions, textures, and mineral assemblages in the footwall ultramafic sill in the Namew Lake mine were extensively modified during metamorphism. After the sill broke into blocks, the edges of blocks served as fluid pathways, and the blocks were metasomatized from the outside inward. Metamorphism produced a series of metasomatic reaction-zones: relatively unaltered ultramafic rock, talc + carbonate, tremolite, and phlogopite. Growth of tremolite in this event produced metamorphic comb-textures, with grains elongate parallel to directions of fluid transport. The metasomatism initially homogenized igneous orbicules, but subsequently produced new compositional zonation in the orbicules, reflecting differences in permeability between orbicules and the matrix.

Metasomatism of the ultramafic rocks involved mobility of nearly all components of the system. The magnitudes and trends of compositional changes varied from zone to zone during the same metamorphic event. The *REE*, for example, were removed from the talc + carbonate zone, whereas the heavy *REE* were preferentially incorporated in the amphibole zone, but not in the phlogopite zone. Although it is possible that the minerals produced in the metasomatic reactions were determined by mobility of a few major elements, the suite of minor and trace elements gained or lost in each zone was controlled in part by the minerals involved. Metasomatism of ultramafic rocks at middle-amphibolite-facies conditions in which alteration in the successive stages was incomplete (such as in the Namew Lake pyroxenite) may be expected to produce compositions that are a combination of those shown here.

Acknowledgements

This work was carried out during geological investigations of the Namew Lake mine funded by Hudson Bay Exploration and Development Company Ltd. and Outukumpu Mines Ltd. We thank the staff of Hudson

Bay Exploration and Development Company for their cooperation and assistance during this project, and in particular David Price, James Pickell, Peter Oshust, and J.J. O'Donnell. This paper has benefitted from reviews by Dugald Carmichael, Rob Kerrich, Graham Nixon, Jack Rice, and an anonymous reviewer.

References

BAILES, A.H. & SYME, E.C. (1989): Geology of the Flin Flon – White Lake area. *Manitoba Energy Mines Geol. Rep.* **GR 87-1**.

BALASHOV, V.N. & LEBEDEVA, M.I. (1991): Macrokinetic model of origin and development of a monomineralic and bimetasomatic zone. *In* Progress in Metamorphic and Magmatic Petrology (L.L. Perchuk, ed.). Cambridge University Press, New York, N.Y. (167-195).

BERG, J.H. (1980): Snowflake troctolite in the Hettasch intrusion, Labrador: evidence for magma mixing and supercooling in a plutonic environment. *Contrib. Mineral. Petrol.* **72**, 339-351.

BRADY, J.N. (1977): Metasomatic zones in metamorphic rocks. *Geochim. Cosmochim. Acta* **41**, 113- 125.

BRUCE, E.L. (1918): Amisk–Athapapuskow Lake district. *Geol. Surv. Can., Mem.* **105**.

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**.

DONALDSON, C.H. (1977): Laboratory duplication of comb layering in the Rhum pluton. *Mineral. Mag.* **41**, 323-336.

DYMEK, R.F., BROTHERS, S.C. & SCHIFFRIES, C.M. (1988): Petrogenesis of ultramafic rocks from the 3800 Ma Isua supracrustal belt, west Greenland. *J. Petrol.* **29**, 1353-1397.

ENZ, R.D., KUDO, A.M. & BROOKINS, D.G. (1979): Igneous origin of the orbicular rocks of the Sandia Mountains, New Mexico: summary. *Geol. Soc. Am., Bull.* **90**, 138-140.

ESKOLA, P. (1938): On the esboitic crystallization of orbicular rocks. *J. Geol.* **46**, 488-485.

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

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.

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

JAHNS, R.H. (1967): Serpentinites of the Roxbury district, Vermont. *In* Ultramafic and Related Rocks (P.J. Wyllie, ed.). John Wiley and Sons, New York, N.Y. (137-160).

KNOPF, A. (1908): Geology of the Seward Peninsula tin deposits. *U.S. Geol. Surv., Bull.* **358**.

KORZHINSKII, D.S. (1970): *Theory of Metasomatic Zoning* (trans. by J. Agrell). Oxford University Press, Oxford, U.K.

LECLAIR, A.D., SCOTT, R.G. & LUCAS, S.B. (1993): Sub-Paleozoic geology of the Flin Flon Belt from integrated drillcore and potential field data, Cormorant Lake area, Manitoba and Saskatchewan. *Geol. Surv. Can., Pap.* **93-1C**, 249-258.

LEVESON, D.J. (1963): Orbicular rocks of the Lonesome Mountain area, Beartooth Mountains, Montana and Wyoming. *Geol. Soc. Am., Bull.* **74**, 1015-1040.

________ (1966): Orbicular rocks: a review. *Geol. Soc. Am., Bull.* **77**, 409-426.

MCKINNEY, D.B. & MUGLER, R.C. (1992): Correlative oscillatory zoning patterns in orbicular plagioclase from Fisher Lake, California. *Geol. Soc. Am., Abstr. Programs* **24**, A261.

MENARD, T., LESHER, C.M., STOWELL, H.H., PRICE, D.P., PICKELL, J.R., ONSTOTT, T.C. & HULBERT, L. (1996): Geology, genesis, and metamorphic history of the Namew Lake Fe–Ni–Cu sulfide deposit, Manitoba. *Econ. Geol.* **91**, 1394-1413.

MOORE, J.G. & LOCKWOOD, J.P. (1973): Origin of comb layering and orbicular structure, Sierra Nevada batholith, California. *Geol. Soc. Am., Bull.* **84**, 1-20.

ORT, M.H. (1992): Orbicular volcanic rocks of Cerro Panizos: their origin and implications for orb formations. *Geol. Soc. Am., Bull.* **104**, 1048-1058.

PAPUNEN, H. (1985): The Kylmakoski nickel–copper deposit. *Geol. Surv. Finland, Bull.* **333**, 264- 273.

PHILLIPS, A.H. & HESS, H.H. (1936): Metamorphic differentiation at contacts between serpentine and siliceous country rocks. *Am. Mineral.* **21**, 333-362.

PICKELL, J.R. (1987): The Namew Lake nickel–copper discovery, Flin Flon, Manitoba. *Geol. Assoc. Can. – Mineral. Assoc. Can., Abstr. Program* **12**, 80.

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

SINCLAIR, W.D. & RICHARDSON, J.M. (1992): Quartz–tourmaline orbicules in the Seagull Batholith, Yukon Territory. *Can. Mineral.* **30**, 923-935.

STAUFFER, M.R. (1990): The Missi Formation: an Aphebian molasse deposit in the Reindeer Lake Zone of the Trans-Hudson Orogeny of North America. *Geol. Assoc. Can., Spec. Pap.* **37**, 121-141.

________, MUKHERJEE, A.C. & KOO, J. (1975): The Amisk Group: an Aphebian (?) island arc deposit. *Can. J. Earth Sci.* **12**, 2021-2035.

SYME, E.C. & BAILES, A.H. (1993): Stratigraphic and tectonic setting of early Proterozoic volcanogenic massive sulfide deposits, Flin Flon, Manitoba. *Econ. Geol.* **88**, 566-589.

SYMES, R.F. & BEVAN, J.C. (1987): The nature and origin of orbicular rocks from near Deshai, Swat Kohistan, Pakistan. *Mineral. Mag.* **51**, 635-647.

TAYLOR, S.R & MCLENNAN, S.M. (1985): *The Continental Crust: its Composition and Evolution*. Blackwell, Oxford, U.K.

THOMPSON, T.B. & GILES, D.L. (1974): Orbicular rocks of the Sandia Mountains, New Mexico. *Geol. Soc. Am., Bull.* **85**, 911-916.

VERNON, R.H. (1985): Possible role of superheated magma in the formation of orbicular granitoids. *Geology* **13**, 843-845.

XIE, QIANLI & KERRICH, R. (1995a): Application of isotope dilution for precise measurement of Zr and Hf in low abundance samples and international standards by ICP–MS. *Chem. Geol.* **123**, 17-27.

________ & ________ (1995b): Optimization of operation conditions for improved precision of Zr and Hf isotope ratio measurement by ICP–MS. *J. Anal. At. Spectrom.* **10**, 99-103.

YAZGAN, E. & MASON, R. (1988): Orbicular gabbro from near Baskil, southeastern Turkey. *Mineral. Mag.* **52**, 161-173.

ZHARIKOV, V.A. & ZARAISKY, G.P. (1991): Experimental modelling of wall-rock metasomatism. *In* Progress in Metamorphic and Magmatic Petrology (L.L. Perchuk, ed.). Cambridge University Press, Cambridge, U.K. (197-245).

Manuscript received March 18, 1997, revised manuscript accepted July 19, 1998.